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SBAS orbit and satellite clock corrections for precise point positioning

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Abstract The quality of real-time GPS positions based on the method of precise point positioning (PPP) heavily depends on the availability and accuracy of GPS satellite orbits and satellite clock corrections. Satellite-based augmentation systems (SBAS) provide such corrections but they are actually intended to be used for wide area differential GPS with positioning results on the 1-m accuracy level. Nevertheless, carrier phase-based PPP is able to achieve much more accurate results with the same correction values. We applied SBAS corrections for dual-frequency PPP and compared the results with PPP obtained using other real-time correction data streams, for example, the GPS broadcast message and precise corrections from the French *Centre National d'Etudes Spatiales* and the German *Deutsches Zentrum für Luft- und Raumfahrt*. Among the three existing SBAS, the best results were achieved for the North American wide area augmentation system (WAAS): horizontal and vertical position accuracies were considerably smaller than 10 cm for static 24-h observation data sets and smaller than 30 cm for epoch-by-epoch solutions with 2 h of continuous observations. The European geostationary navigation overlay service and the Japanese multi-functional satellite augmentation system yield positioning results with biases of several tens of centimeters and variations larger by factors of 2–4 as compared to WAAS.

Keywords GPS · Precise point positioning · Satellite-based augmentation systems

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Introduction

The method of precise point positioning (PPP, Zumberge et al. 1997) to compute receiving antenna positions from Global Navigation Satellite Systems (GNSS) observations has become popular in recent years. Usually, dual-frequency GNSS observations are processed using precise orbits and clock corrections from, for example, the International GNSS Service (IGS, Dow et al. 2009). These orbits and clock corrections are available for post-processing purposes with delays of at least several hours. Real-time IGS products are planned for the near future (Dow et al. 2009).

But already today several sources of real-time GNSS orbits and clock corrections exist. Not all of them are intended to reach the accuracies of IGS products and often they do not aim to be used in PPP-mode, but nevertheless they can be used successfully with these algorithms.

It was our main objective to test the correction data streams of the satellite-based augmentation systems (SBAS), namely the US-American Wide Area Augmentation System (WAAS, GPS WAAS PS 2008), the European Geostationary Navigation Overlay Service (EGNOS, Ventura-Traveset et al. 2006), and the Japanese Multi-functional Transport Satellite Satellite-based Augmentation System (MSAS, Nakaitani 2009). These wide area differential GPS (WADGPS) provide orbit, clock, and ionosphere correction data for North America, Europe, and Japan, respectively. The main objectives of these systems are providing integrity positioning with a safety-of-life quality and providing a better accuracy than stand-alone GPS of about 1–2 m (Ventura-Traveset et al. 2006). They are expected to be used with single-frequency code observations. We, however, used the SBAS orbits and clock corrections together with dual-frequency code and carrier phase observations to compute PPP results.

The idea to this study was stimulated by Rho and Langley (2007) who investigated the use of WAAS corrections for PPP. They successfully applied WAAS orbits and clock corrections for carrier phase-based PPP. They were able to obtain centimeter accurate horizontal positions for a 24-h static observation data set.

In our study, we extended the analysis to all three existing SBAS and we processed 101 days of observation data from 34 continuously operating reference stations (CORS). Thus, we are able to present statistically significant findings for SBAS-based PPP. Two kinds of solutions were produced: static solutions for 24-h data sets and epoch-by-epoch solutions for 2-h data sets simulating kinematic operation of the receiver.

In order to provide an even more complete picture of PPP with real-time corrections, we furthermore extended the study to the less accurate GPS broadcast ephemerides and to the more accurate real-time corrections obtained from the French *Centre National d'Etudes Spatiales* (CNES) and the German *Deutsches Zentrum für Luft- und Raumfahrt* (DLR).

We are not going to discuss in detail the advantages and disadvantages of the various communication channels utilized for the transmission of the different correction data streams. Definitely, broadcasting the correction data together with the GPS ranging signals guarantees maximum availability at a minimum of additional costs for the user.

All our data processing was performed in post-processing mode. This was made possible since all the required real-time information is archived and freely accessible, at least for research purposes.

Precise point positioning (PPP)

PPP is a positioning algorithm that processes undifferenced code and carrier phase observations of stand-alone GNSS receivers. If precise satellite orbit information and clock corrections are introduced and if continuous dual-frequency carrier phase observations are collected, position accuracies of 1 to a few centimeters can be achieved anywhere on the globe.

The PPP solution convergence time amounts to several minutes or even to a few hours depending on the expected positioning accuracy and on the mode of receiver operation, that is, static or kinematic positioning. The convergence time can significantly be reduced by fixing the carrier phase ambiguities. This, however, requires additional information on signal delays which are presently not part of the orbit and clock data streams (Geng et al. 2010).

A PPP solution consists of estimated position coordinates, time information, and tropospheric delays. We deal with the position information only. Positions are determined in the reference frame of the satellite orbits, and thus, the reference frame may vary between different orbit data sets.

PPP is per se a global technique since satellite orbit and clock information is usually produced from globally distributed reference station observations. If, however, the orbit and clock information is based on a regional network of reference stations, as it is the case for the various SBAS, this orbit and clock information supports PPP in the respective region only.

Satellite orbit and clock information

There are various sources of real-time GPS satellite orbit and clock information. Often the absolute satellite orbit values and satellite clock corrections are not distributed. Instead, the correction values with respect to the broadcast ephemeris are disseminated.

For real-time applications, several data formats exist the GPS navigation message for broadcast ephemeris (IS-GPS-200 2010), the RTCA DO229 used by the three SBAS (RTCA 2006), and RTCM 3.1 (RTCM 2011) used by CNES and DLR. Archived orbit and satellite clock information, such as the IGS products, are stored in SP3 (orbits or orbits plus clock corrections, Hilla 2010) and RINEX-CLK (clock corrections only, Ray and Gurtner 1998) formats. The same formats are used by CNES and DLR to archive the information of their real-time products. GPS broadcast ephemerides are usually stored in RINEX format (Gurtner and Estey 2007). The SBAS messages are stored in various formats, for example, EGNOS Message Server (EMS, Toran-Marti and Ventura-Traveset 2004) or RINEX (Suard et al. 2004).

The orbit and clock information in RTCA DO229 format is split into long-term and fast corrections. Long-term corrections contain information on the slowly varying satellite orbit and clock errors, whereas fast corrections provide additional information on the fast varying clock errors. Long-term corrections consist of position and clock offset values only (EGNOS) or they also contain velocity and clock drift corrections (WAAS, MSAS). The resolution of long-term position corrections and also of the fast corrections is 0.125 m, which limits the achievable accuracy of the PPP results.

There may be differences in the definition of the various satellite orbit and clock products which must be taken into account when performing a PPP solution. One difference is the reference point at the satellite. IGS products refer to the center of mass of the satellite (Kouba 2009). Since the measurements are made to the apparent satellite antenna phase center of the ionosphere-free linear combination of dual-frequency observations, corrections must be introduced, which have to be identical to those used by the IGS.

These corrections are published on the IGS internet site in files containing satellite and receiver antenna corrections (e.g., in file igs08.atx). Not applying these corrections yields a position bias which presently amounts to about 4 cm in the height component. CNES and DLR follow the same convention since they do not produce their own orbit products but utilize the predicted part of the IGS ultra-rapid orbits instead (Hauschild 2010; Laurichesse 2011).

GPS broadcast ephemerides refer to the phase center of the satellite antennas (IS-GPS-200 2010), and thus, no satellite antenna phase center corrections must be applied in the PPP data processing when using this source. We were not able to find any information on how the SBAS handle the satellite antenna phase centers. Our processing results, however, showed that the height bias of the WAAS results amount to just 5.5 cm (Table 1) if no satellite antenna phase center corrections are applied. When applying these corrections, the height bias increases by more than 3 cm. With EGNOS, the large height biases averaging -41.1 cm (Table 1) prevent a useful interpretation of which solution is the better one. With MSAS, the large variations in the height errors which result in a large standard deviation of 15.6 cm (Table 2) make it difficult to decide on the best processing approach. We decided to use the same approach for all 3 SBAS, and thus, we did not apply antenna phase center corrections with SBAS products.

A second difference between the various sources of satellite ephemerides refers to the P1–C1 code delays. The satellite dependent difference between C/A (C1) and P1 code pseudoranges can reach up to about 3.0 ns (90 cm). It must thus be defined whether the satellite orbit and clock products correct the ionosphere-free linear combination of P1/P2, C1/P2, or of C1/P2′ where $P2' = C1 + P2 - P1$ is an observable produced by cross-correlation receivers. Originally, the IGS clock products used C1/P2′ observations, but switched to P1/P2 on April 02, 2000 (Kouba 2009, IGS Mail #2744 at www.igs.org). It is expected that this convention is also followed by CNES and DLR. GPS broadcast products belong to the group of P1/P2 (IS-GPS-200 2010), unlike the WAAS products which use C1/P2′ (Collins 2008). We could not find any information on what kind of convention EGNOS and MSAS follow.

These satellite dependent code biases affect the processing of the code observations only. In processing carrier phase observations, these biases are absorbed by the estimated float ambiguities. In the case of the code observations, these bias differences can be corrected by using empirically determined long-term averaged P1–C1 values. Such estimates are made available by the Center of Orbit Determination in Europe (CODE) IGS analysis center in Bern, Switzerland in their archive on Differential Code Biases (DCB, www.aiub.unibe.ch/download/CODE/). Such corrections are also needed by receivers since today's receivers provide either code observations of C1, P1, and P2 or just C1 and P2. In the first case, we selected P1 and P2 for our data processing. In the second case, we corrected the C1 observable.

In a pre-analysis, we estimated code residuals for the various observation sets and satellite orbit and clock products applying the P1–C1 corrections in its various forms in order to identify the best fitting solutions. We could thus confirm that the GPS broadcast corrections, and the IGS, CNES, and DLR products all belong to the P1/P2 group. Every one of the three SBAS produced smallest code residuals when assuming C1/P2′ clock corrections.

Another potential difference concerns the geodetic reference frame which is realized by the satellite positions which in turn are in the same reference frame as the coordinates of the ground stations used to determine the satellite orbits. In the selected time period for our study, IGS used the reference frame IGS05 (which is a different realization but has the same datum as ITRF2005) until April 16, 2011 (day of year 106/2011), and afterward, it is the IGS08 as a realization of ITRF2008. Differences between these realizations are at the 1-cm level (Altamimi et al. 2011; Rebischung et al. 2012) and can thus be ignored for our application. CNES and DLR state in their correction files that they did not perform this change and used IGS05 throughout the entire time period from March to June 2011. This, however, is doubtful since both data products are based on the IGS ultra-rapid orbits.

GPS broadcast orbits are defined in the reference system WGS84 (IS-GPS-200 2010). Its present realization bears the designation WGS84 (G1150) and includes a set of station coordinates and velocities referring to the epoch of 2001.0. The station coordinates were estimated with respect to ITRF2000 coordinates of 49 IGS reference stations. Station velocities were derived from ITRF2000 velocities. Thus, WGS84 is identical with ITRF2000 at the few centimeter level (Merrigan et al. 2002).

WGS84 was adopted as the horizontal reference system for international air navigation (ICAO 2010). Consequently, WAAS broadcasts satellite ephemeris and clock corrections which refer to WGS84 (WAAS 2001). EGNOS fulfills this requirement by maintaining an EGNOS Terrestrial Reference Frame (ETRF) as an independent realization of the International Terrestrial Reference Frame (ITRF). According to EGNOS (2009) and Plag et al. (2006), antenna coordinates and velocities of the Ranging and Integrity Monitoring Stations (RIMS) are determined at least once per year, and thus, a consistency with WGS84/ITRF is maintained at a level of a few centimeters. We could not find any specific information on the reference frame adopted for the Japanese MSAS but an alignment to WGS84 can be expected since the requirements of international air navigation must be fulfilled.

In conclusion, due to the various reference frames used for the satellite orbits (WGS84, ITRF2000, IGS05, IGS08, etc.) the reference frames of our coordinate solutions differ. However, the differences should not exceed a few centimeters, so that they can be ignored for many applications. In the result section, we present station-specific biases between solutions, so that the actual differences between realizations become visible.

Observation data sets and data processing

In order to be able to test and to compare PPP results using the different satellite orbits and clock correction data sets, we selected several CORS from the continental USA (14 stations), Europe (13), and Japan (7); see Fig. 1. Their observations are made publicly available by the IGS, by the US National Geodetic Survey (NGS), or by EUREF Permanent Network (EPN), and their data centers. For each of these 34 stations, all observation data sets of 101 consecutive days (March 1–June 9, 2011) were evaluated.

These data sets are ideal with respect to the use of high-quality receivers and antennas, with none or hardly any signal obstructions at the stations and low multi-path. They are thus especially suited to analyze the quality of the orbits and clock correction data streams. On the other hand, the achievable positioning accuracies can often not be reproduced in practical applications.

The static results are based on a maximum of 101 independent 24-h coordinate solutions for each station shown in Fig. 1. Actually, fewer results were obtained due to observation gaps and the lack of MSAS correction data after the Tohoku Earthquake on March 11, 2011. The static 24-h PPP results presented in the next section are based on 1,064 solutions for WAAS, 1,074 solutions for EGNOS, and 577 solutions for MSAS.

The epoch-by-epoch results are based on four 2-h data sets per day and selected station. In total, we used 4,346 2-h data sets for EGNOS, 4,384 for WAAS, and 2,274 for MSAS.

The data processing was performed by the second author's PPP software called WaPPP. This post-processing software is able to process single- or dual-frequency GPS and GLONASS observations collected in static or kinematic mode. Originally, the software was only able to process orbit and clock information in SP3, RINEX-CLK, and RINEX format. For this study, it was extended to also accept SBAS GPS orbit and clock information.

The reference solutions were obtained by PPP based on the final IGS clock and orbit products. In the case of the North American and European stations, the daily solutions were averaged to yield one set of reference coordinates per station. The repeatability in terms of standard deviation of such daily IGS-PPP solutions was better than 5 mm in north and east components and better 10 mm in the height component for all North American and European stations.

Fig. 1 Geographical distribution of continuously operating reference stations (CORS) used in this study

A slightly different procedure was applied to the Japanese stations. Due to the Tohoku Earthquake on March 11, 2011, the three stations in northern Honshu shifted up to a few decimeters to the east (stations MTKA and USUD) or up to a few meters to the east and south directions (station MIZU). Also post-earthquake position shifts occurred at these 3 stations on the order of 0.1–0.3 m. Thus, we used the daily IGS-PPP results with accuracies of better 10 mm in all 3 coordinate components as reference values for this particular day in order to estimate the accuracies of the other PPP solutions.

Daily solutions

The coordinate results of the 24-h observation data sets of the selected CORS were compared to IGS-PPP solutions as described in the last section. All figures and tables show deviations from these reference solutions. The results are grouped and averaged according to the three regions: USA, Europe, and Japan.

Figures 2 and 3 present daily PPP results as a function of time, Fig. 2 for orbits and clock corrections from the

GPS broadcast messages, and Fig. 3 for SBAS corrections. The lack of MSAS PPP results starting on day 72/2011 (March 11, 2011, bottom panel of Fig. 3) is caused by the aftermaths of the Tohoku Earthquake. Figures 4 and 5 show average solution biases of individual CORS and their geographical distribution. Tables 1 and 2 present numerical values of the average solution biases for the three selected regions and also average standard deviations of the daily solution variations. Here, also the results of the PPP solutions based on orbits and clock corrections from CNES and DLR are included for comparison purposes.

In general and especially for mid-latitude sites, PPP float solutions, that is, without fixing the carrier phase ambiguities to integer values, determine the north component best and the height component worst (Heßelbarth and Wanninger 2008). All day-to-day variations of our results, as presented in Figs. 2 and 3 and also in Table 2, confirm this rule. Standard deviations in the three coordinate components reach 1–2 cm for CNES and DLR, 2–5 cm for WAAS, 5–10 cm for EGNOS, slightly more for MSAS, and 10 to more than 20 cm for broadcast orbits and clock corrections (Table 2). Interestingly, the global solutions of CNES and DLR perform best for European stations. The GPS broadcast messages help to achieve the best PPP results for observation sites in the USA.

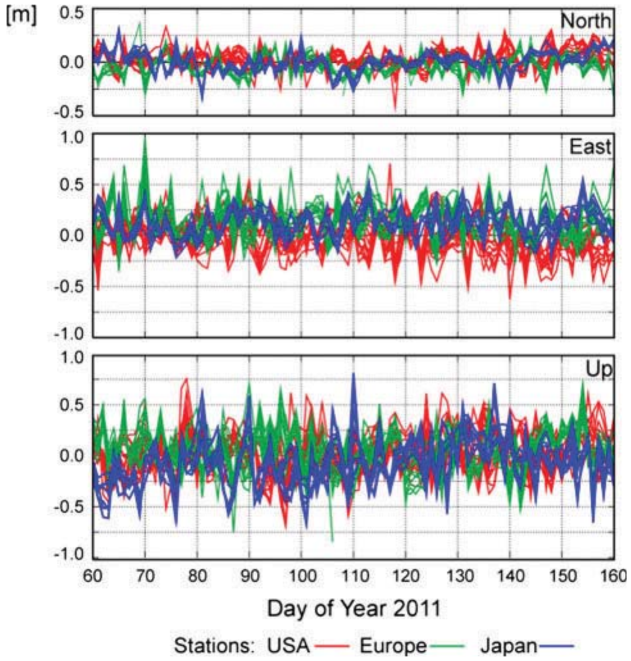


Fig. 2 Differences with respect to reference solutions for PPP results using orbits and clock corrections from the GPS broadcast messages for stations in USA, Europe, and Japan. *Each trace* represents a different station

No significant coordinate biases could be detected in the CNES and DLR solutions. It is worth noting that in all three regions the averaged horizontal CNES biases are smaller than 1 cm. But to our surprise, we found fairly large biases in some of the other solutions. The EGNOS and MSAS results, in particular, reveal biases in the order of tens of centimeters for the east component (EGNOS and MSAS) and the height component (EGNOS only); see Fig. 5 and Table 1. Figure 3 shows that these EGNOS biases are quite stable in time, although a slight drift is detectable in the height component. The biases vary, however, as a function of the horizontal position of the observing station (Fig. 5). The smallest biases are found for sites in the northwest of Europe. The largest biases are associated with sites in the southeast and east of Europe. In our sample, the Macedonian station ORID is most affected and has an average height bias of more than 70 cm. Our conclusion is that the realization of the ITRF by EGNOS seems not to be fulfilled as described in EGNOS (2009).

The WAAS coordinate biases do not exceed 7 cm (Table 1), but their spatial distribution (Fig. 5) reveals systematic effects in the horizontal and vertical components. Small biases in relation to the day-to-day variations are found for the PPP results based on the GPS broadcast

Table 1 Coordinate biases of all static PPP coordinate solutions in north/east/up (cm)

Region	Broadcast	SBAS			Precise	
		WAAS	EGNOS	MSAS	CNES	DLR
USA	3.6/−1.1/2.6	5.4/6.9/5.5	–	–	−0.2/−0.6/−2.0	0.1/−1.6/0.0
Europe	−3.8/10.9/5.4	–	3.4/17.7/−41.1	–	−0.2/−0.8/1.1	0.5/−0.2/−0.8
Japan	0.9/13.9/−8.4	–	–	−4.0/31.3/7.0	−0.4/−0.4/1.2	−2.4/1.8/−1.5

Table 2 Standard deviations of all static 24-h PPP coordinate solutions in north/east/up (cm)

Region	Broadcast	SBAS			Precise	
		WAAS	EGNOS	MSAS	CNES	DLR
USA	9.4/14.4/20.9	2.1/3.5/4.6	–	–	1.1/2.2/2.7	1.0/1.5/2.1
Europe	10.8/16.3/23.2	–	4.7/6.8/10.1	–	0.9/1.2/1.6	0.7/1.2/1.1
Japan	10.3/13.4/27.8	–	–	3.1/8.5/15.6	1.0/1.4/1.6	1.1/1.6/3.2

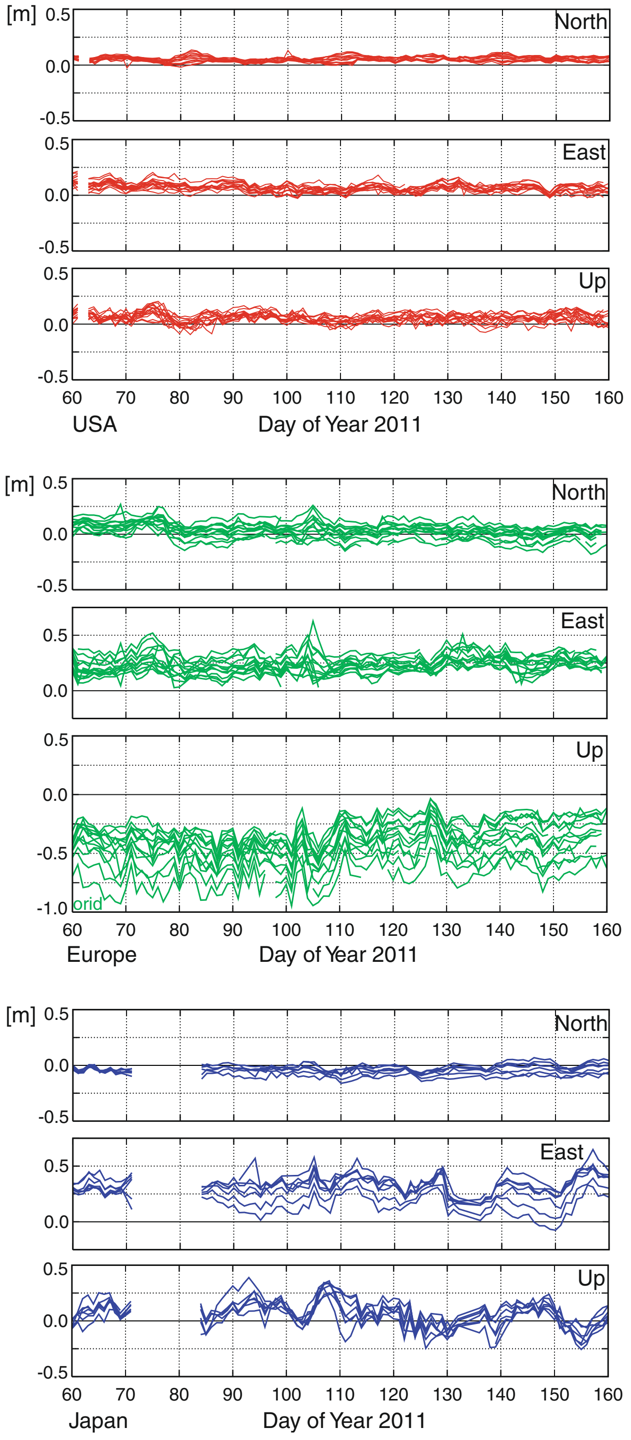


Fig. 3 Difference with respect to reference solutions for PPP results using SBAS products: WAAS in the USA, EGNOS in Europe, and MSAS in Japan. *Each trace* represents a different station

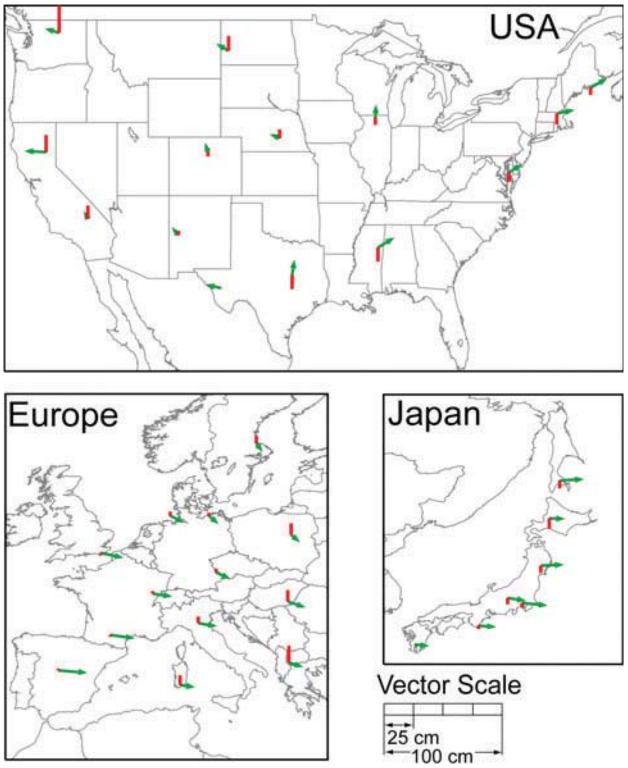


Fig. 4 Coordinate biases in horizontal position and height of all static PPP solutions with orbits and clock corrections from GPS broadcast messages

messages. Especially, for sites in the USA, systematic effects do not exceed a few centimeters (Fig. 2). In Europe and Japan, the east component is affected by a bias of around 10 cm (Fig. 4; Table 1).

Among the three existing SBAS, best results were achieved for the North American WAAS: horizontal and vertical position accuracies were considerably smaller than 10 cm for static 24-h observation data sets. EGNOS and MSAS yield positioning results with biases of tens of centimeters and variations larger by factors of 2–4 as compared to WAAS. The PPP results based on the GPS broadcast messages show smaller biases as compared to the SBAS, but the day-to-day variations are larger by factors of 2–4. As expected, the real-time products of CNES and DLR are able to achieve static positioning results with much better accuracies on the one to a few cm level.

Epoch-by-epoch solutions

Epoch-by-epoch solutions were computed for 2-h blocks of continuous observations, corresponding to a PPP convergence time of 2 h. For each of the 24-h data sets used in the last section, four 2-h periods were cut out and processed in kinematic mode by WaPPP, thus simulating kinematic operation of the receiver. Our results are based on the processing of several thousand such 2-h data sets for each of the three regions. For each such observation data set, we obtained 241 coordinate data sets, one set every 30 s, which is the observation sampling interval of the CORS. Thus, the statistical values presented in Table 3 were

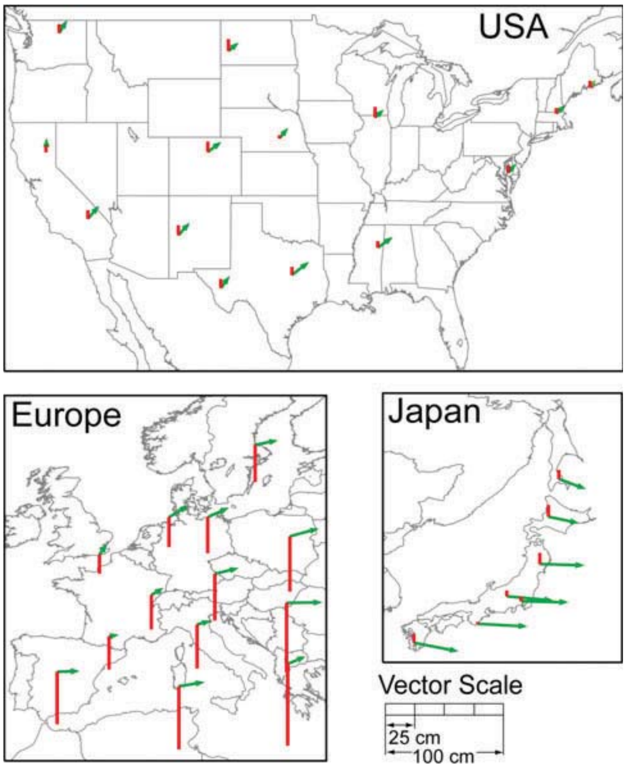


Fig. 5 Coordinate biases in horizontal position and height of all static PPP solutions using SBAS orbits and clock corrections: WAAS in the USA, EGNOS in Europe, and MSAS in Japan

calculated from more than 1 million coordinate data sets for WAAS and EGNOS and more than half a million coordinate data sets for MSAS. In order to obtain coordinate deviations, the calculated PPP coordinate results were compared to the IGS-PPP reference solutions.

Table 3 shows RMS values. Here, it was not necessary to separate biases from variations since the variations dominate by far the coordinate deviations from the reference solutions. The RMS values mainly reflect the findings of the 24-h static results (Tables 1, 2) but now amplified by factors between 3 and 10.

The results based on CNES and DLR corrections are the best: 10 cm 3D-positioning accuracy is obtainable; best solutions were produced for the European stations. Among the three SBAS, again WAAS produced the by far best results. Here coordinate RMS values indicate a 10–30-cm accuracy level. EGNOS and MSAS results are worse by a factor of about 3. Orbits and clock corrections of the GPS satellite messages produced 3D-positioning results on the 2-m accuracy level.

Solution convergence

Some more details about the solution convergence with increasing observation time are presented in Fig. 6. Two different types of solutions are shown: PPP solutions of static observations and epoch-by-epoch solutions of the same static observation data sets used to simulate kinematic positioning. The time span extends from 10 to 120 min (horizontal axis). The figure shows RMS values for the three-dimensional positions (vertical axis). Each of the panels contains three lines: one for solutions based on GPS broadcast ephemerides; one for the WAAS solution which was selected as the best one among the SBAS solutions; and a third one for the results of CNES/DLR. The CNES and DLR results were merged into one line since their orbits and clock products produced convergence results of almost identical quality.

Figure 6 nicely shows the accuracy differences between the three sources of real-time orbit and satellite clock information, between static and kinematic positioning, and the accuracy improvements due to longer times of continuous observations. It confirms that the WAAS orbit and satellite clock information is much more accurate than those taken from the GPS broadcast messages, but as expected they are by for not as accurate as the state-of-the-art real-time products form CNES and DLR.

Conclusions

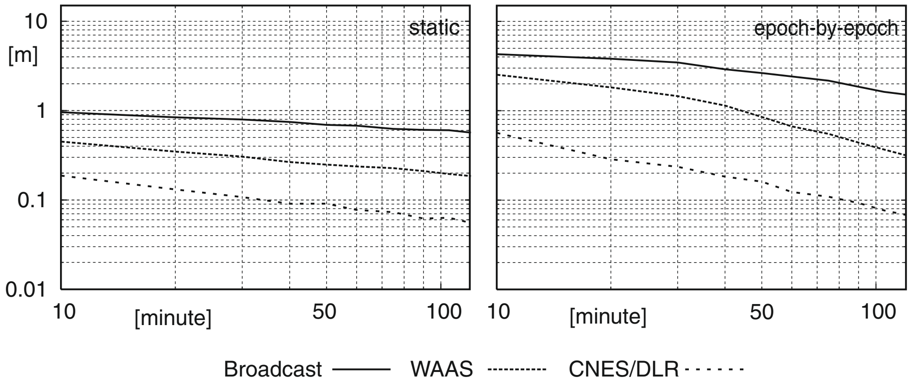
GPS real-time precise point positioning with dual-frequency observation data can be performed using various data streams for satellite orbits and clock corrections. Those from the SBAS and the broadcast ephemerides from the GPS satellites are not intended to be used with PPP. Nevertheless, we could demonstrate that these orbits and clock corrections yield static positioning results of better than a few decimeters in all three coordinate components.

Among the three operational SBAS, the best results were achieved for WAAS: the horizontal and vertical position biases for static 24-h observation data sets were

Table 3 RMS values of all epoch-by-epoch PPP coordinate solutions in north/east/up (cm)

Region	Broadcast	SBAS			Precise	
		WAAS	EGNOS	MSAS	CNES	DLR
USA	55.9/122.7/134.6	13.6/25.7/30.7	–	–	3.3/6.6/8.1	3.6/7.4/8.5
Europe	70.3/128.2/150.7	–	35.2/68.1/100.2	–	3.4/5.8/7.0	3.7/7.0/7.3
Japan	55.2/123.6/174.1	–	–	36.6/74.3/112.0	3.7/7.0/9.7	4.3/7.7/10.7

Fig. 6 RMS values of 3D-coordinates for observation times of 10–120 min for static observation data processed in static or simulated kinematic mode



smaller than 7 cm in all three components, and the standard deviations were smaller than 5 cm; the PPP results of epoch-by-epoch solutions with 2 h of continuous observations were smaller than 30 cm. The EGNOS and the Japanese MSAS yield positioning results with position biases of tens of centimeters and position variations larger by factors of 2–4 as compared to WAAS.

Static 24-h PPP with GPS broadcast ephemerides produced results which mostly show biases smaller than 10 cm and standard deviations of smaller than 20 cm in all three components. Epoch-by-epoch PPP results with 2 h of continuous observations are at the 2-m accuracy level in all three selected regions of the world.

Precise satellite orbit and clock correction from CNES and DLR are able to produce static results on the few centimeter level and epoch-by-epoch results at the 10-cm level. They demonstrate the state-of-the-art real-time orbits and clock corrections.

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