

Investigation of network-based RTK techniques: a case study in urban area

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Abstract Network-based real-time kinematic (NRTK) GNSS (Global Navigation Satellite System) positioning system is one of the most commonly used in many countries for various applications which require instant and highly accurate positioning all around the clock. The main principle of this system is to generate reliable error models that can mitigate dispersive (e.g., ionospheric delay) and non-dispersive (e.g., tropospheric delay and orbit biases) errors which are the main sources for the degradation of the positioning accuracy. There are several correction techniques that have been implemented and used in NRTK concept. The objective of this study is to evaluate accuracy, precision, time to first fix (TTFF), and performance of carrier phase ambiguity fixing while maintaining the same survey conditions for VRS, FKP, and MAC NRTK techniques. The Turkish TUSAGA-Aktif CORS network was used to obtain the three NRTK corrections. In terms of accuracy, our results show that all the techniques are practically the same and the horizontal positioning accuracy is in the order of few centimeters for all techniques. As far as precision and TTFF are concerned, VRS produced slightly better results comparing to the others. When it comes to ambiguity fixing performance in the dynamic environment, FKP produced the best results.

Keywords Network-based RTK · Virtual reference station · Master auxiliary concept · Flat plane correction parameter

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Introduction

Conventional real-time kinematic GNSS positioning technique has been widely used to obtain cm-level positioning accuracy in real-time. This system is based on the principle which at least one of the receivers serves as a base station with known coordinates and the other receivers serve as rover station in which the coordinates are determined relative to the base station. If there are high ionospheric and tropospheric activities, this 15 km distance may become less than 10 km, because dispersive and non-dispersive errors change rapidly from the base station to the rover side (G.R. Hu et al. 2002). Due to this rapid changes, the errors cannot be mitigated effectively for the rover side. This limitation of conventional RTK is the main motivation behind using Continuously Operating Reference Stations (CORS) to model the distance-dependent errors more accurately and reliably for long baselines (several tens of kilometers) between the rover and the base stations. The reference stations continuously stream raw GNSS data to the central server which operates the network. Network software at the central server calculates dispersive and non-dispersive errors at each reference station and interpolates these corrections w.r.t. the position of the users. Then, users receive the interpolated corrections via the different communication means (radio, mobile phone, or internet) between the rover and the central server. These three stages are the main principle of NRTK.

There are several correction techniques on the market for NRTK. Among them, Virtual Reference Station (VRS) (Landau et al. 2002; Vollath et al. 2000), Flat Plane Correction Parameter (FKP, German Flächen- Korrektur-Parameter) (Wübenna et al. 2005; Wübenna et al. 2001), and Master Auxiliary Concept (MAC) (Brown et al. 2005) are the most common ones. Each technique has its own strong and not so strong aspects. For VRS and FKP, calculations of the

errors are performed by the network software whereas in MAC, it is performed by the rover-side software (Brown et al. 2006). Despite the differences in their operations, all of these techniques share a common goal which is to interpolate dispersive and non-dispersive errors at the reference stations for the position of the users. This interpolation is necessary for highly accurate real-time positioning. The studies based on these techniques produce the horizontal accuracy which is in the order of few centimeters. (Berber and Arslan 2013; Gumus et al. 2012; Wang et al. 2010).

Dispersive and non-dispersive GNSS errors change significantly by the time, leading to deviation of the estimated coordinates (Olynik et al. 2002). Therefore, time-dependent changes of these errors need to be in the same order for the NRTK correction techniques in order to investigate the performances of the techniques under the same survey conditions.

In this study, accuracy, precision, TTFF, and ambiguity fixing performance of commonly used VRS, FKP, and MAC NRTK techniques are investigated while maintaining the same survey conditions for each technique in the surveyed urban area.

Review of TUSAGA-Aktif CORS network

TUSAGA-Aktif consists of 147 CORS stations, located across the country (Fig 1). Trimble Zephyr Geodetic II triple-frequency antenna has been used for the all CORS stations. The distances between the CORS stations are in the range of 70–100 km. Trimble GPSNet network software has been used on TUSAGA-Aktif network for generating real-time corrections for the users.

In order to model the all error sources effectively in such a huge network (one of the largest GNSS network in the world) and ease the computational burden on the server, all the CORS stations are divided geographically into four regions. Therefore, four auxiliary servers are set up to operate the CORS stations. Each server is responsible for the adjustment of the raw GNSS data for its own region, and the all regions are adjusted together by the main server. Thus, high interpolation accuracy is maintained throughout the CORS stations near the borders of the regions. The communication between the control centers and the stations are maintained by duplex ADSL and mobile phones (GSM) with using General Package Radio Service (GPRS) and Enhanced Data Rates for GSM (EDGE) (Mekik et al. 2011).

VRS, FKP, and MAC NRTK correction techniques were implemented in TUSAGA-Aktif. NRTK related message types for GLONASS satellites are not available for FKP and MAC; they are only available for VRS. Therefore, users who receive real-time correction from MAC and FKP cannot use GLONASS data, at least at the time of this publication. This is

the major shortcoming for TUSAGA-Aktif, especially during the limited satellite visibility.

Case study

In this study, VRS, FKP, and MAC NRTK correction techniques were investigated in terms of accuracy, precision, time to first fix (TTFF), and kinematic performance. Seven test points were chosen within the urban area. TUSAGA-Aktif CORS network was used to obtain VRS, FKP, and MAC techniques at these points.

The following considerations were taken into account to determine the location of the test points.

- There were no objects around the test points which could lead to multipath effects or signal interference for the observations.
- There were no obstructions above the points to block satellite visibility.

Location of the test points w.r.t. the closest CORS station in the survey area were given in Fig. 2. The static survey and the NRTK measurements are carried out at these test points.

Static survey

In order to investigate the NRTK techniques under the same survey conditions at the test points, a survey apparatus was devised to fix three GNSS receivers (Fig 3).

All the three receivers are $500 \text{ mm} \pm 0.1 \text{ mm}$ to the center of the apparatus. With this original setup, all the conditions affecting the survey (such as satellite geometry, baseline length, obstructions, environmental effects, reference stations and receiver noise level, multipath conditions, tropospheric and ionospheric activity, instrumental effects, and ephemerides errors) can be the same magnitude for each receiver during the static survey and the NRTK measurements.

Epoch50 GNSS (triple-frequency) receivers and Nomad data collectors were used at each test point for the static survey and the NRTK measurements. The static observation was performed approximately 3 h simultaneously for the three receivers on the apparatus at each station (test points) with 5-s sampling rate and 10 degrees of elevation mask angle. The surface of the apparatus has been taken as the reference height. Then, all the receivers have been installed to the apparatus with the same height w.r.t. this reference height.

All static observations were performed consecutive days except for Station 7. Due to the weather conditions, the very last data collection for Station 7 had 6 days delay from the previous one.



Fig. 1 Locations of TUSAGA-Aktif CORS stations

Trimble Spectra Precision Survey Office software was used for post-processing. Since the accurate GPS and GLONASS satellites orbits produced by various centers, (Alçay et al. 2012) precise ephemerides of GPS and

GLONASS satellites (Dow et al. 2005) were used for processing. The Neil mapping function was used to mitigate the tropospheric effect (Neill 1996; Neill 2000). The ionospheric effect was mitigated by using the



Fig. 2 Location of the test points w.r.t. the closest CORS station (KNY1)

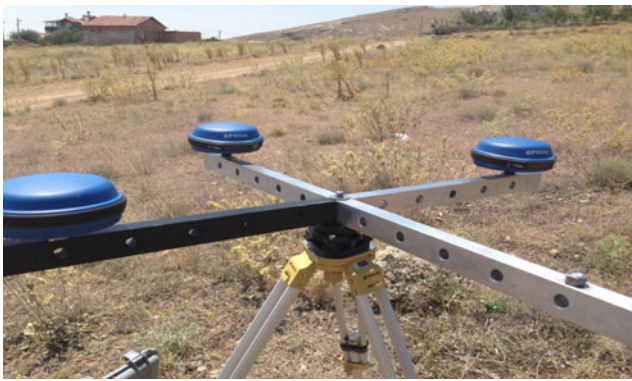


Fig. 3 The survey apparatus set to collect the data

triple-frequency receivers. Constraint adjustment were performed to determine the UTM projection coordinates (northing, easting) and ellipsoidal height in ITRF96 datum (reference epoch: 2005) for each receiver at the stations by the help of the three nearest CORS stations in the survey area. Real-time coordinates from TUSAGA-Aktif CORS network are broadcasting in this datum. In this way, the same datum has been maintained for the coordinates of the static survey and the NRTK techniques.

Coordinates which are determined by the static survey were considered true coordinates for each receiver, and the differences between them and the coordinates obtained from the NRTK techniques are calculated to investigate the accuracy of each technique.

NRTK measurement

Due to the lack of GLONASS message types for MAC and FKP, VRS has been divided as VRS (GPS/GLONASS) and VRS (GPS) to investigate GLONASS effect on VRS. Right after the static survey, each receiver was set to different techniques, VRS (GPS/GLONASS), FKP, and MAC by the data collector. Windowing technique was performed to obtain the NRTK data. The windowing technique, also called averaging technique, is generally applied to improve the positioning accuracy for real-time applications if rover remains stationary for a short period of time. Windowing is achieved by determining the average of several epochs (Janssen and Haasdyk 2011). For each technique, ten epochs (fixed solution) were collected simultaneously with 1-s sampling rate and the average of these ten epochs was recorded as a single measurement. Forty measurements were obtained simultaneously for each technique and each station. Right after these measurements, GLONASS satellites were removed from VRS (GPS/GLONASS), then another forty measurements were performed by VRS (GPS) for the same points.

Differences between the true coordinates and the coordinates of each technique were calculated to determine root-mean-square errors (RMSE) to investigate the accuracy of the techniques.

$$m_{northing} = \sqrt{\frac{\sum_{i=1}^{40} (x_{northing(i)} - t_{northing})^2}{40}} \tag{1}$$

$$m_{easting} = \sqrt{\frac{\sum_{i=1}^{40} (y_{easting(i)} - t_{easting})^2}{40}} \tag{2}$$

$$m_h = \sqrt{\frac{\sum_{i=1}^{40} (h_i - t_h)^2}{40}} \tag{3}$$

$$m_{p_2d} = \sqrt{\frac{\sum_{i=1}^{40} ((x_{northing(i)} - t_{northing}) + (y_{easting(i)} - t_{easting}))^2}{40}} \tag{4}$$

Here, $x_{northing}$ and $y_{easting}$ represent the projection coordinates obtained after the NRTK measurements; $t_{northing}$ and $t_{easting}$ represent true projection coordinates obtained after the static survey; h represents the ellipsoidal height obtained after the NRTK measurements; t_h represents true ellipsoidal height obtained after the static survey; $m_{northing}$ represents the RMSE of northing component; $m_{easting}$ represents the RMSE of easting component; m_h represents the RMSE of ellipsoidal height component; m_{p_2d} represents the RMSE of horizontal position.

To investigate the precision of each technique, standard deviations were calculated from the mean value of the forty measurements.

$$s_{northing} = \sqrt{\frac{\sum_{i=1}^{40} (x_{northing(i)} - \bar{x}_{northing})^2}{40}} \tag{5}$$

$$s_{easting} = \sqrt{\frac{\sum_{i=1}^{40} (y_{easting(i)} - \bar{y}_{easting})^2}{40}} \tag{6}$$

$$s_h = \sqrt{\frac{\sum_{i=1}^{40} (h_i - \bar{h})^2}{40}} \tag{7}$$

$$s_{p_2d} = \sqrt{\frac{\sum_{i=1}^{40} ((x_{northing(i)} - \bar{x}_{northing}) + (y_{easting(i)} - \bar{y}_{easting}))^2}{40}} \tag{8}$$

Here, $\bar{x}_{northing}$ and $\bar{y}_{easting}$ represent the mean value of projections coordinates obtained after the NRTK measurements; \bar{h} represents the mean value of ellipsoidal height obtained after the NRTK measurements; $s_{northing}$ represents the standard deviation of northing component; $s_{easting}$ represents the standard deviation of easting component; s_h represents the standard deviation of ellipsoidal height component; s_{p_2d} represents the standard deviation of horizontal position.



Fig. 4 The survey vehicle

TTFF (cold start) for each technique at each station was determined before the NRTK measurements. Accuracy, precision, and TTFF were taken into account to interpret the results.

Kinematic survey

Three GNSS receivers were attached on the top of a survey vehicle (Fig 4) to investigate the performance of carrier phase ambiguity fixing of the techniques in a dynamic environment.

Two survey routes were determined to test the ambiguity fixing performance of the techniques (Fig 5).

The surveys were performed as round trips between CORS stations. The round trips were carried out between KNY1-CIHA (75 km distance) and KNY1-KAMN (80 km distance) CORS stations. Before each trip, receivers were set to VRS (GPS/GLONASS), FKP and MAC correction techniques. By

the help of the data collector, receivers were set to obtain 1 epoch with 1-s sampling rate for every 250 m (horizontal distance) during the trip. We tried to keep the speed of the vehicle at 75 km per hour for each trip between each stations. The total epoch numbers and fix rates were determined for each technique. The results were given in section 4.4.

Evaluation of the collected data

We evaluated the data for accuracy, precision, TTFF, and kinematic. The results were tabulated and plotted in following sections.

Assessment of accuracy

The differences between the assumed true coordinates (obtained by the static survey) and the coordinates obtained after using the techniques were used to calculate RMSE of northing, easting, ellipsoidal height, and horizontal position. The results are tabulated in Table 1 and plotted in Fig. 6.

As it is seen from the accuracy results, there are no significant differences between the techniques in terms of the horizontal positioning accuracy whereas for the vertical positioning accuracy, this is not the case; the differences are considerable for some stations. The difference of the vertical RMSE between MAC and VRS (GPS) is reached 3.6 cm for Station 2, and the vertical RMSE between MAC and FKP is reached 3.4 cm for Station 6. When all the test data are examined, no technique has distinct advantage over the others.

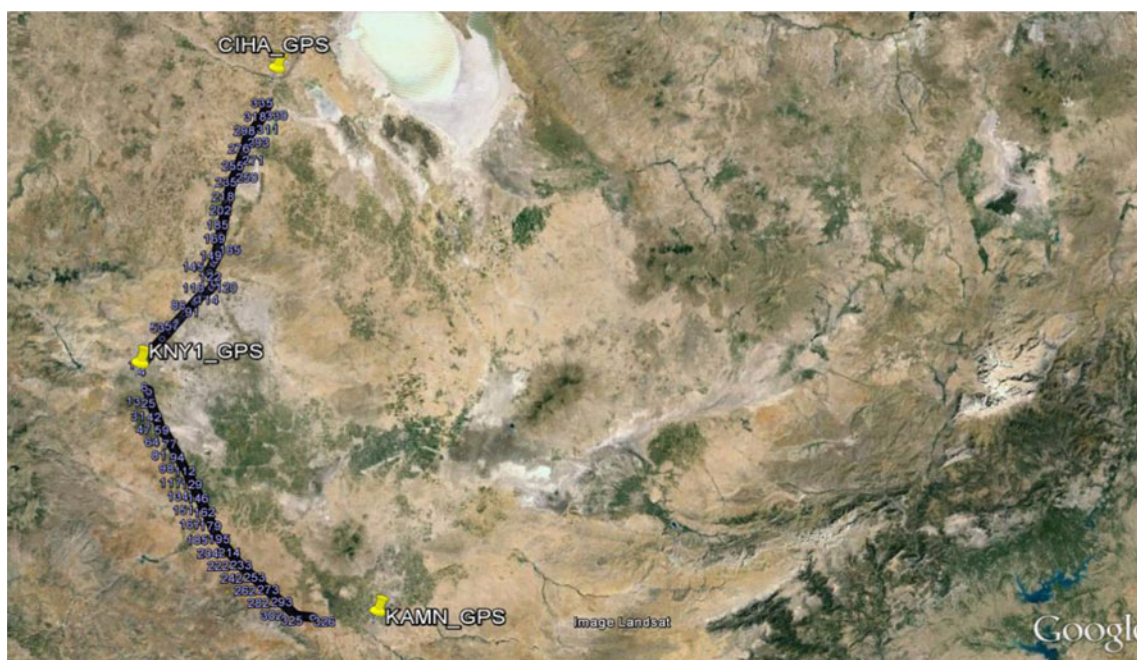


Fig. 5 The survey routes and CORS stations

Table 1 RMSE of northing, easting, ellipsoidal height, and horizontal position (cm)

Stations	VRS(GPS/GLONASS)				FKP				MAC				VRS(GPS)			
	$m_{northing}$	$m_{easting}$	m_h	m_{p_2d}	$m_{northing}$	$m_{easting}$	m_h	m_{p_2d}	$m_{northing}$	$m_{easting}$	m_h	m_{p_2d}	$m_{northing}$	$m_{easting}$	m_h	m_{p_2d}
Station_1	0.2	2.0	5.0	2.0	1.3	2.3	5.1	2.7	0.4	1.8	5.1	1.8	0.2	2.3	4.7	2.3
Station_2	1.0	2.5	6.7	2.7	1.0	2.5	4.7	1.8	2.0	0.9	4.0	2.2	0.6	2.2	7.6	2.3
Station_3	0.7	2.4	4.5	2.5	0.7	2.2	6.0	2.3	1.8	2.0	5.3	2.7	2.1	2.7	5.6	3.4
Station_4	1.3	2.2	4.4	2.6	1.5	2.0	3.9	2.6	1.7	2.5	4.5	3.0	1.3	2.2	3.4	2.6
Station_5	1.9	3.6	5.4	4.1	2.3	3.4	5.3	4.1	3.1	4.2	5.4	5.2	2.6	3.2	3.3	4.1
Station_6	1.1	2.2	8.9	2.4	2.2	2.7	9.2	3.5	2.0	2.4	5.8	3.1	1.7	1.8	6.2	2.5
Station_7	0.7	1.8	7.9	1.9	1.2	1.0	8.8	1.6	0.5	1.7	7.9	1.8	0.6	1.5	9.5	1.6

There is no distinct effect of GLONASS for observed VRS in terms of accuracy. Accuracy of the horizontal components is generally much better than the vertical component at the test points as expected.

To investigate the residual ionospheric errors during the NRTK measurements, I_{95} ionospheric disturbance index (Wanninger, 1999) was used for the survey area. Figure 7 shows the ionospheric activities during the NRTK

measurements at the test points. I_{95} index Kp value around 5 or more indicate increased geomagnetic activity (Wanninger 2004).

Since the height component is more sensitive to tropospheric errors due to high correlation with troposphere parameters (Dodson et al. 1996), estimated tropospheric zenith delay was determined from the raw data of the static survey for each test point to investigate the tropospheric activities during the

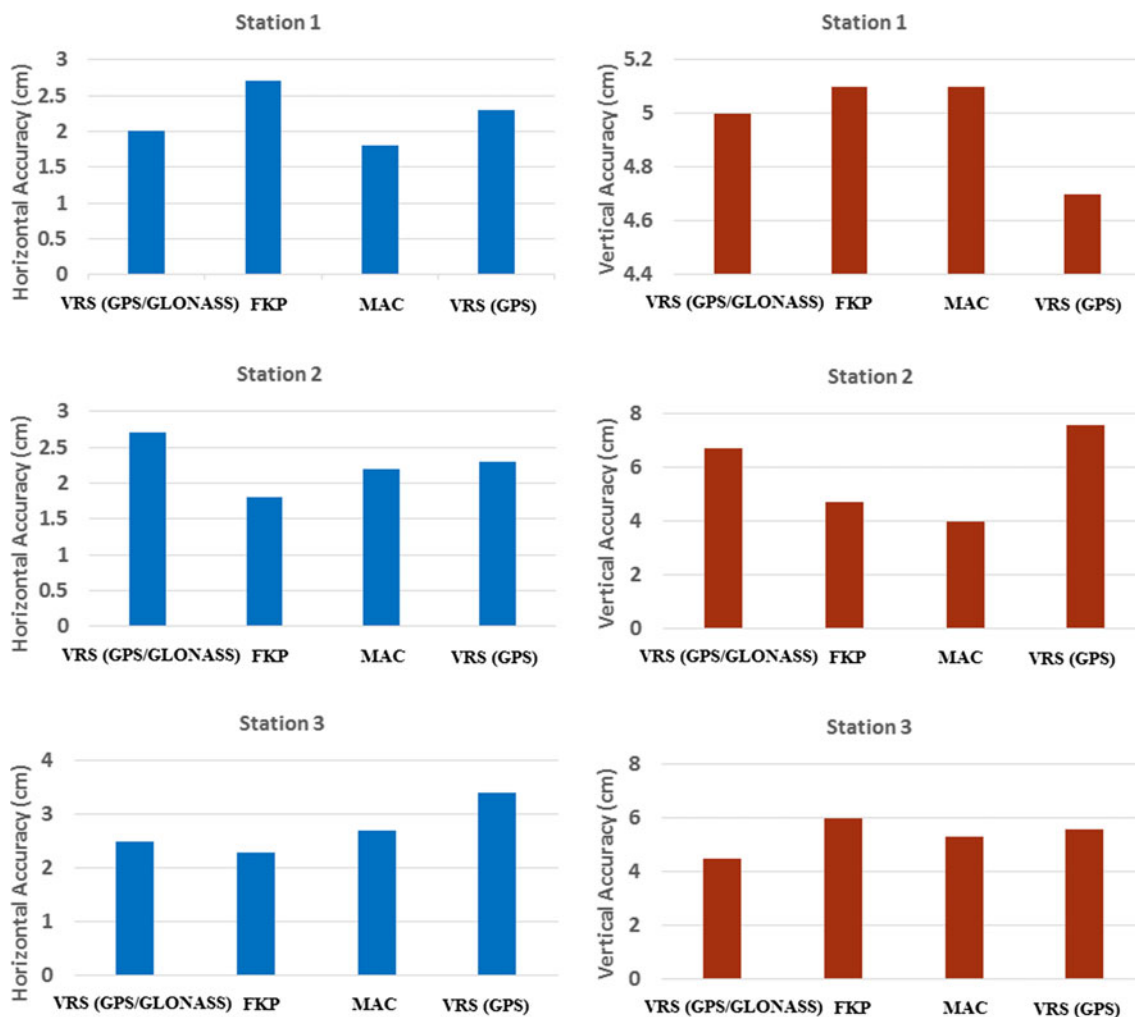


Fig. 6 Horizontal and vertical RMS (cm)

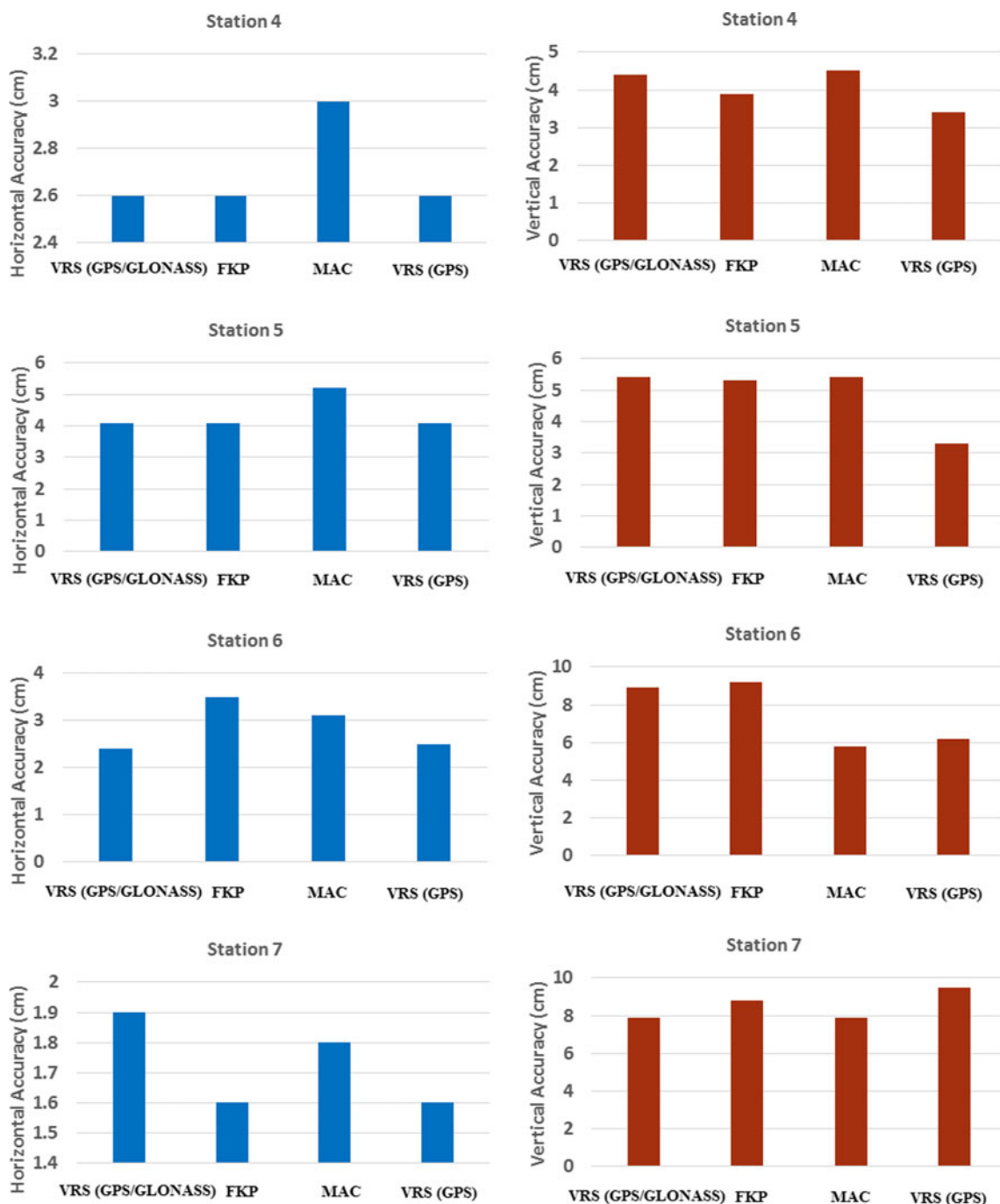


Fig. 6 (continued)

NRTK measurements. Measurements taken in different days show no observable differences for the tropospheric activities.

Assessment of precision

To investigate the precision of the NRTK techniques, deviations from the average of forty measurements were calculated for each technique. Results show that how much the computed position is likely to deviate

from the mean value. Standard deviations for each technique were tabulated in Table 2 and plotted in Fig. 8.

The results show that the standard deviations of the horizontal position are generally in the order of millimeters and the standard deviations of the height component are in the range of 0–2 cm. As it was expected, the standard deviations in the horizontal positions are much less than the standard deviations in the vertical positions. For some points, the horizontal

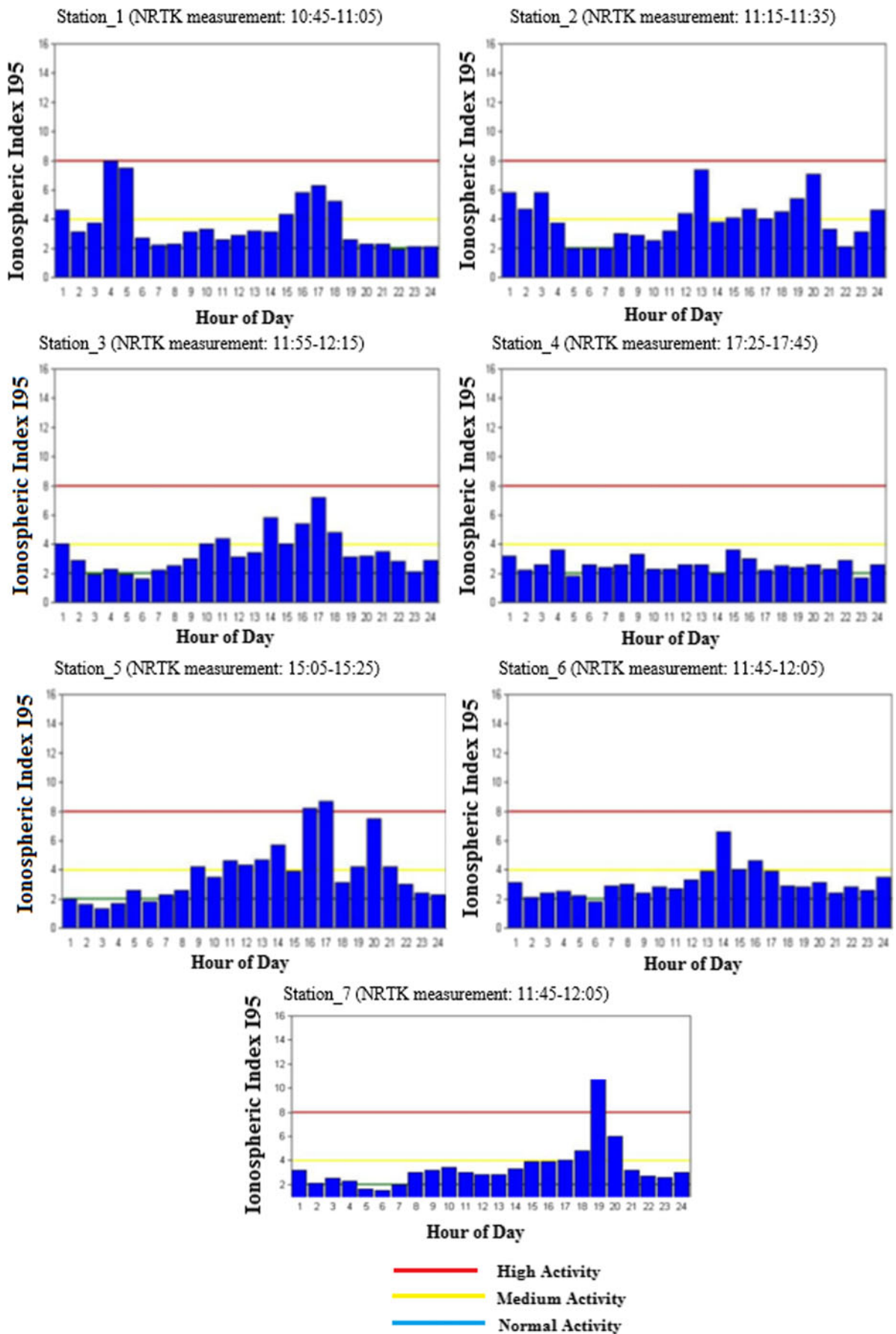


Fig. 7 Hourly variations of I_{95} index Kp value at the test points

Table 2 Standard deviation of northing, easting, ellipsoidal height, and horizontal position (mm)

Stations	VRS (GPS/GLONASS)				FKP				MAC				VRS (GPS)			
	S _{northing}	S _{easting}	S _h	S _{p_2d}	S _{northing}	S _{easting}	S _h	S _{p_2d}	S _{northing}	S _{easting}	S _h	S _{p_2d}	S _{northing}	S _{easting}	S _h	S _{p_2d}
Station_1	1.5	2.4	4.9	2.9	7.4	4.3	6.4	8.6	3.1	4.9	3.6	5.8	2.0	1.6	5.2	2.6
Station_2	8.4	6.6	15.0	10.7	5.3	5.0	20.2	7.3	5.8	2.8	11.2	6.4	5.2	4.9	16.3	7.2
Station_3	2.6	1.8	3.4	3.1	5.5	4.5	26.1	7.1	9.6	7.4	21.0	12.1	7.0	6.6	9.2	9.6
Station_4	3.2	2.5	4.8	4.0	3.7	3.8	7.4	5.3	7.3	7.9	15.1	10.8	3.4	2.6	4.0	4.3
Station_5	7.3	4.7	15.5	8.7	8.7	3.5	7.9	9.4	13.4	4.9	8.3	14.2	4.8	3.5	3.5	5.9
Station_6	2.2	2.3	14.2	3.2	3.9	3.3	11.6	5.1	2.4	2.6	7.5	3.6	2.9	1.5	5.6	3.2
Station_7	2.5	2.0	13.3	3.2	2.7	1.7	15.7	3.2	1.9	2.0	15.2	2.8	3.3	1.5	9.0	3.7

precision is 4–5 times much better than the vertical precision.

The results also show that the precision of VRS (GPS/GLONASS) and VRS (GPS) are slightly better than the other NRTK techniques at the most test points.

Assessment of initializing time (time to first fix)

When using CORS stations to support network-based real-time cm-level kinematic positioning, carrier-phase ambiguities between reference stations and receivers have to be

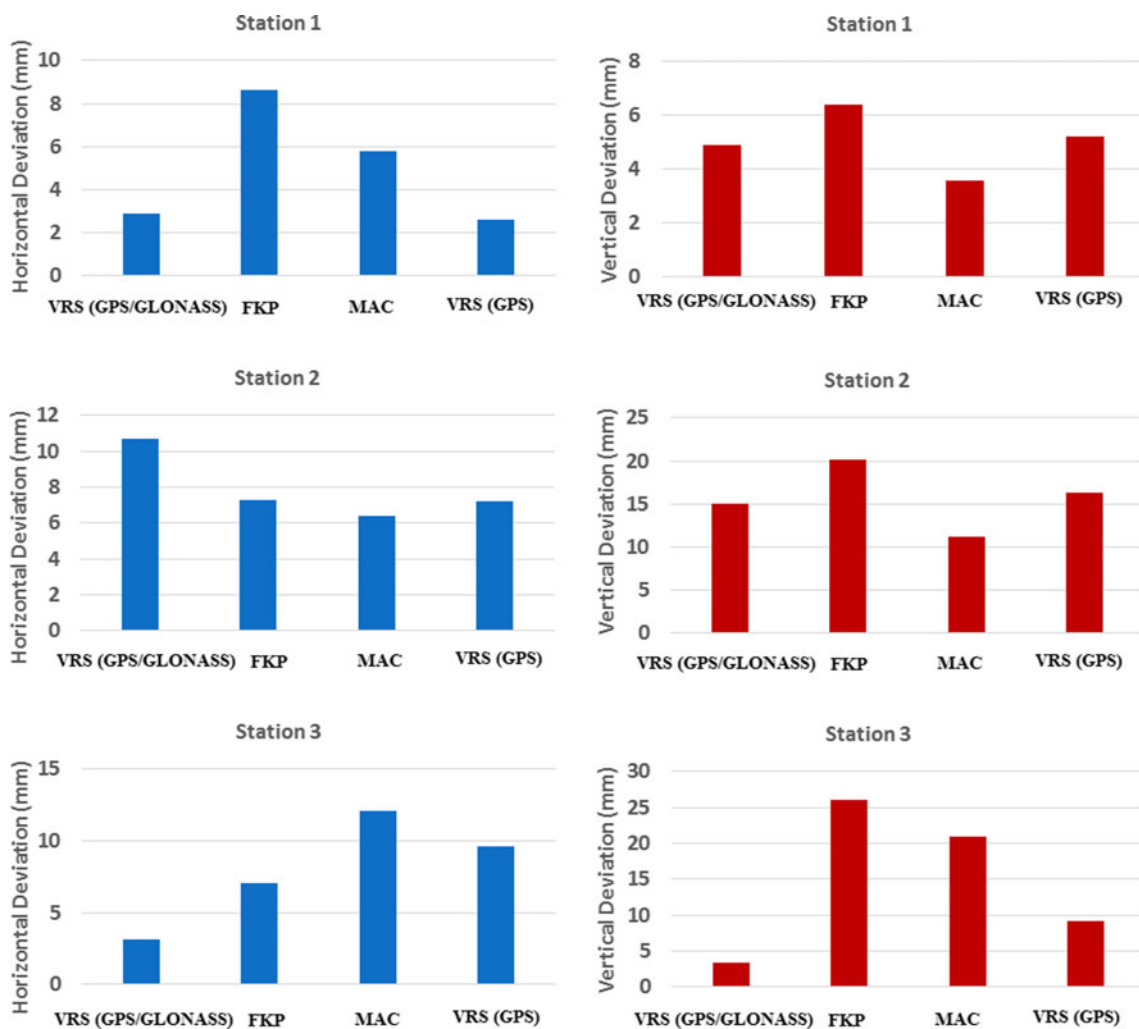


Fig. 8 Standard deviations of horizontal and vertical position (mm)

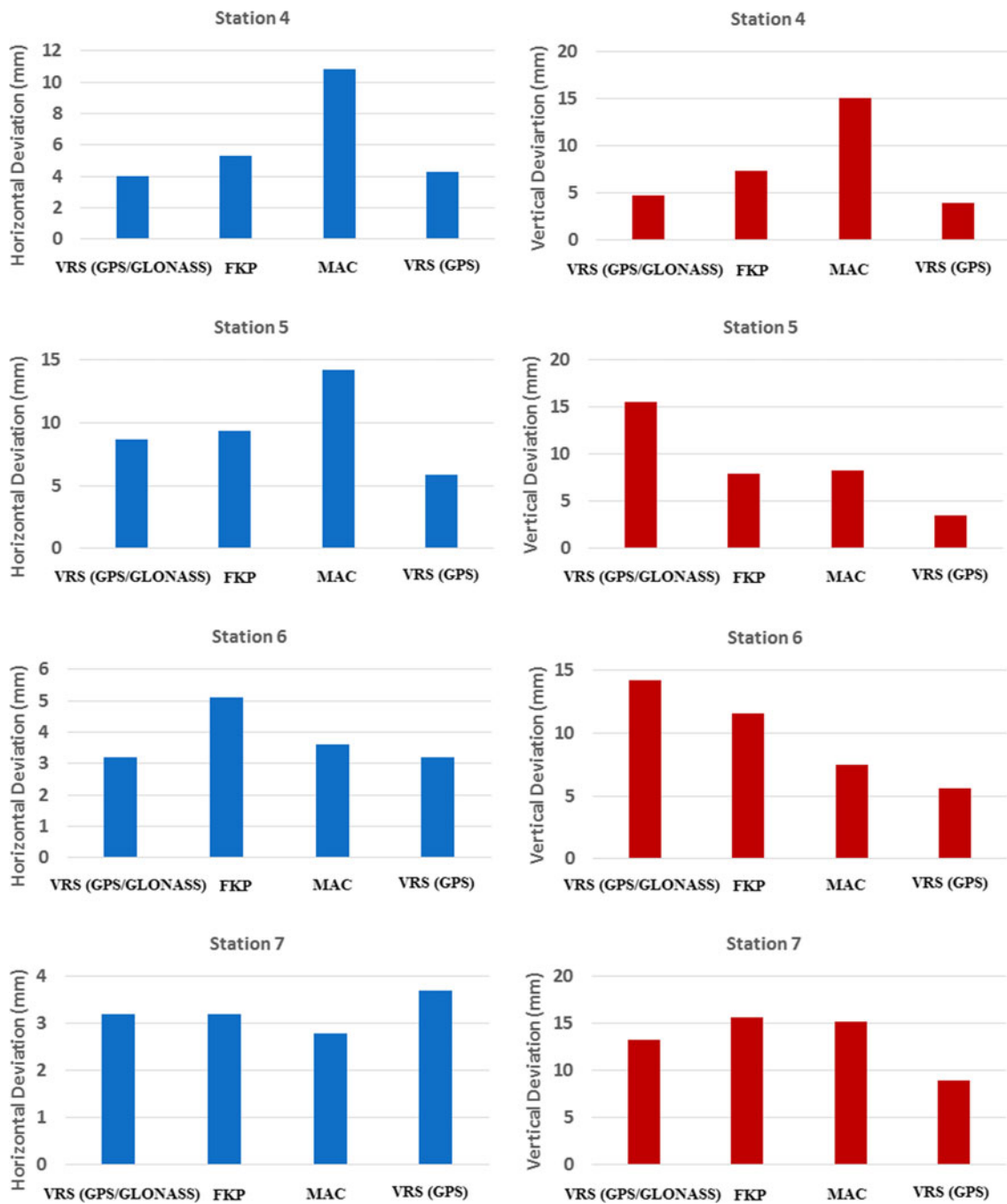


Fig. 8 (continued)

resolved (Dai et al. 2003). The process of this ambiguity resolution is referred to as initialization. Elapsed time to first initialization which is required in order to solve complete ambiguities in real-time was determined for each technique at the test points before the NRTK measurements were taken. Results were tabulated in Table 3.

As it is seen from the Table 3, VRS (GPS/GLONASS) has the fastest TTFB at the most test points and the slowest is observed in FKP at each test point.

Assessment of ambiguity fixing of the techniques in the dynamic environment

After the NRTK measurements in the dynamic platform, as explained in the section 3.3, the total epoch and the fix rates w.r.t. each survey route are given in Table 4.

As it is seen from Table 4, sustainability of carrier phase ambiguity fixing for FKP is longer than the others during the whole kinematic survey. During the survey, each technique

Table 3 TTFF at each test point

Stations	VRS (GPS/GLONASS)	FKP	MAC
Station_1	12 s	2 m 11 s	19 s
Station_2	15 s	2 m 11 s	19 s
Station_3	19 s	2 m 17 s	19 s
Station_4	19 s	2 m 17 s	19 s
Station_5	10s	2 m 13 s	19 s
Station_6	19 s	2 m 3 s	20s
Station_7	13 s	2 m 14 s	18 s

sometimes lost their GPRS connections. This situation explains the differences of the total epochs between the techniques throughout the routes. When the receivers are set to the NRTK techniques, they automatically determined the closest CORS station as a base station. When the base station is no longer the closest one for the techniques while they are in motion, each technique changed their base station to the present closest one instantaneously. Each technique changed their base station at about the same time.

5. Conclusions and recommendations

In this study, the comparison of VRS, FKP, and MAC NRTK techniques from TUSAGA-Aktif CORS network has been carried out under the same survey conditions within the surveyed urban area and the results were tabulated as accuracy, precision, TTFF, and ambiguity fixing performance. The accuracy analysis has shown that there are no significant differences among the techniques and cm-level accuracy in horizontal and vertical positioning can be obtained from each technique. No outliers were observed among the measurements. The achievable

Table 4 Kinematic survey results

Route	Technique	Epochs	Fix (%)
KNYI-CIHA	VRS (GPS/GLONASS)	319	84.64
KNYI-CIHA	FKP	329	90.27
KNYI-CIHA	MAC	338	77.81
CIHA-KNY1	VRS (GPS/GLONASS)	323	79.88
CIHA-KNY1	FKP	325	91.69
CIHA-KNY1	MAC	330	90.91
KNY1-KAMN	VRS (GPS/GLONASS)	326	82.83
KNY1-KAMN	FKP	321	88.16
KNY1-KAMN	MAC	325	86.15
KAMN-KNY1	VRS (GPS/GLONASS)	313	71.57
KAMN-KNY1	FKP	309	89.00
KAMN-KNY1	MAC	309	63.11

accuracy for the horizontal components are generally within 5 cm. The analysis has shown that vertical accuracy of TUSAGA-Aktif CORS network are not satisfactorily consistent for the test points (min 3.3 cm, max 9.5 cm). It would be due to the TUSAGA-Aktif CORS system and further investigations need to be performed. No significant difference of the horizontal positioning accuracy was observed between VRS (GPS/GLONASS) and VRS (GPS) whereas fluctuations in the vertical positioning accuracy between them are slightly bigger for some test points.

The results of the precision analysis have shown that for five test points, VRS has the lowest deviation in horizontal and vertical coordinates among all techniques.

In terms of TTFF, VRS (GPS/GLONASS) produced better performance among the other techniques. This was expected because the satellite constellation of VRS (GPS/GLONASS) was different than the others due to GLONASS satellites availability. Considerable long TTFF delay has been observed for FKP at each station. It is considered that this is receiver related because the delay for other type of receivers takes about 30 s but it is still the longest one among the others. On the other hand, the ambiguity fixing rate is the highest for the FKP technique in the dynamic environment. Depending on the requirements, one would take into account the tradeoff between longer TTFF and the highest ambiguity fixing success when using the FKP technique.

It needs to be taken into account that this study is carried out within the urban area. Therefore, baseline distances between the receivers and the nearest CORS station (KNY1) during the NRTK measurements are short and generally close to each other (except for station_7). Further evaluation needs to be performed for longer baseline distances.

We are expecting that the lack of GLONASS message types for FKP and MAC will be solved soon by the authorities. VRS is the mostly used NRTK technique by the TUSAGA-Aktif users because of the GLONASS availability and the fastest TTFF at this time.

Kinematic measurements have shown that fixing of the integer carrier phase ambiguities in the dynamic environment is more reliable in FKP. All the three techniques demonstrated about the same agility to change the base station when they were switching to the closest station. It is the recommendation of the authors that surveyors of TUSAGA-Aktif CORS network should use FKP technique if they need to survey wide areas with single initialization.

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