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Validation of Reference Frame Consistency of GNSS Service Products

Lennard Huisman and Huib de Ligt

Abstract

In Global Navigation Sattelite System (GNSS) point positioning the coordinate reference frame of the positioning results is determined by the reference frame of the used GNSS service product. These products include broadcast ephemeris, precise orbits, clocks, biases, and reference station observations. Consistency in the reference frame is crucial for analyzing coordinate differences and velocities in earth science and geomatics applications. National agencies calculate coordinates for GNSS reference stations to ensure reference frame consistency within a country, however this approach is not suitable for providers covering multiple countries.

This contribution will introduce two new approaches for reference frame validation of GNSS service products and their relation with the International Association of Geodesy's Reference Frame Sub-Commission for Europe (EUREF) densification guidelines, including results of a first prototype assessing the consistency of a cross-border GNSS RTK service with the EUREF Permanent Network (EPN) reference frame ETRF2000 and consistency of a GNSS PPP service with the International GNSS Service reference frame IGb14.

Keywords

ETRF2000 · GNSS · PPP · Reference frame · RTK

1 Introduction

To obtain GNSS positions from GNSS code and phase observations, information is needed on the state of the satellites, such as the satellite positions and the clock offset to a reference time. For high precision applications, the user also needs information on error sources that affect the observations, such as signal biases and atmospheric delays. GNSS service products provide users with the necessary information for GNSS point positioning. The GNSS service products can be divided into two groups: the State Space Representation (SSR) products and Observations Space Representation (OSR) products as described by Wübbena et al (2001, 2005) and the RTCM standard SC 10403.2 (2013). The SSR products provide information on the state of individual GNSS error sources, while the OSR products provide observations or corrections to observations that can be used by the user to eliminate common error sources of the user observations and the OSR product.

The coordinate reference frame of GNSS point positioning results is determined by the reference frame of the GNSS reference stations used to generate GNSS service products. In earth science applications and geomatics, consistency between the reference frame of point positioning results is of importance in the analysis of coordinate differences and velocities. In many countries, for example Belgium (Bruyn-

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inx et al 2018), Canada (Bond et al 2018), Great Britain (Edwards et al 2010) and the Netherlands (van Willigen and Salzmann 2002), the consistency of GNSS services is achieved through consistent computation of GNSS reference station coordinates by national authorities. Implicitly, these computations usually also result in a quality check of the reference station observations. In case of low quality, the station observations will be rejected in the coordinate computation.

The approach of computing reference station coordinates for each country's individual realization of the reference frame is not suitable for GNSS service providers that provide GNSS service products for multiple countries. These providers can only select one coordinate for each station when operating a cross-border network. This holds for some GNSS real-time kinematic (RTK) service providers, but especially for other GNSS point positioning techniques, such as single point positioning (SPP), precise point positioning (PPP) and PPP-RTK where a global network of reference stations is used to compute the GNSS service products. Also, the approach has some drawbacks for both providers and users, especially as the consistency of the reference frame that is provided by the GNSS service product to the end user is not validated, but only the input data. In a series of interviews, not included in this contribution, we found that users in the Netherlands actually expect that the delivered GNSS service products are validated by the national authority and not only the input coordinates of the GNSS reference stations.

This contribution introduces two new approaches for reference frame validation of GNSS service products, capable of validating the consistency of global but also regional and local GNSS service products and reference frames.

Section 2 provides a short overview of existing approaches to validate the reference frame of GNSS services. Section 3 introduces the new methods for reference frame validation of GNSS services. In Sect. 4 results are presented of a prototype implementation of the approaches for a cross-border GNSS RTK service and a GNSS PPP service. Section 5 gives an outlook on next steps.

2 Existing Validation Approaches

This section describes the approach of coordinate computation for GNSS reference stations in Sect. 2.1 and two approaches for quality control of GNSS service products that are capable of validating the reference frame the user obtains with these products. Section 2.2 describes the Physical quality control and Sect. 2.3 describes the circular quality control approach.

2.1 Coordinate Computation

In the coordinate computation approach, the coordinates of GNSS reference stations are computed using a consistent approach, for example based on the guidelines for densifications of the EUREF permanent network (EPN) in Europe (Legrand et al 2021). GNSS service providers use GNSS reference stations for which coordinates are computed; these stations can be operated by a national agency or by operators themselves. For example, in Great Britain, providers rely mainly on the GNSS reference stations provided by the Ordnance Survey, while in the Netherlands, providers operate their own stations.

In case of coordinate computation, the chain from GNSS reference stations' observations to user positions can be summarized as follows. Coordinates are computed, and possibly monitored, such as in Belgium (Bruyninx et al 2018) and Canada (Bond et al 2018), by a national agency. A GNSS service provider uses the observations and computed coordinates of the GNSS reference stations to create GNSS service products. The end user processes its own observations in combination with the service products to do point positioning for the user location. The obtained position will be in the reference frame of the GNSS service station, provided that this is handled correctly by the GNSS service provider when creating the service products. The latter is not validated in this approach.

2.2 Physical Quality Control

To validate the quality of GNSS service products, a straightforward approach is to perform point positioning at known physical points. For example, Kadaster (2003), Edwards et al (2010), Wang et al. (2010), Cina et al (2015), Sedell (2015) and NavCert (2016) use surveys at known points to assess the quality of GNSS service products. When the reference frame of the GNSS service products and the known points is the same, or the relation between the reference frames is known, such a physical quality control can also validate the reference frame of the GNSS service products. The reference frame can be validated by a comparison of the known coordinates and the point positioning results. These procedures have proven to provide good insight into the quality of service products, but cannot be easily automated and are very labour-intensive, due to a significant amount of fieldwork.

It is, of course, also possible to use permanent stations for such a quality control, as done by Janssen (2013). However, to avoid the risk that an issue with a permanent station remains undetected, this approach requires a network of stations independent of the stations used by the GNSS service provider. This is especially important for OSR based GNSS service products, as the individualized observations of the GNSS service products will be highly correlated with the reference stations' original observations.

In addition, it is also important to be aware of the source of the coordinates of the known points. For example, in the Netherlands, the coordinates of the known points used by the procedure of Kadaster (2003) and NavCert (2016) are obtained using observations and a GNSS service product from the national authority. In this case, the procedure is a comparison between two independent surveys using two different GNSS products. As a result, this procedure is not an independent validation of the GNSS service product and is also affected by the precision of the local setup of equipment at the known point of the two independent surveys.

2.3 Circular Quality Control

The European Position Determination System (EUPOS) is a collaboration between public agencies that provide GNSS services. Within EUPOS, GNSS reference products are validated by monitoring the coordinates of the GNSS reference stations using OSR GNSS service products (Droščak and Smolik 2015). The monitoring takes place in the form of 2-min sessions. The sessions vary using different distances and directions; the individualized OSR products are requested by the monitoring system for distances of 2, 11 and 20 km from the GNSS reference station in different directions with an interval of 15 degrees. Using the open-source software RTKLIB (Takasu and Yasuda 2010), the coordinates of the GNSS reference station are calculated using the observation of the OSR products. The reference frame is validated by a comparison of the known and computed coordinates.

An advantage of this approach is that permanent GNSS reference stations are used for the quality control; hence, no additional measurements need to be carried out in the field. Another advantage is that any organization can monitor the GNSS service products as long as they have access to the GNSS service products and the GNSS reference station data. This access can be made available easily by GNSS service providers, as it requires the same communication protocols as used by customers of the services. A disadvantage of the method is that in EUPOS, most of the reference stations used for checking the product are also used for creating the GNSS product. Because systematic errors in the coordinates of GNSS stations propagate in the GNSS product, such errors will not be detected by this method. In this contribution, this approach is labelled the circular quality control, as the output data is validated with the input data, making it a circular flow of data. In the current EUPOS implementation, the distance for the monitoring is limited to 20 km from the nearest station, which means that nationwide monitoring of the GNSS services is currently not possible when the distance between reference stations is larger than 40 km.

3 New Validation Methods

Section 2 described current approaches that are used to ensure a consistent reference frame of GNSS services, as well as methods that are used to validate the reference frame of GNSS service products. These current approaches for validation have limitations, as they are either not fully independent from data that was used to generate the GNSS service product, can be labour-intensive, or are actually a relative validation compared to another GNSS service product. To overcome these limitations, we introduce two approaches for validation of the reference frame provided by the GNSS reference products: the Grid check approach, described in Sect. 3.1 and an approach that is complementary to the grid check, the Systematic quality control, described in Sect. 3.2.

3.1 Grid Check

The grid check approach was developed to validate the reference frame of OSR GNSS service products. A nationwide OSR based GNSS service can usually provide data for any location. In real-time kinematic positioning, implementations of such services are known as the Virtual Reference Station (VRS), Pseudo Reference Station (PRS) or individualized Master Auxiliary (iMAX) approaches (Wübbena et al 2005; Takac and Zelzer 2008). In the grid check, observations for a grid of virtual stations are collected, using the OSR based GNSS service, covering the area for which the service products will be validated. The coordinate computation approach described in Sect. 2.1 is then used to compute coordinates for the virtual stations. The validation consists of a comparison between the computed coordinates and the coordinates for which the virtual stations were created. This difference is expected to be zero if the reference frame of the service product is consistent with the reference frame in which the virtual stations are requested. The advantage of this approach is that the grid check can be performed independently from the reference stations used to generate the service products; no field measurements are required and the existing coordinate computation approach can be re-used, which adds to the consistency of the validation. A disadvantage of this approach is that it can only be applied to OSR based GNSS service products.

3.2 Systematic Quality Control

To overcome the limitation of only validating OSR based GNSS service products with the grid check, the complementary approach of the systematic quality control was developed. This approach introduces the concept of a grid-checked GNSS service. The grid-checked service is an OSR based GNSS service that is validated using the grid check approach and serves as a benchmark for other services. The grid-checked service generates virtual stations that can be used to validate OSR and SSR based GNSS service products, such as broadcast ephemeris, post-processing kinematic services and PPP services. In this approach, the coordinates for the virtual stations are computed using the OSR or SSR based service products. The validation consists of a comparison between the computed coordinates and the coordinates for which the virtual stations were created. When the service product is provided in a different reference frame than the grid-checked service, a coordinate transformation is required. The advantage of this approach is that it can be used for both OSR and SSR based GNSS service products at any distance from reference stations within the coverage of the grid-checked service. A disadvantage of the systematic quality is the dependency on a grid-checked GNSS service.

Actually, this concept is very similar to the concept of the physical control survey described in Sect. 2.2. The difference is that the relative control is not done by fieldwork, but the actual GNSS service products are directly used. Besides eliminating the labour-extensive fieldwork it also eliminates the uncertainty introduced by local setups and only compares GNSS service providers, which is the actual goal of the validation for both the physical and the systematic quality control. The validation of OSR based service products is also very similar to the validation done by the circular quality control described in Sect. 2.3.

4 Results

This section gives results on the implementation of the grid check and systematic quality control. The implementation is based on a prototype.

4.1 Grid Check for a Cross-Border GNSS Service Provider

This section shows the result of the grid check of the GNSS service product of a GNSS service provider. The service is based on reference stations in Belgium, France and the Netherlands. The reference frame for the GNSS service product is ETRF2000 at epoch 2010.0. Data for the grid of virtual stations were collected from real-time streams and converted to RINEX files. As the data collection was limited to 500 parallel streams to limit the load on the GNSS service, the resulting grid resolution was 35 km. To avoid extrapolation outside the coverage of the active GNSS service, no grid points were used with a distance of more than 50 km to the nearest reference station. A European digital elevation model was used to obtain heights for the virtual stations in the grid at ground level. The coordinate computation was done following EUREF guidelines for EPN densifications (Legrand et al 2021) using the Bernese 5.2 software (Dach et al 2015). Reference station selection was done using the EPN densification online tool. Figure 1 shows the horizontal differences between the computed coordinates and the coordinates for which virtual stations were requested from the service. Table 1 gives metrics for the differences.

In general the validation shows coordinate differences at the millimetre level. In the northwest of Belgium, an outlier is visible of several centimetre in the southwest direction. This outlier actually identified an error in the used coordinates of the nearest reference station of the same magnitude. This example shows how the grid check is able to identify such errors, that directly affect the users point positioning in the same magnitude. In the south of France, systematic errors are visible. The reason for these effects is under investigation. One hypothesis is that station coordinates are incorrect in this region; however, the effect covers an area with multiple reference stations. Another hypothesis is that the atmospheric modelling in the mountain areas of the Pyrenees and Alps regions is less precise than in areas with smaller height differences.

4.2 Systematic Quality Check for OSR and SSR Based GNSS Service Products

This section shows the result of the systematic quality control of real-time and post-processing GNSS service products within the Netherlands. Following the concept introduced in Sect. 3.2, the Netherlands Positioning Service (NETPOS), the nationwide network RTK service operated by the Dutch Kadaster (NSGI 2022), was used as the grid-checked service. To confirm the reference frame of NETPOS, the grid check was performed on a grid of 25 km×25 km. Section 4.2.1 shows results for a real-time OSR service and Sect. 4.2.2 shows results for two post-processing SSR services.

4.2.1 Real-Time OSR Service

To validate the reference frame of a real-time OSR service, a real-time virtual user was created using NETPOS. RTKLIB was used with the observations of the virtual user and the individualized OSR products of the service to compute

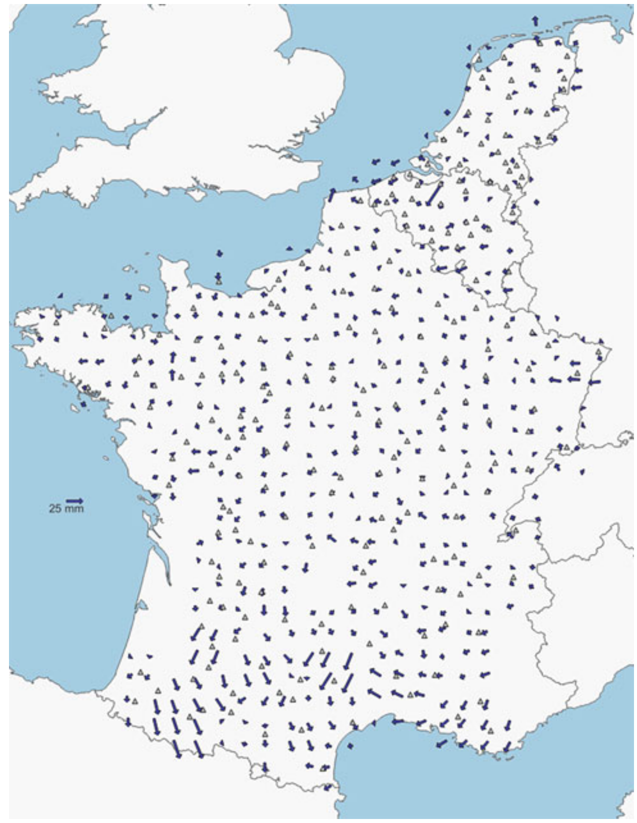

Fig. 1 Horizontal coordinate differences for the grid check of a cross border OSR based GNSS service product

Table 1 Metrics for the validation of ETRF2000 coordinates for a cross-border GNSS service provider using the Grid check approach

	North [mm]	East [mm]	Up [mm]
RMS	8	7	17
95-percentile	16	13	37
99-percentile	25	18	51

coordinates for the virtual user. The coordinate computation was done in sessions of 10 min. The coordinate computation and validation are very similar to the computation done by Droščák and Smolik (2015) in the circular quality control approach described in Sect. 2.3 as our prototype also uses RTKLIB. To minimize the load on the GNSS service provider, a maximum of four simultaneous sessions was run. Each session would randomly select a location for the virtual user from the grid of 25 km×25 km mentioned in Sect. 4.2. The systematic quality control was run for one month resulting in approximately 160 sessions per grid point. The number of sessions differs per point as the points were randomly selected in each session. The validation was done by comparing the computed coordinates of the virtual user obtained with the GNSS service product, with the known coordinates for which the virtual user was generated. Figure 2a shows the results for the validation, metrics for the results are included in Table 2.

The results for the systematic quality control of the real-time OSR service show that the average coordinate difference for the sessions on a single point is below 7.5 mm in the horizontal component and below 15 mm in height, within the borders of the Netherlands. The standard deviation is less than 2 mm for the horizontal components and 7.1 mm for the height. Given the specification of 20 mm in planimetry and 30 mm in height for this service, users can rely on this service to provide them coordinates in the national reference system within the specifications of the service.

4.2.2 Post-Processing SSR Services

To show that the systematic quality control can also be applied to post-processing services, the Canadian NRCAN CSRS-PPP service (NRCAN 2022) and the Trimble RTX post-processing service (TrimbleRTX 2022) were validated using the NETPOS grid-checked network. These online services allow users to upload a RINEX file and will deliver an extensive report on the processing results including coordinates. In this case, both services provided coordinates in the ITRF2014 reference frame at the epoch of observation. For this validation, a single session of 24 h of observations for virtual users on the

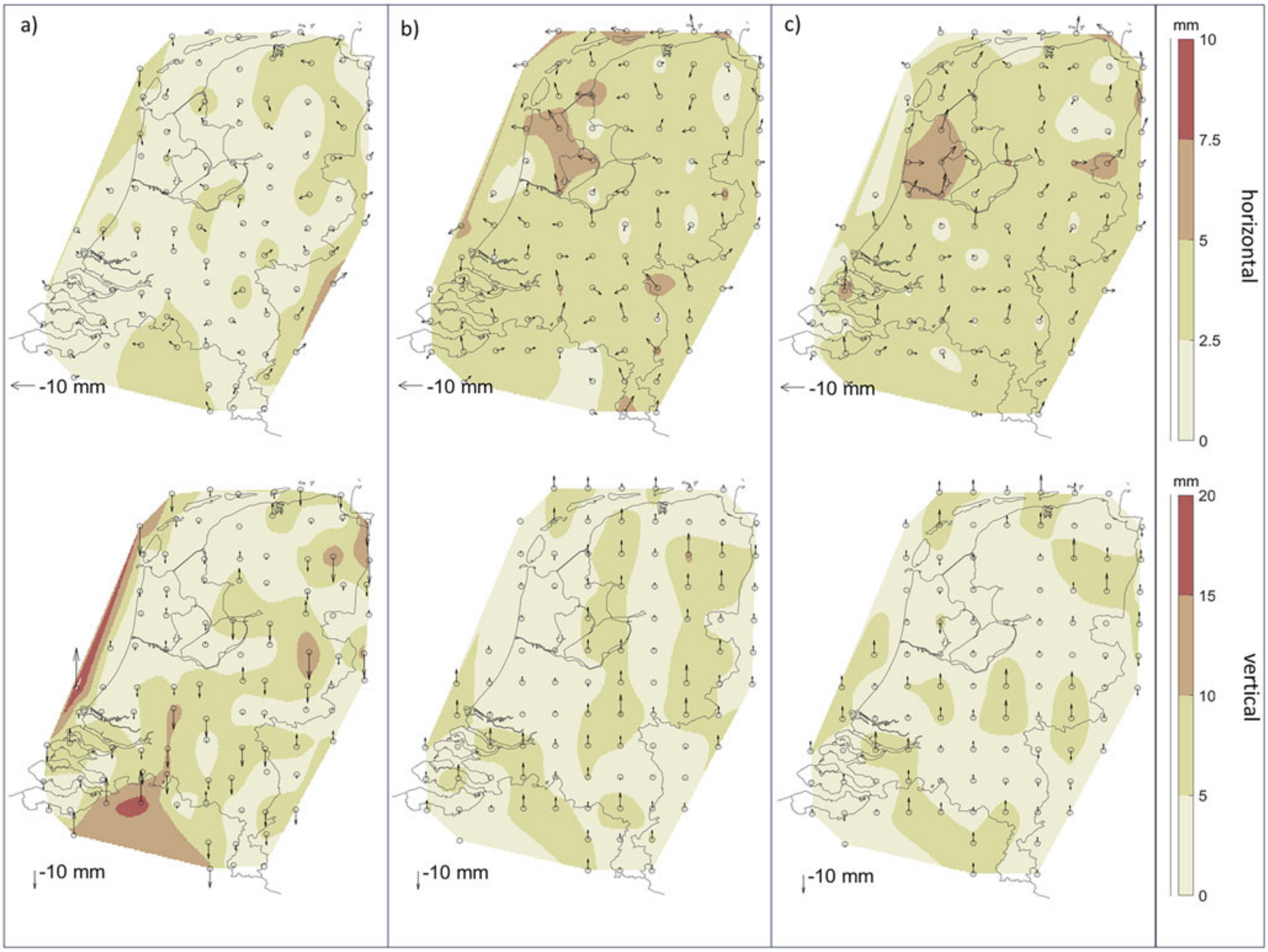

Fig. 2 Coordinate differences for the systematic quality control of three different GNSS service products. Top row shows the horizontal differences, bottom row shows the vertical differences

Table 2 RMS error for the validation of coordinates for OSR and SSR GNSS service products using the Systematic quality control approach

	North [mm]	East [mm]	Up [mm]
Real-time OSR service	1.6	1.9	7.1
Post-processing Trimble RTX	2.8	2.6	4.6
Post-processing NRCAN PPP	2.6	3.0	5.0

same grid of 25 km x 25 km was used for the grid check of NETPOS. The coordinates were validated by comparing the ITRF2014 coordinates obtained for the post-processing services and the known coordinates of the virtual stations. Figure 2b and 2c show the results for the validation, metrics for the results are included in Table 2.

The results for the systematic quality control of the post-processing services show that the services have a good agreement with each-other and the ITRF2014 reference frame at the epoch of observations. The average coordinate difference for the sessions on a single point is below 7.5 mm in the horizontal component and below 10 mm in height. The standard deviation of the differences is less than 3 mm for the horizontal components and about 5 mm for the height. The results show that for these services, users can rely on this service to provide them coordinates in the specified reference system at the centimetre level.

5 Outlook

To ensure the consistency of the reference frames of GNSS service products, current approaches have limitations. These limitations are that the approaches either do not validate the end-user product (coordinate computation), are not fully independent from data that was used to generate the GNSS service product (circular quality control), can be labour-intensive or are actually a relative validation compared to another GNSS service product (physical quality control). To overcome these limitations we introduced two approaches, the grid check and the complementary systematic quality control, for validation of the reference frame provided by the GNSS reference products. Implementation of the approaches in a prototype show that the approaches can be applied to both OSR and SSR based GNSS service products to validate the reference frame.

In this contribution, the systemic quality control approach was evaluated using an independent grid-checked service as a benchmark. In this approach, the GNSS service of the national agency was validated with the grid check and served as the grid-checked service for the systematic quality control. Other services, in this case commercial and public (open) services, were then validated using the virtual OSR based observation generated with this grid-checked network. It can be argued that the dependency on a grid-checked service is a disadvantage of the approach, as it requires an independent infrastructure. We think this disadvantage is relatively small when the national agency already operates a national GNSS service, but are also investigating other approaches. For example, when it is assumed that the majority of the GNSS services are providing the correct reference frame, the approach could be to perform a relative comparison between GNSS services to be validated.

Currently, there are no standards or guidelines for the validation of GNSS service products. Each national agency has its own implementation and interpretation of existing approaches. The described approach can serve as a standardized methodology and it is shown that it can be applied cross-border and for different types of GNSS service products. We are seeking collaboration with other national agencies and service providers to further develop the method. Scientific challenges are the optimum density of the grid and the development of a robust positioning algorithms that can handle different types of GNSS service products.

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