WHITE PAPER

Not just where are you, but when are you

Unveiling the mystery behind GNSS correction service reference frames

Abstract

This white paper provides an overview of various coordinate reference frame systems and their role in calculating GNSS correction data. When evaluating a GNSS correction service, users often need to compare services. Detecting a significant offset between the two indicates using different reference frames. The author unveils the mystery of this offset by exploring what lies behind reference frames and pointing out concrete examples of their use. Through these explanations, readers will understand that a GNSS correction service not only answers the question ‘where are you?’ but also ‘when are you?’

White paper: Not just where are you, but when are you
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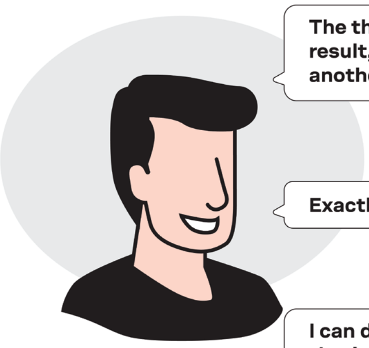
Background / Executive summary

Global navigation satellite systems (GNSS) have transformed our world. Since its commercialization, anyone can quickly and easily pinpoint locations around the planet. GNSS provides location accuracy down to several meters, which is more than satisfactory for most applications. However, emerging use cases, such as driving automation in autonomous vehicles, precision agriculture, or robotic lawnmowers, require far higher accuracy.

To achieve this, GNSS correction data account for satellite clock and orbit errors and signal biases, as well as ionospheric and tropospheric influences. Entities computing these data are known as correction services, and nowadays, many are available. This, combined with the primary GNSS signal, makes it possible to improve accuracy to within centimeters.

But when comparing results from different services for a precise location, users might find a significant offset. Discovering this fact makes them wonder what might be wrong, raising a broad spectrum of inquiries. So finally, after questioning the devices' technology and the reliability of the correction services, users continue to try to find answers to these 'anomalies.' And so here we are, in the middle of a conversation between our author, Bastian, and our customer, Stephan:



Hey Bastian, how are you?

Hey, Stephan. Doing well. How can I help?

Listen. I have something that has been puzzling me for a while, and I know I am not the only one.

Okay, tell me more; I'm listening.

The thing is. Measuring with your correction service gives me a result, but a colleague did the same, only measuring with another service. And guess what?

Mmm. You got different results.

Exactly. How do you know?

Don't panic. You are not the first one to notice this.

I can deal with some offset, but here we are talking about 80cm; that's almost a one meter difference, huge!

Yes... that can happen.

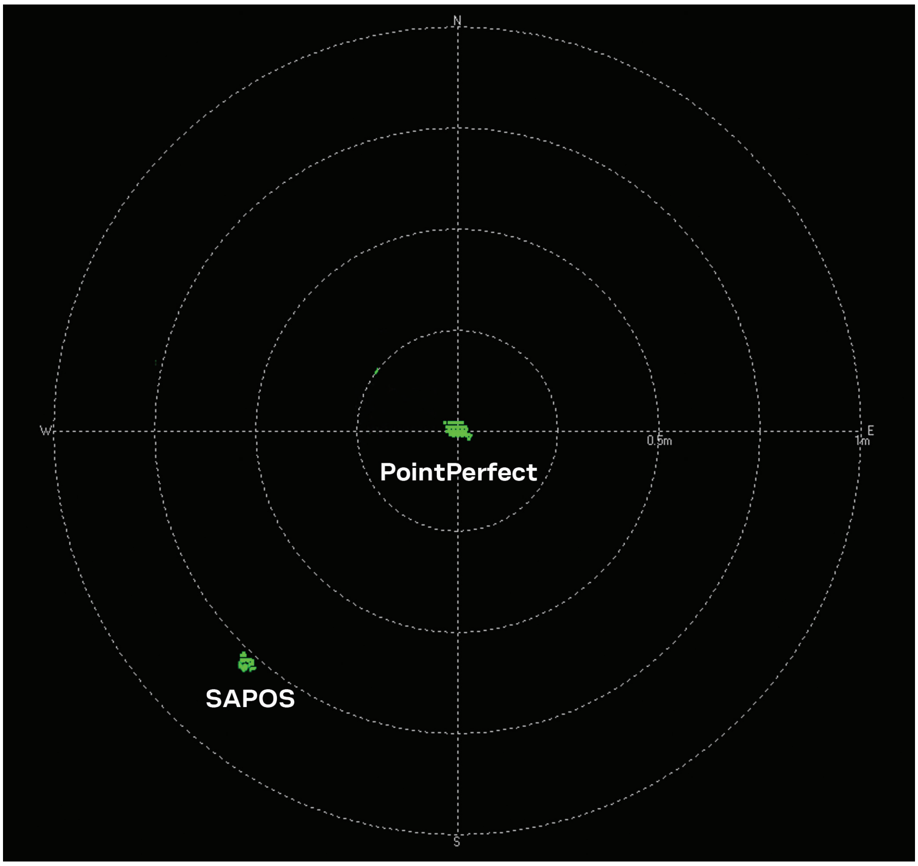
How?

Do you have time? Cause I need some minutes to take you through it.

Sure. Please... go ahead.

Stephan, like other customers, is intrigued by an 80cm offset in position measurements between two different GNSS correction service providers. We discuss it often enough that it becomes helpful to answer it here.

This white paper unveils the mystery by providing an overview of various coordinate reference frame systems and their use when calculating GNSS correction data. We will explore the factors behind reference frames and provide examples of their use. With this, you will understand that for answering the question ‘where are you?’ a correction data service also answers the question ‘when are you?’.


PointPerfect vs SAPOS for F9P

Europe customer case Germany

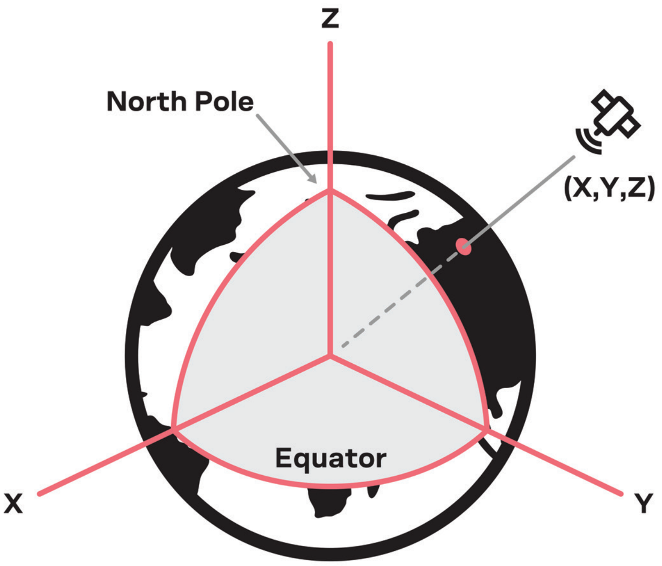
Introduction

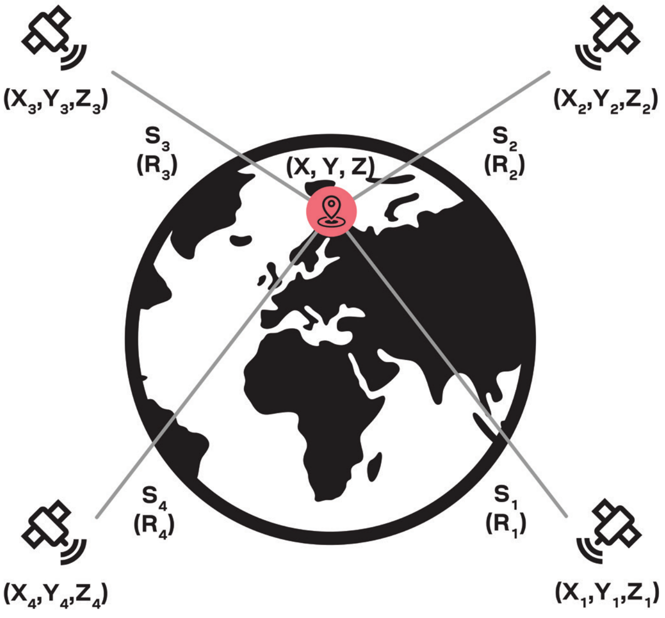
Determining the exact position of an object on Earth has developed through the years in areas such as navigation and surveying. Centuries ago, sailors found their geographical position by using land reference points. But to sail into oceans, they eventually developed methods using the sky as a reference; they found their bearings by watching the motion of birds, the Sun, and the stars. While navigation made significant steps in localizing objects in the ocean, other efforts were taking place on solid ground. By the end of the 19th century, governments started rolling out dense survey control points (markers). These points' networks created regional coordinate systems, aiding in surveying tasks. Over time, these survey markers expanded across regions, states, and countries, enhancing the horizons of coordinate systems. So much so that they have become the basis for mapping vast regions and, eventually, the world. Meanwhile, distance measurement instruments evolved, enhancing accuracy from kilometers to millimeters.

For a time, these developments remained isolated without the need to determine a common ground, a unique reference frame. But becoming more global implied relying on applicable global systems, especially when considering modern technology like GNSS satellites.

Coordinate systems, satellites, and GNSS localization

For centuries, finding an object's position on the Earth relied on physical local systems references and points like the ones mentioned in the previous section rather than on a 3D coordinate system. The advent of GNSS satellites, however, brought a meaningful change. By now, finding the position of an object in space does not rely on physical reference points. Instead, to determine its coordinates, GNSS receivers measure distances to GNSS satellites orbiting the Earth, which can transmit their position to users at any given time. Receivers can triangulate positions once they know both the GNSS satellite position (similar to an Earth-bound marker, creating a virtual reference point) and the measured distance. The obtained numerical value is a consequence of the GNSS satellite's coordinate frame. This worldwide approach enables accurate meter positioning without considering where the measurement takes place.





Alas, the story is more complex. Even though this positioning technique provides precision at a high level, several factors interfere with its accuracy. Atmospheric delays, satellite clock and orbit errors, and signal biases contribute to obtaining inaccurate positions, adding up to meters altogether. As a solution, either correction services (using dense GNSS reference station networks) or local reference stations (also called base stations) can aid in reducing these errors drastically. In both approaches, the reference stations correct the GNSS measurements, hence "overruling" the coordinate frame of the GNSS satellites.

Technically, everybody could use one worldwide coordinate system and one associated reference frame. However, this is not the case. While the coordinate system is static (center of Earth, axis, etc., do not change), the surface of the Earth constantly moves, thus changing points' position and, in turn, their coordinates.

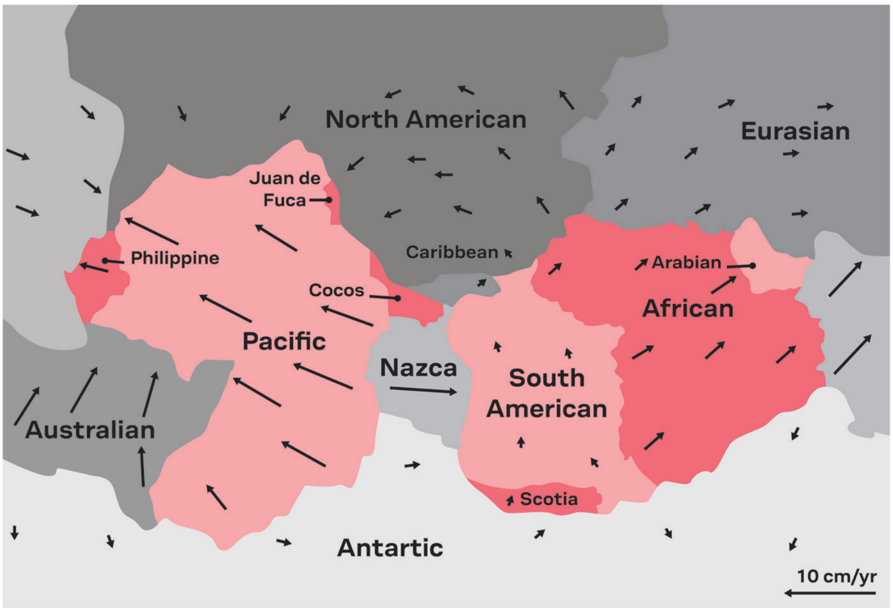
The earth’s surface is not static

Tectonic plates movement and the implications for accurate geopositioning
Let us say you are sitting on your favorite couch at your childhood home. Your position today is different from what it was 30 years ago, assuming you are sitting on the same couch, and it has remained the same since. Say what? It is true. The simple fact is that the Earth’s crust moves, and with it, we all do. The motion is lethargic, almost imperceptible, about 2-3 centimeters per year in Europe and North America, and up to a decimeter worldwide. But if we consider a long enough amount of time, the motion becomes tangible. In those 30 years, your location on your favorite couch has moved almost 80cm. The Eiffel Tower, built between 1887 and 1889, has moved 3.5 meters from its original position. Can you imagine?

Tectonic plates move at different rates and in different directions
The Earth’s crust moves because its outer shell comprises massive moving irregularly shaped slabs of solid rock known as tectonic plates. The formation of mountains, earthquakes, volcanic activity, and tsunamis are surface effects caused by this natural phenomenon.

For instance, the Pacific plate moves in a northwest direction at a speed of 7 to 11 centimeters per year. The image below shows that each arrow (vector) points in a slightly different direction and travels at a different velocity (represented by the length of the arrow). The case of the North American plate is even more noticeable. Although the velocity magnitude is similar for each vector, the direction varies enormously from region to region—more activity results in more variation on the surface of the Earth.

As you might have already figured out, the movement of tectonic plates means that high-precision survey markers will also move, which has repercussions for how we measure positions on the Earth. For precisely determining an object’s location, the movement of a tectonic plate, considering certain speeds and different directions, becomes highly relevant.



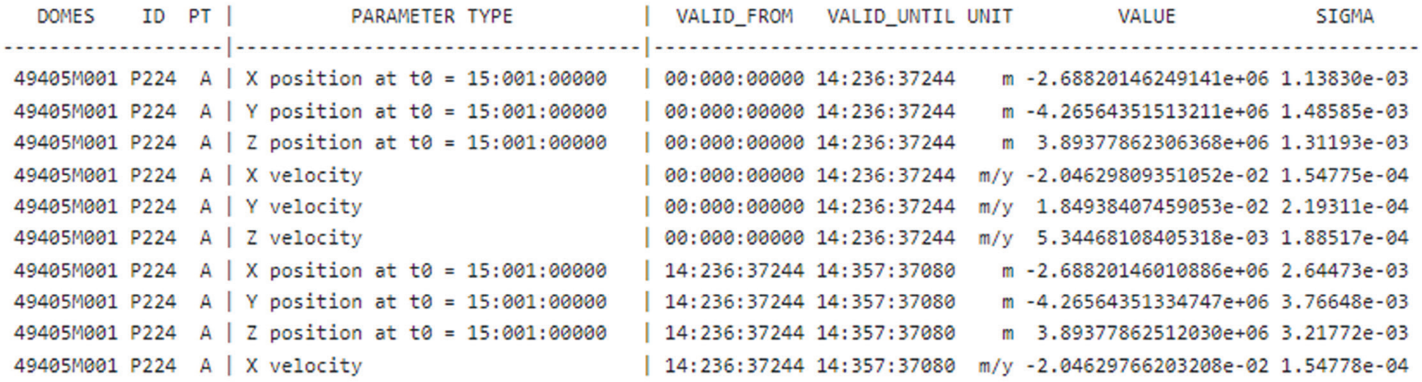
Reference frames

The fact that the coordinate system is static while reference points constantly move on the Earth's surface gives rise to a fundamental problem. International Earth Rotation and Reference Systems Service (IERS) is a global organization providing a continuous solution for this discrepancy. Since its foundation in the late 80s, IERS has served the astronomical, geodetic, and geophysical communities by providing data and standards related to the Earth's rotation and reference frames. IERS calculates coordinates and respective velocities considering hundreds of points worldwide. Over the past decades, refining methods and adding more reference base stations has led to a much more accurate solution–up to mm level.

Before moving forward, since we are defining what frames are, we must also mention what they are based on: systems. A system is a theoretical definition that considers initial coordinates without changing position over time. IERS defines it as a '…set of prescriptions and conventions together with the modeling required to define at any time a triad of axes.'[1] On the other hand, a frame is a practical realization changing over time, supported by marked points connecting measurements to fixed systems. IERS has published this set of points in specific years. Since its launch in 1989, the organization has released twelve realizations (1989, 1990, 1991, 1992, 1993, 1994, 1996, 1997, 2000, 2005, 2008, 2014, and 2020). Each of them provides a more accurate solution as the availability of points increases.

The spatial points plus their velocities are what we refer to as a reference frame. Each point corresponds to an XYZ value defined in the reference frame at a given time, also called an epoch. And when time elapses after the origin epoch, the original x, y, and z values are updated by adding the x, y, and z velocities.

Here is how it works. The image below shows an extract of the International Terrestrial Reference Frame: ITRF 2020. The origin of point P224 is XYZ and is valid for the first day of 2015 (t0). Exactly five years later, considering yearly velocities of x=-2.4cm, y=1.8cm, and z=0.7cm, the original coordinates would shift 12cm, 9cm, and 3.5cm, respectively.



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   DOMES     ID  PT |          PARAMETER TYPE            |  VALID_FROM   VALID_UNTIL UNIT        VALUE            SIGMA
--------------------|------------------------------------|-----------------------------------------------------------------
 49405M001 P224   A | X position at t0 = 15:001:00000    | 00:000:00000 14:236:37244    m -2.68820146249141e+06 1.13830e-03
 49405M001 P224   A | Y position at t0 = 15:001:00000    | 00:000:00000 14:236:37244    m -4.26564351513211e+06 1.48585e-03
 49405M001 P224   A | Z position at t0 = 15:001:00000    | 00:000:00000 14:236:37244    m  3.89377862306368e+06 1.31193e-03
 49405M001 P224   A | X velocity                         | 00:000:00000 14:236:37244  m/y -2.04629809351052e-02 1.54775e-04
 49405M001 P224   A | Y velocity                         | 00:000:00000 14:236:37244  m/y  1.84938407459053e-02 2.19311e-04
 49405M001 P224   A | Z velocity                         | 00:000:00000 14:236:37244  m/y  5.34468108405318e-03 1.88517e-04
 49405M001 P224   A | X position at t0 = 15:001:00000    | 14:236:37244 14:357:37080    m -2.68820146010886e+06 2.64473e-03
 49405M001 P224   A | Y position at t0 = 15:001:00000    | 14:236:37244 14:357:37080    m -4.26564351334747e+06 3.76648e-03
 49405M001 P224   A | Z position at t0 = 15:001:00000    | 14:236:37244 14:357:37080    m  3.89377862512030e+06 3.21772e-03
 49405M001 P224   A | X velocity                         | 14:236:37244 14:357:37080  m/y -2.04629766203208e-02 1.54778e-04
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[1] https://www.iers.org/IERS/EN/Science/ICRS/ICRS.html

Two types of reference frames: fixed epoch versus current epoch

Reference frames can take a fixed or an actual current epoch as a reference. The former corresponds to the origin epoch, whereas the latter considers the current velocities of tectonic plates. Furthermore, since the movement on a tectonic plate is similar on its whole surface, except on the plate boundaries where the change in rate accentuates, we can define a static coordinate reference frame. This possibility gives rise to regional reference frame systems, released at specific times and consistent with ITRF realizations for the sake of interoperability.[2]

Fixed epoch and current epoch reference frames have advantages and disadvantages. The former is less accurate than the latter, fitting better in regions requiring nonchanging coordinates. The design of many applications does not consider current epochs. For instance, maps do not change over time, so a fixed epoch design fits better. In contrast, the current epoch is an up-to-date measurement that suits better worldwide applications.

Relying on this variety of possibilities, correction service providers can apply different systems and reference frames. For example, local or regional Network RTK providers tend to use static frames like SmartNet (Hexagon), VRS NOW (Trimble), and TOPNET (TOPCON). On the other hand, services covering more significant areas consider the tectonic plates' velocities and provide "dynamic" current epoch corrections. Examples of service providers following this methodology are PointPerfect (u-blox) and RTX (Trimble).

Another type of reference frame is the regional, also known as spin-offs. These frames assume that tectonic plates move in the same direction and at the same velocity. Using these frames is convenient for areas moving at a constant speed where the movement is barely perceptible. In addition, with these frames, one can discard the time variable. However, regions where the activity is not constant (same direction and speed) can compromise their use, which is quite common.

Comparing different reference frames

Let us see how theory comes into action. In this example, we use SmartNet (Hexagon) and PointPerfect (u-blox) correction services providers to pinpoint the position of the Eiffel Tower's tip. The image on the following page shows two position measurements offset by 82.5 cm.

We can now explain why SmartNet (Hexagon) uses ETRF89, which is consistent with ITRF89. The points of this reference frame barely move over time; they are 'frozen' and correspond to measurements taken in 1989.

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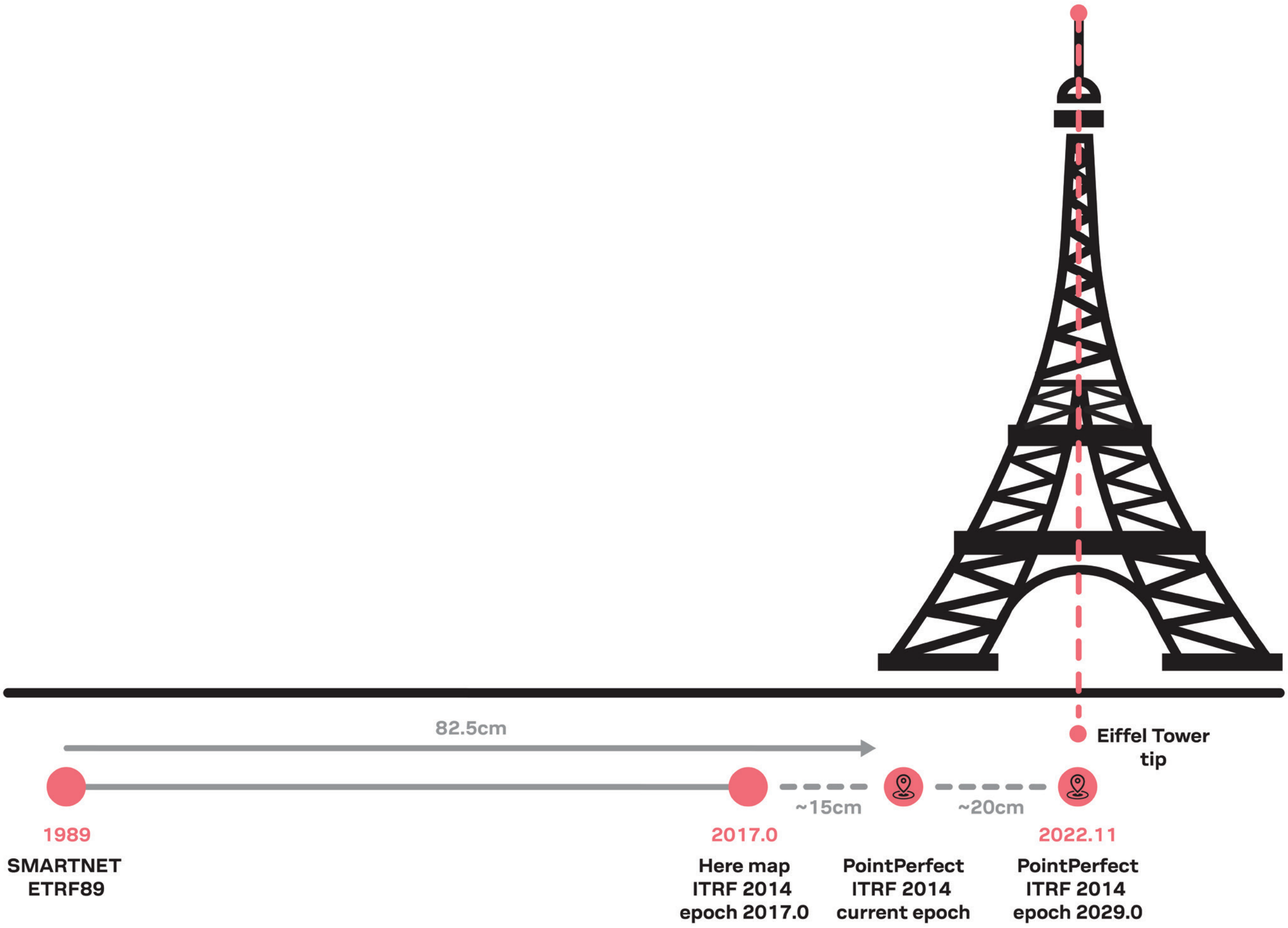
[2] Examples of these regional reference systems, also called "static realizations," are ETRF 89 for Europe. KGD 2000 for Korea, JGD 2011 for Japan, and GDA 2020 for Australia.

PointPerfect (u-blox), on the contrary, uses a ‘current’ approach. In this case, the result is the combination of considering coordinates from frame ITRF2014 plus the addition of the ‘current epoch.’ PointPerfect takes points registered in 2014, plus considering the actual coordinate due to the motion of tectonic plates. As a result, a considerable discrepancy arises between these two correction services. Since the tectonic plate moves at 2.5 cm per year, after 32 years, the actual number is close to 82 cm (32 x 2.5 cm).

Another hypothetical correction service could use the 2017.0 epoch, corresponding to the first day of 2017. This service would find the coordinates of the Eiffel Tower’s tip between the other two mentioned services, 67.5 cm away from ETRF89 and 15 cm from PointPerfect.

One last point to raise when considering different reference frames is that, if necessary, users may navigate from one reference frame to another. The mathematical process requires shifting the center of your coordinate system and rotating each axis. A well-accepted method for conversion is known as the Helmert (seven-parameter) transformation, which uses seven parameters to shift, rotate, and scale coordinates from frame A to frame B. In technical words, the transformed vector (set of final coordinates) will equal a translation vector plus the scale factor times the rotation matrix and the initial vector (set of initial coordinates).



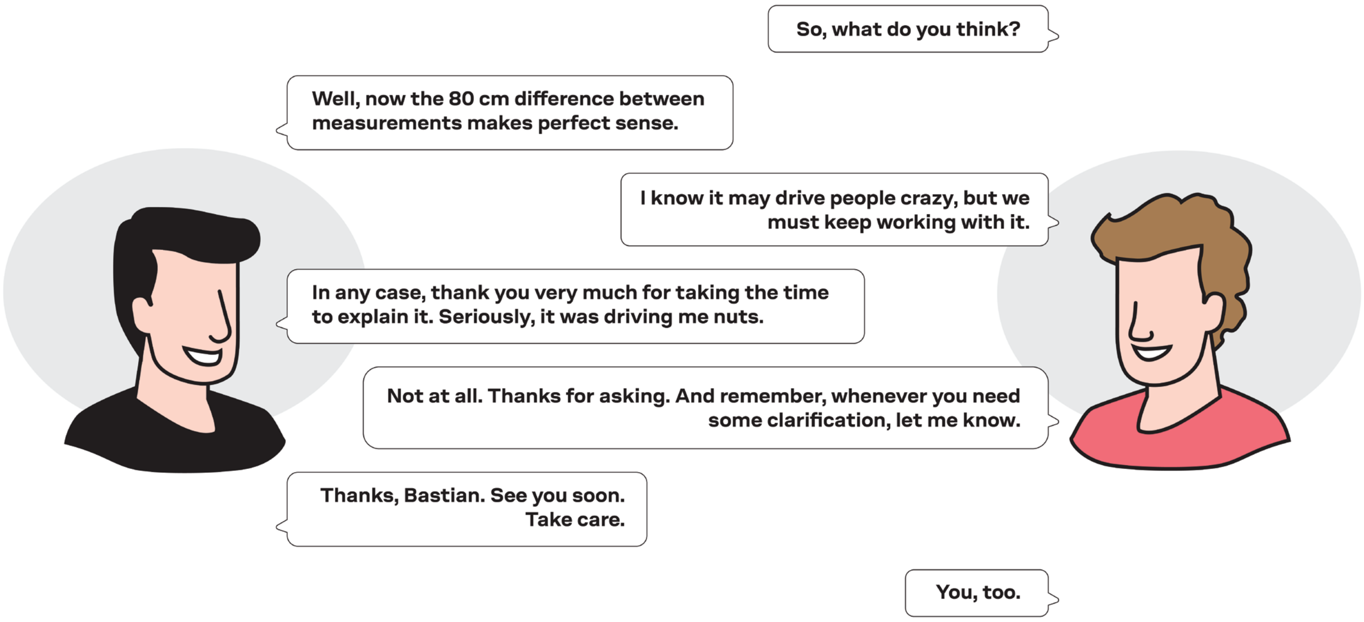
Summary

With today's technology, finding the precise location of an object on the planet should be a repeatable task. But taking a step back reveals a mysterious and relative complexity. What is the exact location of a person or object? This question might have a straightforward answer based on a spatial XYZ reference frame, yet because the Earth's surface is not static, it relies on a hidden variable: time. Time parameters link to spatial parameters when obtaining a precise position; thus, the position of an object or person becomes relative to time. The question becomes not just about where you are but also when you are.

In a nutshell, measuring an object's position is contingent on the GNSS correction service's reference frame. High-precision GNSS measurements depend on the earth's surface movement. Tectonic plates move in different directions and at different speeds over time. Even on each tectonic plate's surface, speed and orientation variations occur. This conundrum finds a solution in various reference frames: fixed epoch, current epoch, and regional statical frames.

If you are using a unique correction service, do not worry; other reference frames do not impact the performance and accuracy of the system. Discrepancies will only occur when comparing results of different correction services. But make no mistake, comparing them will inevitably lead to differences because each uses non-identical reference frames. Measurements will differ, and an offset in the data will appear. Fortunately, mathematical methods are on your side. They permit users to calculate back and forth between reference frames and account for the offset. This does not mean that if you want to compare results, you must dig into the mathematical world without guidance. Some correction services offer easy-access conversion tools.

After elaborating on the topic, the conclusion is that measurements are not right or wrong; instead, they differ because of the disparate reference frames used to obtain those results. As in every detective story, the solution to this mystery does not lie in the facts but in the details.



Find out more: https://www.u-blox.com/en/product/pointperfect
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About the authors

Bastian Huck, Senior Principal Engineer, u-blox

Bastian Huck works for u-blox as a senior principal engineer in the services division. He finished his geodesy studies in 2001, and ever since he has been working in the field of GNSS correction services across different application areas. He started his career at Allsat GmbH setting up some of Germany and Europe's first GNSS/RTK networks, mainly serving surveying and construction applications. After a few years, the company joined AIRBUS, where he had a deep dive into safety-relevant corrections services like EGNOS and the aviation application area. Before joining u-blox, he also gathered experience in the automotive domain, working at Bosch for two years, where he contributed to developing a GNSS sensor.

About u-blox

u-blox (SIX:UBXN) is a global provider of leading positioning and wireless communication technologies and services for the automotive, industrial, and consumer markets. Their solutions let people, vehicles, and machines determine their precise position and communicate wirelessly over cellular and short range networks. With a broad portfolio of chips, modules, and a growing ecosystem of product supporting data services, u-blox is uniquely positioned to empower its customers to develop innovative solutions for the Internet of Things, quickly and cost effectively. With headquarters in Thalwil, Switzerland, the company is globally present with offices in Europe, Asia, and the USA.

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