SBAS Based Single and Dual Frequency Precise Point Positioning

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BIOGRAPHIES

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ABSTRACT

Satellite based Augmentation Systems (SBAS) provide a valuable source of GPS orbits and satellite clock corrections. Although these data streams are intended for code based meter accurate positioning, we used them for carrier-phase based Precise Point Positioning (PPP). All our results are based on static dual frequency observation data from sites of the International GNSS Service (IGS) or other Continuously Operating Reference Stations (CORS). We mainly produced daily coordinate sets.

Among the 4 active SBAS (WAAS, EGNOS, GAGAN, MSAS) WAAS performed best. We found only small (< 10 cm) biases with respect to ITRF 2008 and a repeatability on the few cm level in all three components. The other SBAS, and esp. EGNOS and MSAS, results show larger biases with respect to ITRF.

Similar results were computed for the orbit and clock information from the GPS broadcast messages. Here, only small biases exist, mostly smaller 10 cm. Repeatability is on the 10 to 20 cm level in all three coordinate components.

We also performed single frequency data processing with the same data sets from these high-grade GPS equipments. Here, a clear accuracy advantage is visible of the ionosphere-free combination of single frequency code and carrier phase observations over applying corrections from the SBAS or broadcast ionosphere model to the single frequency carrier-phase (and code) observations.

INTRODUCTION

Several real-time data streams of GPS orbit and satellite clock corrections exist, which are not intended to be used for Precise Point Positioning (PPP), but nevertheless they can successfully be used for it. The most important one comes with the GPS messages, the so called broadcast ephemerides. They are readily available to every GPS user. In general they are used for positioning with single frequency code observations producing absolute or relative (differential) positioning results.

For all those users working in an area covered by one of the Satellite Based Augmentation Systems (SBAS) there is a better alternative. These systems offer real-time corrections to the GPS broadcast ephemerides, resulting in more accurate GPS orbit and satellite clock corrections. Also SBAS information is intended to be used with single frequency code observations.

Precise Point Positioning (Zumberge et al. 1997) gains its high accuracy from carrier-phase observations. Usually dual frequency observations are processed in order to mitigate ionospheric effects. If only single frequency observations are available, other techniques to correct for the ionosphere must be used. There are two main techniques: introducing a correction model for the ionospheric delays or using the ionosphere-free linear combination of single frequency code and carrier-phase observations (Andrei et al. 2009, Choy 2011).

We present dual frequency and single frequency PPP results based on SBAS information from day 80 to 130 2012. Therefore, we processed GPS observations from sites in the service areas of the US-American Wide Area Augmentation System (WAAS, GPS WAAS PS 2008), the European Geostationary Navigation Overlay Service (EGNOS, Ventura-Traveset et al. 2006), the Indian GPS Aided GEO Augmented Navigation (GAGAN, Ganeshan 2011), and the Japanese Multi-functional Transport Satellite Satellite-based Augmentation System (MSAS, Fujiwara 2011). These wide-area differential GPS systems provide orbit, clock and ionosphere correction data for North America, Europe, India, and Japan, respectively. We processed the same observation data with the orbit, satellite clock and ionosphere information extracted from the GPS broadcast messages.

This study is the continuation of an earlier work which was based on dual frequency observation data from 2011 and orbit and satellite clock information from the GPS broadcast messages and 3 SBAS systems (WAAS, EGNOS, MSAS). Details on the data processing and the results were published by Hesselbarth and Wanninger (2012). This earlier paper deals with important aspects in the data processing and in the comparison of different PPP results. Among these are the geodetic reference frame realized by the satellite orbits and whether the satellite 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. The authors found that among the 3 tested SBAS systems, the best results were achieved for 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. EGNOS and MSAS yielded positioning results with biases of several tens of centimeters and variations larger by factors of 2 to 4 as compared to WAAS. Dual frequency PPP results based on GPS broadcast message information showed smaller biases but larger variations than the SBAS results.

The purpose of the continuation of the research in this field is to verify whether the PPP coordinate biases are stable over time and may thus be easily correctable. Furthermore we extended the study to single frequency data processing and to the new Indian GAGAN system.

All data processing was performed in post-processing mode. This was made possible since all the required real-time information is archived and freely accessible.

DUAL FREQUENCY AND SINGLE FREQUENCY PPP

Precise Point Positioning is usually performed with dual frequency carrier-phase (and code) observations and the ionosphere-free linear combinations formed with:

$$\Phi_0 = \frac{f_1^2}{f_1^2 - f_2^2}\Phi_1 - \frac{f_1^2}{f_1^2 - f_2^2}\Phi_2 \qquad (1)$$

$$C_0 = \frac{f_1^2}{f_1^2 - f_2^2}C_1 - \frac{f_1^2}{f_1^2 - f_2^2}C_2 \qquad (2)$$

where the indices 1 and 2 indicate L1 and L2, and *0* the ionosphere-free linear combination; Φ and C stand for carrier-phase and code observations, both in m; *f* is the signal frequency. PPP solutions require the estimation of the carrier phase ambiguities, usually as real numbers. For short durations of continuous observations a pure phase solution produces poor results and therefore should be combined with the unambiguous code observations.

In case of single frequency observations, the influence of ionospheric signal delays may be mitigated applying corrections from an ionosphere model. Then, every single carrier-phase (and code) observation is corrected according to

$$\Phi'_0 = \Phi_1 + I \qquad (3)$$

$$C'_0 = C_1 - I \qquad (4)$$

with *I* being the phase advance correction in meters calculated from the Total Electron Content (TEC) values of the model. Φ'_0 has an ambiguity with L1 wavelength. Appropriate real-time ionosphere models are transmitted with the SBAS messages. A simple prediction model is also available from the GPS broadcast messages (IS-GPS 200 2010).

Another method to correct for the effect of the ionosphere consists of forming the ionosphere-free linear combination of single frequency code and carrier-phase observations (Yunck 1993):

$$\hat{\Phi}_0 = \frac{1}{2}\cdot(C_1 + \Phi_1) \qquad (5)$$

This observable is more affected by multipath and noisier than a carrier-phase observable due to the influence of the code measurement, but it is free of first order ionospheric effects. It has an ambiguity with half the wavelength of L1 and thus its processing is very similar to carrier-phase observations. In order to improve the results in case of short observations durations, this observable is combined with the corrected code observations of equ. (4). In our data processing we first of all correct the single frequency observations applying correction from an ionosphere model. Afterwards we form the ionosphere-free linear combination of code and carrier-phase. Thus, the two observables used are:

$$\hat{\Phi}_0 = \frac{1}{2}\cdot\left([C_1 - I] + [\Phi_1 + I]\right) = \frac{1}{2}\cdot(C_1 + \Phi_1) \qquad (6)$$

$$C'_0 = C_1 - I\ . \qquad (7)$$

TEST DATA SETS

The observation data originate from Continuously Operating Reference Stations (CORS) of the International GNSS Service (IGS) with one station (NEGI) from the CORS network of the National Geodetic Survey (NGS). The dual frequency static observation data of 6 stations in the USA, 5 stations each in Europe, India, and Japan (Fig. 1) from days 80 to 130 of 2012 were processed in different modes including 24 h dual frequency and single frequency data processing and simulated kinematic processing which results in epoch-by-epoch coordinate solutions.

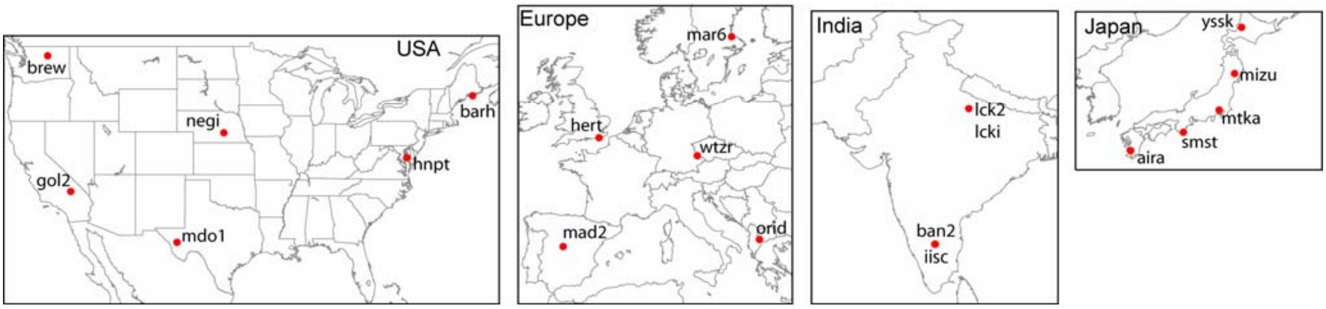

Fig. 1: Geographical distribution of continuously operating reference stations used in this study

Be aware that thus the single frequency observations originate from geodetic grade receivers and the simulated kinematic solutions are actually from mostly low-multipath environments at CORS sites.

PERFORMED COMPUTATIONS AND RESULTS

The data processing was performed by the first author's PPP software called WaPPP. This post-processing software is able to process single or dual frequency GNSS observations collected in static or kinematic mode.

All our PPP solutions using SBAS message or GPS broadcast message information are compared to dual frequency PPP solutions based on satellite orbit and clock corrections from the International GNSS Service (IGS). These reference solutions in the geodetic reference frame ITRF 2008 are usually on an accuracy level of 1 cm and better for 24 h sets of observations. We averaged these daily solutions to obtain even more accurate reference coordinate sets.

The results of the data processing of static dual frequency observations with 24 h duration are presented as coordinate biases with respect to ITRF 2008 reference solutions (Tab.1, Fig. 2 and 3) and coordinate repeatability (Tab. 2).

Tab. 1: Average coordinate biases of dual frequency static 24 h solutions (north/east/up in cm)

Region /SBAS	broadcast orbits + clocks	SBAS orbits + clocks
USA/WAAS	0.2 / -8.2 / -2.9	5.0 / 5.4 / 3.6
Europe/EGNOS	-4.9 / 11.4 / -1.8	4.7 / 13.9 / -39.5
India/GAGAN	4.2 / -6.7 / -11.1	5.4 / 11.2 / 14.5
Japan/MSAS	3.0 / 16.2 / -1.0	-6.1 / 31.8 / 13.0

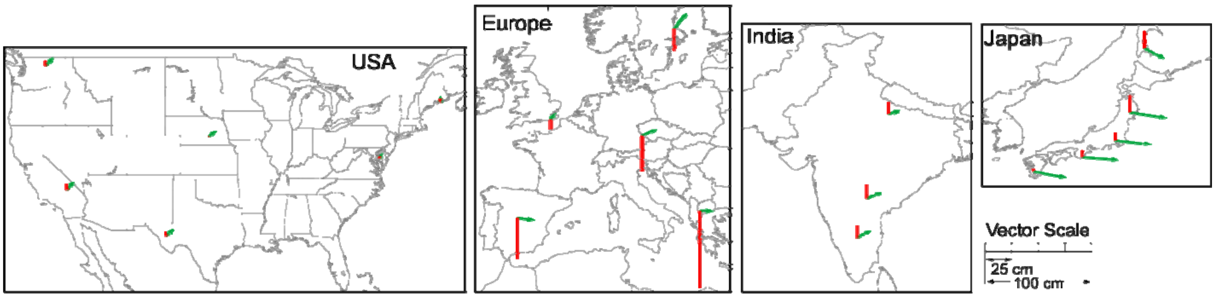

Fig. 2: Coordinate biases in horizontal position and height of all static dual frequency 24 h PPP solutions using SBAS orbit and clock corrections: WAAS in the USA, EGNOS in Europe, GAGAN in India, and MSAS in Japan

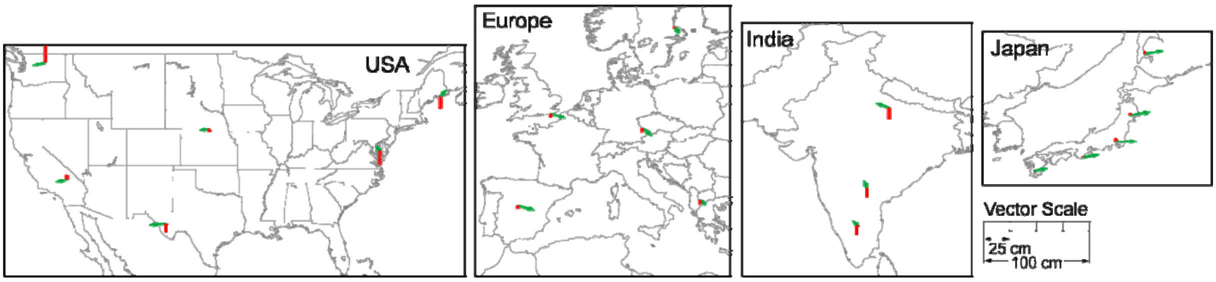

Fig. 3: Coordinate biases in horizontal position and height of all static dual frequency 24 h PPP solutions with orbit and clock corrections from GPS broadcast messages

We suspect that the main cause for the biases are differences in the reference frame of the SBAS (or GPS broadcast) system with respect to ITRF 2008. Two findings support this statement. The biases are regionally highly correlated among the stations (cp. Fig 2: EGNOS, GAGAN, and MSAS, and all regions for the GPS broadcast results in Fig. 3). Furthermore, the biases determined from observation data of 2012 are mostly very similar to those of 2011 (cp. Hesselbarth and Wanninger 2012).

Largest biases are found for EGNOS and MSAS. They amount to several 10 cm in single coordinate components. In our sample the European station ORID is most affected and shows an average height bias of about 70 cm when processed with EGNOS message information. The smallest biases among the SBAS system are produced by WAAS. The GPS broadcast ephemeris produce biases mostly well below 10 cm but with distinct differences among the four regions.

The repeatability of 24 h static dual frequency PPP coordinates is very homogenous among the four regions for the broadcast solutions. It amounts to 10 to 20 cm standard deviation in the different coordinate components (Tab. 2). Better results are obtained for the SBAS. The by far best ones are produced by WAAS with standard deviations of just 2 to 4 cm.

Tab. 2: Average standard deviations of dual frequency static 24 h solutions (north/east/up in cm)

Region /SBAS	broadcast orbits + clocks	SBAS Orbits + clocks
USA/WAAS	9.9 / 14.6 / 17.8	1.7 / 3.1 / 3.9
Europe/EGNOS	9.4 / 14.9 / 18.8	3.6 / 6.1 / 9.3
India/GAGAN	6.2 / 12.0 / 19.2	2.1 / 6.1 / 5.6
Japan/MSAS	8.2 / 14.5 / 19.6	3.3 / 8.3 / 9.5

One could argue that small biases and a good repeatability can only be achieved if the models used in the PPP data processing are identical to the ones used by the different systems in generating orbit and clock products. In our case this would mean that our models are very close to the models used by WAAS and that the models used by some of the other SBAS differ quite a lot. However, none of the models for e.g. earth tides, satellite antennas etc can have an effect on static 24 h positioning of several 10 cm.

We also produced single frequency results. Therefore, we used all the selected data sets again after deleting the observations on the second frequency. Single frequency results were obtained in two ways: applying ionosphere corrections according to equations (3) and (4) which are calculated from the parameters of the ionosphere models of the broadcast messages or of the SBAS messages (Tab. 3); or using the ionosphere-free linear combination of single frequency code and carrier phase observations according to equation (6) together with the corrected code observations according to equation (7) (Tab. 4). In case of SBAS, biases due to differences in the geodetic reference frames were removed before calculating RMS values.

In the case of applying corrections from ionosphere models, the coordinate errors due to remaining ionosphere errors largely depend on the ionosphere region. The larger the overall vertical electron content (VEC) and the larger VEC gradients and ionospheric irregularities, the larger are remaining ionospheric delays. Hence, it is not surprising that the results from stations in the Indian region show the largest coordinate errors and stations in Europe and parts of the USA perform better (Tab. 3). Solutions based on broadcast message information with RMS values of several 10 cm can not be categorized as precise. SBAS corrections yield a better repeatability, but still the RMS values are on the level of 10 to 70 cm.

Tab. 3: RMS values (north/east/up in cm) of 24 h single frequency PPP coordinate errors using broadcast or SBAS ionosphere corrections; in case of SBAS; biases due to differences in the geodetic reference frame were removed

Region /SBAS	broadcast orbits + clocks + iono.	SBAS orbits + clocks + iono
USA/WAAS	59.6/25.2/ 59.0	35.0/15.5/32.6
Europe/EGNOS	39.3/21.5/ 52.9	31.1/12.2/26.2
India/GAGAN	104.8/34.8/110.9	38.7/15.8/62.2
Japan/MSAS	102.8/30.5 / 71.1	28.6/13.8/73.5

Tab. 4: RMS values (north/east/up in cm) of 24 h single frequency PPP coordinate errors using the ionosphere-free code-carrier combination $\hat{\Phi}_0$; in case of SBAS, biases due to differences in the geodetic reference frame were removed

Region /SBAS	broadcast orbits + clocks	SBAS orbits + clocks
USA/WAAS	10.3 / 23.0 / 25.6	4.9 / 4.2 / 9.6
Europe/EGNOS	11.8 / 24.3 / 20.6	3.8 / 14.4 / 14.3
India/GAGAN	8.2 / 17.9 / 25.8	3.8 / 7.4 / 11.8
Japan/MSAS	11.0 / 29.3 / 26.0	4.5 / 11.7 / 16.6

Much better single frequency results are obtainable with the ionosphere-free code-carrier combination (Tab. 4). These results are independent of the (first order) ionospheric effects and thus reflect the orbit and clock accuracies of the different correction data streams. An additional error source is code multipath which depends on the station environments and the quality of the equipment, esp. the antennas. In comparison of Tab. 4 and Tab. 2, and thus of single and dual frequency results, it becomes obvious that these single frequency results are not as accurate as the dual frequency ones. But nevertheless the single frequency accuracies get quite close to the ones of dual frequency.

Please note that all the observation data stem from high-grade GPS equipment. With low cost equipment, especially simpler antennas, these accuracy levels can not be reached due to increased code multipath errors.

In another test we used the static observations data and processed it in kinematic mode. Fig. 4 shows position convergence with observation durations of 1 minute to 2 hours. The 3D RMS values are dominated by errors in the height component. Please note that biases due to differences in the geodetic reference frames were removed for all SBAS results. The values shown for GPS broadcast messages are averaged results from all four world regions.

Most IGS stations provide non-smoothed code observations. Furthermore, the data sets used have a sampling rate of 30 seconds so that the 1 minute results are based on just 3 epochs of observation data. For these reasons the results of 1 to a few minutes of observations with a stronger influence of the code observations may be worse than what can be achieved with other receiver settings.

The main conclusions from Fig. 4 are the following:

- Single frequency results based on the ionosphere-free code-carrier combination are more accurate than single frequency results using the ionosphere model for observation correction. Remember, this conclusion is valid for high-grade equipment only.
- In general: best results are achieved with WAAS orbits and clock corrections.
- Dual frequency data processing with durations of more than 30 minutes obtains the best results with correction from WAAS and MSAS; broadcast corrections perform worst.
- Single frequency results do not differ much among the systems

SUMMARY

We introduced SBAS and GPS broadcast orbit and satellite clock corrections to PPP processing of observation data sets of CORS stations equipped with geodetic receivers and antennas.

The 24 h dual frequency results revealed that WAAS corrections are the most accurate among the 4 tested SBAS. Coordinate accuracies (biases and standard deviations) of a few centimeters could be achieved. The other three systems produced coordinates with larger biases and worse repeatability (esp. EGNOS and MSAS). These biases are very stable over time (2011 – 2012) and thus we consider them as reference frame differences; which could be removed easily.

PPP results based on GPS broadcast ephemerides allow static point positioning on the 20 cm level.
The best single frequency results were obtained using the ionosphere-free combination of code and carrier-phase observations. Please note that due to code multipath errors such results can only be achieved with high-grade GPS equipment. The SBAS and GPS broadcast ionosphere models were of little help in the single frequency PPP data processing.

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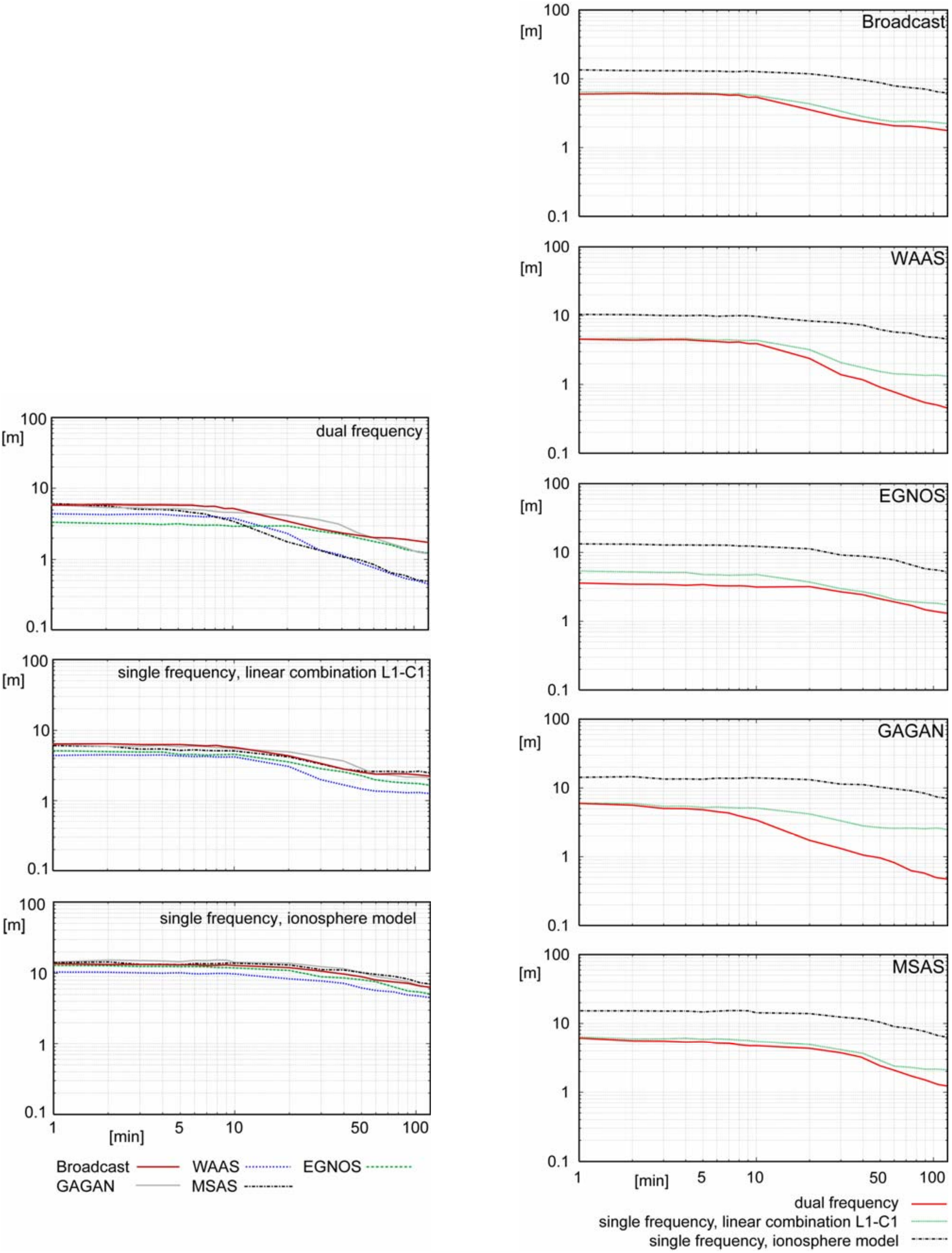

Fig. 4: RMS values of 3D-coordinate errors for observation durations of 1 to 120 minutes for static observation data processed in kinematic mode; left column: results arranged according to solution types; right column: results arranged according to systems; in case of SBAS, biases due to differences in the geodetic reference frame were removed

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