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2023-04-20 different kinds of differential

On the front page of HN today was an [article with a confusing headline], "Farmers 'crippled' by satellite failure as GPS-guided tractors grind to a halt." Of course the headline doesn't actually say this, but it does seem to imply that there has been some kind of failure of GPS.

This is not quite as outlandish as it might sound. The GPS system, maintained by the US Space Force, has occasionally suffered from serious funding shortages and bureaucratic paralysis. In 2009, the GAO issued a concerning report. They found that the program to launch a new generation of GPS satellites was so far behind schedule that the system was in danger of falling below the required 24 satellites. This would result in partial outages of GPS in different parts of the world, and could potentially take years to resolve. In response the Air Force issued a set of strongly worded statements insisting that they had kept GPS working for fifteen years and would consider to do so, and moreover made some changes to accelerate the GPS-III program.

Fortunately, we are now largely out of the woods on this issue, as not just GPS-III but subsequent designs are in service and the GPS constellation has been restored to its full planned size---including on-orbit spares for use in case of an unexpected failure. This is not to say that the administration of GPS is all good news; the GAO continues to issue more or less annual reports on how military programs to acquire more advanced GPS receivers (supporting the newer "M-code" signal) are badly mismanaged. But at least the civilian aspect of GPS should be quite reliable for years to come.

In any case, any significant failure of GPS would become major international news. Another perennial topic of GAO reports is the failure of the US government and infrastructure operators to develop any meaningful backup or alternative for GPS. A GPS failure would cause huge swaths of transportation and communications infrastructure to malfunction. While I remain a huge advocate for the construction of the terrestrial PNT (position, navigation, time) technology called eLORAN, it would cost money, and not in the F-35 kind of way, so it's unlikely to happen.

What happened in Australia, the article tells us about halfway through, was actually a problem with Inmarsat-41. Inmarsat is a bit of a historical oddity, in the same category as ARINC (Aviation Radio Inc.). It was founded as the International Maritime Satellite Organization, a non-profit entity sponsored by the UN's International Maritime Organization to develop a satellite network for emergency communications at sea. In 1998, though, Inmarsat was privatized, becoming a British company. Despite its historic legacy, Inmarsat is today just one of several major commercial satellite communications networks. It offers two-way telephony and data service, and carries both first and third-party broadcast services.

One of these services is SBAS, the Space-Based Augmentation System. "Augmentation System" is a common, if not very specific, term for GPS correction systems. The topic of GPS correction systems is sort of complicated, and we're going to celebrate 04/20 by going into them in some depth. Speaking of celebrating 04/20, this might be more of a ramble than a well-formed narrative, but there's a lot of interesting ideas related to PNT correction.

First, let's start with the concept of GPS augmentation systems. GPS fixes are subject to a number of sources of error. A high-quality GPS receiver with a sufficiently long observation time can eliminate most of the receiver-based positioning error, but there remain some pernicious errors which are hard to eliminate. Two of the most prominent are orbital ephemera and atmospheric effects.

First, orbital ephemera: to produce a GPS fix, receivers need to know the locations of the GPS satellites in orbit. In order to provide this information, ground stations observe the locations of GPS satellites and produce orbital ephemera, sets of parameters that describe the satellite's elliptical paths in relation to the earth. As the term "ephemera" suggests, these are "point in time" measurements that describe the current path of the satellites. Details of how space works like gravitational perturbations mean that satellite orbits are prone to changes, and satellites sometimes navigate to correct their orbits. This is why observations are used to determine the ephemera, and these observations are carried out on a continuous basis.

The GPS operators at the Second and Nineteenth Space Operations Squadrons regularly upload updated ephemera to the GPS satellites which transmit them for receivers to use. For practical reasons the ephemera are transmitted at a very low bitrate and can take some time to receive, which can contribute to "cold start" times on traditional GPS receivers of upwards of ten minutes. Most modern GPS receivers use some form of "assisted GPS" to reduce this time, with the most common example being the widespread practice of smartphone GPS receivers obtaining current ephemera from a web service instead of "waiting for it to come around" on the low-rate GPS data feed.

The problem is that new ephemera are only produced hourly, and the orbits of satellites varies on a minute level too rapidly for hourly observations to keep up with. Additional latency in the upload process means that the ephemera transmitted by GPS satellites can be several hours old. The observations are somewhat limited in precision anyway, considering the incredible precision modern GPS receivers are capable of. So, variation in the actual orbit of satellites from the ephemera leads to ephemeris error in GPS fixes.

Ephemeris error isn't actually that big of a source of error, but it's an interesting one so I wanted to talk about it anyway. Besides, it has introduced us to the term "assisted GPS" or "AGPS," which is unrelated to but often confused with augmentation systems. Assisted GPS just refers to the use of an alternate data path, such as IP, to obtain the current GPS network information that receivers need to make a first fix.

Second are atmospheric effects. GPS positioning relies on extremely accurate time-of-flight measurements. Unfortunately, the atmospheric is a weirdly complex thing, and numerous effects (such as "weather") result in radio frequency radiation traveling by indirect, non-linear paths. This problem is especially acute when dealing with satellites since, well, they're up in space, and so the received signals have to travel through a whole lot of atmosphere to get down here. This includes the ionosphere, which interacts with RF in particularly strange ways and can add significant travel time.

There are a number of approaches to reducing these errors, but one of the most common is differential GPS or DGPS. DGPS relies on a convenient property of most sources of GPS error: satellite position, satellite clock drift, and atmospheric conditions all tend to contribute a pretty similar error across a region. This means that if you can measure the error of GPS fixes in one place, the error at other nearby places is probably pretty similar. This is exactly what DGPS does: a reference station with a precisely surveyed location uses a high-quality GPS receiver to obtain very accurate fixes. The difference between the GPS fix and known location is then distributed as a correction signal that can be applied by other GPS receivers in the same area, canceling much of the inaccuracy. DGPS is one of the most common types of augmentation system, and is widely used by higher-quality GPS receivers.

Numerous augmentation systems exist, which makes them more complicated to talk about. The big issue is how the correction signal is distributed. Historically, one of the earliest major DGPS systems was the NDGPS or Nationwide DGPS. NDGPS is operated by the US Coast Guard (having originally been developed for maritime navigation) and uses a network of site across the US that transmit correction signals at around 300kHz. NDGPS has a great historical detail: when it was expanded from coastal stations only to a nationwide system, a great deal of the new inland correction stations were installed on recently retired sites of the Ground Wave Emergency Network (GWEN). GWEN was a short-lived survivable radio system operated by the military for continuity of government and command and control purposes, and much of the modern conspiracy theory around 5G can be directly traced to historic conspiracy theories surrounding GWEN as a government mind control system.

NDGPS is now being retired, though, as WAAS is viewed as a replacement. WAAS, the Wide Area Augmentation System, is the FAA's version of the same concept, intended for aviation use. Most WAAS reference stations are installed on the roofs of air route traffic control centers, with some others added as needed to fill gaps. WAAS differs from NDGPS in an important way: WAAS correction signals are actually distributed by three different commercial communications satellites. WAAS comes from space, just like GPS itself.

This is a good time to point out an odd bit of terminology: DGPS and augmentation systems are essentially the same thing, but for largely historic reasons "DGPS" usually refers to correction signals distributed by terrestrial radio while "augmentation system" usually refers to correction signals distributed by satellite.

You can probably see where this goes with Inmarsat. WAAS provides complete coverage of North America, but not of elsewhere. Inmarsat operates equivalent space-based augmentation signals as a contractor to several national governments, including Australia, New Zealand, and likely soon the UK. And *that's* what broke: some kind of problem with the satellite caused a disruption of the SBAS feed for Australia.

While we're talking about GPS augmentation, we should also talk briefly about RTK, Real-Time Kinematic correction. RTK, DGPS, and augmentation are sometimes used almost synonymously, but once again there is a conventional difference in the meanings. RTK most literally refers to the observation of the phase of the the GPS signals. The phase can be used as additional timing information to estimate the distance between the receiver and the satellite. Microwave GPS signals have a short wavelength (about 19cm), and electronics for observing phase difference can be made very precise, so this method can produce extremely accurate fixes. The problem is that RTK only tells you where the receiver is within a wavelength, or in other words it tells you where you are in a 19cm window, but not which 19cm window you're in.

To resolve this mystery, RTK is almost always used with a reference station so that the phase can be compared between a fixed point (with a location determined through long, 48-hour+ observation) and the moving receiver used for surveying in the field. Since RTK is mostly used by surveyors who are striving for huge accuracy and aren't in a hurry, it's most often done with a portable reference station installed nearby for the duration of the surveying project. If you've ever run into a skywards antenna connected to a chained-down Jobox with a solar panel, it's very likely an RTK reference station installed for some highway construction project. While RTK tends to imply DGPS, it's a separate technique, and produces even higher precision than DGPS or augmentation. It's also possible to use RTK without a reference station at all, by analyzing fixes from multiple locations later... a method referred to as virtual reference station.

So how much does this stuff actually impact our lives? Well, for the most part we tend to use smartphones for PNT in our daily lives, and smartphones have a somewhat different bag of tricks that relies on the cellular network to assist positioning. The thing is, smartphone GPS receivers really aren't very accurate at all. They rely on network assistance not for precision but in order to obtain any fix at all. Smartphones are constantly used in situations like urban environments and even indoors where GPS reception is poor and subject to huge multipath error. Cellular receivers bootstrap based on hints from the network (using the known locations of cellular towers) to accelerate GPS fix, and to produce a fix at all when they can't detect signals from a sufficient number of GPS satellites.

And that's it on PNT for today, but maybe I'll come back to shill more for eLORAN in the future.