GNSS Network RTK for Automatic Guidance in Agriculture: Testing and Performance Evaluation

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Abstract. The paper reports the results of a research on validation and optimization of automatic and semi-automatic guidance systems for agricultural machinery based on Real-Time positioning services provided by GNSS Networks (NRTK). The research is based on experimental campaigns performed on test areas, located in Umbria (central Italy) on the land of six farming companies.

The tests have interested many processes of the agricultural work carried out in different seasons and environmental conditions, by means of agricultural machinery of various size, power and characteristics. For the performance evaluation of different guidance systems and positioning methods, reference solutions obtained in post-processing with geodetic GNSS receivers have been utilized.

To reach generalized conclusions, appropriate parameters have been defined and evaluated in order to compare the quality of the results of tests performed with different equipment and conditions, and to quantify the economic benefits achieved through the GNSS guidance systems. Further tests have been performed to evaluate the ability of machine control systems to acquire a series of useful agronomic and geometric data during the work to be included in a farm-level GIS, including the three-dimensional geometry of the crops, the creation of reports about processes and treatments and the optimization of the machine paths and related agricultural activities.

Keywords: Precision agriculture · Machine control · Automatic guidance · GNSS real time positioning · Network RTK

1 Introduction

The control and guidance systems for agricultural machinery based on Real-Time GNSS positioning have emerged in the latest years as a significant cost reduction and increased productivity factor [1, 2].

The few-meters positioning accuracy supplied by a single GNSS receiver in standalone mode is not sufficient for precise agriculture, where it is necessary to achieve a

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decimeter or, for some applications, sub-decimeter accuracy [3, 4]. This is possible if the receiver placed on the equipment is able to acquire a code (DGNSS, accuracy < 1 m) or code/phase (RTK or NRTK, accuracy < 5 cm) RTCM correction stream via Ntrip protocol.

Most of the RTCM-based systems used in agriculture need a GNSS base station (located in a point with known coordinates) that sends RTCM corrections to the on-board receiver through a radio modem (base/rover RTK). In Italy and other European countries, the transmission power of a private radio signal is limited by law to a maximum of 0.5 Watts, which strongly limits the covered area and makes it necessary to locate the base in the proximity of the rover.

In the present research RTCM correction was not sent by a base station, but by means of the Control Center of the regional GNSS permanent network (GPSUMBRIA) [5]. This approach (Network RTK or NRTK) has the considerable advantage of covering very large areas without the need (and the cost) of a base station [6].

One of the purposes of this research was to test the applicability, the coverage and the reliability of NRTK approach on agricultural applications. The position obtained in real time from GNSS systems is used for driving the agricultural machines during the fieldwork. The GNSS guidance can be "assisted" (semi-automatic) or fully automatic, even if the driver is always on board for security reasons.

The experiments have compared three guidance modes: manual, assisted and automatic [7, 8]. The tests have been performed during different agricultural processes and the results have been compared for evaluating the geometric accuracy and the operator stress. The research has been carried out in the frame of a Rural Development Plan (PSR) promoted by the Umbria Regional Council and financed by UE, and has developed into a series of successive steps. The first step has been the individuation of test areas for each company of the project, then digital maps have been acquired and implemented on a GIS (software platform Topcon SGIS) integrating them with other metadata information (cultivation sheets with environmental and agronomic parameters). Preliminary inspections have been carried out in the test areas to check the coverage by the Network RTK positioning services and testing protocols have been developed. The relevant amount of experimental data collected has made possible to develop a deep and wide analysis, the results of which are described in this paper.

2 GNSS Infrastructures and NRTK Positioning Services

The NRTK technique is based on the existence of an infrastructure (Network of GNSS permanent stations) offering positioning services by sending RTCM correction messages. Each user sends to the network Control Center a service access request including his approximate position in NMEA format. The Control Center sends a custom RTCM correction stream based on the user location. One of the most common correction type is VRS, creating a "Virtual Reference Station" in the proximity of the user [9]. There are alternative approaches (MAC, FKP,…) but the results are similar (a real-time 3D positioning with accuracy < 5 cm) with comparable efficiency [10].

The experimentation described in the present paper has been supported by the GNSS network GPSUMBRIA realized since 2004 by the University of Perugia and the Regional

Administration of Umbria including 13 GNSS permanent stations (Fig. 1), with a short average spacing (about 40 km) giving the network a redundancy which permits to overcome malfunctions of some stations [5, 11]. All stations are equipped with geodetic multicostellation/multisignal receivers with choke-ring antennas.

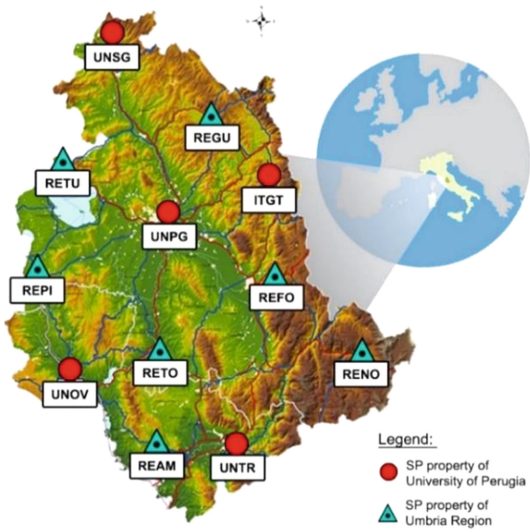

Fig. 1. The GNSS network GPSUMBRIA

The GPSUMBRIA network has the primary function of maintaining a stable reference frame for the whole region, consistent with the official datum ETRF2000. It also provides public and private users a wide range of positioning services in post-processing and real-time, distributed free of charge to promote the use of this infrastructure supporting technological innovation in various fields of work. For further information, please refer to [5] and [11].

3 Instruments and Machines Used in the Tests

For the experimental campaign tractors of different characteristics were used, all equipped with the GNSS guidance system Topcon System 350, including an AGI-4 receiver and a X30 console (Fig. 2). Some tractors were equipped with a Topcon AES-25 electric steering wheel, other machines used the included servo-assisted steering wheel, appropriately interfaced with the guidance system. An estimated cost for the complete system is of about 20000 €; if the tractor is already equipped with the electric steering wheel the cost is considerably reduced.

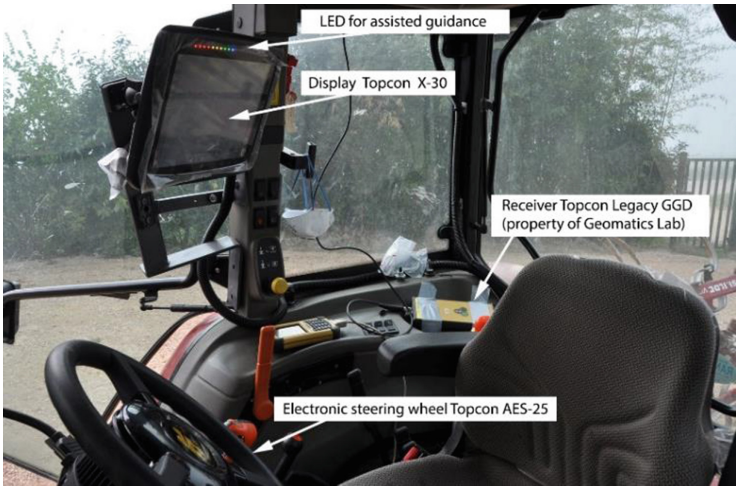

Fig. 2. Topcon 350 guidance system mounted on a tractor participating to the tests

During the tests a second GNSS receiver (Topcon Legacy-E GGD, dual-frequency GPS/GLONASS, connected to a geodetic LegAnt-2 antenna) was installed in the machines. This second receiver was operating completely independently from the machine guidance system, in order to perform a control of the results without any interference (Fig. 3). The planimetric and height offsets between the two different antennas were appropriately measured and taken into account.



Fig. 3. GNSS receivers and antennas mounted on the top of a tractor cabin

The tests have been performed using tractors of various sizes and types, wheeled and tracked, for different agricultural processes. The control receiver (Topcon Legacy) has been used as rover for kinematic post-processing, acquiring GNSS raw data during the test sessions. In the proximity of each test area a second Topcon Legacy receiver has been installed, as base station for the determination of the rover trajectories (Fig. 4). For both receivers the sampling frequency was set to 1 Hz (1 measure or "epoch" per second). The base stations coordinates have been calculated from post-processed static GNSS solutions with connection to GPSUMBRIA network.



Fig. 4. Base-Rover post-processing for control purposes

4 Execution of the Tests

The tests here presented have been carried out in two different locations. The first test area (Fig. 5), located near Spina (Perugia) and characterized by a slope of about 9,5% with East exposure, has interested sowing, fertilizing and harrowing operations. The second site is a flat ground near Tavernelle (Perugia) which was interested only by harrowing process (Fig. 6).



Fig. 5. Sowing in manual mode (left) and automatic mode (right)



Fig. 6. Harrowing in manual mode (left) and automatic mode (right)

The agricultural processes were performed in three driving modes (e.g. Figs. 5, 6):

- manual;
- assisted;
- automatic.

In manual mode the operator has a complete control of the vehicle and proceeds with the usual methods based on alignment by sight. In assisted mode a row of LEDs shows the deviation from the ideal line and the correction is performed manually by the operator according to the LED indication. In automatic mode, the trajectory correction is automatically performed by the electric steering wheel and the operator only has to control the vehicle speed.

The trajectories followed by the machines were computed in two different ways:

– recording by the machine guidance system the positions calculated in real time;
– post-processing kinematic solutions obtained from the data gathered by the control GNSS receivers (Fig. 4).

A psychologist observed the reactions of the tractor drivers during part of the tests to evaluate the state of psycho-physical stress.

5 Data Processing

The post-processing of the GNSS data for control purposes was performed with the Topcon Tools 8.2.3 software (Fig. 7). The steps of the calculation were the following:

- computation of the 3D coordinates of the base stations by static GNSS connection with two permanent stations of the GPSUMBRIA network;
- assuming as fixed the coordinates of the base stations, GNSS kinematic computation of the trajectories of the tractors (3D position each second).

The processing was performed in the datum ETRF2000, the same of the positions obtained in real time by the on board GNSS guidance system.

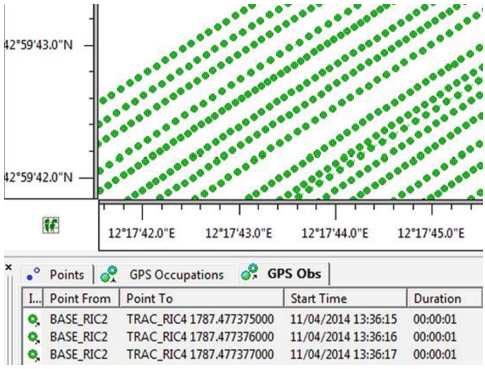

Fig. 7. Topcon tools post-processing solution of a tractor trajectory (example)

The post-processing trajectories were superimposed on the test areas ortophotos in GIS for a rapid check. Then, a comparison with the trajectories recorded by the guidance system was carried out.

The post-processing coordinates are referred to the antenna phase center. To compare them with the positions calculated in real time by the guidance system, the horizontal and vertical offsets were considered. The comparison also required an alignment of epochs, formats and units. A very good agreement was found between post-processing and real time solutions, at a few centimeters level.

5.1 Evaluation of the Efficiency of the Guidance System

In order to evaluate the efficiency of GNSS-supported guidance systems with respect to the manual guide, the following analysis was carried out:

- the trajectories were divided into individual rectilinear strips, excluding the initial and the final parts, affected by the U-turns of the tractor;
- for each strip the transverse displacements of each position with respect to a straight line indicating the hypothetical ideal path were evaluated;
- a statistical analysis was performed on the transverse displacements;
- a comparison between the results of the three different driving systems (manual, assisted and automatic) was finally performed.

In Fig. 8 are shown, as example, some graphs comparing the transverse deviations from the average straight line. The results have been grouped for tests performed under the same experimental conditions (test area, tractor, accessories, type of agricultural process, soil conditions) with the three different guidance systems.

The statistical parameters referring to Fig. 8 are summarized in Table 1. The mean value of the transverse deviation is always zero because the values are computed with respect to the average straight line, assumed as the ideal path.

The graphs A, B and C refers to test series effected with narrow wheels tractors on a variable slope terrain. The tests of the group A were carried out on dry terrain, while for

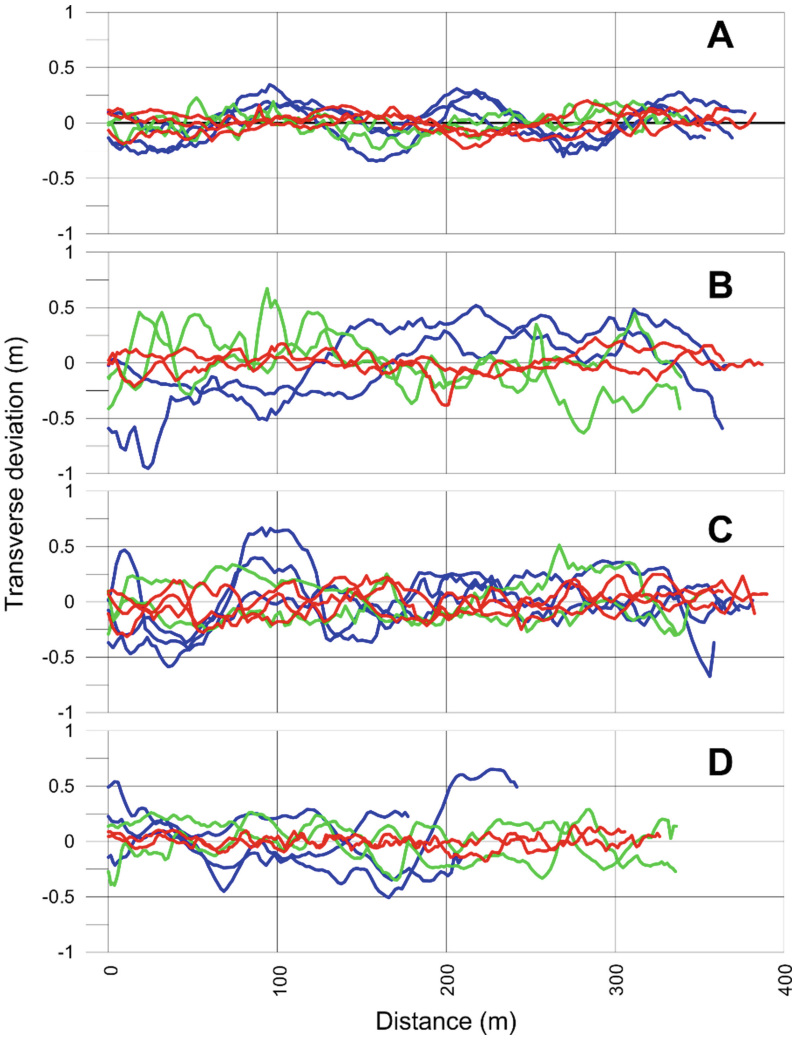

Fig. 8. Transverse deviations from an average rectilinear path vs. distance for different processes and machines: A) Sowing, wheeled tractor; B) Fertilization, wheeled tractor; C) Harrowing, wheeled tractor; D) Harrowing, rubber tracked tractor. Colour legend: blue = manual drive, green = assisted drive, red = automatic drive. (Color figure online)

the graphs B and C the driving conditions were quite difficult due to the moistened and muddy soil. The graph D refers to a test group performed with a rubber tracked tractor on a flat and dry ground (Fig. 6).

It can be seen that with the manual system there are relevant transverse displacements from the average ideal path, up to some decimetres for a trajectory of some hundreds of meters. An exception is the sowing process (graph A) where the traditional alignment aid (Fig. 5, left) helps to obtain a good accuracy even in manual mode.

Table 1. Statistical parameters of the experimental transverse deviations for different guidance systems on various test groups (referring to Fig. 8 graphs)

A - Sowing, wheeled tractor			
Parameter	Manual	Assisted	Automatic
Mean (m)	0,00	0,00	0,00
RMS (m)	0,16	0,09	0,08
RMS %	100	58	53
Max (m)	0,35	0,23	0,20
Min (m)	−0,35	−0,24	−0,23
V_{med} (m/s)	2,32	2,09	2,33
B - Fertilizing, wheeled tractor			
Parameter	Manual	Assisted	Automatic
Mean (m)	0,00	0,00	0,00
RMS (m)	0,31	0,24	0,10
RMS %	100	76	31
Max (m)	0,52	0,67	0,23
Min (m)	−0,95	−0,63	−0,38
V_{med} (m/s)	2,66	2,87	2,30
C - Harrowing, wheeled tractor			
Parameter	Manual	Assisted	Automatic
Mean (m)	0,00	0,00	0,00
RMS (m)	0,25	0,18	0,12
RMS %	100	73	48
Max (m)	0,67	0,51	0,24
Min (m)	−0,67	−0,30	−0,31
V_{med} (m/s)	2,66	2,98	2,72
D – Harrowing, rubber tracked tractor			
Parameter	Manual	Assisted	Automatic
Mean (m)	0,00	0,00	0,00
RMS (m)	0,26	0,16	0,06
RMS %	100	61	22
Max (m)	0,65	0,29	0,14
Min (m)	−0,51	−0,40	−0,18
V_{med} (m/s)	1,97	1,62	1,40

The deviations are reduced with the assisted driving system. With respect to manual driving, with the assisted guidance the RMS value reduces in the range of 58% to 76%.

In other situations (e.g. graph B) the driver seems to have difficulties to follow the system indications.

The automatic system always provided the most accurate results, with the smallest transverse deviations: RMS value of 6 cm in the most favourable case (graph D) and 12 cm in the worst one (graph C). With respect to manual drive, with the automatic guidance the RMS value reduces consistently (22% to 53%).

The deviations obtained in automatic mode are in good agreement with the accuracy level of a NRTK positioning (a few centimetres). However, in some cases the graphs show higher deviations. This is due to the fact that the graphs show the actual, raw results of tests carried out in the field. As already mentioned, in the B and C tests the tractor had narrow tyres and the ground was muddy and sloping. In such condition lateral displacements up to 20-25 cm are likely, because the steering, the mechanics and the inertia of the tractor make impossible to prevent the wheels from slipping down into the side grooves.

5.2 Evaluation of the Benefit of the Guidance System in Terms of Areas

In order to carry out an economic assessment of the actual benefit obtained by a precision guidance system, the main parameter to evaluate is the gaps and/or overlaps area between adjacent processed "strips", and its percentage on the total area worked. This concept is graphically expressed in Fig. 9. The costs are in fact generally proportional to the areas actually worked. Therefore, the processing extra costs are proportional to the overlaps and the losses due to lack of process are proportional to the gaps.

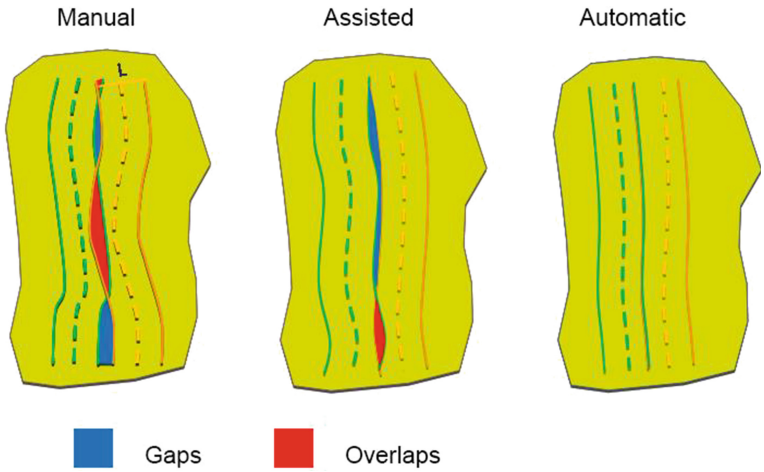

Fig. 9. Gaps and overlaps between contiguous processed strips

In this study, we started from an *a posteriori* evaluation and subsequently tried to define parameters and indexes for an *a priori* estimate of the benefits.

For the *a posteriori* evaluation we proceeded as follows. Starting from the trajectory axes and considering the width of the processed strip (different according to the type of

equipment towed by the tractor), the footprints on the ground of the processed areas have been traced in a graphical environment (CAD and/or GIS). From the footprints, the actual areas of overlaps and gaps has been determined. Overlaps are defined as intersections between contiguous strips areas. Gaps are defined as difference between supposed total area and actually processed total area for each pair of contiguous strips.

The areas of overlaps and gaps were compared with the total area, in order to evaluate the actual benefits or losses related to different guidance systems.

Table 2 and Fig. 10 summarise the results for the same tests of Table 1 and Fig. 8.

Table 2. Evaluation of gaps and overlaps between contiguous processed strips for different guidance systems on various test groups (referring to the graphs of Fig. 10)

Tractor	Process	Guidance	Area (m^2)	Gaps (m^2)	Overlaps (m^2)	Gaps %	Overlaps %
wheeled	sowing	manual	11566	516	60	4,5	0,5
wheeled	sowing	assisted	8644	342	83	4,0	1,0
wheeled	sowing	automatic	9553	143	107	1,5	1,1
wheeled	fertilizing	manual	10468	0	973	0,0	9,3
wheeled	fertilizing	assisted	10672	17	43	0,2	0,4
wheeled	fertilizing	automatic	12474	63	0	0,5	0,0
wheeled	harrowing	manual	12448	0	2032	0,0	16,3
wheeled	harrowing	assisted	10595	166	181	1,6	1,7
wheeled	harrowing	automatic	8689	120	107	1,4	1,2
tracked	harrowing	manual	9873	2	1043	0,0	10,6
tracked	harrowing	assisted	7960	50	343	0,6	4,3
tracked	harrowing	automatic	7038	49	68	0,7	1,0

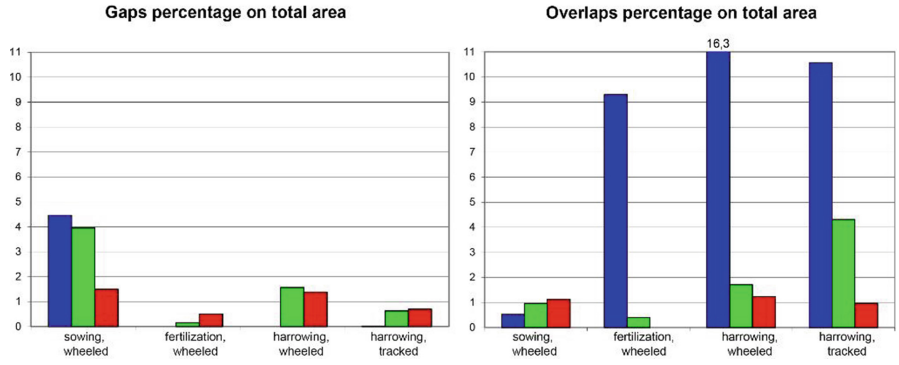

Fig. 10. Gaps and Overlaps percentage on total processed area for different guidance systems on various test groups (referring to Table 2). Legend: blue = manual drive, green = assisted drive, red = automatic drive. (Color figure online)

It can be noticed that with manual guidance, to avoid gaps strong overlaps often occurred (10% and more of the processed area), with a consequent relevant increase of the costs for processing and consumption of seeds and fertilizer. With the GNSS-guided systems, the overlaps are greatly decreased. However, in few cases gaps occur more than with manual drive but with a small percentage, around 1% or less.

6 Analysis and Parameterization of the Results

It can be useful to define some parameters that synthetically express the efficiency of a guidance system for agriculture and evaluate *a priori* the savings achievable by adopting a high accuracy GNSS guidance system.

Overlaps and gaps are caused by transversal deviations of the tractor from the ideal trajectory.

To assess their entity, the graphs have been analysed in terms of areas between the actual trajectory and the ideal one for all the guidance systems.

Figure 11 shows an example graph of the transversal deviations in which the positive error areas (A_P) and the negative ones (A_N) of the ideal trajectory have been highlighted.

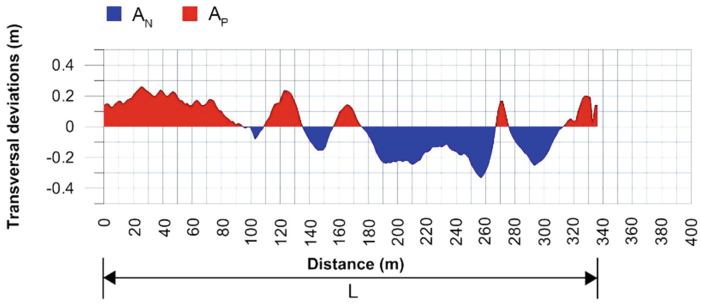

Fig. 11. Areas between the actual trajectory and a straight ideal line

Referring to the Fig. 11, it is possible to define as **Mean Deviation *D**** the following parameter, expressed in meters:

$$D^* = \frac{\sum(|A_P| + |A_N|)}{L} = \frac{A_D}{L} \tag{1}$$

where A_P and A_N are the areas defined as above, A_D is the total "deviation area" (which could also be called "error area") and L is the total trajectory length in meters.

In other terms, D^* is the height of a rectangle having area A_D and base equal to L, and evaluates the amount of error area (gaps or overlaps) referred to one-meter length. The lower D^*, the better the efficiency of the guidance system.

The Mean Deviation D^* can be expressed as a percentage $D^*\%$, representing the percentage of the deviation area for a unit width strip (1 m):

$$D^*\% = D^* \cdot 100 \tag{2}$$

The results obtained with different driving systems in the tests previously described have been analysed in terms of the parameters defined above. The mean values of the D*% parameter for the analysed strips is shown in the following graph.

The parameterization in terms of Mean Deviation (Fig. 12) helps to obtain a good summary of the results of the research.

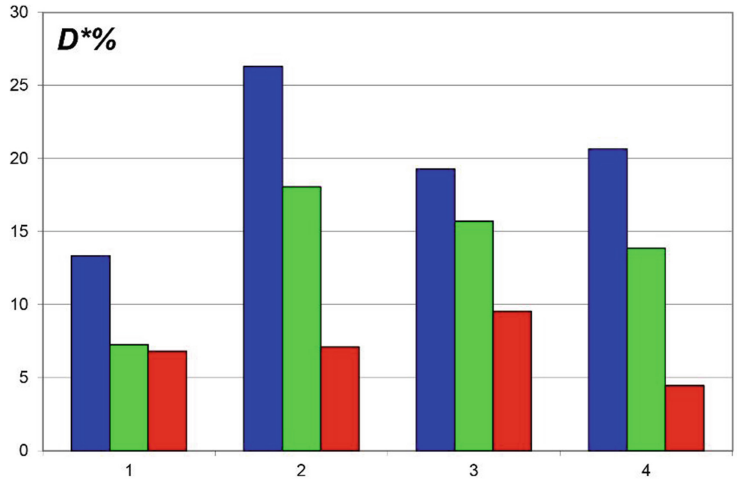

Fig. 12. Mean values of Mean Deviation *D*%* trend for different guidance systems on various test groups: 1 sowing, 2 fertilizing, 3 harrowing (wheeled tractor), 4 harrowing (tracked tractor). Legend: blue = manual drive, green = assisted drive, red = automatic drive. (Color figure online)

It is clear as the automatic guidance is the most advantageous one, leading to obtain *D*%* values on the 5-10% order, whilst for manual guidance *D*%* is in the 15-25% range. The reduction of the error areas in automatic mode compared to manual driving varies from ½ to ¼ factor.

The assisted guidance has shown results between manual and automatic driving, showing some difficulties to calibrate the system and highly driver-depending.

The evaluations carried out by psychologists indirectly confirm these results, advising a higher stress for the driver in assisted guide compared to the manual one.

The *D** parameter allow to evaluate the savings achievable with the installation of a GNSS automatic guidance system.

As define, D*% is referred to a unit width strip (S = 1 m) but actually the width of the field strip processed is different depending on the accessory towed by the tractor.

For a generic width S and length L strip, it is possible to define a **Deviation Index *ID*** as the percentage of the error area on the total area processed (A_T):

$$ID = \frac{A_D}{A_T} \cdot 100 = \frac{D^* \cdot L}{S \cdot L} \cdot 100 = \frac{D^*\%}{S} \tag{3}$$

where A_T, the total field area processed for one strip, is:

$$A_T = S \cdot L \tag{4}$$

The graph on Fig. 13 refers to the expression (3) and represents the trend of the percentage of the error area as a function of the width of the processed strip and of the *D*%* value and was drawn using an interpolation function.

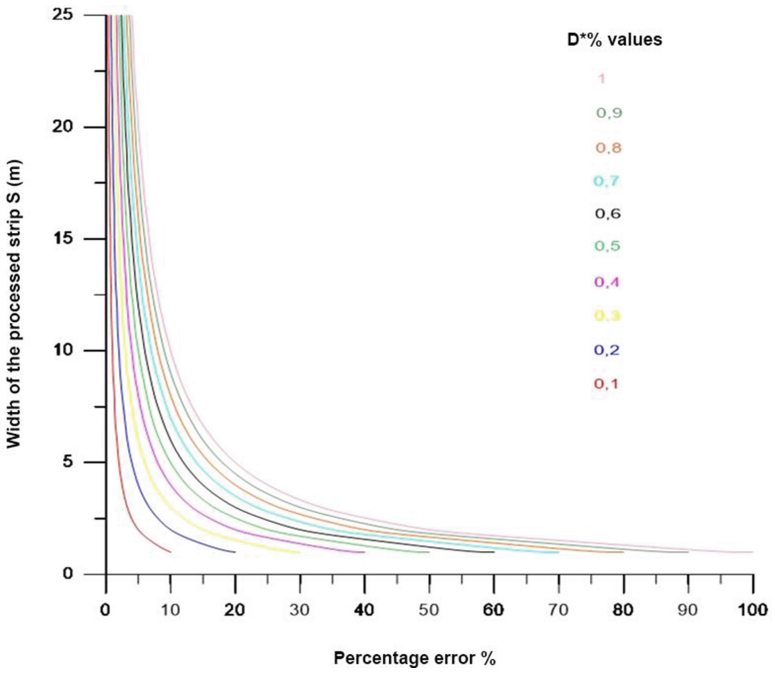

Fig. 13. Graph for the ID evaluation

The ID percentage value can be estimated according to the width *S* of the processed strip and the *D*%* value that can be assumed in relation to the guidance system adopted.

This graph shows how much the width of the field strip varying the D*% parameter can influence the process efficiency in terms of error percentage, so as to be able to determine the increase or the reduction of costs and times for the process.

To use this graph and define the cost reduction, by switching from one driving mode to another one, it is first necessary to estimate D*% value in manual and automatic guidance for a certain process and the strip width S. Entering the graph with S and D*%, the error area percentage is determined.

Two examples of the use of the graph in Fig. 13 follow. For a width of S = 5 m:

- in manual guidance (D* = 0.2), area percentage error 4% (m)
- in automatic guidance (D* = 0.1), area percentage error 2% (m)

For a width of S = 20 m:

- in manual guidance (D* = 0.2), area percentage error 1% (m)
- in automatic guidance (D* = 0.1), area percentage error 0.5% (m)

From the cost of the product supplied (fertilizer, treatment, …) per unit area, it is possible to evaluate the savings due to automatic guidance. For a width of 5 m and a parcel of 100 ha, considering a hypothetical product cost of 400 €/ha, in manual guidance the extra costs are equal to 16 €/ha for a total of 1,600 €; with automatic guidance these values are halved, so there would be a saving of 800 € for this single process.

6.1 Code Correction (DGNSS) and EGNOS

In order to evaluate the efficiency of the guidance systems, the code correction modes (DGNSS - EGNOS) were also tested. The results are summarized in Fig. 14, expressed in terms of D*% parameter as defined in the previous chapter. It can be noticed that with assisted guidance, the code correction from GPSUMBRIA network (DGPS) provided a mean deviation parameter of about 0.50; with the same guidance mode, the code correction from the EGNOS [12] gave a slightly better result, with an average D*% of about 0.35. As expected, phase corrections produce better results than code ones, and confirm as the most suitable approach for obtaining good results, especially with automatic guidance system.

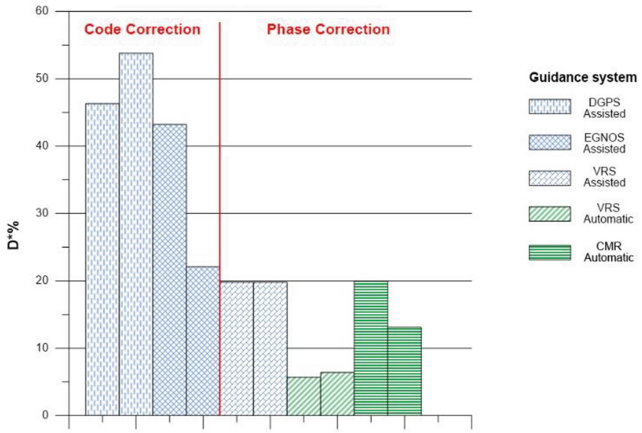

Fig. 14. Graph of mean deviation D*% for different correction mode

7 Final Remarks

The results obtained from this research have highlighted many aspects of the GNSS techniques application in precision agriculture and are encouraging: the advantages of the adoption of these techniques appeared clearly. GNSS NRTK technology based on real-time corrections and applied to agricultural equipment brings significant benefits under several points of view.

The use of network corrections compared to the base/rover ones shows remarkable advantages in terms of accuracy, greater reliability and stability as well as the possibility

of covering a large territory operating in a global reference system. The analyses carried out on different driving modes show how the automatic mode reduces the D *% parameter of about 50% with respect to manual guidance; automatic guide is more precise and it is preferred by the operators, since less stressful.

A study was later carried out to evaluate the theoretical error area percentage based on S and D *% parameter in order to provide a tool to early analyse how much one driving mode is more efficient than another one. The tables and graphs developed show that as the width of the processed strip increases, there is an asymptotic reduction in the theoretical errors area percentage. On the contrary for reduced processed strip widths, the difference between the percentage error area of a manual guidance and the automatic one is much greater. The error area percentage therefore decreases as the width of the processed strip increases, reaching error percentage values between the various driving modes that are always less wide.

The accuracies achievable in assisted and automatic driving modes were assessed through the application of different types of real-time signal correction. Tests on code correction (DGPS, EGNOS) show a lower accuracy compared to the one achievable with phase correction. The VRS real-time correction gave the best accuracy results with both the assisted and automatic guidance.

Precision agriculture has a dual positive impact: on the economic-managerial front, which mostly concerns the agricultural entrepreneur, and on the environmental one, which affects the whole community.

The economic benefits derive from a general optimization of the agricultural procedures and from a better use of the agricultural areas and equipment, with a reduction of the associated costs. In addition to the economic aspect, the use of variable intensity agricultural procedures contributes to an intuitive and rational use of chemical products and to a bigger efficiency in the water resources use, with a greater reduction in environmental impacts.

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