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Validation of the dynamic accuracy of different GNSS receivers

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The precision of RTK-GNSS receivers (Real-Time Kinematic Global Navigation Satellite System) is a key factor for the digitization of crop farming. A high dynamic accuracy is of utmost significance, requiring suitable reference systems. Based on a machine vision approach, the position measurements of seven different GNSS sensors were compared in two test scenarios (straight ahead, cornering) and analyzed for factors potentially influencing the accuracy. In addition to the reference system, the speed, the number of satellites used and the HDOP as well as the time of day have an influence on the measured accuracy. The differences between the dynamic accuracy of the investigated RTK-GNSS receivers proved to be negligible in the agricultural context.

Keywords
GNSS receiver, dynamic accuracy, RTK correction data, satellite navigation, comparison test

GNSS receivers are key components in digital agriculture. Accurate positioning lays the foundation for automatic steering of agricultural machines and implement automation (variable rate control, section control). Global navigation satellite systems (GNSS) are applied for positioning, which can achieve an accuracy of 2.5 cm using Real-Time-Kinematic(RTK) corrections. Important is the reliable position determination in the movement, rather than the static accuracy, which in comparison can be determined much easier.

Dynamic positioning with GNSS systems is based on two independent measuring methods: the trilateration or pseudo range measurement for position determination and the Doppler effect with which speed and direction of movement (heading) are determined. The frequency of the received signal changes as a function of the relative movement of the antennas to the satellites. The relative speed can therefore be determined from the frequency change with the aid of the Doppler effect. From the relative speeds to all received satellites, the absolute speed over ground and the direction of movement (heading) is determined. It is thus possible to estimate future positions from the current position, the speed and the direction of movement. The estimated value of the position is used within the scope of filtering methods to validate position measurements for plausibility (e.g. with Kalman filters). Since the Doppler effect may only be applied during movement, it is to be expected that GNSS receivers achieve higher accuracy in motion. Both the quality of the input parameters as well as the parameterization of the filters influence the accuracy of the filter output (Agarwal and O'Keefe 2023).

In addition to well-known manufacturers of geodetic RTK-GNSS receivers, fewer known companies have established themselves on the market in this product segment in recent years. They have developed inexpensive GNSS sensors which are also suitable for automatic steering, VRA (Variable Rate Application), section control and data logging (e.g. yield mapping).

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The Weihenstephan-Triesdorf University of Applied Sciences, in cooperation with the journal profi, investigated if the accuracy of established and new GNSS receiver generations differs while in movement. Track accuracy was considered, i.e. the deviation from a target line transverse to the direction of travel. In the measurements, two scenarios were explored: straight lines (tramlines) and the curves/turns.

State of Knowledge

Investigations into the dynamic accuracy of RTK-GNSS receivers are rare. The validation against a suitable reference system represents the greatest challenge (Kaděrábek et al. 2021).

A frequently used approach is the comparison with an already established GNSS receiver. However, Janos et al. (2022) showed that this is not always sufficient. In a test for the dynamic accuracy of a cost-efficient u-blox ZED-F9P-receiver (u-blox AG, Thalwil, Swiss), a Leica GS18T-receiver (Leica Geosystems GmbH, Munich, Germany) was used as reference. However, the receiver tested in parts achieved better results than the reference system, which was shown both in the stability of the RTK status and tested by visually plausibility assessment.

In 2003, various GNSS receivers were tested for their accuracy on behalf of the company geo-konzept (geo-konzept GmbH, Adelschlag, Germany, https://geo-konzept.de/). On a test bench, the sensors were moved on a defined circular path and the track accuracy was compared. The test was carried out at the DLG test site for agricultural machinery in Groß-Umstadt, Germany. The accuracy was assessed with a tolerance of ± 5 cm (DLG 2003). In this test, however, the test specimens only applied L1 corrections or PPP services (precise point positioning) with an expected accuracy of ± 10 cm.

To test the position accuracy of RTK-GNSS sensors, more accurate reference systems are required which can detect deviations in the range of millimeters. The approach of a fixed circular path was adopted by Kaděrábek et al. (2021). The dynamic accuracy of different RTK receivers on a circular path with a radius of 3 m was tested with a robot arm developed specifically for this purpose. Easterly et al. (2010) developed a method that examined the track accuracy of two automatic steering systems. A machine vision approach was used as a reference. For this purpose, images were recorded with a camera mounted in the middle of the vehicle. The relative position of a rope in the image was determined from the gradients of the grayscale images. The deviation of the tractor from the target track could be calculated based on the fixed ground sampling distance given in cm/pixel. Easterly et al. (2010) could thus determine the track deviation with a tolerance of 2 mm and thus set a standard for the evaluation of automatic steering systems.

In addition to the reference system, other factors also have an influence on the accuracy of position measurements. Filters and their parameterization, number of satellites used, and their constellation are the most relevant factors. Varying solar activity also affects the ionosphere and thus the transit time of the satellite signals. RTK correction data, such as the SAPOS HEPS used here, cannot eliminate the resulting errors. Gümüş (2024) examined the influence of daytime and three different correction data sources on the static accuracy of a GNSS receiver from Topcon. It was found that both variables influenced the accuracy as well as the precision of the receivers. When using correction data from RTK networks, the accuracy decreased during the noon period, varying to a different extent with the correction sources. The FKP correction method (area correction parameters) achieved a somewhat higher accuracy than the method of the virtual reference stations (VRS).

Material and methods

Test setup and data transmission

In total, seven different RTK-GNSS receivers were tested over a period of six days between 24th of July 2024 and 1st of August 2024. An overview of the systems and their properties is given in Table 1. A mobile agricultural robot was used as a carrier platform for all receivers and the reference system. The SAPOS HEPS (High-precision real-time positioning service, LDBV (2025)) served as a common correction data source for all tested GNSS receivers.

Table 1: Specification for antenna and receiver chipset of the investigated RTK-GNSS receiver (profi 2024)

	AGRA-GPS CRG	ArduSimple simpleRT-K2B	John Deere StarFire 7500	Raven RS1	Reichhardt RGS700	Satcon-System All in One 4G	Trimble NAV-900
Antenna	Emax Patch	u-blox Patch	Aero	Novatel	Novatel Vexxis	Harxon	Trimble Cyclone
Receiver chipset	u-blox F9P and D9S	u-blox F9P	John Deere	Novatel OEM7	Novatel OEM7	U-blox F9P	Trimble BD940
Communication	4G-E-Modem, Bluetooth, USB, SD-Drive	USB [1)]	CAN, USB, RS232	2 x RS232, 2 x CAN, WLAN, Bluetooth, Ethernet [2)]	3 x RS232, 1 x CAN	4G-E-Modem plus SIM, RS232	Bluetooth, Ethernet, RS232, CAN
Transfer standard	NMEA0183, NMEA2000, John Deere	NMEA0183	John Deere, NMEA0183	NMEA0183, NMEA2000	NMEA0183, NMEA2000	NMEA0183	NMEA0183, NMEA2000, Trimble
Cold start times Position/ RTK_fix	20 s/ 2 to 5 min	25 s/ 35 s	80 s/ 140 s	n. s./ <5 min	40 s/ 60 s	15 s/ 45 s	n. s.
Maximum RTK bridge	4 min	n. s.	14 days [3)]	20 min	20 min	3 min	5 min
IMU integrated	yes	no	yes	yes	no	yes	yes
Price, VAT excluded	4,999 €	211 €	3,300 € [4)]	8,500 € [5)]	6,500 €	2,100 € [6)]	3,500 €

Manufacturer details, n. s. no specification, [1)]optional with Bluetooth, Wi-Fi, CAN, RS232, 4G-E modem, [2)]optional integrated mobile modem, [3)]with RTK Extend, [4)]without RTK license, [5)]with mobile modem, [6)]inclusive 1 year GSM access.

The receivers were attached to a bracket (1.1 × 1.0 m) made of construction steel on the robotic platform Tipard 350 (digital workbench GmbH, Wettstetten, https://digital-workbench.de/) which ensured a fixed position of the receivers relative to one another during the test drives (Figure 1). As shown in Figure 1, the GNSS receivers were arranged along three axis perpendicular to the driving direction over the entire test. All sensors thus were submitted to the same conditions, so that measurement errors may be attributed to the hardware and software of the GNSS sensors. Since the position of the antenna center in the housing of some receivers was not clearly visible from the outside, a two-hour static measurement took place on July 12th, 2024. The average value was calculated to determine the distances between the antennas of the GNSS sensors (Figure 2). The NMEA data was transferred to a laptop with a frequency of 1 Hz and recorded with the software Tera Term (version 5.3 x 86, TeraTerm Project (2004-2024), with Tera Term Pro version 2.3, Copyright (C) 1994-1998 T. Teranishi, IPv6 extension version 0.81 (C) 2000 - 2003 Jun-ya KATO, Oniguruma 6.9.9 und SFMT 1.5.1, Japan, https://teratermproject.github.io) and the software u-center (u-blox AG, Thalwil, Switzerland).

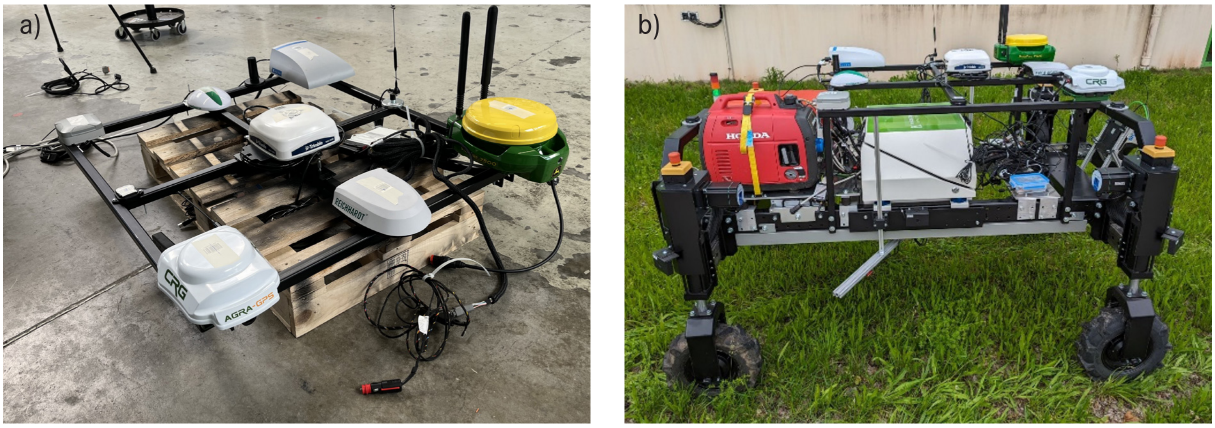

Figure 1: a) Bracket with RTK-GNSS receivers (© Lea Obermaier), b) Bracket mounted to the carrier vehicle Tipard 350 (© Magnus Hofmann)

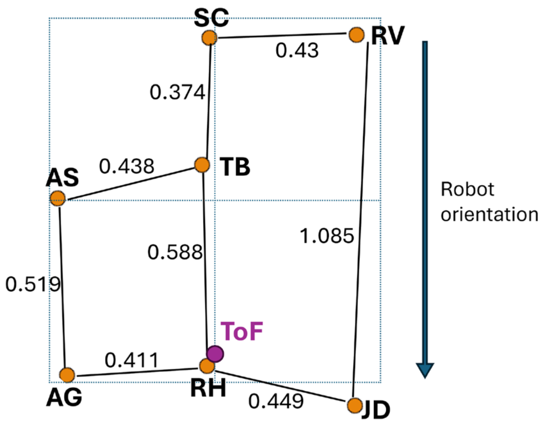

Figure 2: RTK-GNSS receiver layout (orange) and position of the Basler ToF-camera blaze-101 (purple) on the bracket (light blue) determined from the mean values of a two-hour static measurement on July 12th, 2024.
ToF = Basler ToF-camera blaze-101, AS = ArduSimple simpleRTK2B, SC = Satcon All-in-One 4G, AG = Agra-GPS CRG, TB = Trimble NAV-900, RV = Raven RS1, RH = Reichhardt RGS700 and JD = John Deere Starfire 7500.

To determine any misalignment of the receivers during the repeated passage, the robot must always follow the exact same line. For the simulation of a turning manoeuvre, the Tipard was attached to a fixed point with lifting slings, forcing the test setup on a fixed circular path (Figure 3). The lifting slings were fixed on the inner tires and the robot moved in two different setups: on full tension (wheels pointing straight forward) and with a given speed and a steering angle. The curve radius was 7.4 m. To create the same conditions for all receivers, the test drives were conducted both clockwise and counterclockwise, and the robot platform was rotated, running it in and against the direction of travel. Overall, 52 test drives were performed.

Figure 3: Curve test setup. The Tipard 350 is attached to a fixed point via lifting slings and is thus held on a fixed circular path (© Competence Centre for Digital Agriculture (KoDA) at the Weihenstephan-Triesdorf University of Applied Sciences)

The machine vision sensor approach from EASTERLY et al. (2010) was used as a reference for the accuracy test while following a straight track. To determine a potential offset of the vehicle with respect to the reference line, a hemp rope (diameter 1.8 cm) was fixed on the ground along the predetermined track. During the test ride a downward-facing Basler Time-of-Flight (ToF) camera (blaze-101, Basler AG, Ahrensburg, Germany) took images at a frequency of 1 Hz. If the hemp rope appears in the middle of the picture, the robot is located exactly on the target track. If a lateral offset of the test platform occurs, the image center shifts in comparison to the reference line (Figure 4). Based on the position of the camera in the front part of the center axis of the vehicle and the known pixel resolution, the offset transverse to the direction of travel could be determined with a theoretical accuracy of 3 mm based on the position of the rope in the image (Figure 4). Since the pixel size increases with increasing deviation from the center of the image, the system was first calibrated with a squared timber. The angle to the lane (yaw angle) was not considered. Since the reference camera is fastened in the front part of the Tipard, deviations could occur particularly in the rear of the test platform if the Tipard moves rotated onto the target track. In total 43 repetitions took place at different speeds (2 km/h, 4 km/h, 6 km/h).

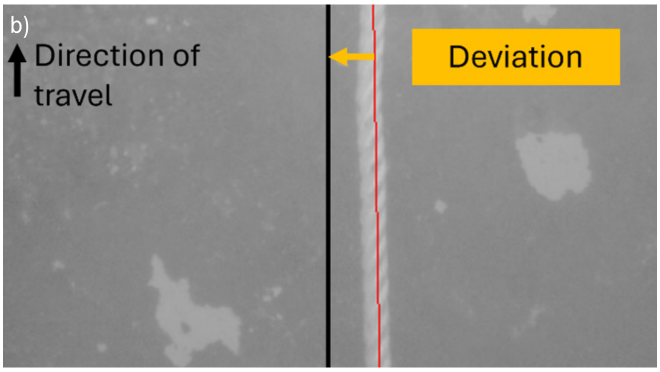

Figure 4: Reference method of straight travel; a) Position of the Basler Time-of-Flight-camera (type blaze-101) on the carrier vehicle (red circle), above the hemp rope serving as a reference track (© Farina Schildmann, editorial board profi); b) picture detail of the Time-of-Flight-camera. Red line = light hemp rope serving as a reference track. Black line: middle of the picture. The deviation of the test platform to the target track is calculated from the number and the known size of the image pixels (© Competence Centre for Digital Agriculture (KoDA) at the Weihenstephan-Triesdorf University of Applied Sciences).

Data evaluation

Data recorded during the straight-line scenario was preprocessed accounting for the track deviation determined by the camera images, correcting the error caused by a possible vehicle displacement. After conversion into a line, the positions collected during the first test drive were used as the reference for determining the track deviation of the following repetitions. For the curve scenario, the first measurement of each day had to be used as a reference track, because of differences in the setup. The analysis was performed separately for the different travel directions (clockwise/counterclockwise, forward/backward).

To quantify the deviation of the recorded position from the reference track, statistical indicators were calculated. In addition to minimum, maximum, mean, standard deviation and median, the 2.5 %, 25 %, 75 % and 97.5 % quantiles were calculated. Furthermore, the proportion of the data points within the tolerance range of 3.5 cm deviation was determined. The threshold was chosen because of the specification of the accuracy of ± 2.5 cm by the manufacturers and an assumed error of ± 1 cm caused by the setup.

To investigate differences in the accuracy of the receivers, we carried out an ANOVA with a post-hoc test (Least significant difference test with bonferroni correction from the agricolae package (De Mendiburu 2023)). In addition to the positional error, the influence of the time of day has also been investigated. For this, the data had to be divided into three groups: morning (09:00 to 10:30), noon

(10:30 to 14:00) and afternoon (14:00 to 15:30). Furthermore, the influence of other factors on absolute deviation was investigated with a multiple linear regression model. The parameters receiver model, test day, driving speed, number of visible satellites, HDOP as well as the distance traveled were examined in the model. The deviation was calculated with python 3.13 (Python Software Foundation). All further analyses were carried out with the statistics software R (v4.2.2; R Core Team, https://www.r-project.org/) in R Studio (Posit team, https://www.posit.co) using the packages dplyr, agricolae, ggplot2 and sjPlot.

Results

Tracking accuracy of the straight track

During the straight track, 4,930 data points were recorded over all test days. 96 % of the values are within the tolerance range of ± 3.5 cm. The mean deviation from the reference track was between 0.6 cm (Raven RS1) and 1.2 cm (ArduSimple simpleRTK2B) (Table 2), while standard deviations of up to 2.1 cm (Raven RS1) were observed. The median of the deviation was between 0.6 cm (John Deere Starfire 7500 and Raven RS1) and 1.0 cm (ArduSimple simpleRTK2B). All receivers showed a positive deviation (to the right in the direction of travel), as shown by the distribution of the quantiles in Table 2. Throughout the test, all receivers had the RTK status “fixed”, except for the ArduSimple receiver, which changed to the RTK status “float” in 0.7 % of the cases (5 values). The change in the RTK status occurred on 30.07.2024 during two different test drives.

Table 2: Statistical values of the measured deviation [m] of the investigated RTK-GNSS receiver on the straight line

	Agra-GPS CRG	ArduSimple simpleRTK2B	John Deere Starfire 7500	Raven RS1	Reichhardt RGS700	Satcon All-in-One 4G	Trimble NAV-900
Min	-0.031	-0.034	-0.018	-0.069	-0.037	-0.052	-0.043
Max	0.099	0.101	0.070	0.078	0.051	0.059	0.082
Average	0.011	0.012	0.007	0.006	0.008	0.007	0.008
SD	0.012	0.012	0.008	0.021	0.010	0.015	0.014
Count	753	711	777	723	548	684	734
Q_025	-0.009	-0.011	-0.009	-0.041	-0.014	-0.027	-0.018
Q_25	0.003	0.004	0.002	-0.002	0.003	0.001	0.002
Median	0.008	0.010	0.006	0.006	0.008	0.007	0.007
Q_75	0.017	0.018	0.011	0.015	0.014	0.015	0.013
Q975	0.044	0.038	0.023	0.053	0.028	0.043	0.049
RTK_fix in %	100	99.3	100	100	100	100	100
Share in % ± 3.5 cm	95.4	96.6	99.5	90.2	99.3	94.7	94.7

Min = minimum, Max = maximum, Average = average deviation over all test drives, SD = standard deviation, Count = number of measured data points, and four relevant quantiles: Q_025, Q_025, Q_75 and Q_975, corresponding to 2.5 %, 25 %, 75 % and 97.5 % quantiles and the median (50 % quantile). RTK_fix [%] = percentage of RTK status fixed. Share ± 3.5 cm = proportion in % of the data points within the tolerance limit of ± 3.5 cm

With respect to the absolute deviation from the reference track only small differences between the receivers were observed (Figure 5). The Starfire 7500 by John Deere performed particularly well. Only 4 data points are located outside the tolerance range. The RS1 receiver of Raven, on the other hand, recorded almost 10 % of the data above or below the tolerance limit (Table 2).

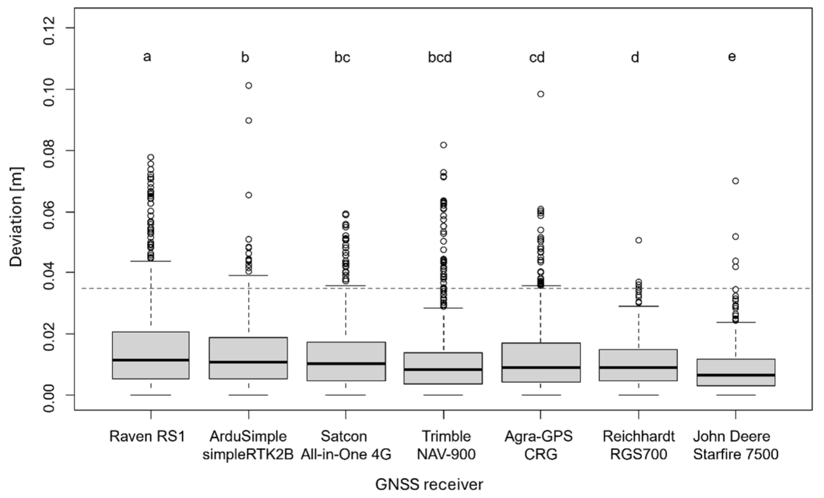

Figure 5: Absolute deviation of receiver positions from the reference track during straight travel

Significantly higher absolute deviations were recorded at noon, while in the afternoon the best results were achieved (Figure 6). At noon, 89.4 % of all measured data were within the tolerance range of 3.5 cm, while in the morning, 97.2 % and in the afternoon 97.4 % of the values were within the tolerance limits.

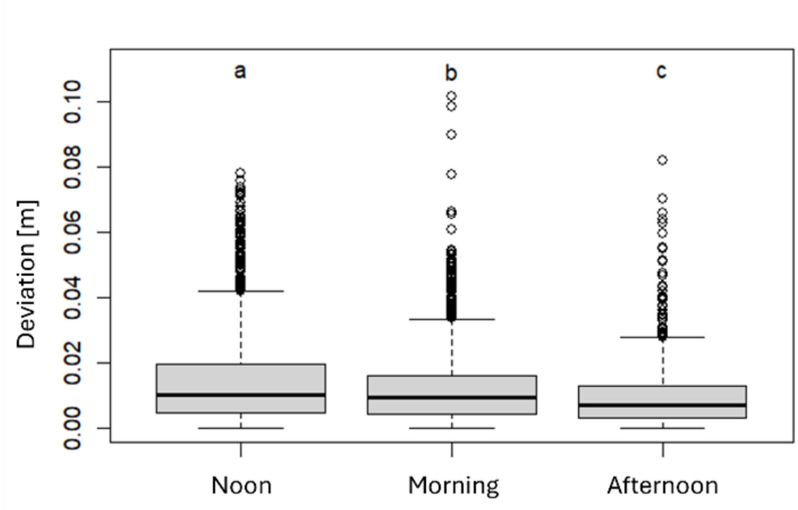

Figure 6: Absolute deviation of the position of all receivers from the reference track during straight travel, grouped by daytime

The parameters examined with the regression model could only explain the absolute deviation to a small proportion. Although the F statistics with $F(14,4915) = 35.47$; $p < 0.001$ sufficiently explains the model, R^2 is only 0.092 (adjusted $R^2 = 0.089$). Apart from the HDOP, all included parameters had a significant influence on the deviation and all the test days showed significantly lower absolute deviations, compared to the first test day (Table 3).

Table 3: Test result of the multiple linear regression model during straight travel

Factor	Estimate	Significance
26.07.2024	-0.0037	***
29.07.2024	-0.0052	***
30.07.2024	-0.0037	***
01.08.2024	-0.0043	***
Speed	0.0003	*
Number of satellites	-0.0003	**
HDOP	0.0007	
Distance	-0.0003	***

The estimated value indicates the influence of the factor on the position deviation: for the metric variables speed, number of satellites, HDOP and distance, a positive estimate indicates an increase with increasing value of the factor. In the day-by-day comparisons, the estimated value shows the change compared to the first test day (25.07.2024). Negative values thus mean lower absolute deviations.
Significance code: p < 0.0001 = ***, p < 0.001 = **, p < 0.01 = *

Track accuracy on curved track

In comparison to the straight track a higher deviation was observed during the curve test scenario. 92 % of the 8,619 data points were within the tolerance range of ± 3.5 cm. The mean deviation varied between - 0.2 cm (Satcon All-in-One 4G) and - 0.7 cm (Reichhardt RGS700). Compared to the straight-line test, larger standard deviations of ± 1.9 cm to ± 2.3 cm were found. Overall, the data showed a higher deviation to the outside of the circle (Table 4). As with the straight-line trip, the simpleRTK2B-receiver of ArduSimple lost the RTK signal for a few seconds (< 0.2 %). All statistical data on the deviation during the curve are shown in Table 4.

Table 4: Statistical values of the measured deviations [m] in the curve scenario

	Agra-GPS CRG	ArduSimple simpleRTK2B	John Deere Starfire 7500	Raven RS1	Reichhardt RGS700	Satcon All-in-One 4G	Trimble NAV-900
Min	-0.130	-0.144	- 0.119	- 0.141	- 0.185	- 0.154	- 0.138
Max	0.073	0.060	0.043	0.051	0.034	0.036	0.042
Average	-0.005	-0.004	- 0.004	- 0.004	- 0.007	- 0.002	- 0.004
SD	0.021	0.021	0.021	0.022	0.019	0.019	0.023
Count	1,250	1,250	1,244	1,248	1,128	1,249	1,250
Q_025	-0.051	-0.051	- 0.047	- 0.062	- 0.045	- 0.047	- 0.058
Q_25	-0.018	-0.013	- 0.016	- 0.011	- 0.018	- 0.006	- 0.013
Median	-0.002	-0.001	- 0.001	0.001	- 0.004	0.001	0.001
Q_75	0.010	0.010	0.011	0.009	0.006	0.008	0.011
Q975	0.028	0.029	0.026	0.023	0.023	0.021	0.027
RTK_fix [%]	100	99.8	100	100	100	100	100
Share ± 3.5 cm	92.0	92.7	92.7	91.7	91.5	95.5	90.8

Min = minimum, max = maximum, Average = average deviation over all test drives, SD = standard deviation, count = number of measured data points, and four relevant quantiles: Q_025, Q_025, Q_75 and Q_975, corresponding to 2.5 %, 25 %, 75 % and 97.5% quantiles and the median (50 % quantile). RTK_fix [%] = percentage of RTK status fixed. Share ± 3.5 cm = proportion in % of the data points within the tolerance limit of ± 3.5 cm

The All-in-One 4G-receiver from Satcon-System achieved the best results during the curve test (Figure 7). It was the only receiver that achieved more than 95 % of the points measured within the tolerance range. The other receivers reached values above 90 % (Table 4).

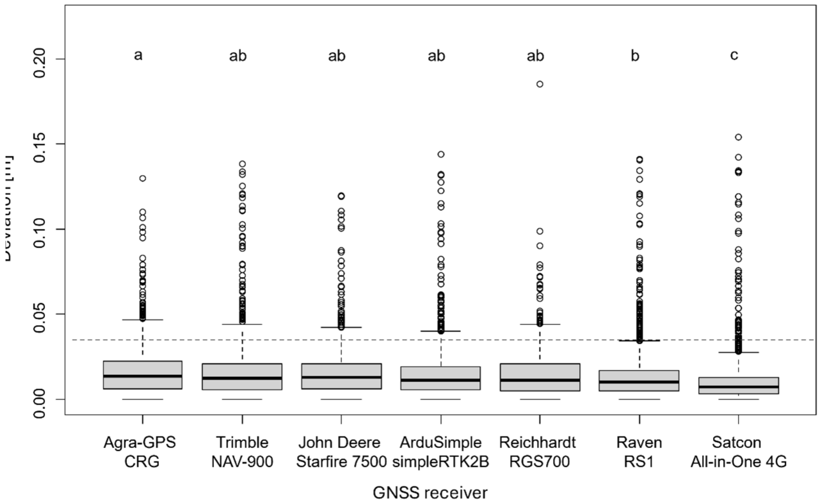

Figure 7: Absolute deviation of the position of the receiver from the reference track during cornering

In total, 7,542 positions have been collected, 1,077 at noon. In the morning, there were significantly higher average deviations than at noon, but larger outliers occurred at midday (Figure 8). The proportion of data within the tolerance range was 92 % in both cases.

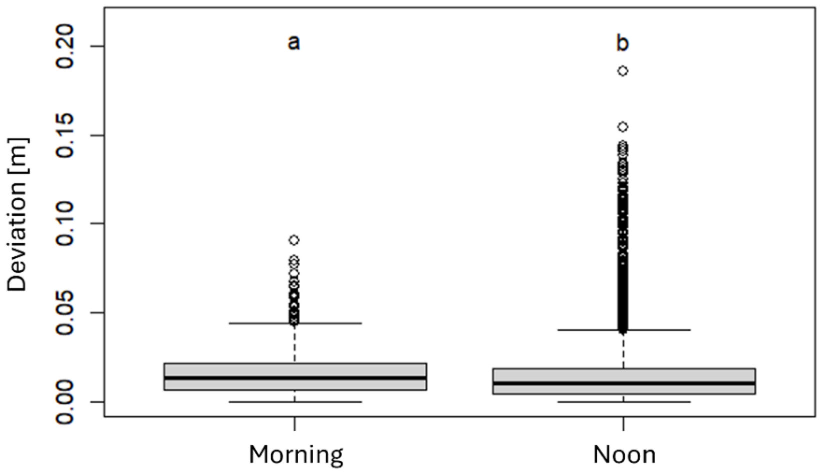

Figure 8: Absolute deviation of the position from the reference track of the curve test grouped by daytime

The regression model showed a higher quality of adjustment to the model with R^2 = 0.1478 (adjusted R^2 = 0.1464), with a F statistic of F (14,8604) = 99.91; p < 0.001. The parameters analyzed were relevant for the deviation, with all parameters having a significant influence (Table 5). With decreasing speed or HDOP and increasing number of satellites used or distance traveled a higher accuracy was achieved. Compared to the repetition on the first day, the data from the second test day showed slightly higher deviations. Significantly higher deviations were observed for the last two days.

table 5: Test result of the multiple linear regression model during curve test

Faktor	Estimate	Significance
25.07.2024	0.0022	*
26.07.2024	- 0.0010	
30.07.2024	0.0114	***
01.08.2024	0.0046	**
Speed	0.0045	***
Number of satellites	- 0.0007	***
HDOP	0.0062	**
Distance	- 0.0009	***

The estimated value indicates the influence of the factor on the deviation: for the metric variables speed, number of satellites, HDOP and distance, a positive estimate means an increase with increasing value of the factor. In the day-by-day comparisons, the estimated value shows the change compared to the first test day (24.07.2024). Negative values thus mean lower absolute deviations.
Significance code: $p < 0.0001$ = ***, $p < 0.001$ = **, $p < 0.01$ = *

Discussion

When comparing the dynamic accuracy of different RTK-GNSS receivers, no significant differences between the sensors relevant for agricultural operations have been revealed.

The results also show how important a suitable test setup is to investigate the accuracy of RTK-GNSS sensors. The methods applied produced plausible results. However, the methodology can still be optimized. In the camera-based approach for determining the track error, the deviation of the vehicle from the target track is captured in the front of the vehicle. Unintentional rotation of the vehicle could produce deviations which are not attributable to the sensor.

This issue, for example, may explain the higher deviation of the Raven RS1 receiver, which had the greatest distance from the reference point (Figure 2). A rotation of the vehicle to the target track by one degree would result in a deviation of 2.3 cm from its original position. Overall, the machine vision sensor approach enables precise testing for track accuracy. However, the distance to the reference point should be considered. In addition to the lateral offset of the Tipard, the angle of the test platform to the lane (yaw angle) should be determined and considered in the evaluation.

The test setup could also have contributed to inaccuracies during the test in the curve scenario. Although the slings were at full tension, movements deviating from the circular path nevertheless may affect the radial forces on the wheels. A rigid system, as developed by Kaděrábek et al. (2021), can eliminate this source of error.

As shown by Gümüs (2024), we were able to determine an influence of the time of day on the accuracy of the GNSS receivers and captured higher deviations at noon. This could be associated with an increased solar activity. It interferes with the ionosphere and thus affects the satellite signal. The TECU (Total Electron Content Unit) is a measure of solar activity. With increasing electromagnetic radiation, the number of free electrons in the ionosphere increases, whereby the satellite signal is deflected.

Trimble Terrasat GmbH provides the TECU values on the GNSS Planning Online platform, version 1.8.0.0 (Trimble Inc., Colorado, USA). During the test days, the highest TECU values were measured at noon. The only exception is the 25th of July 2024, where the highest values were already reached at 10 o'clock in the morning (TECU = 42.5). The comparison of the average TECU values during the investigation period shows that the highest solar activity prevailed on the 25th of July 2024 (TECU = 38.9 during the straight line; 41.2 during the turn). The lowest TECU values were measured on 26th of July 2024 (curve: 25.5; straight: 25.1). Consequently, the higher deviations on July 25th 2024 can be attributed to the higher solar activity during straight travel. On the other hand, the influence of the TECU during the turn appears to be lower than other factors resulting from the test setup.

The overall very good results of the GNSS sensors under investigation show that the currently market-available receivers achieve good results while in motion. In principle, however, it should be noted that the tests carried out here do not reflect the conditions in the field. As a result of an increased slip of the tires, e.g. in the case of wet conditions, as well as unevenness, jerky position changes can occur. How precise the GNSS sensors can process or compensate them would have to be clarified in a field test.

In addition, the test track was quite short in this study: the distance of 17 m during the straight-out operation was not sufficient to reach the maximum speed of 6 km/h. Furthermore, the target speed was maintained only over a short period of time. The significant increase in the deviation with increasing speed suggests that even larger deviations could occur at higher speeds. Further investigations should therefore provide a longer section of the route and consider more factors such as the influence of acceleration and deceleration. The change in speed and the direction of movement can affect the position accuracy via the Kalman filtering, depending on the weighting of the actual position measurement from the trilateration and the position predicted from speed and direction.

Conclusion

We showed that both established and new, cost-effective RTK-GNSS sensors comply with the manufacturer's specifications regarding horizontal accuracy. The marginal differences are barely relevant in the agricultural context and are most likely the result of the test setup and variations in the environmental conditions (ionosphere, clock errors, ephemeral errors etc.).

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