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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Efficiency of GNSS-based Tractor Auto Steering for the Uniformity of Pass-to-Pass Plant Inter-Row Spacing*

GNSS Esaslı Traktör Otomatik Dümenleme Sistemlerinin Ekim İşleminde Paralel Geçişlerde Sıra Arası Mesafe Düzgünlüğüne Etkisi

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Abstract

Precision agriculture (PA) includes advanced technologies to increase efficiency and profitability of agricultural operations from tillage to harvest and offers sustainability of the natural resources and the environment. Automatic steering (AS) is the mostly-used PA technology in the world and in Türkiye providing many benefits. It has potential for efficient and sustainable agronomic practices including soil ridge tillage and sowing. Adequate spacing is needed to provide equal living area for each plant in sowing. Thus, in mechanized planting, pass-to-pass plant inter-row spacing (PIRS) should be equal in parallel passes. Research on the benefits of the AS for providing uniform PIRS in sowing is very limited. This work aimed to appraise the pass-to-pass PIRS deviations in planting with GNSS-based AS with three signal correction sources (RTK, CORS, SBAS) and without AS (manual steering) for comparison. The data were obtained from 24 farmer fields (cotton and corn) with PIRS set values of 70-75 cm located in the Cukurova region of Türkiye. Pass-to-pass PIRS values were manually measured and the deviations from the set value were analyzed in terms of root mean square error (RMSE). The mean PIRS variations in sowing by manual steering (7.4 cm) were found as significantly higher than the AS based soil ridge tillage and / or sowing (CORS: 5.0 cm, SBAS: 5.9 cm, RTK: 6.7 cm) ($p<0.05$). In sum, it was found that the AS technology offers benefits in lowering the pass-to pass PIRS variations but the level of benefit changes from farmer to farmer; hence, the AS should be used cautiously with proper settings for greater benefits.

Keywords: Precision agriculture, Auto steering, GNSS, Sowing, Plant inter-row spacing

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Öz

Hassas tarım (HT), toprak işlemeden hasada kadar tarımsal faaliyetlerin verimliliğini ve kârlılığını artırmayı, doğal kaynakların ve çevrenin korunmasını ve böylelikle sürdürülebilirliği hedefleyen ileri teknolojileri içerir. Otomatik dümenleme (OD), dünyada ve Türkiye'de en yaygın kullanılan ve birçok fayda sağlayan HT teknolojisidir. OD; sırta toprak işleme ve ekim dâhil olmak üzere tarımsal işlemlerde verimli ve sürdürülebilir uygulamalara imkân sağlar. Makinalı hassas ekimde, her bitkiye eşit yaşam alanı sağlamak için bitki sıra aralarında yeterli boşluk gereklidir. Bu nedenle makinalı ekimde paralel yan yana geçişlerde bitki sıra arası mesafesi (BSAM) eşit olmalıdır. Ekimde eşit BSAM sağlamak için OD'nin faydalarına ilişkin yapılan araştırmalar oldukça sınırlıdır. Bu çalışma, üç farklı sinyal düzeltme kaynağı (RTK, CORS, SBAS) kullanan GNSS esaslı OD ile ekimde yan yana paralel geçişlerdeki PIRS sapmalarını karşılaştırmak amacıyla yapılmıştır. Çalışmada OD kullanılmayan (manuel yönlendirmeli) tarlalardaki BSAM değerleri de karşılaştırma amacıyla incelenmiştir. Veriler, Çukurova bölgesinde, sıra arası mesafe değerleri 70-75 cm olan 24 çiftçi tarlasından (pamuk ve mısır) elde edilmiştir. Paralel yan yana geçişlerdeki BSAM değerleri manuel olarak ölçülmüş ve ayarlanan değerden olan sapmalar hata kareler ortalamasının karekökü (RMSE) değeri ile analiz edilmiştir. Manuel dümenlemeli ekimde ortalama BSAM sapmaları (7.4 cm), OD ile yapılan sırta toprak işleme ve/veya ekime göre daha yüksek bulunmuştur (CORS: 5.0 cm, SBAS: 5.9 cm, RTK: 6.7 cm) ($p<0.05$). Özetle, OD teknolojisinin yan yana paralel geçişlerde BSAM değişimlerini azaltmada fayda sağladığı ancak fayda düzeyinin çiftçiden çiftçiye değiştiği belirlenmiştir. Bu nedenle, ileri düzeyde faydalar elde edebilmek için OD sistemleri uygun ayarlarla dikkatli bir şekilde kullanmalıdır.

Anahtar Kelimeler: Hassas tarım, Otomatik dümenleme, GNSS, Ekim, Bitki sıra arası mesafe

1. Introduction

Precision Agriculture (PA) also known as smart agriculture, digital agriculture and agriculture 4.0 includes advanced technologies to increase efficiency and profitability of agricultural practices from tillage to harvest and provide sustainability of the natural resources and the environment (Bora et al., 2012; DeLay et al., 2022; Mizik 2022; Vrchota et al., 2022). Along with developed countries, PA technologies are being adopted in some developing nations such as Türkiye especially in the last decade (Ozguven and Turker, 2010; Tekin, 2011; Akdemir, 2016; Keskin and Sekerli, 2016; Yaghoubi and Niknami, 2022).

Automatic guidance or automatic steering (AS) enables a tractor to move on a desired predetermined route. It is one of the most widely adopted PA tools (Say et al., 2017) and has been used in developed countries as early as by the end of 1990s while farmers started to use them in Türkiye after 2009. The adoption level of the AS systems has increased to 70-90% in some regions of some developed countries (Say et al., 2017; McFadden et al., 2023). Leonard (2014) stated that 80% of the grain growers in Australia use AS. In the USA, the GPS-based AS (83%) was the most popular PA system (Erickson and Widmar, 2015). Verma (2015) stated that AS is the mostly accepted technology in the Heilongjiang region of China while Silva et al. (2011) reported that the most preferred PA systems by sugar and ethanol producers were AS (39%) and satellite imaging (76%) in the Sao Paulo state of Brazil. AS systems are also widely used by Turkish farmers (Keskin et al., 2018; Topcueri and Keskin, 2019).

Various methods are employed for auto steering including mechanical, electrical, geomagnetic, image processing, ultrasonic and satellite-based techniques (GNSS) (Keskin et al., 2018; Juostas and Jotautiene, 2021). In the image based technique, tractor is guided by referencing the crop rows or soil ridge furrows detected by a digital camera (Garcia-Santillan et al., 2017; Yun et al., 2021; Vrochidou et al., 2022). In the ultrasonic method, ultrasonic sensors measure the distance to the plant row or soil ridge while in the mechanical contact method, an elastic touch sensor detects the plant row (Reichhardt, 2012). But the most common AS method is the GNSS-based technique (GNSS: global navigation satellite system). In addition, in greenhouses and orchards, guidance can be accomplished by detecting the distance to plant rows or trees with LASER, LIDAR, RADAR or ultrasonic sensors (Li et al., 2009; Unal and Topakci 2012; Mousazadeh, 2013; Bayar et al., 2015). Furthermore, driverless autonomous tractors and field robots are subjected to ongoing field trials and will be available soon. Steering is also used for the equipment attached to the rear of the tractor called “implement guidance” by using active or passive guidance methods which is mostly beneficial on sloped terrains and turns (Oksanen and Backman, 2016).

AS systems have two types: a) In the semi-automatic type, the operator steers the vehicle by following an indicator (display or lightbar), b) In the full automatic system, steering is done by means of an electric motor on the steering wheel or a hydraulic actuator mounted on the wheel steering system. In both methods, when needed, the operator can take the control of the tractor by using the steering wheel (Scarfone et al., 2021).

A GNSS-based AS system has four basic parts; a GNSS antenna, electric steering motor or hydraulic control unit, computer and a terminal (display). Steering angle sensors are also used usually on large tractors to increase steering accuracy. In the operation of an AS system, after a starting pass (A-B line) is created between two starting points (A and B), passes (swaths) parallel to the starting A-B line are established based on the working width of the equipment. When the machine comes to the end of the row, the tractor is turned to the side row manually but updates are on the way to do the end-of-row turnings automatically.

When properly used, the fully automated AS systems provide many benefits that can be summarized in four groups (Grisso et al. 2009; Ashworth et al., 2018; Baillie et al., 2018; Keskin et al., 2018; Kharel et al., 2020; Jotautiene et al., 2021; Burgers and Vanderwerf, 2022; Keskin and Sekerli, 2022): a) Efficiency: better work quality; equidistant parallel passes; parallel and straight soil ridges in tillage; eliminating markers in sowing; working at night; working at higher speeds; reduced overlaps and gaps in pesticide, fertilizer and lime applications without foam or flags; savings of fuel, pesticide, water, fertilizer and labor; maximized working width in harvest and spraying, b) Agronomic: better crop growth and yield; reduced plant damage and soil compaction when same tramlines are used, c) Ergonomic: easy to learn and operate encouraging young operators to work on farms; working in adverse weather conditions (fog, dust, sun glare); reduced driver workload and fatigue; safer work conditions, d) Sustainability: protection of environment, natural resources, health of humans, animals and other plants by reducing chemical inputs, irrigation water, fossil fuel and greenhouse gas emissions.

Sowing is one of the most crucial processes affecting crop yield. For better germination, plant growth and yield, a sufficient living space is needed for each plant to acquire sufficient light, heat, oxygen, water and nutrients (Blessing et al., 2020; Tilley et al., 2021). In modern farming, sowing must provide an equal amount of living space for each plant. Thus, the plant inter row spacing (PIRS) in parallel passes should be equal to the spacing of the other rows. If the PIRS is less than the set value, sufficient living space cannot be provided for the plants while if this distance is greater, the field area cannot be efficiently utilized and yield would be lower. AS systems can precisely adjust the PIRS in parallel passes if used properly.

There have been numerous studies on the benefits of AS systems especially in spraying (Batte and Ehsani, 2006; Hudson et al., 2007; Topcueri and Keskin, 2019). However, studies in planting are very limited. Baio and Moratelli (2011) found a parallelism error of 3.3 cm using AS with RTK which is five times better than the manual steering in sugarcane planting. Similarly, Voltarelli et al. (2013) determined errors up to 4.9 cm by using AS with RTK in sugarcane planting with 1.5 m row spacing. Santos et al. (2017) reported positioning errors lower than the manufacturer's specified value (3.8 cm) using an AS system with RTX (Real Time eXtended) signal correction in peanut sowing but field slope increased the error. In a similar work, a mean error less than 2 cm was reported in parallel passes in peanut sowing with AS using RTX (Santos et al., 2018). AS was effective reported by Zerbato et al. (2019) for improving the accuracy and quality of peanut sowing. Scarfone et al. (2021) reported that semi-auto guidance allowed to sow 1.2 extra ha per day lowering the planting cost by 2.4%.

AS systems are usually tested under controlled conditions on concrete or asphalt surfaces (Easterly et al., 2010; ASABE 2015); however, working conditions significantly differ in real field studies. Although some studies were conducted on the use of AS systems in planting, no study was found on the benefit of the AS in creating uniform plant inter-row spacing (PIRS) in parallel passes in real farmer field conditions. Thus, the goal of this work was to assess the performance of GNSS-based AS systems for uniform PIRS in parallel passes in planting in real farmer field conditions and compare it with the case in manual steering.

2. Materials and Methods

2.1. GNSS-based automatic steering (AS) systems

The accuracy of the GNSS-based AS systems depends on the signal correction method. The AS systems require precise error correction with high accuracy (up to 2 cm). In the study area (Adana and Mersin provinces), farmers usually use one of the three GNSS correction services in AS systems (Keskin et al., 2018):

a) Satellite-based augmentation system (SBAS): In this method, the correction signal is sent from SBAS satellites to the receivers. An annual subscription fee is paid by the farmers for this service. For example: Trimble RTX.

b) Continuously operating reference stations (CORS): Correction signal is sent over GSM mobile phone internet. Farmers in the study area use this correction source developed by the Turkish government (TUSAGA-AKTIF). An annual subscription fee and monthly mobile phone fee is paid by the farmers.

c) Real time kinematic (RTK): Farmers use an additional receiver to obtain correction signal which is stationary located on a nearby building or near the field (~5 km). Subscription fee is not needed but it is more expensive since an extra receiver must be purchased by the farmer.

The most common GNSS signal augmentation method in the study region was previously reported as CORS (49.1%) followed by SBAS (29.1%) and RTK (21.8%) (Keskin et al., 2018). RTK method is considered as the most accurate correction source usually in centimeter level (Jotautiene et al. 2021).

2.2. Study location and field data

The study was conducted in the Cukurova region (near: 36.971°N; 35.475°E) of Türkiye in which agricultural production is intensively carried out and many farmers utilize AS systems. Field data were obtained from farmer fields in different locations in Adana province (districts of Ceyhan, Saricam, and Yuregir) and Mersin province (district of Tarsus).

Farmers plant cotton and corn on soil ridges in the region. Some farmers use the AS only for ridge tillage and do the planting by referencing the ridges; so they do not utilize AS in sowing. The main cause for this is that farmers cannot afford to purchase multiple AS systems due to their high costs (Civelek, 2022, Masi et al., 2023). However, some farmers although their number is relatively lower, use the AS systems for both ridge tillage and planting. Tillage and sowing by manual steering is common mainly on small farms due to economic constraints.

The study data were taken from the fields belonging to different farmers in the spring months of 2018. A total of 24 fields growing cotton and corn were examined; thus, the benefit of AS systems was studied under real farmer conditions. All fields had flat ground surface without sloping. Straight parallel passes (swaths) were utilized in all fields. The variations among the fields were also compared.

2.3. Plant inter-row spacing (PIRS) data

The PIRS created in the parallel passes may be smaller than the desired value leading to a narrower row spacing (*Figure 1a*) or it may be larger than the desired value resulting in wider row spacing (*Figure 1b*). Both situations are undesirable because ideally, the PIRS should be the same as the set row spacing.

The PIRS values were measured on the adjacent rows of the parallel passes. The measurements were conducted manually using a tape measure from 27 different locations per row on the beginning, middle and end of each pass-to-pass row (*Figure 2*).

a) Measurement near the beginning of the row (BoR) (nine data points)

b) Measurement near the middle of the row (MoR) (nine data points)

c) Measurement near the end of the row (EoR) (nine data points)

The means of the nine measurements were then averaged to obtain mean PIRS data for BoR, MoR and EoR locations (*Figure 2*). Average of these three means was also calculated to represent one PIRS value for each of the pass-to-pass adjacent plant rows. Measurements were taken from 10 to12 rows (27 data points per row) per field yielding data points of 270 to 324 for each of the 24 fields.

2.4. Deviations in PIRS values

The PIRS deviations from the set plant row spacing were calculated as the root mean square error (RMSE) values as in the Equation 1 presented below (Gisgeography, 2018):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(PIRS_m - PIRS_s)^2}{N}} \quad \text{(Eq.1)}$$

where; RMSE=Mean deviation (cm), PIRSm=Measured plant inter-row space (cm), PIRSs=Set (desired) inter-plant row space (cm) and N=the number of data.

Also, percent deviation values (%) were computed as the mean deviation value divided by the set row spacing and multiplied by 100.

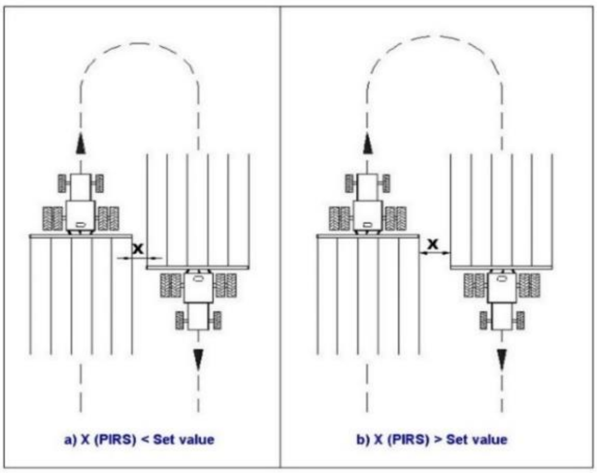

Figure 1. Plant inter row spacing (PIRS) in parallel passes in planting process with a six-row planter; a) row spacing is narrower than the set value b) row spacing is wider than the set value (not to scale)

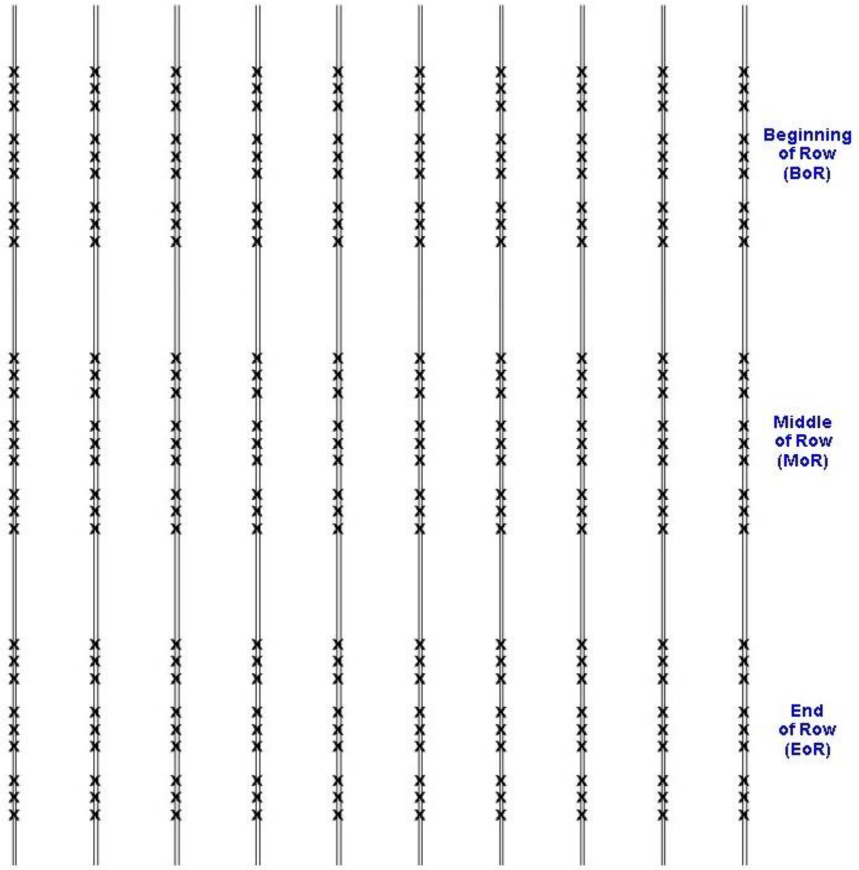

Figure 2. Measurement locations of the plant inter row spacing (PIRS) in parallel passes (double vertical lines represent pass-to-pass adjacent plant rows while crosses indicate individual measurement locations; 27 measurements per row)

2.5. Data analysis

The mean and standard deviation values for the PIRS deviations in parallel passes were calculated in MS Excel software (MS Office 2016). Statistical comparisons were made between AS signal correction methods, between fields and between the measurement locations (BoR, MoR, EoR) by using the analysis of variance (ANOVA) and Duncan's test for comparison in SPSS program (version: 17.0; IBM, NY, USA).

3. Results and Discussion

The effectiveness of the GNSS-based tractor automatic steering (AS) on the uniformity of plant inter-row spacing (PIRS) in parallel adjacent passes in sowing was examined in the study. For comparison, the case in fields ridge-tilled and planted by manual steering was also investigated. For this purpose, the PIRS values in parallel passes were measured and investigated in 24 farmer fields in different locations on which cotton or corn was planted (AS with different correction services in 18 fields and manual steering in 6 fields).

The pass-to-pass PIRS data in five farmer fields on which both ridge-tillage and planting was conducted with AS systems using RTK correction signal are presented in *Table 1*. In all five fields, both ridge tillage and sowing were conducted by using AS with RTK service and corn was planted with a row spacing of 70 cm. It was observed that the pass-to-pass PIRS values varied between the minimum of 55.0 cm and the maximum of 96.6 cm despite the set PIRS value of 70 cm in all fields (*Table 1*). The mean deviation (RMSE) values varied between the lowest 4.8 cm and highest 9.2 cm while the percent deviations were between 7.1 and 11.9%. Differences were observed between the fields in terms of mean PIRS deviations; the lowest mean percent deviation was in Field3 (7.1%) while the Field1 had the highest mean percent deviation (11.9%) (*Table 1*). The mean PIRS values on one of these fields (Field 3) are shown in *Figure 3* as an example.

Table 1. Plant inter-row spacing (PIRS) deviations (RMSE) for the fields both tilled and sowed by the GNSS-based auto steering (AS) with RTK signal augmentation

Field and location	Use of AS	Crop, PIRS[1]	PIRS Min, Max	Tractor power[2]	Data location[3]	Deviation mean±SD (cm)
Field 1 (Yuregir, Adana)	Tillage:+ Sowing:+	Corn 70 cm	55.2 cm 96.6 cm	HP1: 130 HP2: 120	BoR	7.0 ± 1.53
					MoR	8.9 ± 0.35
					EoR	9.2 ± 1.29
					Mean	**8.3 ± 1.40 (11.9%)**
Field 2 (Yuregir, Adana)	Tillage:+ Sowing:+	Corn 70 cm	57.9 cm 84.0 cm	HP1: 130 HP2: 120	BoR	6.4 ± 0.24
					MoR	6.8 ± 0.22
					EoR	6.6 ± 0.53
					Mean	**6.6 ± 0.38 (9.4%)**
Field 3 (Yuregir, Adana)	Tillage:+ Sowing:+	Corn 70 cm	55.0 cm 82.0 cm	HP1: 130 HP2: 120	BoR	4.8 ± 1.29
					MoR	5.0 ± 0.93
					EoR	5.3 ± 1.02
					Mean	**5.0 ± 0.96 (7.1%)**
Field 4 (Yuregir, Adana)	Tillage:+ Sowing:+	Corn 70 cm	59.7 cm 87.6 cm	HP1: 240 HP2: 130	BoR	7.0 ± 0.70
					MoR	6.3 ± 0.45
					EoR	7.3 ± 0.71
					Mean	**6.9 ± 0.69 (9.9%)**
Field 5 (Yuregir, Adana)	Tillage:+ Sowing:+	Corn 70 cm	57.4 cm 85.3 cm	HP1: 240 HP2: 130	BoR	6.2 ± 0.19
					MoR	6.2 ± 0.46
					EoR	7.1 ± 0.79
					Mean	**6.5 ± 0.66 (9.3%)**

"+" sign: operation done with the use of AS
[1] PIRS: Plant inter-row spacing set value
[2] HP1: Power of the tractor used in soil ridge tillage (HP), HP2: Power of the tractor used in sowing (HP)
[3] BoR: Beginning of the row, MoR: Middle of the row, EoR: End of the row

Table 2 shows the PIRS values in parallel passes in seven farmer fields in which ridge tilled and/or planted with AS system using the SBAS correction. Corn was planted with 72.5 cm set row spacing in the first two fields while the spacing was 70 cm in the third and fourth fields with corn and in the last three fields, cotton was planted with 75 cm spacing (*Table 2*). In the first two fields, the lowest and highest pass-to-pass PIRS values were 54.3 and 97.0 cm, respectively despite the set value of 72.5 cm. The PIRS values varied from 65.1 to 77.4 cm even if the set value was 70 cm in the 3rd and 4th fields while in the last three fields, the set value was 75 cm but PIRS changed from the lowest 60.9 to the highest 84.2 cm. The mean deviation (RMSE) value was observed as varied between 2.3 and 13.3 cm while the percent deviations were between 3.5 and 17.7% in all seven fields (*Table 2*). It was observed that the variations in PIRS in the first two fields were much higher (14.6 and 17.7%) more than doubling the other five fields (from 3.5 to 7.2%). In both of these fields the ridge-tillage was done by using AS and the seeding was conducted by manual steering by referencing the ridges. In the interview with the farmer of the first two fields, no satisfactory answer was obtained as to the reason for this highest variations. The cause for this higher deviation in these two fields could be from the operator and/or the equipment settings such as the driver not showing enough care during the machinery operations in ridge tillage with AS and sowing with manual steering, for instance, when the GNSS augmentation signal was not suitable or interrupted, he/she continued to work manually and slippage occurred due to the settings of the planter not being attached properly. Also, the operator may not have precisely followed the ridges while sowing by manual steering (without AS). Significant differences were observed between the fields in terms of mean PIRS deviations of the minimum 3.5% and maximum 17.7% (*Table 2*). The mean PIRS measurements on one of these fields (Field 2) are shown in *Figure 4* as an example. In *Table 2*, Field 1 and 2, owned by the same farmer, were ridged-tilled by AS while planted by manual steering by referencing the ridges showing a mean PIRS deviation of 14.6% and 17.7%, respectively. However, Field 5, 6 and 7, owned by another farmer and were tilled and sown in same manner as in Field 1 and 2 reflected much lower PIRS deviations of 3.5%, 4.6% and 7.2%. This shows that both farmers used same method of tillage and sowing but got very distinct PIRS deviations in parallel passes which could be tied to the operator care for decent operation of the AS system and sowing machinery settings (Altinkaradag et al., 2017). Thus, these findings show that the farmers must be careful about the operation of the AS systems with proper tillage equipment and planter settings to get higher benefits from the AS systems in sowing.

Table 2. Plant inter-row spacing (PIRS) deviations (RMSE) for the fields tilled and/or sowed by the GNSS-based auto steering (AS) with SBAS signal augmentation

Field and location	Use of AS	Crop, PIRS[1]	PIRS Min, Max	Tractor power[2]	Data location[3]	Deviation mean±SD (cm)
Field 1 (Ceyhan, Adana)	Tillage:+ Sowing:−	Corn 72.5 cm	57.7 cm 92.1 cm	HP1: 95 HP2: 90	BoR	10.2 ± 1.63
					MoR	11.5 ± 0.50
					EoR	10.1 ± 2.05
					Mean	**10.6 ± 1.51 (14.6%)**
Field 2 (Ceyhan, Adana)	Tillage:+ Sowing:−	Corn 72.5 cm	54.3 cm 97.0 cm	HP1: 95 HP2: 90	BoR	11.9 ± 1.03
					MoR	13.2 ± 1.17
					EoR	13.3 ± 2.26
					Mean	**12.8 ± 1.54 (17.7%)**
Field 3 (Yuregir, Adana)	Tillage:+ Sowing:+	Corn 70 cm	65.2 cm 77.4 cm	HP1: 115 HP2: 115	BoR	3.6 ± 0.53
					MoR	3.5 ± 0.25
					EoR	3.1 ± 0.53
					Mean	**3.4 ± 0.45 (4.9%)**
Field 4 (Yuregir, Adana)	Tillage:+ Sowing:+	Corn 70 cm	65.1 cm 76.3 cm	HP1: 115 HP2: 115	BoR	3.1 ± 0.26
					MoR	3.6 ± 0.45
					EoR	3.0 ± 0.26
					Mean	**3.2 ± 0.38 (4.6%)**
Field 5 (Saricam, Adana)	Tillage:+ Sowing:−	Cotton 75 cm	64.6 cm 82.3 cm	HP1: 110 HP2: 110	BoR	2.3 ± 0.65
					MoR	2.7 ± 0.70
					EoR	2.8 ± 0.85
					Mean	**2.6 ± 0.66 (3.5%)**
Field 6 (Saricam, Adana)	Tillage:+ Sowing:−	Cotton 75 cm	60.9 cm 84.2 cm	HP1: 110 HP2: 110	BoR	5.1 ± 1.35
					MoR	5.0 ± 0.04
					EoR	6.2 ± 1.19
					Mean	**5.4 ± 1.09 (7.2%)**
Field 7 (Saricam, Adana)	Tillage:+ Sowing:−	Cotton 75 cm	61.8 cm 80.6 cm	HP1: 130 HP2: 110	BoR	2.7 ± 0.10
					MoR	3.6 ± 1.35
					EoR	2.9 ± 0.48
					Mean	**3.1 ± 0.85 (4.1%)**

"+" sign: operation done with the use of AS; "−" sign: operation done without the use of AS
[1] PIRS: Plant inter-row spacing set value
[2] HP1: Power of the tractor used in soil ridge tillage (HP), HP2: Power of the tractor used in sowing (HP)
[3] BoR: Beginning of the row, MoR: Middle of the row, EoR: End of the row

The PIRS values in parallel passes in six farmer fields on which ridge tillage was done with the AS system using CORS correction and the sowing was carried out with manual steering (without AS) are presented in *Table 3*. Corn and cotton were planted with a set row spacing of 70 cm in all six fields. While the PIRS value was set to 70 cm, it varied between the lowest 52.8 cm and the highest 88.6 cm and the mean deviations (RMSE) were observed between 1.9 and 8.7 cm and the percent deviations were between 2.7% and 9.6% in all six fields (*Table 3*). The PIRS measurements of the first field are shown in *Figure 5* as an example.

Table 4 shows the PIRS values in parallel passes in six farmer fields which were both ridge tilled and planted with manual steering (without AS). Corn was planted with 75 cm set row spacing in the first three fields while in the remaining three fields, cotton was planted with 72.5 cm row spacing. It was found that even if the PIRS value was set to 75 cm in the first three fields, the lowest PIRS was 52.6 cm and the highest was 94.1 cm (*Table 4*). In the last three fields, the PIRS value varied from the lowest 51.7 cm to the highest 85.2 cm despite the set value of 72.5 cm. The mean deviations (RMSE) varied between 5.2 and 9.4 cm while the mean percent deviations were from 7.1 to 12.3%. The PIRS measurement values of the fifth field is displayed in *Figure 6* as an example.

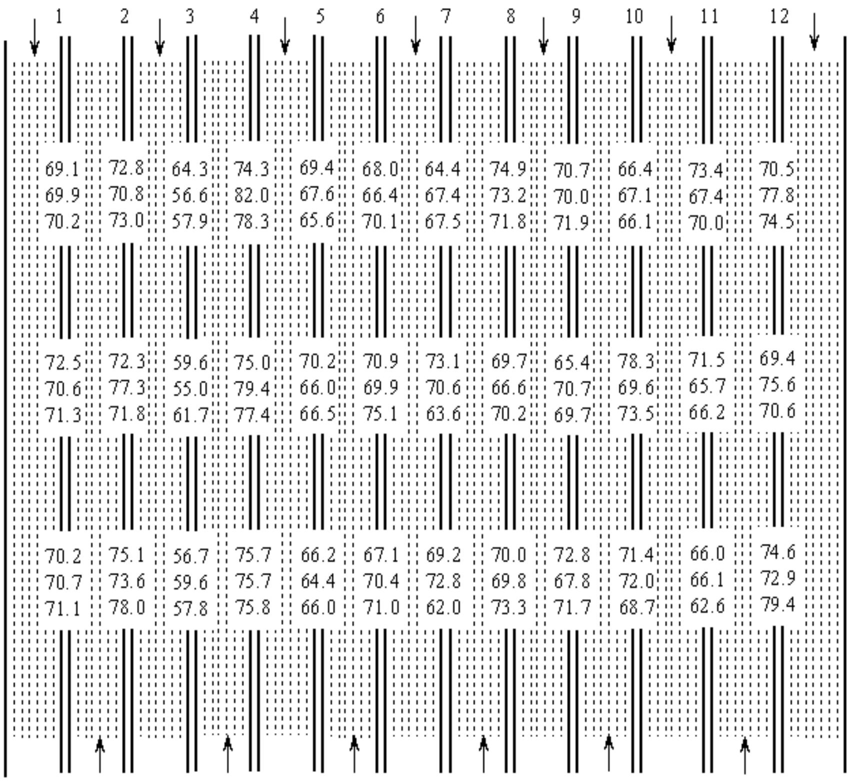

Figure 3. Mean PIRS values (n=3) in parallel passes in the field number 3 both ridge-tilled and sown with the GNSS-based AS with RTK augmentation (eight-row planter, set row spacing: 70 cm)

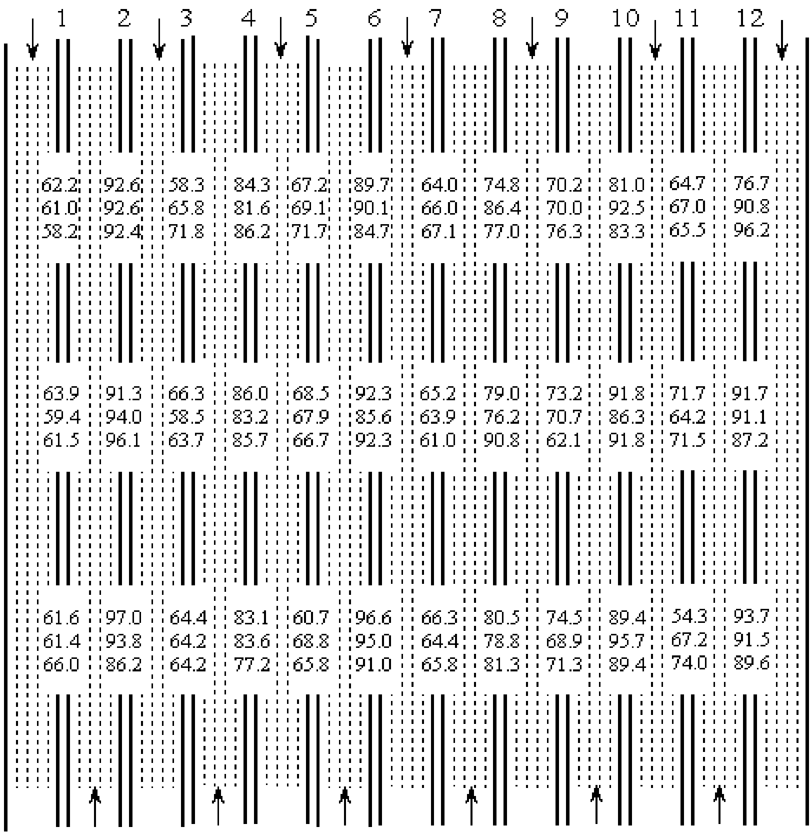

Figure 4. Mean PIRS values (n=3) in parallel passes in field number 2 ridge-tilled with the GNSS-based AS with SBAS service but planted by manual steering (six-row planter, set row spacing: 72.5 cm)

Table 3. Plant inter-row spacing (PIRS) deviations (RMSE) for the fields tilled by the GNSS-based auto steering (AS) with CORS signal augmentation

Field and location	Use of AS	Crop, PIRS[1]	PIRS Min, Max	Tractor power[2]	Data location[3]	Deviation mean±SD (cm)
Field 1 (Yuregir, Adana)	Tillage:+ Sowing:−	Corn 70 cm	60.2 cm 81.6 cm	HP1: 165 HP2: 110	BoR	4.4 ± 0.64
					MoR	3.3 ± 0.65
					EoR	4.9 ± 0.12
					Mean	**4.2 ± 0.82 (6.0%)**
Field 2 (Yuregir, Adana)	Tillage:+ Sowing:−	Corn 70 cm	59.2 cm 88.6 cm	HP1: 165 HP2: 110	BoR	7.1 ± 0.21
					MoR	7.0 ± 0.91
					EoR	6.1 ± 0.39
					Mean	**6.7 ± 0.68 (9.6%)**
Field 3 (Yuregir, Adana)	Tillage:+ Sowing:−	Corn 70 cm	52.8 cm 87.0 cm	HP1: 165 HP2: 110	BoR	8.7 ± 0.63
					MoR	8.5 ± 0.21
					EoR	8.4 ± 0.50
					Mean	**8.5 ± 0.41 (12.1%)**
Field 4 (Ceyhan, Adana)	Tillage:+ Sowing:−	Cotton 70 cm	65.3 cm 73.9 cm	HP1: 110 HP2: 110	BoR	2.0 ± 0.15
					MoR	1.9 ± 0.18
					EoR	1.9 ± 0.56
					Mean	**1.9 ± 0.33 (2.7%)**
Field 5 (Ceyhan, Adana)	Tillage:+ Sowing:−	Cotton 70 cm	67.9 cm 76.2 cm	HP1: 110 HP2: 110	BoR	2.1 ± 0.21
					MoR	2.2 ± 0.05
					EoR	2.2 ± 0.19
					Mean	**2.2 ± 0.16 (3.1%)**
Field 6 (Ceyhan, Adana)	Tillage:+ Sowing:−	Cotton 70 cm	57.3 cm 83.2 cm	HP1: 110 HP2: 110	BoR	7.4 ± 0.35
					MoR	6.4 ± 0.53
					EoR	5.5 ± 0.33
					Mean	**6.4 ± 0.89 (9.1%)**

"+" sign: operation done with the use of AS; "–" sign: operation done without the use of AS
[1] PIRS: Plant inter-row spacing set value
[2] HP1: Power of the tractor used in soil ridge tillage (HP), HP2: Power of the tractor used in sowing (HP)
[3] BoR: Beginning of the row, MoR: Middle of the row, EoR: End of the row

From the *Tables 1* to *4*, it is possible to see differences in the variations of the mean PIRS values. The reasons for these differences among the fields even belonging to same farmer may be tied to some factors such as different operators, tractor sizes, equipment settings, different field locations and planting at different times. Locations of the fields and the time of the operation have a potential to affect the GNSS signal quality and thus the positioning and signal augmentation accuracy. Also, some farmers use the AS only for ridge tillage and do the planting manually without AS (*Table 3*) by simply referencing the ridges mainly due to the high equipment cost and this caused higher variations in some fields. Operator experience and operational care is very important in planting by manual steering and an important factor to affect the variations in PIRS.

Figures 3, *4*, *5* and *6* depict the mean PIRS values observed in the fields. As can be seen in these figures, it was found on a general trend that the PIRS values, which were smaller than set row spacing value in one pass were larger in the next (adjacent) pass. It is thought that the smaller sowing width in one pass is compensated with wider width in the next pass with both AS and manual steering. For example, this is easily visible in *Figure 4* in which the PIRS values are lower than the set value (72.5 cm) in the first, third, fifth passes, etc. while they are higher in the second, fourth, sixth passes, etc.

In the statistical data analysis, the deviations in the mean plant inter-row spacing (PIRS) in parallel passes were statistically compared between the manual steering vs. automatic steering (AS), among the 24 fields and among the measurement locations (BoR: Beginning of the row, MoR: Middle of the row, EoR: End of the row) using Duncan's multiple comparison test.

Table 4. Plant inter-row spacing (PIRS) deviations (RMSE) for the fields both tilled and sowed by manual steering without the use of auto steering (AS)

Field and location	Use of AS	Crop, PIRS[1]	PIRS Min, Max	Tractor power[2]	Data location[3]	Deviation mean±SD (cm)
Field 1 (Saricam, Adana)	Manual steering	Corn 75 cm	52.6 cm 94.1 cm	HP1: 110 HP2: 110	BoR	6.0 ± 0.30
					MoR	9.0 ± 1.38
					EoR	6.6 ± 0.58
					Mean	**7.2 ± 1.59 (9.6%)**
Field 2 (Saricam, Adana)	Manual steering	Corn 75 cm	61.1 cm 89.2 cm	HP1: 110 HP2: 110	BoR	7.5 ± 0.20
					MoR	6.0 ± 0.49
					EoR	6.4 ± 0.40
					Mean	**6.7 ± 0.67 (8.9%)**
Field 3 (Saricam, Adana)	Manual steering	Corn 75 cm	64.1 cm 84.6 cm	HP1: 110 HP2: 110	BoR	5.2 ± 0.20
					MoR	5.5 ± 0.23
					EoR	5.3 ± 0.56
					Mean	**5.3 ± 0.35 (7.1%)**
Field 4 (Ceyhan, Adana)	Manual steering	Cotton 72.5 cm	56.1 cm 85.2 cm	HP1: 110 HP2: 110	BoR	8.5 ± 0.41
					MoR	8.5 ± 0.32
					EoR	7.8 ± 0.52
					Mean	**8.2 ± 0.50 (11.3%)**
Field 5 (Ceyhan, Adana)	Manual steering	Cotton 72.5 cm	54.6 cm 82.1 cm	HP1: 110 HP2: 110	BoR	9.4 ± 0.31
					MoR	9.1 ± 0.36
					EoR	8.1 ± 0.05
					Mean	**8.9 ± 0.66 (12.3%)**
Field 6 (Ceyhan, Adana)	Manual steering	Cotton 72.5 cm	51.7 cm 78.9 cm	HP1: 110 HP2: 110	BoR	8.4 ± 0.08
					MoR	8.2 ± 0.03
					EoR	7.3 ± 0.14
					Mean	**8.0 ± 0.51 (11.0%)**

"–" sign: operation done without the use of AS
[1] PIRS: Plant inter-row spacing set value
[2] HP1: Power of the tractor used in soil ridge tillage (HP), HP2: Power of the tractor used in sowing (HP)
[3] BoR: Beginning of the row, MoR: Middle of the row, EoR: End of the row

Table 5 lists the mean PIRS deviation values compared according to the steering methods (manual vs. AS) including the AS used in ridge-tillage and planting or only in ridge-tillage but not planting. The mean PIRS deviation value in the manual steering (7.4 cm) was found to be significantly higher compared to the deviations obtained in AS method with different correction services (CORS: 5.0 cm, SBAS: 5.9 cm, RTK: 6.7 cm) ($p<0.05$) (*Table 5*). However, it was observed that the differences between AS with different correction signals (CORS, SBAS, RTK) were not significant ($p>0.05$).

Table 5. Mean PIRS deviation values in parallel passes according to the steering method

Method of steering	RMSE; Mean ± SD*
AS with CORS signal augmentation	5.0 ± 2.52 cm ^{a}
AS with SBAS signal augmentation	5.9 ± 3.98 cm ^{ab}
AS with RTK signal augmentation	6.7 ± 1.36 cm ^{bc}
Manual steering (no AS system)	7.4 ± 1.40 cm ^{c}

AS: Automatic steering
*Different letters over the numbers (a, b, c) indicate significant differences ($p<0.05$).

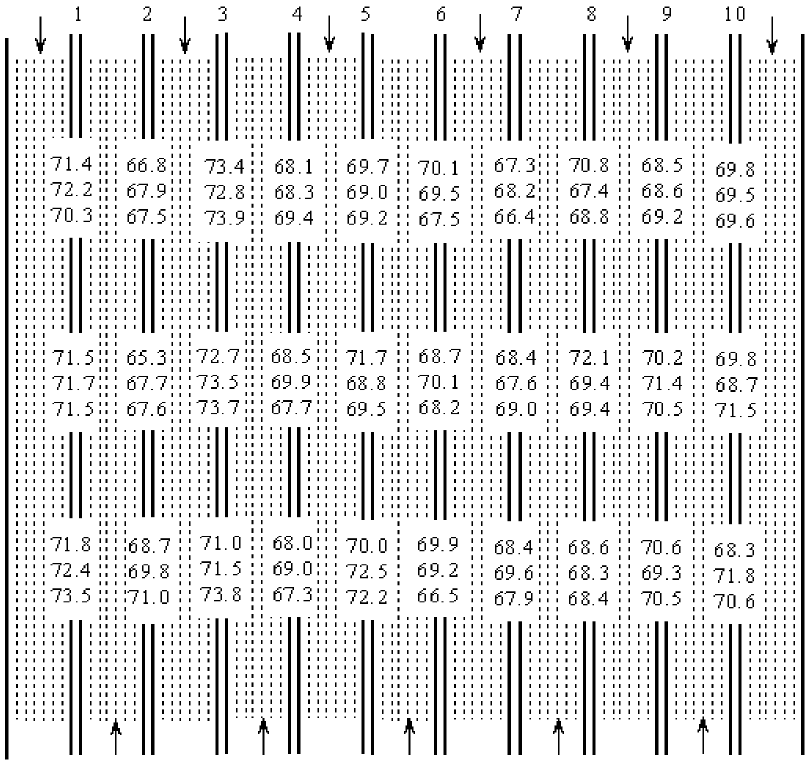

Figure 5. Mean PIRS values (n=3) in parallel passes in the field number 4 ridge-tilled with the GNSS-based AS systems with CORS service but planted by manual steering (eight-row planter, set row spacing: 70 cm)

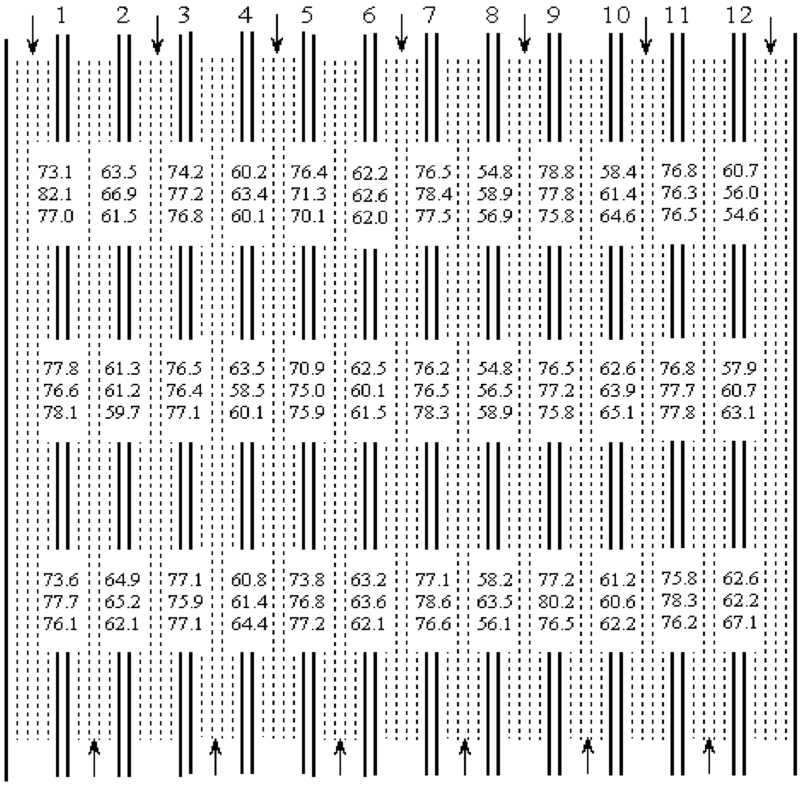

Figure 6. Mean PIRS values (n=3) in parallel passes in the field number 5 both ridge-tilled and sown with manual steering (six-row planter, set row spacing: 72.5 cm)

The mean deviation values in the PIRS in parallel passes taken from all 24 fields are presented in *Figure 7* and *Table 6*. It was observed that the mean PIRS deviation values were significantly different in most of the fields showing high variability among the fields ($p<0.05$). However, the differences within each steering method were relatively lower except two fields (F3 and F4) in which the ridge tillage was conducted with AS with SBAS correction service and the sowing carried out by manual steering (*Figure 7*, *Table 6*). The reasons for these differences among the fields may be tied to some factors such as different operators, tractor sizes, equipment settings, field locations and planting at different times (important for GNSS signal quality). It was also observed that some fields (Field 1 and Field 2) ridge-tilled by AS with SBAS correction service and planted by manual steering showed higher PIRS variations compared to the fields tilled and planted by manual steering (*Figure 7*). This is probably due to the low quality of work during the planting with manual steering. This means that the farmer did not get a good benefit from the AS to reduce the PIRS variations.

In field operations with machinery such as tillage and planting, higher deviations are usually expected after turning after finishing a row pass and beginning a new parallel pass in both automatic steering (AS) and manual steering during the system is adjusting to new row pass. Thus, the mean PIRS deviation values were compared according to the steering methods (manual vs. AS) used in ridge-tillage and/or planting as well as the PIRS measurement locations (BoR: Beginning of the row, MoR: Middle of the row, EoR: End of the row) (*Table 7*). It was observed that these differences were at very low levels according to the measurement locations (BoR, MoR and EoR) and can be considered as insignificant.

Sufficient spacing is required between plants and crop rows to provide enough living area, nutrients, water and light for each plant (Blessing et al., 2020). Crop inter row spacing is a crucial factor for plant growth, yield and farm's income (Tilley et al., 2021). Furthermore, equal plant inter-row spacing (PIRS) must be obtained in parallel adjacent passes in mechanized sowing with automatic steering (AS) or manual steering. If the PIRS value between the adjacent rows of the parallel passes is less than the desired set value, sufficient living space cannot be provided for the plants. Moreover, this may adversely affect the other future machinery operations such as hoeing machinery, fertilizer application machinery, sprayers and harvesters in row crops such as cotton, corn, soybean, etc. On the other hand, if this distance is greater than the desired set value, the area cannot be utilized sufficiently and yield would be lower (Tilley et al., 2021).

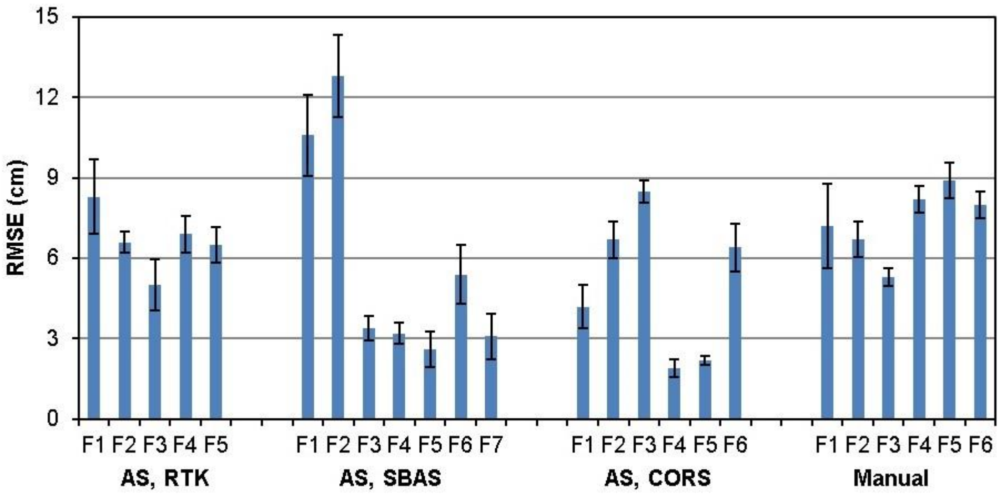

Figure 7. Mean PIRS deviations (RMSE) in parallel passes in all 24 fields according to the steering method (auto steering: AS and manual steering)

Table 6. Mean PIRS deviations in parallel passes according to the fields in each steering method

Method of steering	Fields	RMSE; Mean ± SD*
AS with RTK signal augmentation	F3	5.0 ± 0.96 cm [a]
	F5	6.5 ± 0.66 cm [b]
	F2	6.6 ± 0.38 cm [b]
	F4	6.9 ± 0.69 cm [b]
	F1	8.3 ± 1.40 cm [c]
AS with SBAS signal augmentation	F5	2.6 ± 0.66 cm [a]
	F7	3.1 ± 0.85 cm [a]
	F2	3.2 ± 0.38 cm [a]
	F1	3.4 ± 0.45 cm [a]
	F6	5.4 ± 1.09 cm [b]
	F3	10.6 ± 1.51 cm [c]
	F4	12.8 ± 1.54 cm [d]
AS with CORS signal augmentation	F4	1.9 ± 0.33 cm [a]
	F5	2.2 ± 0.16 cm [a]
	F1	4.2 ± 0.82 cm [b]
	F6	6.4 ± 0.89 cm [c]
	F2	6.7 ± 0.68 cm [c]
	F3	8.5 ± 0.41 cm [d]
Manual steering (without AS)	F3	5.3 ± 0.35 cm [a]
	F2	6.7 ± 0.67 cm [b]
	F1	7.2 ± 1.59 cm [b]
	F6	8.0 ± 0.51 cm [c]
	F4	8.2 ± 0.50 cm [cd]
	F5	8.9 ± 0.66 cm [d]

AS: Automatic steering
*Different letters over the numbers (a, b, c, d) indicate significant differences (p<0.05).

Table 7. Mean PIRS deviations in parallel passes according to the measurement locations

Method of steering	PIRS measurement location *	PIRS deviations RMSE ± SD **
AS with RTK service	BoR	6.3 ± 1.16 cm [a]
	MoR	6.7 ± 1.39 cm [ab]
	EoR	7.1 ± 1.49 cm [b]
AS with SBAS service	BoR	5.6 ± 3.79 cm [a]
	MoR	6.1 ± 4.15 cm [a]
	EoR	5.9 ± 4.17 cm [a]
AS with CORS service	BoR	5.3 ± 2.71 cm [ab]
	MoR	4.9 ± 2.62 cm [b]
	EoR	4.9 ± 2.34 cm [bc]
Manual steering (no AS)	BoR	7.5 ± 1.54 cm [a]
	MoR	7.8 ± 1.53 cm [b]
	EoR	6.9 ± 1.02 cm [b]

AS: Auto steering;
*BoR: Beginning of the row, MoR: Middle of the row, EoR: End of the row
**Different letters over the numbers (a, b, c) indicate significant differences (p<0.05).

AS systems are expected to adjust the PIRS value more precisely in parallel passes compared to manual steering if the equipment settings are properly set and the system is used suitably by the machinery operator. Various studies have been carried out on the utilization of AS systems that provide reductions in overlaps and gaps especially in spraying with significant savings in fuel, time, water, fertilizer, pesticide, labor and marking foam (Batte and Ehsani, 2006; Topcueri and Keskin, 2019; Kharel et al., 2020; Anastasiou et al., 2023; D'Antonio et al., 2023). However, studies on the effect of AS technologies in planting process on PIRS uniformity in parallel passes have been very limited. Baio and Moratelli (2011) found a parallelism error of 3.3 cm with AS and RTK service which is five times better than the manual steering in sugarcane planting. Similarly, Voltarelli et al. (2013) determined errors up to 4.9 cm by using AS with RTK signal augmentation service in sugarcane planting with row spacing of 1.5 m. Santos et al. (2017) reported that positioning errors were lower than the value specified by the machinery producer (3.8 cm) in AS system with RTX service in peanut sowing. In another study, the same authors determined an amount of mean error less than 2 cm in parallel passes in peanut sowing with AS using RTX service (Santos et al., 2018). In addition, Zerbato et al. (2019) stated that the AS system was more effective for improving the accuracy and quality of the peanut sowing compared to manual steering.

In this present work, comparable findings were obtained in regards to the findings of the previous studies. In the sowing process of cotton and corn on soil ridges under farmer conditions, the mean PIRS variations (RMSE) in parallel passes were from a minimum of 5.0 cm to a maximum of 6.7 cm for AS with different signal augmentation services while it was significantly higher (7.4 cm) with manual steering used both in ridge-tillage and sowing. Very low deviations in PIRS values in parallel passes as low as 2.7% were observed in some farmer fields while much higher values were also determined in other farmer fields as high as 17.7% with the usage of AS. Hence, it was found in this present study that AS systems reduce the PIRS variations in parallel passes in ridge tillage and/or sowing; however, the benefit level changes from farmer to farmer. The AS systems should be used with care with proper settings of the tillage and sowing equipment.

In regards to the three GNSS signal augmentation services used by the farmers in the study region, the mean RMSE variation in the pass-to-pass PIRS was slightly lower with CORS method (5.0 ± 2.52 cm) as compared to SBAS (5.9 ± 3.98 cm) and RTK methods (6.7 ± 1.36 cm) (*Table 5*). However, the differences between these signal correction methods (CORS, SBAS, RTK) were not significant pairwise ($p>0.05$) (*Table 5*). It should be noted that these values are average of five, seven and six fields for the RTK, SBAS, and CORS methods, respectively (*Figure 7*). In general, RTK and subscription-based precise SBAS services are considered to give better positioning accuracy with centimeter level than the CORS method; however, in the process of sowing, many factors affect the pass-to-pass PIRS including the care of the machine operator, machine settings, and the availability of the AS system in both ridge tillage and sowing, etc.

4. Conclusions

It was found that the mean pass-to-pass plant inter-row spacing (PIRS) deviations in manual sowing (7.4 cm) were higher than the AS based soil ridge tillage and / or sowing with three different GNSS augmentation methods (CORS: 5.0 cm, SBAS: 5.9 cm, RTK: 6.7 cm) ($p<0.05$). Hence, the AS technology was determined as favorable in mitigating the pass-to-pass PIRS variations compared to the manual steering along with other benefits such as easiness of usage, less operator fatigue, working at night, etc. But, some farmers employed AS only in ridge tillage but done the planting without AS by aligning the tractor according to the ridges created by AS. The use of AS both in ridge tillage and sowing reduced the deviations and increased the benefit of AS in some fields. It was observed that the degree of benefit obtained from the AS technology vary among the fields and farmers; hence, the AS should be employed with care and with proper tillage and planting equipment settings for greater degrees of benefits.

Limitation of the Study

The data of this study were collected from 24 fields belonging to different farmers in various locations in the Cukurova region of Türkiye. Factors such as different tractor operators, different models of tractors, different ridge tillage and planters, different geographical locations of the fields, and tillage and planting operations at different times (important for GNSS signal quality) can have influences on the data. However, this study is important since it reflects the real farmer conditions of the effect of AS on the deviations of pass-to-pass plant inter row spacing.

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Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Keskin, M.; Design: Keskin, M., Topcueri, M.; Data Collection and Processing: Keskin, M., Topcueri, M., Sekerli, Y.E.; Statistical Analyses: Topcueri, M., Sekerli, Y.E.; Literature Search: Keskin, M., Topcueri, M.; Writing, Review and Editing: Keskin, M., Topcueri, M., Sekerli, Y.E.

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