GNSS Solutions:

Precise Point Positioning and Its Challenges, Aided-GNSS and Signal Tracking

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnists, **Professor Gérard Lachapelle** and **Dr. Mark Petovello**, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. Their e-mail addresses can be found with their biographies at the conclusion of the column.

What is precise point positioning (PPP), and what are its requirements, advantages and challenges?

Precise point positioning (PPP) is a method that performs precise position determination using a single GPS receiver. This positioning approach arose from the advent of widely available precise GPS orbit and clock data products with centimeter accuracy. These data can be applied to substantially reduce the errors in GPS satellite orbits and clocks, two of the most significant error sources in GPS positioning.

Combining precise satellite positions and clocks with a dual-frequency GPS receiver (to remove the first order effect of the ionosphere), PPP is able to provide position solutions at centimeter to decimeter level, which is appealing to many applications such as airborne mapping, as shown in **Figure 1**. PPP is different from double-difference RTK (real-time kinematic) positioning that requires access to observations from one or more base stations with known coordinates. The word "precise" is also used to distinguish it from the conventional point positioning techniques that use only code or phase-smoothed code as the principal observable for position determination.

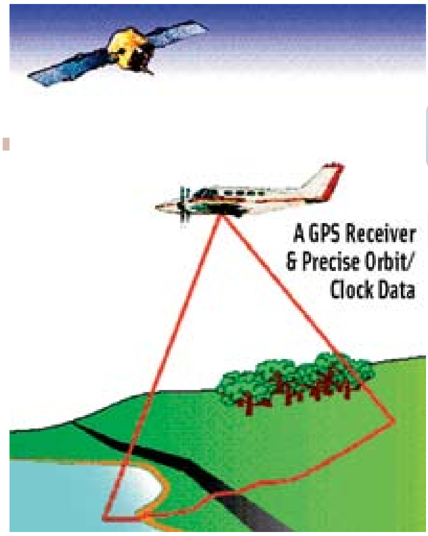


FIGURE 1 Airborne mapping without ground base stations

To illustrate the accuracy of PPP, **Figure 2** presents the position errors for PPP static positioning over 24 hours at a control station with known coordinates. **Figure 3** shows the position errors (compared to the double-difference RTK solutions) for PPP kinematic positioning with an aircraft. **Tables 1** and **2** are the

	Latitude	Longitude	Height
Mean	0.8	0.3	0.0
RMS	0.9	1.0	0.7
STD	0.3	0.9	0.7

TABLE 1. Static positioning accuracy (cm)

	Latitude	Longitude	Height
Mean	-0.2	-1.5	-1.5
RMS	2.8	6.8	4.9
STD	2.8	6.7	4.6

TABLE 2. Kinematic positioning accuracy (cm)

Product	Parameter	Accuracy	Latency
Ultra-Rapid (predicted)	orbits	~10 cm	real-time
	clocks	~5 ns	
Ultra-Rapid (estimated)	orbits	<5 cm	3 hours
	clocks	~0.2 ns	
Rapid (estimated)	orbits	<5 cm	17 hours
	clocks	0.1 ns	
Final (estimated)	orbits	<5 cm	~13 days
	clocks	<0.1 ns	

TABLE 3. IGS Precise Orbit and Clock Product Accuracy and Latency

corresponding position accuracy statistics after initialization.

Position determination with PPP has been widely based on the processing of the following ionosphere-free combinations of the *un*differenced code and phase observations (called the *traditional* mode):

$$P_{IF} = \frac{f_1^2 \bullet P(L1) - f_2^2 \bullet P(L2)}{f_1^2 - f_2^2} = \rho - cdT + d_{trop} \quad (1)$$

$$\Phi_{IF} = \frac{f_1^2 \bullet \Phi(L1) - f_2^2 \bullet \Phi(L2)}{f_1^2 - f_2^2} = \rho - cdT + d_{trop} + \frac{cf_1 N_1' - cf_2 N_2'}{f_1^2 - f_2^2} \quad (2)$$

where f_1 and f_2 are the GPS L1 and L2 frequencies; $P(Li)$, $\Phi(Li)$ are the code and phase observations; ρ is the true geometric range; c is the speed of light; dT is the receiver clock offset; d_{trop} is the tropospheric effect; N_i' is the phase ambiguity term in $\Phi(Li)$. **Equations (1)** and **(2)** indicate that the unknown parameters to be estimated in PPP include position coordinates, phase ambiguity terms, receiver clock offset and the tropospheric effect.

Precise orbit and clock products with the centimeter-level accuracy needed for PPP techniques are now widely available, in post-mission and real-time, from a number of public organizations, such as the International GNSS service (IGS), Natural Resources Canada (NRCan) and Jet Propulsion Laboratory (JPL), as well as commercial sources. IGS, for example, offers precise orbit and clock products in varying accuracy and latency from Final Estimated to Ultra-Rapid Predicted, as shown in **Table 3**.

Precise point positioning also requires a number of unconventional corrections to mitigate systematic effects that could cause centimeter variations in the undifferenced code and phase observations. Phase wind-up correction, satellite antenna offset, and site-displacement effects due to solid earth tide and ocean loading are some examples. Those corrections are not typically considered for standard point positioning and double-difference RTK positioning.

Precision benefits. The PPP method can offer several significant advantages to applications compared to differential precise positioning techniques. First, PPP involves only a single GPS receiver and, therefore, removes the need for GPS users to establish local base stations. As a result, it eliminates the spatial operating range limit as well as the constraint of simultaneous observations on both rover and base receivers imposed by the differential RTK technique.

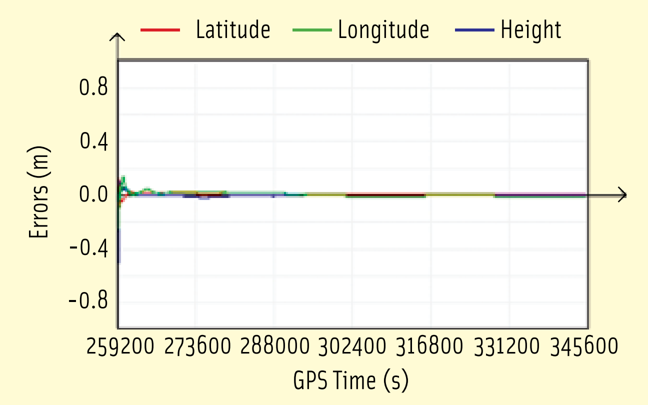


FIGURE 2 **Static positioning errors**

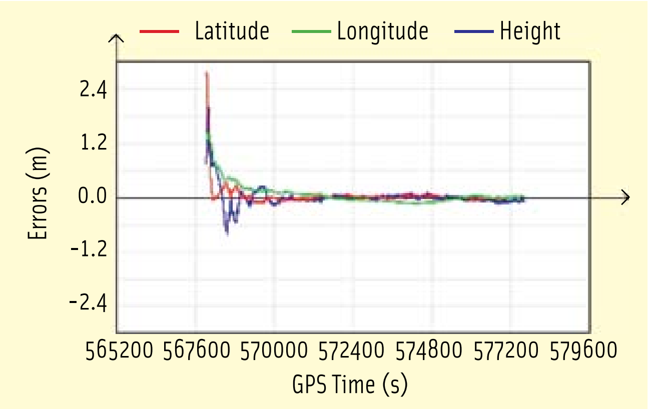


FIGURE 3 **Kinematic positioning errors**

Next, PPP can be regarded as a global positioning approach because its position solutions are referred to a global reference frame. As a result, PPP provides much greater positioning consistency than the differential approach in which position solutions are relative to the local base station or stations (although we should note that, if the base station coordinates are known in an absolute sense, the absolute position of the user is then obtained).

Another significant benefit that PPP can bring to applications is that it reduces labor and equipment cost and simplifies operational logistics to field work since it eliminates the dependency on base station(s). Further, PPP can be applied to support other applications beyond positioning. For example, PPP needs to estimate receiver clock and tropospheric effect parameters in addition to position coordinate parameters as indicated by equations (1) and (2), and, therefore, it provides a new way for precise time transfer and water vapor estimation using a single GPS receiver.

Challenges and Prospects. PPP faces several challenges in order to achieve its full potential to applications. A long initialization time, typically more than 20 minutes necessary for the float position solution to converge to the centimeter accuracy, has limited its use in real-time applications. Some methods have been proposed but no significant improvement has been made to date.

Another challenge is that the ambiguity terms N'_1 of the undifferenced carrier phase observations are no longer integer because they are corrupted by satellite and receiver initial phase biases as shown below:

$$N'_i = N_i + \varphi_i^r(t_0) - \varphi_i^s(t_0) \quad (3)$$

where N_1 is the integer ambiguity term, $\varphi^r{}_i(t_0)$, $\varphi^s{}_i(t_0)$ are the receiver and satellite initial phase biases.

Research work on the identification and determination of these two biases is currently under way. A positioning model, developed at the University of Calgary and based on the following ionosphere-free observation combinations, has already been proposed which can support integer ambiguity resolution after the initial phase biases are eliminated.

$$P_{IF,L1} = 0.5[P(L1) + \Phi(L1)] = \rho - cdT + d_{trop} + 0.5\lambda_1 N'_1 \quad (4)$$

$$P_{IF,L2} = 0.5[P(L2) + \Phi(L2)] = \rho - cdT + d_{trop} + 0.5\lambda_2 N'_2 \quad (5)$$

$$\Phi_{IF} = \frac{f_1^2 \bullet \Phi(L1) - f_2^2 \bullet \Phi(L2)}{f_1^2 - f_2^2} = \rho - cdT + d_{trop} + \frac{cf_1}{f_1^2 - f_2^2} N'_1 - \frac{cf_2}{f_1^2 - f_2^2} N'_2 \quad (6)$$

A need to access precise orbit and clock products might also concern some users. For instance, significant delays occur in the availability of some IGS precise orbit and clock products (see Table 1). Commercial service providers charge fees to access real-time precise orbit and clock data in order to develop PPP-based precise positioning products.

In summary, PPP is a novel precise positioning technology that can be an efficient alternative to current differential RTK positioning techniques for many applications. Increased use of this technology is currently taking place, including commercial product development. The addition of GLONASS and Galileo clock and orbit data would probably further enhance PPP's overall performance in terms of accuracy and reliability.

Yang Gao, Ph.D., is a professor in Department of Geomatics Engineering at The University of Calgary. His research focuses on the development of innovative methods and applications using GNSS and other enabling sensors. He has developed a precise point positioning software used by worldwide users. Dr. Gao is chair of the International Association of Geodesy's Sub-Commission 4.5: Next Generation RTK.

Does Aided-GNSS improve signal acquisition, tracking, or both?

A-GPS (Aided/Assisted-GPS) and more recently its extensions, A-GNSS, have been introduced to substitute for missing satellite broadcast data when access is intermittent, difficult, or impossible due to signal obstruction. It has expanded the capabilities of the traditional receiver in reducing the time to first fix (TTFF), enabling "high sensitivity" modes, improving the performance in urban canyons and indoors, and incidentally, boosting the receiver's efficient use of power.

Multiple ways have been developed to deploy an A-GPS server, and to distribute the process flow between the server and the mobile. The mobile station–based method places the position determination in the receiver, while the network-based method relegates it back to the server.

Other notable factors influence the architecture. The assistance can be one-way, where information accessible at the server flows down to the receiver, or in closed loop, where the information is uploaded to the server, processed remotely applying far larger computational resources and extra knowledge not available to the receiver, and then pushed back to the receiver in its final form.

We will now introduce two simple rules that will illustrate the rest of the explanations:

Rule 1: For A-GPS to be practical, the assistance information should not be stale when ready to be used at the mobile. In more technical

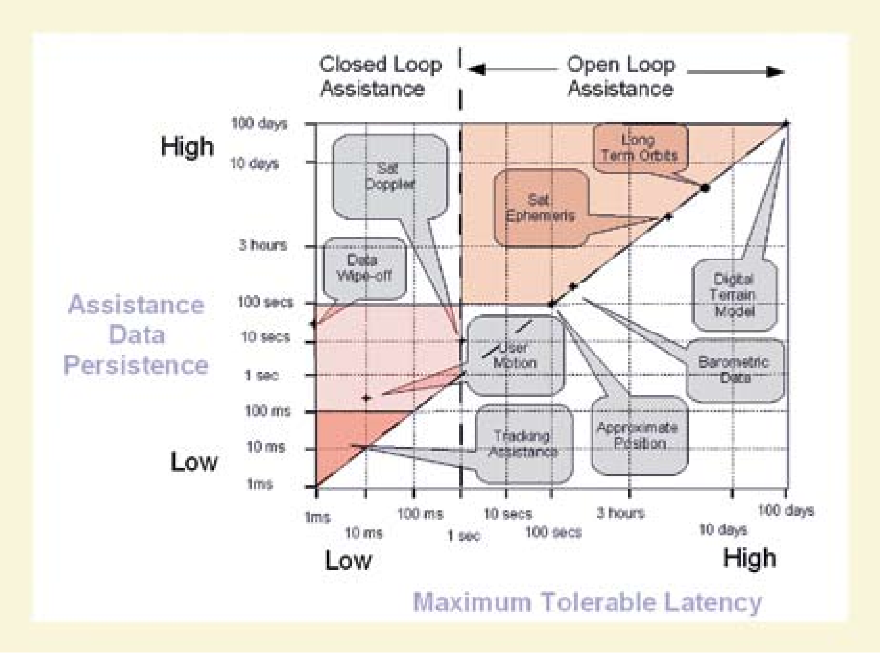


FIGURE 1 A-GPS Assistance Persistence time vs. Maxiumum Tolerable Latency at the receiver for various assistance data.

terms, the assistance information persistence needs to be longer than the sum of network latency plus server and mobile processing times,

Rule 2: In a closed loop architecture, the information collected at the mobile, and processed at the server should be returned fast enough before the internal state of the mobile changes too much. We can reformulate it as the sum of the round trip network delay plus server and mobile processing times have to be shorter than the process time constant to control the mobile.

Armed with this new insight, it becomes obvious that the overwhelming majority of the acquisition assistance is of the open loop type, and fulfills only Rule 1. To reduce the TTFF, an A-GNSS server brings the receiver logic state in a mode similar to "hot-start," where all information for a fix is handy, except ranging data. Satellite position, approximate user position, and even timing information — all exploited for reducing the satellite search domain — are indeed delivered by the server, albeit originating in a reference network of monitoring stations.

Receiver sensitivity. Another important role of acquisition assistance is improving receiver sensitivity. The satellite navigation data stream can be predicted at the server from the past collected data and transmitted to the receiver. During the PRN code correlation step, the receiver can flip the data bits, and artificially and arbitrarily extend the duration of the coherent integration beyond the 20 milliseconds in the L1 C/A-code.

The navigation data persistence is about 30 seconds and beyond, but the tolerable latency at the mobile is about 1 millisecond. Data wipe-off can be implemented only as a one-way assistance, delivering up to 30 seconds of accurately time-tagged predicted data bits.

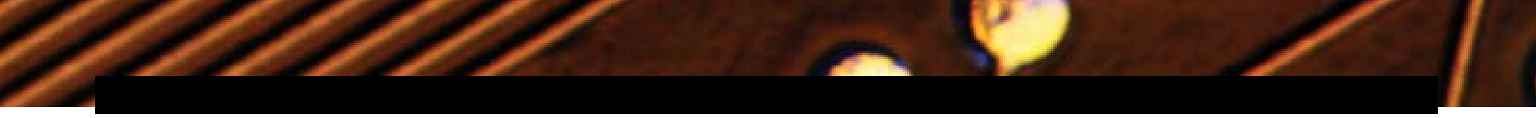
To align these predicted navigation data bits with the received navigation data bits requires an external sub-millisecond time synchronization, not part of the one-way assistance. This is usually accomplished either by extracting an approximate GPS time from the navigation message or by alignment with a GPS-synchronized local cellular base station.

The closed loop latency issue raised by Rule 2 is difficult to fulfill in cellular networks. Beyond the time needed to establish a connection between the base station (server) and the mobile station, which can take up to 10 seconds, a typical turn-around latency time fluctuates around one second. This simple observation rules out closed loop implementations for the current A-GPS architectures, where 100 milliseconds are the typical process time constants. When it comes to tracking, no direct real-time assistance can be given by the server to the receiver in the signal tracking. The tracking loops have a sampling rate typically between 1 to 100 milliseconds, one order of magnitude faster than the round-trip transmission time.

Local environmental factors. A little more hindsight will reveal that, beyond space segment information — which satellites are healthy, where they are, what is their proper motion, and what is their navigation message — absolute information (time and frequency) is highly dependent on knowledge of user motion (how fast is the receiver moving and in what direction) and the immediate surroundings (blockage of satellite signals by buildings, signal attenuation by tree canopy, or the interference of other moving elements such as cars or pedestrians). All are types of local environment-based information that server is not aware of.

If we encompass the position determination step in the tracking, the server regains its meaning by providing some environmental data that will be directly exploited in the receiver algorithms. Differential GPS correction assistance is natural and a well understood technique for improving position accuracy, with a correction model valid within 10-30 seconds, in an area up to 10 kilometers around the current receiver position. Less obvious, but widely used assistance information comes from downloading sections of a road network that can be used for map-matching.

Another more recent approach is the use of a digital terrain model (DTM) that supplements the number of satellites with a virtual one positioned at the center of earth. Barometric assistance supplies a standard atmosphere model and few adjusted coefficients that provide quite precise altitude change information.



Assistance data types. One will easily figure out that all these types of assistance are delivered as models, with a validity domain large enough to accommodate latency plus the data persistence. As an illustration, the DTM is a spatial area model around the known receiver position, wide enough to trigger another download before the receiver wanders out of the covered area, guarding against data interruption.

Figure 1 shows the maximum assistance data persistence plotted against the maximum latency the receiver can tolerate for various assistance data types. This plot will become quite handy for illustrating the rest of this article.

Several well-known assistance data types are plotted; thanks to Rule 1, they all lie on or above the main diagonal in the persistence/latency space. The closer to the origin of the plot, the more useful and powerful is the assistance. All close loop assistances are concentrated on the left of the 1 second vertical line.

The traditional server architecture usability domain is represented in orange, in the upper right corner. The A-GNSS usability domain does not extend to the pink area, with the exception of the data wipe-off where the server latency issue is circumvented by a separate synchronization means. This is where the domain of the true tracking assistance lies, still in its early phase.

The area in red, at the lowest leftmost corner, represents where the expectations for improved performance are the highest. The future of assistance certainly lies in how close (i.e. how relevant) to the end user the data can be collected, and how fast is can be communicated to the end user's mobile.

One of the ways to enter the red area of low-persistence/low-latency is to explore cooperative location techniques in which other GNSS users located near the GNSS user requiring assistance have a role in providing assistance. They have the major advantage of "being there" in the field and sharing the same signal distortions and can provide the same radio propagation information from another angle.

In principle these nearby "assisting" users could deliver assistance data to the user needing additional aid. This opens another Pandora's box: will those nearby users be willing to compromise their location privacy and commit valuable power resources from their mobile devices for the benefit of the user community?

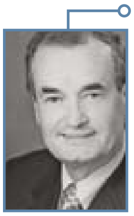
So, the A-GNSS server might still be in the picture even in the case of the "community assistance" model, to perform data aggregation, filtering, and persistence management from the other mobiles as sensors, but without resources (or users willing to share them) to do the aggregation. Time will tell. . . .

LIONEL J. GARIN

Lionel J. Garin, chief technical officer, NemeriX SA., is in charge of development initiatives to advance NemeriX's GPS, assisted-GPS (AGPS), and other location technologies for mobile devices and consumer applications. He previously held the position of director of systems architecture and technology at SiRF Technology, Inc. Garin holds fundamental patents in multipath mitigation, among others, the "Strobe Correlator" also known as the "Double-Delta Correlator." Since 1998 he has focused on AGPS capabilities and indoor high-sensitivity applications. He has been heavily involved in GPS initiatives for the mobile phone market, where he holds a number of fundamental patents on the topic. IG

Mark Petovello is a Senior Research Engineer in the Department of Geomatics Engineering at the University of Calgary. He has been actively involved in many aspects of positioning and navigation since 1997 including GNSS algorithm development, inertial navigation, sensor integration, and software development.

Email: mpetovello@geomatics.ucalgary.ca



Professor Gérard Lachapelle holds a CRC/iCORE Chair in Wireless Location in the Department of Geomatics Engineering at the University of Calgary. He has been involved with GNSS since 1980 and has received numerous awards for his contributions in the area of differential kinematic GPS and indoor location.

Email: lachapel@geomatics.ucalgary.ca