TERRASTAR-C: A GLOBAL GNSS SERVICE FOR CM-LEVEL PRECISE POINT POSITIONING WITH AMBIGUITY RESOLUTION

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ABSTRACT

This paper provides an overview of the TerraStar-C service, a new global high accuracy positioning service enabling PPP with ambiguity resolution through the broadcast of orbit, clock and observation bias information via geostationary satellite channels.

TerraStar, a GNSS service provider based in the UK, provides GNSS product manufacturers with the opportunity to offer precise positioning solutions as part of their product range, without the need for them to support the underlying reference station infrastructure. TerraStar compatible products are manufactured by several well-known GNSS companies and are available on the market.

In recent years TerraStar has been providing global metre level and decimetre level services under the names “TerraStar-M” and “TerraStar-D” respectively. The latter uses the Precise Point Positioning (PPP) technique. A new service, “TerraStar-C” has now been introduced which offers further improvements over the regular PPP technique, by enabling ambiguity resolution.

By resolving the ambiguities, GNSS receiver systems can achieve an accuracy of just a few centimetres in real-time, globally and independent from their location relative to the GNSS reference station network. The service provides GPS and GLONASS augmentation data, allowing users to benefit from all satellites in view in a wide range of application environments.

This paper describes how the TerraStar-C service is enabled through a dedicated global GNSS monitoring and communications infrastructure. In order for GNSS receiver systems to resolve carrier phase ambiguities they require orbit, clock and observation bias information with an optimum data quality and data latency and these are aspects that are key to delivering the TerraStar-C service. The paper will explain the global GNSS tracking and communication infrastructure, the correction generation processes and the service data delivery to the end users via geostationary satellites.

Two of the key benefits of PPP with ambiguity resolution over regular PPP are (a) fast recovery after small GNSS data gaps and (b) higher accuracy. The paper presents results to demonstrate these benefits.

BIOGRAPHIES

Kevin Sheridan is Technical Services Manager for TerraStar. He provides a technical interface to TerraStar partners, helping align current and future services to the needs of the land services market. He has worked in the GNSS industry for over 15 years, developing positioning solutions for a range of applications. He has a PhD in Geomatics from the University of London.

Pieter Toor graduated with an MSc in Geodetic Engineering from the Technical University in Delft. From 1996 to 2006 he worked for Thales GeoSolutions and Thales Positioning (UK) on the development of GNSS augmentation systems.
and services for land and marine applications. He joined VERIPOS in 2006 where he is the GNSS Technology Manager. His primary responsibility is the development of next generation high accuracy GNSS augmentation services and the integration of these services onto GNSS products.

David Russell graduated with a PhD in Geodesy from the IESSG at the University of Nottingham in 2001. He joined VERIPOS in 2003 as Technology Development Manager with responsibility for developing GNSS augmentation services and products. Currently he is the Technology Manager responsible for exploiting VERIPOS technology and working with clients to determine their current and future product requirements. Previously worked for Subsea Offshore and Thales GeoSolutions.

Christian Rocken received his PhD in geophysics from the University of Colorado at Boulder. Dr. Rocken is a Fulbright scholar whose research has been focused on applications of high accuracy GPS to atmospheric sensing, tectonic studies and surveying. Dr. Rocken was chief scientist at UNAVCO and later for the COSMIC radio occultation satellite mission at the University Corporation for Atmospheric Research (UCAR). Since 2012 he is focusing his efforts on GPS Solutions Inc. He is a co-founder and President of GPS Solutions Inc. He is author/co-author of about 50 peer-reviewed papers and holds 6 U.S. patents.

Leos Mervart received his first PhD in astronomy from the Astronomical Institute, University of Berne, Switzerland, and a second PhD in geodesy from the TU Prague, Czech Republic. Since 2004 he is a director of the Institute of Geodesy at the Technical University Prague. Since 2001 L. Mervart works with the GPS Solutions, Inc. He is responsible for the development of the RTNet software.

INTRODUCTION

TerraStar provides GNSS augmentation data which is used to support precise position solutions for land, airborne and near shelf applications. These solutions are applied for uses such as precision agriculture, land survey, airborne mapping and dredging. Positioning requirements range from sub-metre to sub-decimetre, with users typically needing the operational flexibility to be able to work away from reference stations. Orbit and clock corrections delivered over L-Band can also be used within network-RTK solutions to bridge gaps in the regular data stream caused by interruption to the terrestrial communications channel. TerraStar works with GNSS receiver manufacturers to utilise their data services within the solutions they provide to end-users or equipment integrators. Currently TerraStar services are supported on NovAtel, Leica, Septentrio and Altus products.

In March 2015 TerraStar introduced a new global high accuracy service called TerraStar-C. This new service extends the capabilities offered by the existing TerraStar-D service [1], by enabling PPP with ambiguity resolution. The technique enables a higher accuracy and improved re-convergence compared to regular PPP. A near-instantaneous return to high accuracy positioning after short gaps in GNSS observations is a significant benefit of PPP with ambiguity resolution and this feature improves the robustness and availability of the solution.

In order to resolve carrier phase ambiguities within a user receiver, additional correction data needs to be determined and broadcast. The server processing the observations from a global network of reference stations needs to estimate code & phase biases in addition to the orbit & clock corrections required by regular float PPP applications. These additional parameters are then broadcast to users via geostationary communication satellites. At the receiver, these additional messages must then be decoded and applied correctly within the positioning algorithms to provide improved performance.

INFRASTRUCTURE

A key requirement for operating a real-time global positioning service is to have a network of GNSS reference stations that provide high quality GNSS data in real-time, with a maximum continuity and minimum latency. Therefore all GNSS reference stations are situated in secure locations and are equipped with dual redundant systems plus back-up power. Diverse communications are also employed at the reference stations, with a minimum of two separate communication links for each site. The majority of stations are gathering data using Septentrio multi-constellation receivers and AeroAntenna Technology choke ring antennas. All sites are controlled from our fully redundant Network Control Centres (NCCs), located in Aberdeen (UK) and Singapore, with a 24/7 response system available at each reference site. Raw GNSS observation and navigation data from the entire tracking network are sent to both NCC’s through the communication network in real-time. Altogether TerraStar operates a global network of ~85 stations capable of tracking the four global GNSS constellations and QZSS. Fig. 1 indicates the locations of these reference stations. The network density and distances between stations in the network are of key importance for reliable ambiguity resolution.
The raw binary GNSS data from stations is delivered to the Orbit and Clock Determination Systems (OCDS) installed in three NCCs, two located in Aberdeen and one located in Singapore. The choice of locations for the NCC’s in Aberdeen gives good logistical support as well as reliable communications infrastructures, with Singapore in addition being the major communications hub for South East Asia. Fig. 2 shows the multiple servers (5) that are simultaneously operated. Only data from one of the servers is uplinked at any time for broadcast to users, with the other servers acting as hot spares. The system will automatically switch to an alternative server should the primary server fail to meet thresholds in terms of augmentation data quality or availability. The multi-server and multi-location architecture is key to providing the TerraStar services to a wide range of professional applications that require augmentation data with a maximum continuity and availability.

Each server estimates GPS & GLONASS satellite orbit & clock correction data as well as code and phase biases for the GPS constellation and this data is delivered to the users via geostationary communication satellites. TerraStar leases bandwidth on 7 geostationary communication satellites for the distribution of the augmentation data. This data is broadcast at L-band frequencies of ~1539Mhz and with a data rate of 1200bps. The augmentation data is encoded in a proprietary correction data format in order to deliver the optimum GNSS positioning performance within the limited bandwidth available on GEO satellite channels.

**AUGMENTATION DATA ESTIMATION**

The TerraStar-C augmentation data, enabling ambiguity resolution, consists of:

1. satellite orbit corrections,
2. satellite clock corrections,
3. satellite hardware biases of the code observations, and
4. satellite hardware biases of the phase observations.

The augmentation data are estimated in real-time by the orbit and clock determination system (OCDS) developed by GPS Solutions, Inc. The tracking network GNSS data is first processed by the NAPEOS orbit determination software (installed by PosiTIm of Darmstadt, Germany) to generate predicted orbits for use in real-time. New predicted orbits are computed every 15 minutes to keep the prediction time window as short as possible, generally well below 30 minutes. This process is capable of estimating the GPS and GLONASS orbits to better than 5 cm. This statistic is derived from orbit overlap monitoring (see Fig. 4) as well as from comparisons with IGS final orbits.
The remaining components of the augmentation data are estimated in real-time by the RTNet software which is based on a Kalman filter algorithm. The predicted orbits and the real-time station data streams are inputs to the estimation of the real-time clocks as shown in Fig. 3. The real-time server run has two parts – the PPP_NB filter and the PPP_AR filter. The PPP_NB filter estimates clocks and code biases using the code & phase observations available from the network. The estimated orbits, clocks, and code biases are then passed to the PPP_AR filter that resolves the ambiguities to their integer values and estimates the Melbourne-Wuebbenna and ionosphere-free biases. The biases are subsequently converted into signal specific biases for the observables processed by the PPP_AR filter.

![Diagram of Orbit, Clock & Bias Determination](image)

**Fig. 3. Orbit, Clock & Bias Determination**

The hardware code biases are divided into two parts. The larger, constant in time, part of the code bias is added to the satellite clock corrections. Thus a PPP client can work using the satellite orbit and clock corrections only (the remaining code bias is small enough to be neglected for the purposes of a PPP client that does not attempt to resolve the initial phase ambiguities to their integer values). The satellite clock corrections refer to the ionosphere-free linear combination of the original measurements.

The code biases, their small remaining parts, as well as the phase biases are vital for resolving the ambiguities in the TerraStar-C client applications. The biases are transmitted for all observation types (tracking modes) that are being processed at the server side, currently for C-code at the first GPS carrier and P-code at the second GPS carrier. Taking into account the received biases the client is able to resolve the wide-lane ambiguities using the Melbourne-Wuebbenna linear combination and the narrow-lane ambiguities using the corresponding ionosphere-free linear combination, see [2]. The ambiguities are being resolved on the single (between satellites) difference level.

All estimated parameters are passed on to the correction encoding & scheduling software and the encoded proprietary messages are then included in the data stream for GEO satellite transmission.

**PERFORMANCE**

The quality of the augmentation data is monitored by the OCDS servers in real-time. Fig. 4 shows the RMS errors of the estimated satellite positions based on comparing overlapped orbit results.

![Graph of Operational orbit quality monitoring for the TerraStar system, errors in 3D](image)
Fig. 4 indicates that the real-time orbits for GPS and GLONASS are computed with an accuracy of typically 2-4 cm. In addition to the orbit overlap comparisons that are performed routinely, TerraStar has also compared the estimated orbits and clocks to IGS final results. The statistics of a 1-month comparison (day 280 - 319, 2013) is shown in the following table:

Table 1. TerraStar Orbit accuracy by the comparison to IGS final product

<table>
<thead>
<tr>
<th>Product</th>
<th>Orbit 1-D [mm]</th>
<th>Orbit 3-D [mm]</th>
<th>Clock [mm]</th>
<th>Clock [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-Time</td>
<td>30</td>
<td>50</td>
<td>40</td>
<td>120</td>
</tr>
</tbody>
</table>

It should be noted that the statistics in Table 1 are for GPS only. The accuracy of GLONASS orbits and clocks are only slightly worse.

Fig. 5 below illustrates the behaviour of the signal specific biases. These are inherently stable for code observations. The phase biases are equally stable in principle but their values may occasionally need to be reset depending on the observability of the satellite in the network. In that case a phase bias discontinuity flag is passed on to the client application.

The ultimate test of the quality of the augmentation data is provided by the usage of these data for the estimation of the client position. The positioning algorithms, as well as the signal processing, within the user receiver will clearly play a key role in the final performances achieved. These implementations are specific to each receiver manufacturer, but as an indicator, routine monitoring of user positioning performance is carried out in the OCDS using a client solution developed in-house. 

The server is running continuous real-time client tests to monitor the corrections generated by the server. These client tests use corrections directly from the server – not packaged for over-the-air transmission. The main purpose of these tests is to evaluate the quality of corrections coming from the server. These tests do not account for errors introduced by data latency (~1-2 sec) experienced by regular users of the service who receive the corrections via satellite link. Also the client receiver data used for this monitoring comes from the reference network which has a slight data quality advantage over typical user equipment. However this advantage is considered small.

Fig. 6 shows the time series and RMS values for 4 client solutions at different monitoring locations, in Australia, USA, Europe and Africa on 26 March 2015. Although the monitoring takes place at fixed sites, these client solutions are processed in full kinematic mode to be representative of users in dynamic scenarios. The time series show that steady-state performances are achieved at a 1-2 cm horizontal and a 2-5 cm vertical level. The parameter F4 indicates the percentage of fixes that have ambiguities resolved (fixed to their integer values) for 4 or more satellites. For the Australia site this was 100%, whilst the lowest fix percentage was at the African site (74%). The time series for the Africa site shows some impacts of scintillation during the period 21:00-24:00, when the GNSS tracking was degraded, though it is also clear from the plot that the TerraStar-C positioning capability remains stable and to a large extent accurate during this period.
Client convergence tests are also routinely conducted. For these tests we restart a test receiver every hour and monitor the position error relative to known truth as a function of time. The Horizontal results for several days of such reset tests are shown below in Fig. 7.

**GPSS Convergence**

Fig. 7 shows typical client convergence behaviour (1-sigma and 2-sigma) as a function of time after start-up in minutes. The yellow lines show results where the correction latency is zero, i.e. GNSS observations and corrections with the same time tag are processed, the red lines show results for a position solutions with actual correction latencies experienced by users. It can be seen that 5-cm horizontal errors (1-sigma) are achieved after approximately 25 minutes. The latency of the clock corrections does not appear to have a major influence on the behaviour of the solutions.

The results in Fig. 7 highlight a limitation of the PPP solution for end users. It takes nearly half an hour to reach the specified accuracy level after a cold start and even more time to reach the steady state accuracies shown in Fig. 6. It should however be pointed out that for many applications it is possible to start operations with an intermediate level of accuracy, while the solution continues to improve further.
While cold-start convergence is rather slow, for PPP and PPP with ambiguity resolution, the situation is much better for hot-start re-convergence of a PPP with ambiguity resolution solution. For example if a user enters a tunnel and exits after a minute or two the PPP-AR solution can achieve pre-tunnel positioning quality almost instantly, whilst a float PPP solution generally needs to be fully reset and repeat the cold-start process. This fast re-convergence can be achieved if the client software estimates the satellite specific line-of-sight ionospheric delays at all times. These delays can then be applied after exiting the tunnel as a constraint to fix the carrier phase ambiguities almost instantly. Tests of this technique are indicated below in Fig. 8.

![Fig. 8. Position errors of a client solution with several 2-minute gaps.](image)

In Fig. 8 the ambiguity-free solutions are shown in green, the ambiguity fixed solutions are shown in red. The left panel illustrates how long it takes after the gap before carrier phase ambiguities are re-resolved without using pre-gap ionosphere as a constraint. The right panel shows the much faster gap recovery succeed if the pre-gap ionosphere is used as a constraint. Fig. 8 indicates that the TerraStar-C service enables client users to achieve rapid gap recovery, which for many land based applications offers a significant benefit compared to regular PPP.

**TERRASTAR-C APPLICATIONS**

The TerraStar-C augmentation data may be used by receivers serving a wide range of applications. TerraStar acts as the data service provider and works with GNSS manufactures who develop their own client implementations. The receiver manufacturers can develop positioning solutions which best suit the characteristics of their equipment and the needs of specific applications. The biggest market for TerraStar solutions today is precision agriculture, in which technologies are applied to improve efficiency, increase yields and reduce environmental impact. Precise positioning is used to guide, or even control, farm machinery to allow a very accurate path to be followed. TerraStar-D and TerraStar-C solutions are also being used for dredging, land survey, construction, machine guidance and airborne mapping applications.

NovAtel is one TerraStar partner who has adopted the TerraStar-C dataset to provide a client PPP solution with ambiguity resolution. In steady state monitoring their solution obtains a horizontal accuracy 95% of better than 4cm (Fig. 9), in line with the references solutions computed within the OCDS monitoring, described above.

![Fig. 9. Horizontal Position errors over 24 hours, NovAtel solution using TerraStar-C data.](image)
The principal benefit of adopting a solution with ambiguity fixing is the rapid re-convergence capability. Following a temporary loss of signals due to trees or other obstructions, the positioning solution will return quickly to its specified accuracy level – in many cases instantly. Fig. 10, below, shows results from a test drive around Calgary in which the performance of a PPP with ambiguity resolution solution (TerraStar-C, red) was compared against a PPP float solution (TerraStar-D, green). It is clear to see that after signal disruptions, the float solution re-converges slowly whereas the AR solution re-converges instantly following short gaps, and very rapidly following longer or compounded gaps. Further testing in agricultural scenarios is consistently demonstrating the operational benefits of the TerraStar-C service with high accuracy positioning being maintained when operating close to tree lines.

**SUMMARY AND CONCLUSIONS**

Global PPP with ambiguity resolution is enabled by a reliable and redundant global GNSS infrastructure estimating precise orbits, clocks and signal specific observation biases in real-time. A key benefit of ambiguity resolution, compared to regular float PPP, is that a positioning accuracy of <5cm can be quickly restored in most operational environments where short gaps in GNSS observation data are inevitable. This makes TerraStar-C an attractive solution for many land based applications in precision agriculture as well as for other applications like dredging, land survey, construction, machine guidance and airborne mapping.

The current system architecture can be extended to process orbits, clocks & biases for any GNSS signal. Adding augmentation data for the QZSS, BEIDOU and GALILEO signals into the corrections streams will further enhance the PPP with ambiguity resolution performance, particularly in terms of convergence time and in terms of availability and stability in non-clear sky environments.

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**REFERENCES**
