Global Correction Services for GNSS

Hemisphere GNSS Whitepaper

Overview
In the world of GPS new industries have emerged, and existing industries have evolved to the use of position data in real-time. As part of that evolution, the appetite for greater location and navigation accuracy has dramatically increased. To answer the call, multiple satellite constellations and augmentation schemes have been deployed to increase accuracy. Along with the need, the technology has also evolved so efficiently that it is hard to define the boundaries of positioning technology when looking towards the future.

During the last decade or so, high-accuracy (i.e., few centimeters) correction augmentation technologies have been an area of interest to many in academia and the GPS industry, as this type of technique has the potential of extending the accuracy capability of GNSS systems. We now can maintain accuracy while maintaining the core concept of a GNSS system available anytime and anywhere on earth. In this paper, we discuss high-accuracy correction techniques using Hemisphere GNSS' Atlas® GNSS Global Correction Service as the platform for a state-of-the-art solution.

Origins of Precise Global Positioning
Precise global positioning is a modality in GNSS positioning that has become very popular over the last several years. In this type of operation, a single receiver is used to determine a position solution for a static point or a moving platform. It is often called “precise” because this technique makes use of accurate information about the GNSS satellites, such as orbital position and clock errors. These have been incorporated in the compilation of the “precise products”, originally created for allowing data post-processing. The precise products are generated by several institutions, including the IGS (International GNSS Service), by means of post-processing GNSS data from several worldwide distributed monitoring ground stations. The main advantage of those products is that they provide better quality information than the typical broadcast ephemeris messages used in the different constellations.
The usage of precise products in GNSS positioning was proposed for the first time in 1995. At that point in time, certain institutions were already generating post-processed GPS satellite orbits and clocks in a standard format, which were used to contribute to IGS. The idea was that these products could be used in point positioning software to provide high-precision positioning to users operating a single GPS receiver. Although back in 1995 the implemented approach could only offer precision of about one meter, this was the starting point of high-precision global positioning.

The techniques utilized to process GNSS data with precise products were developed and refined in the subsequent years, and became standardized to a certain degree. In the early 2000s it was documented that it was possible to process carrier-phase and pseudorange measurements of a dual-frequency GPS receiver with IGS precise orbit products and obtain centimeter-level accuracy for the position solution.

High-accuracy global techniques established themselves as a powerful option to enable users to obtain centimeter-level positioning accuracy without being directly tied to a local GNSS reference network infrastructure. However, these techniques suffered from long convergence times, on the order of tens of minutes, to achieve sub-decimeter-level accuracy. This delay results from the difficulty in accurately modelling the ionospheric layer on a global scale. Long convergence time is the greatest hurdle in real-time, worldwide, high-accuracy GNSS positioning, since some applications require solution (re-) initialization times of a few seconds.

**Standard Single-Receiver Positioning**

In a simplified theoretical model of how GNSS code (or pseudorange) measurements are processed, it would be assumed that the code measurement could be modeled as a perfect line-of-sight measurement of time or distance between satellite and receiver antennas. In reality, this is not the case. There are several effects that play a role in the final mathematical model of the measurements in a GNSS receiver, as shown in the next figure.

![Diagram showing various error sources in GNSS signal propagation](image)

Each GNSS satellite broadcasts its coordinates as determined by ground tracking stations, resulting in absolute position accuracy of 1-2 meters. Similarly, satellite clock error with respect to GNSS system time is also communicated as part of a broadcast message, and can be in error by 1-2 meters.

Before reaching earth’s surface, a GNSS signal must propagate through the atmosphere. As the signal travels through the ionosphere, it may experience refraction resulting in an additional path length on the order of tens of meters. In addition, ionospheric refractive effects are different for each GNSS frequency band. Multi-frequency GNSS receivers are able to exploit this frequency dependence in order to reach centimeter-level accuracies. In case of a single-frequency receiver, the ionosphere remains one of the main limiting factors in GNSS accuracy.

Another atmospheric region that affects GNSS signals is the neutral atmosphere, often simplified as the troposphere. This region causes refraction on the GNSS signals, introducing propagation delay and path length variations before the signal reaches the receiver antenna on earth’s surface. This impact can also reach several meters.

Table 1 (next page) shows the order of magnitude, mitigation technique, and post-mitigation order of magnitude for some of the effects that play a role in single-frequency, single-receiver positioning.
<table>
<thead>
<tr>
<th>Effect</th>
<th>Magnitude</th>
<th>Mitigation</th>
<th>Post-Mitigation Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite orbit/clock error</td>
<td>1 – 2 m</td>
<td>None</td>
<td>1 – 2 m</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>Up to tens of meters</td>
<td>Broadcast ionospheric model</td>
<td>Up to several meters</td>
</tr>
<tr>
<td>Troposphere</td>
<td>2 – 20 m</td>
<td>Tropospheric model</td>
<td>0 – 2 m</td>
</tr>
<tr>
<td>Code measurement</td>
<td>1 – 3 m</td>
<td>Filtering</td>
<td>0.5 – 1.5 m</td>
</tr>
<tr>
<td>Phase measurement</td>
<td>0.5 – 10 cm</td>
<td>None</td>
<td>0.5 – 10 cm</td>
</tr>
</tbody>
</table>

Table 1. Effects in single-receiver positioning

The figure to the right shows an illustration of the impact of effects, mitigation, and observation quality on overall GNSS observation error budget. One of the interesting aspects that become evident in this illustration is, given the order of magnitude of the errors affecting the observation modeling, there is little benefit in using the carrier-phase measurements as a primary observation, as opposed to using code measurements combined with a filtering process.

After applying all mitigation techniques that are available for standard single-receiver processing, the overall error budget for each measurement is still several meters, which typically results in meter-level position accuracies for modern GNSS receivers using state-of-the-art algorithms.

The way the system typically works is similar to what was mentioned in the introduction about the generation and usage of the so-called ‘precise’ products. One of the characteristics of correction services, is that the augmentation data is generated and broadcast to final users in real-time.

The figure to the right illustrates the typical steps that are part of a global correction service system. The system infrastructure is based on a global network of GNSS receivers. These receivers operate 24/7 collecting measurements from the GNSS satellites.

Each receiver in the network is connected to a communication system, typically via the internet, sending measurement data to one or more processing centers. At the processing facilities, the network data is combined with other auxiliary data and is processed, aiming to generate satellite precise information. That information includes the satellite orbits, the clock errors, and other quantities that are relevant for high-accuracy global positioning.

The correction data can be sent to end-users via L-band satellite transmission.

In addition to precise satellite orbits and clocks, correction data might contain other information. These can include e.g. regional or global

Global Correction Services

Correction Services is a modality of GNSS positioning where users can typically operate their receivers virtually anywhere on the globe and, by means of receiving data from a control center, are able to achieve accuracies that can be at the centimeter-level depending on the hardware platform and application.
In addition to accurate orbits and clocks, other information such as atmospheric models can be generated.

The end user receiver user the accurate satellite orbits and clocks to compute an accurate position solution.

The receiver implementation employs specialized algorithms that take advantage of carrier phase measurements, accurate satellite data, and comprehensive observation models.

In addition to the GNSS observations and the correction data, the user's receiver must employ specialized algorithms to properly account for a number of different effects in order to reach centimeter-level accuracy. Some of these effects are receiver and satellite antenna phase center disposition, solid earth tides, phase wind-up due to antenna orientation changes, relativistic effects, and others.

The receiver's algorithms used in high-accuracy global positioning make use of the carrier-phase measurements as their primary observable. Because of that, one of the unknowns that must be resolved in order to compute the receiver position is the carrier-phase ambiguity of each satellite. This quantity is unknown because the carrier-phase measurements are ambiguous measurements of the distance/time between receiver and satellite antennas. After accounting for, or cancelling all other biases and delays, the carrier-phase ambiguity term is an integer number of cycles.

Another quantity that is not known in the position computation process is the ionospheric effect experienced by each satellite signal. This is the reason why centimeter-level global positioning is only possible with multi-frequency receivers. As mentioned earlier, the ionosphere is a dispersive medium and as such the different GNSS frequencies are affected differently. Receiver algorithms take advantage of that behavior and by combining signals of the same satellite observed at different frequencies, are able to virtually cancel the ionospheric effect experienced by the user's signals.

The other atmospheric region that needs to be considered is the troposphere. The tropospheric effect is also unknown in the problem of determining an accurate position solution, as the prediction models that can be used to estimate the delays experienced in GNSS are only accurate to a few tens of centimeters to a few meters. The tropospheric delays are typically estimated as one single parameter, as there are reasonably accurate models, called mapping functions, that can be used to relate the delay experienced by each satellite signal and therefore allowing this particular effect to be estimated as with common parameters in the data processing.

As previously discussed, there are a few unknown quantities that need to be solved before an accurate position can be determined (or at the same time, depending on how the processing model is built). This extended mathematical process imposes a limitation on the positioning resolution, which is often referred to as convergence time. This means that the position solution provided by a receiver using global corrections can take a few minutes to reach its final accuracy level of a few centimeters. Examples of this behavior are shown later in this whitepaper.
**Atlas® GNSS Global Correction Service**

Atlas is the name of the correction service platform created and provided by Hemisphere GNSS. The Atlas platform was created with the vision of enabling as many users and businesses as possible with correction service technology.

The architecture of the Atlas platform is similar to what was described before. The primary source of data in the system comes from a global network of more than a hundred GNSS stations distributed worldwide. The data is used to generate satellite correction data, which includes orbit and clock error information. This information is then encoded into the Atlas correction message format, which is then sent from the many Atlas control centers located across the globe to the final users. The message is then transmitted to the users via L-band satellite signal.

As previously mentioned, the solution experiences a convergence time before the final accuracy level can be reached. In this case, the convergence time was around 20 minutes. After convergence, the position error is in the order of a few centimeters, as it can be seen in the plot below, which shows a closer view of the positioning error for a period of 10 days.

**Positioning Performance**

The plot below shows an example of positioning performance obtained with an Atlas-capable receiver, getting correction data over L-band. The plot shows the horizontal error of the position from the time the receiver is started.

The same horizontal error can be visualized in the scatter plot below. It can be seen that the position quality is well within the 10 cm region.
The vertical error of the same run can be seen in the plot below.

Another way to look at the position quality is to measure the repeatability of the position over certain periods of time. In certain applications such as agriculture, this is called pass-to-pass accuracy. The pass-to-pass accuracy offers the position repeatability measurement over a period of 15 minutes. An example of the Atlas system typical pass-to-pass performance is shown below. In this example the pass-to-pass accuracy was 2.5 cm and 5.7 cm, for 1-sigma and 2-sigma, respectively.

Urban and forested environments pose a unique challenge for L-band satellites and global correction services. Due to buildings, trees, overpasses and bridges, satellite availability is rapidly changing and is sometimes lost altogether. In these events, systems may require a complete re-convergence, which can cause significant down time and lead to inefficiencies. Hemisphere has addressed these challenges with a unique outage recovery algorithm which instantly re-initializes the filter to its previous accuracy in the event of an outage, allowing for continuous high accuracy positioning evening in harsh environments. The figure below shows a receiver which experiences a complete blockage of all signals for 30 seconds every 30 minutes. After each outage the receiver is able to quickly recover to its previous accuracy level without a full re-convergence period. This type of functionality is critical in urban and canopy environments to ensure continued productivity.
**AtlasLink® GNSS Smart Antenna**

The AtlasLink antenna (pictured above) was designed to be one of the main hardware platforms delivering the Atlas correction service for users of Hemisphere and/or other brands of products. It carries the capabilities of state-of-the-art multi-frequency GNSS, allowing users to reach centimeter-level accuracies in various ways, including RTK and Atlas L-band. AtlasLink was not only designed for accuracy, but also for user readiness. It contains an internal memory of 2 GB of data that can be used for internal data storage, data upload, data download, and diagnostic data collection in the field. It is also ready for communicating with the user in a number of ways, including Wi-Fi and Bluetooth. AtlasLink offers a user-friendly web user interface (webUI) that can be used to configure, monitor, and manage the receiver from virtually any modern computing device, such as computers, phones, and tablets. The figure below shows an example of how the AtlasLink webUI looks like on a smartphone.

**Special Features**

The Atlas platform was conceived to enable as many people as possible to have access to the correction service technology, either as an end-user, or as part of their business. In order to move towards that goal, Hemisphere has created several innovative features with the objective of enabling users who currently use non-Hemisphere positioning systems to have access to the Atlas service.

One of these special features offered as part of the Atlas platform, and specifically within AtlasLink, is called SmartLink™. When operating in SmartLink mode, AtlasLink is capable of feeding an external receiver standardized messages (e.g. RTCM) in order to allow the user’s receiver to produce Atlas positions. This feature was designed for users who have an installed platform that they want to change, but would like to have access to the Atlas correction service over L-band. The chart below illustrates the setup of an AtlasLink antenna in SmartLink mode. In SmartLink setup, the AtlasLink antenna operates as an “Atlas receiver” that moves along with the user’s existing hardware, while feeding it with Atlas-enabling data in an existing industry standard format.

The two following plots show the results obtained by two different non-Hemisphere receivers being fed by an AtlasLink antenna operating in SmartLink mode. As can be seen below, even though those hardware platforms had no knowledge of the Atlas system, they were able to produce Atlas position solution accuracies with virtually the same quality as an AtlasLink. The first plot shows the convergence phase of the position solution, while the second plot shows the final solution accuracy for both receivers being fed by an AtlasLink.
Another special feature implemented as part of the Atlas platform is BaseLink™. This feature is also available in AtlasLink, and is tailored for applications where users need to establish reference stations with positions that are of a certain level of accuracy. In a typical workflow the reference station receiver must be either located on a point with known precise coordinates. The other alternative is to establish precise coordinates for a new reference point. That requires communication with an existing infrastructure, if done in real-time, it is necessary to collect and post-process data collected at that new position in order to achieve the required position accuracy.

With BaseLink, the user simply needs to configure the antenna with the appropriate accuracy level for the new reference position, and AtlasLink will collect the data while receiving the Atlas correction signal to establish its own position at the proper accuracy level, which can be at the centimeter-level. After the accuracy is reached, the receiver automatically starts to output corrections for RTK rovers operating in the field. Once the correction output starts, the RTK rovers can operate at typical RTK levels of performance. The figure below shows an illustration of the BaseLink setup using an AtlasLink antenna.

Summary

Atlas is the new global correction service platform created by Hemisphere to be the most flexible and accessible service in the industry. It not only offers state-of-the-art positioning performance, it also offers innovative and unique features that allow the Atlas service to be used in applications and platforms where no other service has been made available before.
Hemisphere

atlas

GNSS Global Correction Service

Athena RTK (1 cm)
Atlas H10 (4 cm (2D))
Atlas H30 (15 cm (2D))
Atlas Basic (30 cm (2D))
SBAS (50 cm)
No Corrections (>1 m)

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