Oral History of Frank van Diggelen

Interviewed by:
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RinoWe are at the Computer History Museum to record the oral history of Frank van Diggelen. Frank is one of the architects of what we'll call AGPS, and we'll get into that as we go .

van Diggelen: I'm Frank van Diggelen, and I've worked on GPS almost forever. Actually, I have worked in navigation forever. I started off as a teenager in the South African Navy where I went to navigation school and learned navigation. I didn't know back then I was going to end up in the GPS industry, but that's where I've been since I graduated from college. I now work at Google just down the road.

Rino: You said that you were in the South African Navy?

van Diggelen: Yes

Rino: Midshipman?

van Diggelen: Yeah, that's right. I was a midshipman, and then an ensign which is a junior officer after high school, so that was in the early '80s.

Rino: And what were your duties as a midshipman?

van Diggelen: Like I said, I went to navigation school.I was on a small ship, and I was responsible for the navigation of that ship.

Rino: So that was an early introduction to navigation?

van Diggelen: Yeah, it was. I've been doing racing sailing since about five years old. My dad was a sailor, and he taught me. Racing sailing has got its own form of navigation in that you're trying to go faster than the other boats. So you have to be aware of the surroundings, the wind and all that, so it was very natural for me to go from that in the Navy and then it kind of led to a whole career of GPS.

Rino: So how did you transition into technical? Were you interested in math or science or things in the early part of your life?

van Diggelen: Yeah, it was the draft in South Africa. White boys, men, young men got drafted out of high school into the military, and so I was there for two years, and then went to college, which was always the plan, to go to college. And I studied electrical engineering and then went on to a Ph.D. in Cambridge in England, and that's when I met someone who had a GPS company. Her name is Alison Brown, and maybe you'll interview her for this series, too.

Rino: Yes, we'd enjoy that.

van Diggelen: So she recruited me to her GPS company in Colorado, and that brought me to the U.S.

Rino: Okay, there's some big jumps there. Can you tell us a little bit about how you got from South Africa to Cambridge?

van Diggelen: Yes, I did my undergraduate degree in South Africa, and I wanted to carry on and do graduate studies, and Cambridge seemed like the best place to me because of the scientific heritage. So, I applied there, and I got in, and got a scholarship.

Rino: That's the legacy of Isaac Newton, too.

van Diggelen: Definitely. Yes,

Rino: Even Charles Babbage.

van Diggelen: Yes, just a lot of names.

Rino: And then you mentioned how you got recruited when you were at Cambridge when you were doing your Ph.D., finishing your Ph.D., but that got you all the way to Colorado. That seems to be another big jump.

van Diggelen: Yes, that's right. That was a big jump. So Alison Brown, who ran this company called NAVSYS in Colorado Springs, and she still does. It's still there. They do government contracting on GPS, and she'd won a contract with the Coast Guard to do some research in GPS. and she needed someone to do that work, and she was visiting. She went to Cambridge too, and her professor was my professor. She was visiting him.

Rino: So she just happened to be there at the time?

van Diggelen: And I was looking for a job at the time, and my professor knew I was looking for a job. He just called me up in the lab. He said, "Do you want to come talk to someone who's looking for a researcher in GPS?" and he knew I did, of course. So I went up, and lucky for me, I was busy writing up my Ph.D. right then and so I wasn't sleeping very much. I don't think I'd changed clothes in about three days, hadn't shaved, so I looked like the perfect candidate to her. She was like, this is exactly the kind of guy that I want, so that's how I got the job.

Rino: And so what was your major in Cambridge?

van Diggelen: It was control theory.

Rino: Control theory, so that was kind of a lot in the math department.

van Diggelen: Yeah, pretty much math, and that's kind of what took me into-- that's why Alison wanted me on that project, and so that's what brought me out to America and then I stayed.

Rino: So we're all the way from South Africa to Colorado Springs now, and that would've been in the early 1900s? I mean apartheid had just ended about that time.

van Diggelen: Yes, my son would say it's the early 1900s. He's always kidding me about being too old, but 1990s. It was 1992 when I came to Colorado Springs, and that was two years before the first Democratic elections in South Africa.

Rino: It was in 1991, I think, when apartheid officially ended.

van Diggelen: I think it was '94 before they actually had the elections. I remember my parents came and visited us, and it was all in the news so they-- and I don't know if you remember, but it was on the news in the U.S. every night and that was their first time in America. They were like, "Oh, South Africa is really famous."

Rino: Are your parents, still alive?

van Diggelen: My mother is still alive.

Rino: Where is she?

van Diggelen: In Johannesburg.

Rino: She's still there. Is that the area you were mainly raised in?

van Diggelen: Well, we moved around a bit. I was in Mozambique for a while, Durban. I was born in Cape Town which is the really the place to be, and that's where I ended up in the Navy again.

Rino: All right. Fascinating. So we are in Colorado Springs now. You had a number of associations then with companies at that time that really got you introduced to GPS?

van Diggelen: Yes.

Rino: Tell us about that.

van Diggelen: In Colorado Springs?

Rino: Yes. You started with, what was it, the NAVSYS Corporation?

van Diggelen: Yes, so it was NAVSYS in Colorado Springs, and that was a small company, and I was doing this work with the Coast Guard and then did some work with U.S. Air Force. So, I got to do a lot things, like we built a receiver from scratch there. It was a prototype. so it was spread out in the lab, front end and processing system, and so I got to learn a lot from Alison Brown. I knew some people from Trimble and Ashtech, which were two survey companies.

Rino:. Trimble was already in operation then?

van Diggelen: Yes, it was, and it was very interesting. because that was really the first commercial use of GPS. It was very high-accuracy survey use in oil fields for geologists in the oil industry. They were prepared to pay thousands of dollars for an instrument that could tell them exactly where they were and so Trimble Navigation developed systems that did that by measuring the carrier phase of GPS. Ashtech was a competitor . I worked for Ashtech and I worked on a high-precision GPS in the mid-'90s. And what's really interesting is that's where GPS began. The commercial GPS was very high-accuracy GPS, and it slowly evolved into consumer use in phones at medium levels of accuracy as you're used to. You can navigate your car, but the loop is going to close. We're going to have very high accuracy again, we're going to have very high accuracy in the hands of consumers in phones because those kind of measurements, those carrier phase measurement, are now available in phones and it's just a matter of time before people write the software to make use of those measurements and get the kind of accuracy out of a phone that these companies like Trimble pioneered in big boxes that sold for $50,000.

Rino: Were the early systems then just using ranging? I mean they didn't use the carrier phase at all ?

van Diggelen: Well now, the early system, the early military systems just used the range from the code phase on the signal, but the early Trimble systems just used the carrier phase. It's an interesting thing to explain when you explain the different levels of accuracy to people with GPS. Most people who are used to the GPS in their phone are surprised to hear that GPS is capable of centimeter accuracy, and then they're even more surprised to find out that that was actually the first use of GPS People say, "Oh, so when did the centimeter GPS happen?" and the answer is, that was the very first thing in the commercial world. The first commercial use of GPS was the very highest accuracy, funnily enough, and then we sort of learned to do low accuracy, but that's really a joke. We learned to do low-cost.

Rino: You like to make it less expensive. You worked with the company Magellan, too, at that time?

van Diggelen: Yes, so that company Ashtech merged with Magellan. There was a whole period of consolidation of GPS. There were a lot of little companies. There were medium-sized companies. They consolidated, and yes, so Ashtech and Magellan merged. So I didn't really change jobs. The company name changed. My job didn't change.

Rino: So at that time you were really getting into commercial applications of GPS that had to keep costs down and processing. And what kind of signal processers were you using at that time? I mean these were not dedicated chips that early?

van Diggelen: Yeah, those companies did dedicated Application Specific Integrated Circuits (ASIC) to do the signal processing. They'd sometimes, yeah, they'd prototype on DSPs, but they would make their own

ASIC to do the GPS signal processing because it's really a matched filter process where you've got a signal coming in, you know the structure of the signal, and you're just trying to match it and get that. So it's simpler processing than what you have in Long Term Evolution (LTE) or something like that where the main purpose is data communication. GPS does have a data communication component, but the main goal is just to match this incoming signal because the signal at the satellite has got a spreading code on it that's a known spreading code and you align yourself with that spreading code and then you know how much delay there was from the satellite to you because if you move further from the satellite that codes appears to shift in time.

Rino: Yes, it's really measuring a change in position from that point.

van Diggelen: Yes, and so that's really it. So in a way, it's a lot simpler than communications systems, right, and so I like to say that's why I like it, because it's kind of simple.

Rino: Well, you still have to demodulate the signal, but at such a low rate. So from there, let's see. Did we jump past the firstcellphone application?

van Diggelen: We're still in the '90s now, Ashtech and Magellan. Magellan, what's interesting about them, they made the first handheld GPS. There was a thing called the Magellan Pioneer, I think, or the GS-100 .

Rino: It looked like a phone?

van Diggelen: Yes, it looked like a big old phone, like a big brick and there was,it was about that long, and it just told you latitude and longitude on it, just a number like 37-point-something north, 122...

Rino: What did you do, log it by hand?

van Diggelen: Yeah, that's what it was for, but for people like sailors, especially sailors, it was terrific. You had this thing in your hand that did for you what used to be a big box to use something like the Transit system and then people like hikers, emergency workers used that. So that was Magellan in the '90s and then cellphones, so GPS got in cellphones around about 2000 and the thing that spurred that was the E911 mandate from the FCC and so maybe I should explain that.

Rino: Yes.**van Diggelen**: Everyone in America knows you dial 911, you get through to emergency services, and in other countries there's a similar thing like 112 in Europe, and so on. And what was happening when cell phones came out.Before cell phones, your phone number was registered to an address. So when you dialed from a landline phone, they knew where you were calling from, from the phone number.and with cell phones what would happen is the cell phone itself would be registered to some region like where you got your area code, and what they were finding was people calling on cell phones had no idea were they were. They'd put the emergency service that answered the call would maybe contact the Sherriff's department or something in the home area of that person. The person is on vacation somewhere else, and they [the emergency service] didn't know.

They didn't have a way of knowing where the person was and more and more 911 calls were going out over cell phones so the FCC mandated something called E911 or Enhanced 911 and said that when a call was made from a cell phone, the carrier that placed the call, so Verizon or AT&T or whoever, had to provide location when they connected the call. They had to also provide the location of that device and so that was in the late 1990s. That mandate was made and there was a period of about 10 years where it was phased in and there had to be a certain number of phones with a certain accuracy by a certain time.

Rino: So is there more than one way people were thinking about doing it?

van Diggelen: Exactly, and GPS was not the number-one choice at all.

Rino: I would've thought, so.

van Diggelen: It's really interesting now. It seems obvious you do it with GPS, but it was not like that at all. There were several other choices and GPS was considered not the favorite to win, and so the choices that were the favorite to do this were location systems based off of the signal from the cell towers because the carriers already knew where the cell towers were. Any cellular system knows where all its towers are, and that's how it works; so as you roam around they keep track of you so that they know which cell tower to connect to you next or if someone calls you they know.

They don't ring you from every cell tower on earth hoping to find you, right? That would never work. They ring you from the cell tower in the region that you are in. So cell towers, they really know where you are roughly, and then they developed systems to measure the time of flight from the cell tower and so that was something you could do quite easily off the existing system. So that was considered the logical way to satisfy the E911 mandate, but the trouble was you don't get such high accuracy like that because the cell towers don't have the precise clocks in them that the GPS satellites have. So, with GPS, you can get much better accuracy. With the cell tower you get accuracy just by knowing which cell tower you're talking to. It's accuracy of a few miles. By measuring the time of flight of the signal from the cell tower, you get accuracy of something like 100 meters. With GPS, as everyone knows, you get accuracy of about five meters, but the trouble was the GPS didn't run in the phones. The signal was too weak.

It just took too long to get the signal, and then because it took so long, the GPS chip was running at full speed trying to acquire the signal. That's the matched filter I was talking about before where you use a lot of battery, and so you'd run your battery down really fast.

So, GPS was considered, but the signal was too weak to go into a phone, and the battery use was too much, and so it was just a few entrepreneurs who had the foresight to say, well, that's going to change because you've got Moore's law working in your favor so the power is going to come down. And a few companies started up specifically to design chips to go in cell phones for GPS to satisfy this mandate with the hope that GPS would become the way to do location in phones, for all phones, and that proved to be the case, and so that's kind of how GPS got in phones Now just about everybody uses GPS. I don't know if you've ever been in a lot of traffic, and you take a side road because Google Maps told you to, and I've had this happen often. You see the six cars in front of you all take that same side road that's a little detour, and they've each got their phone up and their phones are all telling them the same way around the blockage.

Rino: Now, the companies were starting to look at-- even Hewlett-Packard at some point was trying to get into that business?

van Diggelen: Well, in the cell phone business, let's go back to what companies there were. So one of the first companies to do this was a company called SnapTrack that developed some chips for cell phones and then one of the other early ones was a company called Global Locate. the founders of that were friends of mine, and I joined that company the day they got funding. So I was one of the first four employees and then we developed.

Rino: Okay, so that's how you got from Magellan to Global Locate?

van Diggelen: Yes, to Global Locate. So yes, one of the founders, Charlie Abraham, had been at Magellan with me so he left and was one of three founders of this company Global Locate and then he brought me in. So we worked at making chips that would have enough sensitivity that they would work in phones and acquire the signal much quicker than traditional GPS and we did that. So you mentioned Hewlett-Packard. Actually, the first smartphone to have GPS in it was a Compaq phone. It was called the IPAQ, I-P-A-Q, I guess it was before "I" became the property of Apple and it was evolved from a Compaq handheld computer, and it was this iPAQ. So, Compaq and Hewlett-Packard had merged and this IPAQ 6500 was actually the first smartphone to have GPS in it and it actually had almost all the functionality that modern cellphones use.

This was in 2005, so this is now, what, 13 years ago, and that phone, if you look at it now, it had a keypad or keyboard. It had a keyboard. It kind of looked like some of the later Blackberries, had a keyboard, had a screen. It ran TomTom navigation, so Google Maps in phones wasn't a thing yet, didn't exist. TomTom was a company from the Netherlands and Britain that did car navigation systems, and so their software ran in that phone so you could do navigation. It didn't know about traffic like the maps of today but it could route you and tell you estimated time of arrival based on speed limits and so you could do that. You could send someone your location if you were diligent about it. It wasn't like now. You can just go "Share Location." You would bring up an app. It would show you your position. You could cut and paste it. You got another app and paste it in. You say, "Here I am," and you send that. It was all-- so it was a real prototype of current things. If you had-- someone sent you an email with an address, you could copy the address and then go to the TomTom app and paste it in there.

Rino: All on your device.

van Diggelen: All on your device, and so it was like it did everything that the current phones do, but in a very primitive way Sometimes you'd have to get a piece of paper and write down an address and then type it in again in a different app, but you could do the same things you can do now.

Rino: That's interesting. We take a lot for granted now as we look back, so...

van Diggelen: Yes. In those days, we used to talk about things like, "Oh, wouldn't it be nice if you had a calendar entry that said, 'Be at Computer History Museum at 2:00 P.M.' or it could know how far you are away and it could warn you, 'Time to leave because of traffic'?" and that's exactly the kind of things that happen now in phones.

Rino: One question now that was back there and at that time, these companies that were designing these devices, you say they were building their chips. Now, that meant they were designing those chips and sending them out to be fabricated .

van Diggelen: Yes, so I think in all cases, these companies were fabless semiconductor companies, meaning that they didn't have the fabs like Intel did at that stage, and they were mostly small companies doing this. Even some of the established companies like Trimble and Ashtech were small-to medium-sized companies with a few hundred employees back then. So they would design the chips, and then they'd get manufactured by big manufacturers like TSMC, that's Taiwan Semiconductor, similar companies like that.

Rino: Yes, so innovators with ideas had the wherewithal to put together what they wanted and then move it forward. Okay, so we got to the magic transition, 2005. That's when the upgrade to GPS started. **van Diggelen**: Well, —are you talking about when they had switched off selective availability?

Rino: Well, more when they made the plan for upgrading the entire GPS.

van Diggelen: Right. I forget what date that actually was. In the meantime, there was this. I'm sure some other people in this series will talk about this. In 2000, they switched off the deliberate degradation of the GPS system and because they did that, it made it possible for consumer products to have good enough accuracy to navigate you around the streets and so companies like TomTom came into being then, and that was 2000. So yes, and then with the GPS system there was a continual renewal going on. The satellites last about 20 years, and so as they start to get old they'll replace them with newer satellites and so in the mid-2000s they were going from what was called Block II to Block IIR satellites and Block I was the original ones. And I never really think about that as a specific moment because there's 32 satellites and they get old sort of one at a time.

Rino: The key point is that there would be a natural progression of improvement.

van Diggelen: Yes, so at the moment, for example, they've already designed what they call GPS III so it's the third generation of GPS.

Rino: I think that's more what I was talking about changing the signal structure so you could get more accuracy I guess there's been a lot of controversy about it. GPS was started as a military system more or less, like the internet. I think it was always understood that there would be commercial civilian applications, but they never anticipated that the civilian applications would drive GPS.

van Diggelen: Yes. Well, it's true. It was developed by the Air Force, so it was meant to be a military system but from the original design they did intend it to be for civilian use. It wasn't like GPS was a military system that later got used for civilian use. It was meant as a dual-use system from the very beginning. And you can see that because the signal structure has

this open code, so-called C/A code which is public, and then they had a proprietary code, a precision code which is military only. So they had this dual use from the very beginning, but I think nobody anticipated you'd have billions of users by now. I think if you look at some of the early studies, and they talk about millions of users by 2000-and-something and now just in cellphones there's over 2 billion GPS receivers out there.

Rino: I always like Brad Parkinson's talks when he lays that all out, how many GPS receivers there are in every cellphone.

van Diggelen: Yeah, every cellphone, many watches, and just about every car..

Rino: I started out saying that you were the architect of one of the architects of AGPS, so tell us what AGPS is all about now.

van Diggelen: Okay, so AGPS, in a nutshell, is what makes GPS work in phones, and the "A" stands for "Assisted". GPS on its own takes a fairly big antenna, meaning about this size, something that's much bigger than the kind of thing that you could stick on to a cellphone. You need that size antenna to get a strong enough signal to be able to acquire the signal in the first place and observe this range delay that you're measuring from the satellite, and so people who had some of the early hiking receivers might remember that they either were fairly thick and they had this patch antenna inside. It was about that size, about the size of a square of chocolate hidden in there or it was a helical antenna that would stick up so it was thicker than your thumb. It would stick up out of the device and once smartphones came along, that kind of thing , there's no place for it in a smartphone, and the antennas inside a smartphone are really tiny, and there's lots of them because there's all the cellphone antennas.

There's Wi-Fi. There's Bluetooth. So, the GPS antenna is a tiny little piece of metal that's hidden away in there, and as a result the signal is very weak, and a regular GPS receiver just won't get the signal that it needs to be able to measure the distance to the satellite. So, you need something else to help the receiver pick up this weak signal and make measurement from it, and that "something else" was this assisted GPS technology. So that's what it is, and how it works is you have reference stations that are fixed GPS receivers scattered around the world. ou set up some network of reference stations and those things observe the satellite signal and then they send a hint over the wireless data system, over the internet to a phone and say, okay, if you were at this location, these are the satellites you can see, and these are the signals that they're sending.

And so it's completely analogous to: suppose you get off a plane and you pick up a rental car. You're driving someplace you don't know and you want to find a particular station on the radio, right? So,you'll just start turning the dial, right, though nowadays maybe you just press a button, but if you didn't have a radio station where you turned the dial, you'd start searching. Every now and again, you might hear some crackle. It'll be noise and then crackle, and you have to spend some time there, and you search some more and spend some time, but the signals are kind of weak. Maybe you're driving through the countryside. It would take you a long time to find that signal, but suppose somebody could tell you, by the way, I know where you are, and I know what radio stations are there. Go to 97.3, and there's the radio station you're looking for. Well, then you go there. Even if as you got there the signal was weak because maybe you're driving through a tunnel or something, if you knew in advance to go there you'll pick up that radio station and you'll do it quickly because you'll know exactly, and so assisted GPS is the analogous thing in GPS.

It's this network that's watching where the satellites are moving and can tell you in advance which satellites are overhead where you are and then technical details, like what's the Doppler frequency that you should be observing of that satellite at that moment, and so then your receiver doesn't search over all possible satellites and all possible frequencies. It just looks where it knows the satellite is going to be in terms of frequency search and so it's quicker and then because it doesn't have to spend time searching around it can search deeper in terms of signal processing at that particular frequency for each particular satellite and so you get extra sensitivity and you get extra sensitivity in big numbers. Like your GPS receivers before assisted GPS had-- they could pick up a signal up to maybe 10 times weaker than the nominal signal.

Rino: That's normally where it is in the noise.

van Diggelen: Yes, so then normally where it is, they could get that and maybe 10 times weaker, so then if you walked under a tree, often they would stop working and the people who had hiking receivers probably remember this. When you first switch it on, you couldn't stand under a tree. You'd have to move in the open and assisted GPS in cell phones allows you to get signals that are 1000 times weaker than a nominal signal. So the dynamic range increased by 20 dB over what was nominal there which means it increased by 100 times. So you went from being able to get 10 times weaker than the nominal down to, what, 1000 times and even more.

Rino: Well, once you compress the signal you've got 30 dB. You're still integrating on top of that?

van Diggelen: Yes, so I'm saying beyond that extra 30 dB. I'm talking about beyond the nominal, so this is on top. So, ordinary GPS has some processing gain and assisted GPS, when I talk about this extra 30 dB, that's extra on top of what you already get. The total gain from when you first pick up the signal to when you observe it in a assisted GPS system, is like a million times. You make that signal a million times stronger than what it was when it came into the antenna.

Rino: And that's done with more integration time?

van Diggelen: Yes, more integration time at the particular frequency of interest, and so these integration times are something like a millisecond, but it used to be without assisted GPS you spend a millisecond at a whole lot of different search locations. And if you can know in advance that 99.9 percent of those are not useful and you should spend all your time in one spot, well then, that's it. It's a simple idea and then there's the question of design and implementation and that's what was going on in the early 2000s.

Rino: Okay, so for all of that then, there have been so many applications that have come from that kind of technology, and you wrote the textbook on the assisted GPS applications, a big one being for airplane navigation. Can we now make a GPS landing with the systems that are available and improved?

van Diggelen: Oh yes, and in fact I think most aircraft have got auto-landing systems that will work off GPS. They don't necessarily use them all the time because they've got things like microwave landing systems in airports, like if you're flying to San Francisco Airport, for example, and a lot of other things, you'll see those. At San Francisco it's obvious because there's a jetty going out into the bay. And there's all these things put on there and that's part of the microwave landing system, so there's a lot of basically sending up a beam into the sky that the plane flies down. So, there's a lot of infrastructure that they make use of but auto-landing from GPS was demonstrated quite some time ago, and up the road here at Stanford a group there under Per Enge worked on that, in that area and now-- and they continue to work with the FAA and demonstrated autolanding quite some time ago.

Rino: I know he passed away earlier this year. I knew him. He's a wonderful individual. Okay, so we've got the expanding technology, the applications from every conceivable thing you can think of to put a GPS system.So how is the evolution of that impacting the design of the systems and integration and augmentation? That must be what you're heavily engaged in right now.

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van Diggelen: Yes. Well, maybe I should explain how big these GPS chips are that are in the phone. If you have a discrete chip that's just a GPS chip, the die size is something like 2 millimeters by 2 millimeters. And that's thanks to Moore's law that it's got so small. They used to be 20 millimeters by 20 millimeters. So that's just Moore's law, and if you work it out, you think well over 20 years it would've got about 1000 times smaller because every two years your chip size is cut in half for the same functionality, but what's been happening in GPS is over the last 20 years is the chips have been getting smaller and more capable. So 20 years ago, a GPS chip would be a big thing like this and it was capable of tracking 12 GPS satellites typically, and that's what it was.

Rino: And it's a single frequency?

van Diggelen: Then it was, right? A typical consumer chip back then.There were two frequencies available, but the typical consumer chip was single frequency. Now, you'll have a 2 millimeter by 2 millimeter chip in a phone, and it'll be capable of tracking over 100 satellites and you think well, why do you need 100? It's because you've got GPS now. There's the Russian system called GLONASS. They have 24 satellites up there. There's the European system called Galileo, and they have 18 to 22 satellites. They just launched four more a couple of weeks ago, so I think they have 18 operational and 22 in space. There's the Chinese system called BeiDou which has 30 satellites and then there's regional systems such as QZSS, a Japanese system with four satellites, and IRNSS, the Indian system which has about six satellites in space. So you have well over 100 satellites available, and you now have dual-frequency signals available to civilians.

There's a signal called L5, which is on GPS and Galileo and BeiDou and QZSS so on four of those systems, basically, all except GLONASS, you have this L5 signal, and there are now chips available for cell phones that include all those satellites I mentioned, plus the dual frequency. So you can just track a whole lot more signals and the benefit of that is you can start getting better accuracy in cities, and people probably get used to this as well.

So back to your question, how is the use case driving the design? So possibly the number one use case of GPS that people are used to is navigating around in your cars, and nowadays calling Uber or Lyft, calling a rideshare service, right. That's-- two of the things that almost everybody with a cell phone does at a certain stage, and anyone who lives in a city has probably had this experience, that they'll call up Uber or Lyft, and the GPS will think they're on the other side of the street, and that's because the signals are blocked by the buildings, and with these extra signals, and with the extra satellites you can solve that problem. And so to solve that problem that's been driving the design and the first phones are coming out with dual-frequency GPS in it this year, and so that's a big step, and that's part of what I was talking about before. The kind of technology that used to be in these big receivers that were sold for industrial commercial use is now making its way into cell phones, and in a way even more capability than we used to have because of these new satellites and the new signals.

Rino: Yes. I know from my own experience that multi-path has always been the biggest problem that we've ever had with a GPS receiver, because we put one up on the roof at a company I was working in with all of the roof top units,and the performance was terrible.

van Diggelen: Yes, and in a city, before we had assisted GPS, you just wouldn't get a position in an urban canyon, and like Wall Street or anywhere in Manhattan, any kind of narrow street in Manhattan, or the financial district of San Francisco, for example, if you used GPS in one of those narrow streets you wouldn't get anything because there weren't enough satellites in view directly overhead, and the satellites were blocked by the building; the signal that bounced off other buildings was too weak. So then with assisted GPS we added all of this processing gain that I was talking about. So you have all this extra sensitivity, so now you start tracking the satellites in the urban canyon. But what you're tracking is something that is being reflected off another building, and so now the accuracy gets bad.

Rino: Do you know where the buildings are? I mean, do you make use--

Rino: --of this calculating where those signals could come from?

van Diggelen: Google knows where all the buildings are, so this is something that, you know, if you look on Google Maps, for example, you can see 3D models of all the buildings.

Rino: I've seen that technology.

van Diggelen: Yes. So that information is there, and that, together with these new signals, means that this problem will be solved in the future, this problem of being on the wrong side of the street.

Rino: That does sound like a more direct approach than trying to unravel multiple signals in a single channel, by ncreasing the number of delays you look for, for example.

van Diggelen: Yes, well, when you get these reflections you might get many reflections from one satellite, and so you just can't figure it out just by measuring the channel. You have to have some knowledge, of where the buildings are and so that's, that will, that's part of how you would solve this problem. It's still not a solved problem right now. If you take any phone and you go stand in the financial district of San Francisco or some similar dense area and switch on the GPS, that very first blue dot you get is probably going to be on the wrong side of the street. Any time I talk to a large audience about this or ask people, "Who's had the blue dot on the wrong side of the street?" everyone puts up their hand.

Rino: Yes. I had the experience of the <laughs> GPS telling you you're on the wrong side of the road.

van Diggelen: Yes.

Rino: Okay. So that technology, it's coming along. I know. There was one other question that you hadn't talked about that's a little outside, but one of the major impacts of GPS too is globe alignments for monitoring, for example. That very signal, that little 10 meters that you're correcting for the ionospheric can be tracked and we can now get maps of the entire ionosphere over time scales of inside of 10, 20 minutes or so or updated.

van Diggelen: Right. Maybe I should explain that a little bit.

Rino: Please

van Diggelen: I haven't talked about that explicitly, but when, the whole system of GPS is working you have an atomic clock in the satellites. It sends a signal with a time tag on it. Says, "Here's a signal and this is the time," and then some time later, about 70 milliseconds later, which by the way, is this long. <taps mic>

Rino: Yes.

van Diggelen: That's 70 milliseconds. If I tap on the mic**,** you hear that very well. But in that short amount of time, a signal travels to you on earth and your clock inside your receiver, your phone, for example, will time tag the signal when it sees it. So your GPS receiver has got its own clock, and the difference in those two times tells you about the range. You just multiply the time difference by speed of light and that would be the range, if it was all vacuum between you and the satellite.

Well, it's not all vacuum. It's mostly vacuum. The signal's traveling from the satellite through the vacuum of space. Then it hits the ionosphere, which is an area outside our atmosphere where there's a lot of free ions and free electrons, and that changes the propagation characteristic of the signals and slows it down, and then the signal hits the air, the troposphere, which is where we live. The air lows down the signal even more, and so you get extra delay that is not accounted for in just saying, "Multiply by the speed of light," because when we say the speed of light, we really mean the speed of light in a vacuum. The speed of light is different in a medium such as air. So in a typical application like in a phone, we'll just compensate for that with fairly-well-known models of how much that delay is. But to do more precise work, what you can do is if you have a device at a known location, the satellite is at a known location, then you can measure the exact delay caused by the ionosphere and the troposphere and you can infer properties of the ionosphere from that.

So in GPS, instead of trying to eliminate the ionospheric delay, you can use the GPS as something to observe this ionosphere that tells you what the characteristic of the ionosphere is at any particular moment, and it changes during the day. At night the ionosphere is very quiet, there are not many free ions, and then as the sun rises over a particular area the energy from the sun will cause more ions to be freed up and you get a peak of ionospheric activity at about 2:00 P.M. local time, and then it goes off, and then this changes as well with solar activity.

So people know about sun spot cycles and sun being more active, and it's a big deal, because when you have a tremendous amount of solar activity, you get a lot of-- every now and again, I'm meaning, like, every few years, you can get enough activity in the ionosphere that'll disrupt satellite communications. So your TV might not work so well, or any other form of communications through satellites, and you can measure this and then actually predict it with GPS.

Rino: But, you can use the dispersive nature, I mean, the frequency dependence. That would allow you to correct and back that error out in a single channel.

van Diggelen: Yes.

Rino: Would that be routine-- in fact, that's why they had two frequencies for the original GPS design.

van Diggelen: Yes, that's true. The original reason for having two frequencies was the ionospheric delay, as you mentioned, is a function of frequency.

Rino: Yes.

van Diggelen: So if you can observe the relative delay on two different frequencies you can figure out the ionospheric delay. That's not really the benefit of two frequencies these days, because you've got internet connections to just about every device, especially your phones. So you can just find out the ionospheric delay if you care about it that much. If you really care about high accuracy you can get corrections for it from some other device, like a GPS reference station that's measuring it. The more interesting thing I think is the science that comes out of it where instead of trying to measure the ionospheric delay to remove it, which is what people do for high accuracy, is use the stationary receiver that's at a known point to measure the ionospheric delay.

Rino: Yes.

van Diggelen: They do Ionospheric diagnostics at the University of Colorado at Boulder. Professor Jade Morton is of one of the leaders in this areaShe showed that you can measure the effects such as when they were doing some nuclear testing in North Korea, the effect of the nuclear blast disturbed the ionosphere, and it could be measured with GPS stations nearby, like in Japan and South Korea. You can measure a disturbance and tell that a nuclear blast has happened nearby. Who would've thought that when they first built GPS they were intending that, they anticipated building devices that we'd all carry around. I'm sure they also didn't anticipate you could make such sensitive measurements of things like the ionosphere and infer things like nuclear blasts.

Rino: That's very interesting. You think that the way to measure the ionosphere is to make comparisons to known distances rather than to use the frequency.

van Diggelen: Well, the first military use of the GPS system was for the Air Force. So you imagine some Air Force plane flying far away from its home base. It would need a stand-alone method of doing this.

Rino: Jack Klobuchar was the architect of those ionospheric correction.

van Diggelen: Yes.

Rino: Early models that put the ionosphere into it?

van Diggelen: Yes.

Rino: I worked with him around 1980. We used a GPS receiver that weighed a hundred pounds and cost a hundred thousand dollars.

van Diggelen: Right.

Rino: --To make two-frequency measurements so we could check his model.

van Diggelen: Right. And so that model is now in use in every cell phone, I think.

Rino: Yes.

van Diggelen: I think that's the standard>

Rino: That's interesting..

van Diggelen: I thought that at any moment there's millions of cell phones running that model to model the ionosphere and remove it to at least the kind of accuracy you get from a cell phone.

Rino: Yes. It's probably five meters, or so you could get the accuracy of that model.

van Diggelen: Right.

Rino: Okay. More about as you look at GPS now in your own interest, and where it's taking you. How do you see it? What are the new technologies that are really going to drive it? Augmentation seems to be like marrying GPS with inertial navigation as a means of really changing the dynamic in the near term. If you had a good enough inertial system, GPS would become an augmentation rather than the other way around? Or how do you see that?

van Diggelen: Right. Well, that's something that's happening. It's in cell phones, for example, you have an inertial system in there, and that all cell phones have an accelerometer in there, and all high-end cell phones have rate gyroscopes.

Rino: That's interesting.

van Diggelen: Any flagship, any top-of-the-line, Samsung or iPhone or Pixel or any one of the big-name phones thatall have rate gyros,actually have three, one for each axis. They have rate gyroscopes, so the phone knows when it's rotating. So for example, people experience this all the time. When you take a panorama picture and you rotate the phone. It knows how it's rotating.

Rino: So just to establish its orientation is the primary use of that?

van Diggelen: Yes. Well, that's where the accelerometers come in. So it's kind of a good Trivial Pursuit question. "What was the first navigation sensor in a smartphone?" and the answer is, "An accelerometer," and accelerometers were put in every phone. In every smartphone there's accelerometers. They were put in there in the first place so when you put your phone down on the table, it could sense that it was still. Because if you hold the phone in your hand, no matter how little coffee you've had to drink, you're actually shaking at a level that the accelerometer can measure and when you put it down on the table it's very steady, and so to save battery, as soon as the phone's put down on the table it goes into a different mode.

Rino: Yes.

van Diggelen: And so the accelerometer was the first motion sensor to go in any phone and all phones have them, and for that reason. Then they put in three-axis accelerometers so that your smartphone could switch from portrait to landscape when you flip it. You know, so you can see that. Then they added gyroscopes for things like sensing orientation and camera use, and those two things together, being combined with GPS, so when you're driving in your car, they will integrate the GPS and the accelerometers and the gyros, so it makes it an inertial system.

So if anyone's watching this and they actually want to learn something useful, one of the things you can do, if you're navigating with your phone in a car, and you put it in the cup holder and leave it alone or put it on a dash mount so it's being held still with respect to the car, the software in the phone will sense that. It'll sense that when the car stops the accelerometer is stopping and it'll realize that it's somehow mounted. So mounted means either something holding it on the dash or even just sitting still in the cup holder as long as it's not flopping around. The software in the phone will sense that and then combine the GPS with the accelerometer and the gyro. The result is your blue dot will move a lot smoother, and so people might have experienced that already. You get better resultsif you mount the thing up on the dashboard. You have a better user experience than if you hold it in your hand or if it's like laying around and sliding around.

Rino: But you're implying that the positioning in the cell phone itself is being tracked on the map or is it using a scheme where it knows you're on roads in the first place, and takes some of that jitter out by...

van Diggelen: Well, there's layers of it though. So if you're using the GPS, it'll use the GPS so if you bring up Google Maps, for example, it'll use the GPS. Then the software in the GPS chip will integrate the GPS position with information from these inertial sensors. If the software determines that the phone is not being held in hand, if it's mounted with respect to the car, and then that position will then be combined with the map information.

Rino: Okay.

van Diggelen: Right. So there's layers of improvement. Yes.

Rino: Because you really don't want to see the thing jumping around on the road the way the positions are coming out.

van Diggelen: Yes. So back to your question about so what do I see in the future? Well, this use of inertial technology is moving into handheld use cases now, so when you hold your phone in your hand you can see it's a more difficult problem. Your hand's moving around all over the place as you walk, and so now you can't do the kind of integration of the accelerometers and the gyros that you can do in a car where the phone's nice and stationary. You know, you think of the car. The car behaves very well. You turn a corner, the gyro changes very steadily, and if it's in your hand, and you turn a corner, well, your hand might be swinging as you turn, so it's much harder to use inertial information for navigation of a pedestrian. But that is something where companies that do location like Google are bringing that kind of feature into phones and might've seen the recent Google I/O, they did a brief preview of walking navigation, and they showed what that might look like, that use augmented reality, you lift up the phone, it sees through the camera. So it can sense what buildings are around it and you can navigate as a pedestrian the way you would in a car. Tells you, "Turn right here, turn left there," and show you on the video screen, like, little arrow right at the building. "Go around this building."

Rino: Yes. I saw a beautiful application of that with a person that was impaired mentally. —Usually, you have to have somebody walk along with them.

van Diggelen: Right.

Rino: The GPS substitute for that improved their mental acuity just by virtue of the fact they were doing it themselves, you know, or it felt like they were doing it themselves.

van Diggelen: Yes

Rino: Well, let me pose, the question this way. Still on the market there are commercial GPS receivers for diagnostic applications, ionospheric monitoring like NovAtel and Septentrio.

van Diggelen: Right.

Rino: And those things cost a few thousand dollars still.

van Diggelen: Mm-hm. Yes.

Rino: Why are they so expensive for doing what they do when you can put it on a chip and get meter accuracy in a cell phone? I'd like to buy one for a few hundred dollars instead of a few thousand.

van Diggelen: Yes, right. Well, the companies that make these have scientific grade GPS's. They also make their own chips, but they make them in very small volumes, like a few thousand. So they have to pay a lot more to get those chips made, and then those chips are designed to recover very high fidelity carrier phase signals, and the carrier wave of GPS is only 19 centimeters long. Those chips are designed to measure the phase in that carrier wave to a fraction of the wave itself. So that means a fraction of a centimeter. Now, the GPS in your phone is optimized to have low power and high sensitivity and so there's the gap right now, that the GPS in your phone has not been designed to measure this carrier phase very, very accurately. But as the capability of the chips increase, and that just keeps happening because a lot of this is digital signal processing, and so with each iteration of Moore's law you, on the same size chip, you can do more processing. So even the carrier phase measurement is done with digital signal processing. So the chips in the phones are getting closer and closer to the high-performance chips.

Rino: Yes.

van Diggelen: Yes. So in a way it's already happened. There used to be these high-end receivers for measuring things like ionosphere, and then there's things for doing surveying, and in the middle there used to be a class called GIS receivers. GIS is geographic information systems, and there was a class of receivers that also cost a few thousand dollars, but single thousands, not tens of thousands, and they were kind of big receivers. They would measure the carrier phase and get sub-meter accuracy maybe, but not centimeter accuracy, and they would use those for mapping things. So if a city wants to map all the fire hydrants, for example, like map each fire hydrant to 20-centimeter accuracy, for example. Well, the phones are good enough now that a lot of organizations that do this mapping just use the phone. Now, even though maybe it's not 20-centimeter accuracy, but it's good enough, and it's-- it will get to that 20-centimeter accuracy as these carrier phase measurements become available, and they are available from phones. The Android operating system makes the raw measurements available, so there's a public Application Programming Interface (API) on android that you can get these measurements out of a phone. So people can take that, and there are apps out there that take the measurements from the phone, process them and give you accuracy at the sub-meter level from your phone today.

Rino: But that's still single-frequency measurements.

van Diggelen: Yes, And as I said, dual-frequency's coming.

Rino: Yes.

van Diggelen: And so it's just going to get better, more and more accurate..

Rino: Okay. So, this covered that territory very nicely.—Can you say anything about GPS in general, I guess the miracle that was a system that was never intended for what it came to be, and is free?

van Diggelen: Yes.

Rino: The users don't pay a fee for using GPS, and so far we're putting up with that.

van Diggelen: Yes. It is an amazing thing. I think it's up there with the internet as one of, you know, America's great gifts to the world. Maybe America's last great gift to the world, true gifts.

Rino: Yes, could be.

van Diggelen: You know there are many other systems, as I mentioned. But they're all copies of GPS.. It's certainly, as I mentioned earlier, it was meant as a dual-use military civilian system from the beginning, but the number of uses has far exceeded anybody's early predictions.

Rino: Yes. So is there anything in any of the systems outside of GPS that are functional improvements or things that are in GPS or are they all pretty much interchangeable?

van Diggelen: What do you mean by "things outside of GPS"?

Rino: Well, I mean, if there's a signal architecture that actually would improve on your ability to acquire the signal or integrator.

van Diggelen: Right.

Rino: Or beyond, like, L5, for example?

van Diggelen: So what's interesting is the GPS system was designed in the '70s, right. So the signal architecture's relatively simple by modern standards of what kind of signals people use in communication systems now, and so GPS has, of the different systems that are out there, the GPS system itself, the U.S. system, actually has the simplest signal architecture, and the Galileo system from Europe has the most complicated, and in theory you can get more accuracy out of the more complicated system. But in practice, the simple one often works better because the signal-- especially for consumer uses like cell phones, because the signal's so weak, as we discussed earlier. That some of the stuff that works in theory, so more complicated signal, that would give you slightly higher accuracy in terms of measurement of time of arrival, just doesn't

It just takes so long to acquire that signal because it's a much finer signal that the more simple signal actually often works better in practice. So I'm a big fan of the simple GPS signal structure that was designed in the '70s, and you can look at it in theory and see why a more complicated signal structure would be better for something like these industrial use cases, these scientific use cases. Where you have a big antenna, a receiver that's outside and gets the full signal. But for the use cases for the masses, you know, those industrial receivers, represent .1 percent of all GPS's. For the use cases of the 99.9 percent, you're dealing with weak signals because of small antennas, and I don't think you actually benefit from a more complicated signal. So to answer your question is like are there things outside of GPS that would help GPS? The answer's, yes, for scientific use. But maybe not for your typical consumer use case.

Rino: That's a powerful perspective, something to keep in mind. Just listening to you talk. You have a passion for teaching, and especially working with students and stuff. So how are you teaching GPS, and are you having success and getting interest?

van Diggelen: Okay. Well, I teach a class at Stanford on GPS. It's a one-quarter graduate class on GPS. I've been doing that for six years, so that's, that's how you teach grad students about this, and we go through all the main parts of how the system works. Its signal structure, it's signal processing, orbit mechanics, so how you work out where the satellites are, receiver design, so little bit of hardware. So it's a course that covers sort of broad, not very deep. Each of these areas you can dig really deep if you want to and this is a broad course and so that's how we teach it in terms of an introductory system, and then there's quite a lot of fairly well-established places. If people want to learn GPS, and you're not a student at Stanford. There's a Coursera course that Per Enge, who we mentioned before, and I did. We developed it and it's available from Coursera and it's on YouTube. So if you just go to YouTube and look up GPS, Introduction to GPS class.

Rino: Yes.

van Diggelen: You find several, Ithink it's 53 or something. I remember it was the same number of lectures as there are episodes in "Breaking Bad," so I was very happy that that turned out like that.

<laughter>

Rino: Yes.

van Diggelen: And there's that many lectures introducing GPS that's meant for people who really don't have any background, and want to learn quite a lot. So we go through that, so that's another place, and then there's the Institute of Navigation, which is the U.S., so which you belong to and I do, that's the U.S. Institute for Navigation, which is the premier institute for GPS in the world, I think. They have conferences each year, and they have tutorial sessions before the conferences.

Rino: Yes..

van Diggelen: So that's a great place to learnWhen I first came to the U.S. and joined Navsys back in the '90s, that's actually where I started learning about GPS. So there's that, and then in Europe there's a similar thing through ESA, European Space Agency. They sponsor a summer school for grad students. So any students in Europe who want to learn about GPS, that's a great way to do it.

Rino: So does it stimulate interest in science, mathematics?

van Diggelen: Yes, I suppose. These things are all targeted at university students who are either graduate students or well on their way, you know.

Rino: They've already gotten into that.

van Diggelen: They're already in the STEM program. So yes, that's a good point. I don't know. So anyway, those are the big areas where you can learn about this is that there's, every year, when The Coursera class is up there on YouTube so you can find that any time, and then these, these conference, these things that go along with the conferences, happen every year. So the ION conference coming up next month in Miami, and it's always in September, and so they have these classes before the conference. Some of them you have to pay for, and some of them are free, so that's a great way to learn about it, and then for a student, that's so anyone can attend their conference, and for students in Europe, these summer schools are very good. But for to get young students like, middle school students involved in STEM.

Rino: Yes, just playing with it.

van Diggelen: Every middle school student knows about GPS. It's in their smartphone.

Rino: That's what I was thinking..

van Diggelen: I've done a fewclasses for students, but on an ad hoc basis.

Rino: Try to get them interested.

van Diggelen: When my own kids were in middle school, and my brother's kids, I went and taught kids about navigation and GPS and it was great fun. Actually here in San Jose we got middle school students to learn how to work out their latitude-longitude just from the sun and just using a stick and shadow and a watch. They actually worked out their latitude by understanding how the sun moves, and they loved it. But an established program for that I think would be a great thing. Maybe I'll do that one day.

Rino: Yes.

van Diggelen: Once we've solved all the problems in the cell phones.

Rino: Yes, there's one thought. People probably don't appreciate it, butthe GPS satellite itself has to know where it is very accurately.

van Diggelen: Yes.

Rino: And that has to be updated. It's good for about two hours.

van Diggelen: Right.

Rino: I think I'm correct in this. The orbital prediction codes that were used just for keeping track of where satellites are like NORAD, had to put extra terms in the pseudo-moment equations that keep track of the positions. In fact, now, I think that probably if you pull out a piece of code to put in a satellite number and say, "Where is it?" It's probably calculating it with an upgraded set of codes that came about because of GPS.

van Diggelen: Yes, well, that's right. What you're saying is that for the GPS its complete backwards of how someone that doesn't have any knowledge of this, they talk about it backwards. People say GPS tracks you, and it's actually the other way around. The GPS satellite has no idea where you are.

Rino: Yes, GPS knows where it is.

van Diggelen: --Broadcasting a signal and, technically, your receiver, your phone, for example, it learns where the GPS satellite is.

Rino: Yes.

van Diggelen: Not vice versa.

Rino: That's nice way to look at it..

van Diggelen: And yes, and you have to know the satellite orbit accurate to whatever accuracy you're hoping to get to, better than what. If you're hoping to get five-meter accuracy, and we've discussed there's ionospheric and tropospheric errors and there's multi-path errors from buildings on the ground. So whatever error there is in the satellite orbit, that's going to get in there as well. So typically, you want that error to be down to a meterIt is remarkable and that all starts, for GPSm with the U.S. Air Force, and then there's similar organizations for Galileo and so on. Each system has its own control station, and there they have people who do the modeling, and they predict to within a fraction of a meter where the satellite's going to be at every moment and they put that in an orbit model and when you think of a satellite's moving at something like three miles per second or, you know, five kilometers per second. So to know where, and it's way out there in space, 20,000 kilometers out in space. So to know where that thing is, to better than a meter is a remarkable feat.

van Diggelen: But it's really something, and then apart from the orbit, what's really cool and a lot of people don't know about but they should know about, is that because you got an atomic clock up there that's so precise in sending the signal and you're measuring, you're subtracting two times and multiplying by the speed of light, even an error of a nanosecond shows up as one foot error in your position, so you have to have those times right to order of a nanosecond and because of the satellite's moving so fast and it's far enough away that the gravity is much less, both special relativity and general relativity from Einstein are big effects on GPS, and so when you're sitting in traffic and you're looking at the blue dot on your screen, your phone is busy running calculations to take out the effect of general and special relativity on the clock that's on the satellite, and so I think most people don't realize that, that every time they use a GPS it's like they're running a little experiment proving or using Einstein's equations, and those equations are actually running in the software in the phone, every single time they get a position. So that's a very cool thing.

Rino: Yes. Think we should turn this interview around, let you say that at the beginning.

<laughter>

Rino: Yeah. That's a very powerful thought. We've covered the ground pretty well. It's been a pleasure to go through all this with you.

and it's been very informative. Is there anything we've left out? Anything you want to add to the historical document?

van Diggelen: Well, you took us through very methodically, thank you. So I guess the interesting thing is kind of looking to the future, right?

Rino: Sure.

van Diggelen: What's going to happen next? And I suppose we think in the short term we're going to see just more of the same where there's more signals. People who use GPS should know that already. Today it's almost impossible to use GPS, the U.S. system alone. When you're using a phone, the chips in the phone are all tracking multiple satellite systems. So you're always using multiple satellite systems already today. You don't have the capability to go and say, "Just use the GPS system," or, "Just use the Galileo system," in most devices. So it's already a multiple constellation system which makes the thing more accurate, and as we talked about, there's a second civilian frequency now available on many of these satellite systems, including GPS and Galileo and that's making it more accurate.

So we're going to see more accuracy. We'll solve this problem of being on the wrong side of the street in urban canyon, and I think you'll start to see things like mapping-- survey level accuracy coming out of phones and what that'll mean for use cases is kind of-- it's hard to say right now like, what- -if your phone could measure your location to 10-centimeter accuracy, what would you do with that? And it's hard to say right now because it can't do it. So people don't write apps to make use of that, but once it becomes available, I can see people starting to go, "Oh. Well--" for one, like, things like golf come to mind. You know, you could very precisely measure distances, and then some other things might come to mind, and people might map out, you know, if you're doing some landscaping, you know, and instead of getting a surveyor in to map out your yard you'd do it yourself and things like that are going to happen for your average consumer just based on the evolution of the technology.

Rino: Yes. Maybe in California you could check your neighbor's position very accuracy and see if you're moving relative to one another.

van Diggelen: Yes. Well, that is an interesting thing that you can see today from the scientific use of GPS. If you go to-- if you Google "UNAVCO tectonic plate shift" or something like that, similar words, you can bring up a map that shows you how anywhere, California for example, but anywhere else in the world, you can see how the earth is moving, and we here in Mountainview, we're moving at about three centimeters per yearasignificant amount. So if you bought a house 10 years ago, it is now about one foot further northwest. We're moving up towards Alaska.

Rino: Yes.

van Diggelen: So your entire house has moved a foot since you bought it if it's 10 years old. Now, the thing is, everything else around you moved the same, so you didn't notice. But compared to Nevada, for example,, the whole of the California coast, is moving northwest at that speed, you can actually go look on a daily basis, if you feel like it, at this site, UNAVCO, University Navigation Consortium. So if you Google “UNAVCO and GPS and crustal motion” or some similar words, you can discover this.

Rino: Again, it’s been a pleasure, and a very informative discussion.

van Diggelen: Great. Well, thanks very much, Chuck.

END OF THE INTERVIEW

