Sveučilište u Rijeci
POMORSKI FAKULTET
FACULTY OF MARITIME STUDIES
University of Rijeka

University of Zagreb
Faculty of Transport
and Traffic Sciences

Royal Institute of Navigation
Science Technology Practice

Under the High Auspicies of
The European Academy
of Sciences and Arts

12th
Annual
Baška GNSS
Conference

GNSS PRECISE POINT POSITIONING FOR AUTONOMOUS ROBOT NAVIGATION IN GREEN-HOUSE ENVIRONMENT FOR INTEGRATED PEST MONITORING

Michael Pattinson[1], Smita Tiwari[1], Yuheng Zheng[1], María Campo-Cossio[2], Raúl Arnau[2], David Obregón[2], Ander Ansuategui[3], Carlos Tubio[3], Iker Lluvia[3], Oscar Rey[4], Jeroen Verschoore[5], Libor Lenza[6], Joaquin Reyes[7]

[1] Nottingham Scientific Limited, Nottingham, United Kingdom
e-mail: michael.pattinson@nsl.eu.com (Corresponding author)

[2] Centro Tecnológico CTC, Santander, Spain

[3] Fundación Tekniker, Eibar, Spain

[4] Inkoa Sistemas, Erandio, Spain

[5] Aerovision BV, Amersfoort, Netherlands

[6] Mendelova Univerzita v Brně, Brno, Czech Republic

[7] European GNSS Agency (GSA), Prague, Czech Republic

Abstract

GreenPatrol robot is an autonomous robotic solution for early detection and control of pests in greenhouses. The importance of robot precise positioning inside the greenhouse is a key aspect to endow the robot with the ability to scout the environment, precisely register the detected pest location into accurate maps and to allow the later treatment. Greenhouses are a challenging environment in terms of multipath and signal blockage due to its metal-reinforced complex structures of glass or polycarbonate. GreenPatrol *robot localization takes advantage of the higher accuracy and the multiple signal frequencies provided by the European Global Navigation Satellite System (EGNSS) of the Galileo constellation (E5Alt BOC), by means of precise positioning techniques combined with inertial measurement sensors, odometry and maps to provide an accurate global localization mechanism. This paper shows the results of a comparative analysis carried out in a Greenhouse environment in order to evaluate the performance of different processing techniques such as Precise Point Positioning (PPP) and Post Processed Kinematic (PPK). The purpose of this analysis is to study the advantages of the use of Galileo new signals and to determine the best global localization solution for the GreenPatrol robot. The results experimentally show that the use of PPP Galileo E5 AltBOC signal in a multi-constellation solution offers better signal quality and better positioning performance for the intended environment.*

Keywords: *GNSS, Precise Point Positioning, Precision Farming, Integrated Pest Monitoring*

1. INTRODUCTION

Timely pest detection in agriculture increases the quantity of crop production and reduces the use of pesticides. Nowadays there are several automatic Integrated Pest Management (IPM) tools and techniques available (Ueka and Arima, 2015); nevertheless, there is no automatic method using robotic platforms for early and online pest detection in greenhouse crops.

There are different conventional ways to detect pests on crops. Eye observation methods have been extensively used until recent years, but they are not efficient in large crops. Automatic inspection by computer vision has become very common since it reduces the burden of repetitive tasks, improves the accuracy and leads to a productivity increase.

With this aim, the main objective of the GreenPatrol project is to design and develop an innovative and efficient robotic solution for IPM in crops, which has the ability to navigate inside greenhouses while performing pest detection and control tasks in an autonomous way. GreenPatrol navigation capability is enabled by EGNSS new signals and the implementation of sensor fusion techniques.

The additional use of external sensors can provide very precise measurements with good short-term stability that is not affected by external interference, multipath or obstructions. It can be an effective measure to help overcome some of the limitations of GNSS in urban areas:

- The additional sensors provide an independent measure of change in state – not affected by same errors as GNSS – so can be used to help detect problems with GNSS (fault detection, cycle slips),
- Once initialized, the additional sensors can provide a solution even when GNSS is not available (increase availability),
- Additional sensors can be combined with GNSS to improve accuracy and give greater confidence in results.

The goal is to get timely, accurate (in terms of pest detection but also in the location of the infested plants) and reliable scouting records in a cost-effective way to allow growers to exploit the IPM associated benefits.

To reach this goal, GreenPatrol relies on *1)* Robot precise positioning solution able to operate in the intended challenging environment, providing accurate and detailed pest maps for decision making about precise case-specific treatment, *2)* Integration of Galileo's new signals and modulation in light indoor environment, *3)* Perception with visual sensing for on-line pest detection, including reasoning mechanisms for efficient action selection and *4)* Control strategies for manipulation and motion planning based on pest monitoring system feedback.

The use of Galileo's new signal and modulation is a fundamental building brick in the development of the GreenPatrol solution as it provides the mechanism (i.e. new signals and modulations providing better performance) to cope with the inherent sources of error present in light indoor scenarios (multipath, signal blockage, etc.).

2. AUTONOMOUS NAVIGATION OF MOBILE ROBOTS IN AGRICULTURAL ENVIRONMENT

The problem of autonomous navigation of mobile robots is divided into three main areas: localization, mapping and path planning. Localization is the process of determining where a mobile robot is located with respect to its environment. Mapping integrates the partial observations of the surroundings into a single consistent model and path planning determines the best route in the map to navigate through the environment. Initially, these areas were studied separately, but they are closely dependent. In order to build a realistic map of the environment the robot must know its position and orientation all along, and to localize itself inside the environment, the robot needs an accurate map. This problem is known as Simultaneous Localization And Mapping (SLAM) (Berns and Puttkamer, 2009).

The solution to the localization, mapping and path planning of mobile robots strongly depends on the information that is available on the state of the robot and the environment. Many types of sensors have been used with this aim (inertial sensors, odometry, SONAR, LIDAR, etc.).

According to the source of the input data given, many popular SLAM implementations use laser range information as input to simplify the estimation process to a pure localization and registration since laser range finders estimate the 3D locations of the imaged points directly. Information about the current orientation changes relative to a previous estimate can be calculated from the encoder information in the odometry on the robot until a localization update becomes available again. The situation changes considerably with the introduction of a robot designed to operate in off-road environments where it can bounce from the ground and tilt in an unexpected way making any estimates of the odometry information nearly useless. As a consequence, an inertial system becomes necessary to deal with these alterations in the robot's movement since it provides a six degree-of-freedom motion sensing. However, these systems measure the velocities and accelerations directly so that the data has to be processed to obtain an absolute position and orientation, i.e. pose of the mobile platform. This estimation is susceptible to errors due to offsets and noise in the measurements, so an external system of localization should give accurate information for this purpose.

Autonomous navigation in an agricultural environment is a difficult task due to the inherent uncertainty in the environment where shapes, sizes and colors of plants, light intensity and overall surroundings vary. As a result, it's complicating to maintain a realistic and updated map with which a visual-based system can perform an efficient matching. For this reason, GreenPatrol proposes to use a method resistant to those limitations based on a combination of robot localization techniques with global positioning sources of information, such us global navigation satellite systems (GNSS). The fact that it calculates the pose based on the signals received from satellites makes the GNSS a good choice for the system localization as it is independent of the limitations of the environment.

3. GNSS POSITIONING

***3.1** GNSS techniques*. The main types of solution that have been analyzed for the experimentation in this paper include GNSS: Single point code solution, GNSS Post Processed Kinematic (PPK) and GNSS Precise Point Positioning (PPP).

3.1.1 Single point code solution. A single point code solution is robust and easy to compute but suffers from several limitations. Firstly, this code (or pseudorange) measurements suffer from noise and other errors that limit the performance and mean that the precision of the position solutions is ~1-2 m at best. This is fine for many types of applications but would not be good enough for the navigation of the robotic platform and geo-referencing of photographs or treatments.

3.1.2 Real Time Kinematic (RTK)/Post Process Kinematic (PPK). RTK has been used extensively over the years and can provide the positioning of high precision and accuracy (a few cms) with rapid convergence in both real-time (RTK) and post processing (PPK) mode. Basically, the main difference between the RTK and PPK is the mode in which the correcting takes place. RTK corrects in real time while PPK correct in post processing. However, it has two main drawbacks (Guo *et al.*, 2018). The first is the need for a dedicated base station, which means that either the user needs to set-up their own local base station (which can increase equipment costs) or else make use of existing reference stations that provide real-time corrections (either for a single reference station or using a network Virtual Reference Station VRS approach), although this incurs a service charge. Additionally, there is performance degradation with the distance between base station and users, and so if there are no nearby reference stations or the application covers a wide area then the performance of RTK is limited.

3.1.3 Precise Point Positioning (PPP). PPP is an efficient positioning technique that uses the undifferenced pseudorange and carrier phase measurements from a single (multi frequency) receiver, together with the precise orbit and clock corrections and the application of additional error models (earth tides, satellite phase wind-up, etc.), in order to compute a precise solution. This removes the need for a local reference station and means that PPP is applicable anywhere in the world as the accuracy is not dependent on the distance from a reference station. In addition, the user position can be computed directly in a global reference frame rather than positioning relative to a single reference station. However, PPP relies on external correction products (i.e. precise orbit and clock products) in order to get the best performance.

***3.2** GNSS constellations*. Different combinations of constellations and signals are also compared in this paper for GNSS processing: The United State GPS, Russian Glonass and the European Galileo. The potential advantage for a user of combining satellites from different constellations is that it increases the number of measurements available, which can be critical in situations where there may be blockages or interruptions to the signal (like inside a greenhouse). Using multiple frequency measurements allows more accurate positioning, as the combination of two frequencies can remove errors caused by ionospheric refraction of the signals.

***3.3** Galileo new features in the light indoor environment.* GNSS positioning techniques provide real-time measurements that can be used in some scenarios as the primary sensor in agricultural robot navigation systems (Perez and Upadhyaya, 2012). However, in covered areas such as orchards or greenhouses, satellite signal occlusion and multiple reflections may degrade the solution. The effects of strong multipath and signal blockage, typical in greenhouses due to its metal-reinforced complex structures of polycarbonate and glass, can be alleviated by using the Galileo E5 broadband signal. This signal includes a new modulation scheme with higher power and better tracking performance, AltBOC, that can drastically reduce noise and multipath effects leading to a more robust and reliable precise positioning solution when the robotic system is operating under adverse conditions (Shivaramaiah and Dempster, 2009, Toho *et al.*, 2012).

4. TEST SCENARIO IN GREENHOUSE ENVIRONMENT

A greenhouse scenario usually consists of a metal structure with partially dielectric coverage that can cause signal attenuation, blockage, multiple reflections, etc. that can drastically hinder the navigation solution. Moreover, some crops are vertically grown (such as tomatoes) reaching more than 2 meters high which cause many times signal occlusion in the narrow corridors.

Figure 1. Greenhouse location and roof detail

The test scenario for this paper is a group of greenhouses located in Lezama, Bizkaia (Spain) on a flat zone limited by two mountains lines at coordinate 43°17'12.2" N 2°50'01.0" W. Tests were performed in an aluminum and glass building with rectangular shape and gabled roof where the plants grow in rows perpendiculars to the longest side.

5. EXPERIMENTAL SETUP

5.1 *GreenPatrol robot.* The robot platform used for the GreenPatrol solution is a Segway® Flex OMNI, a true holonomic mobile robot platform ideal for use in an environment with limited space that requires precise mobility and handling. Its four mecanum wheels allow it to move in any direction without needing to turn – and it can turn in place just as easily as it can drive sideways.

The platform carries wheel encoders and an Inertial Measurement Unit (IMU), whose data are combined to get an improved odometry estimation. It also has a Velodyne VLP-16 LiDAR, a Real-time, 3D distance and calibrated reflectivity measurements sensor. It has a 360° horizontal field of view and a 30° vertical field of view, with +/- 15° up and down.

Figure 2. GreenPatrol test robot

5.2 *Sensors.* Apart from the available sensors in the platform (INS and odometry), a high-grade Galileo-capable GNSS receiver and antenna have been selected for this test and mounted onboard the robot. It provides the core data for post-processing and assessment of different types of GNSS solution. This multi-frequency multi constellation GNSS receiver has the following features: GPS: L1, L2, L5, GLONASS: L1, L2, L3, Galileo: E1, E5a, E5b, E5ab (AltBOC), BeiDou: B1, B2, SBAS: EGNOS, WAAS, GAGAN, MSAS, SDCM (L1, L5), QZSS: L1, L2, L5, L6.

As well as the equipment of the robotic platform, a local GNSS reference receiver was installed during the data collection campaign. This receiver was installed in an open sky area to provide measurements for a short-baseline kinematic solution for comparison with other techniques.

5.3 *External data providers.* In addition to the sensor data from the robotic platform, some additional external data is required in order to generate all the required post-processing solutions.

For the static data performance assessment, a reference position is required for the points in order to be able to compute errors and generate statistics. For the outdoor location this is achieved by providing the RINEX data to the NRCan website where there is a service to process the data and provides an estimated accurate position. Also, to compute a Precise Point Positioning (PPP) solution, high quality satellite orbit and clock products are required. For this data collection and post-processing, it is sufficient to retrieve this data after the event[1]. In addition to precise orbit and clock correction, other products may also be useful: IONEX[2] and DCB[3].

6. STATIC TESTS

In order to understand the impact that the greenhouse has on the data quality, and ultimately on the position solution, static tests have been performed inside and outside the greenhouse. In addition, the performance of the Galileo E5 AltBOC signal compared to other signals is analyzed in this paper as it is hoped to offer improved performance in the greenhouse.

[1] ftp://cddis.gsfc.nasa.gov/gnss/products/mgex

[2] ftp://cddis.gsfc.nasa.gov/gnss/products/ionex

[3] ftp://igs.ign.fr/pub/igs/products/mgex/dcb

To assess the performance, various quality parameters, including the number of satellites tracked, cycle slip, multipath and signal to noise ratio (SNR) have been measured at GPS L1, Galileo E5a and Galileo AltBOC frequency.

The position solution at the receiver improves if there are more satellites available. In difficult environments some of these signals may be blocked, and this can affect the positioning performance. Comparing the number of satellites tracked indoors and outdoors allows us to see the impact of the greenhouse on tracking.

For PPP carrier phase measurements are the key parameter, they can be very precisely measured and hence are necessary to be used in order to get down to the performance required for robot navigation. Nevertheless, carrier phase measurements contain an unknown ambiguity term that must be solved. The success of resolving this ambiguity term relies on having continuous data, but if there are interruptions in tracking this causes a cycle slip and can make it more difficult to obtain a precise carrier phase solution. Therefore, having a low number of cycle slips is desirable. The number of cycle slips detected in the measurements inside and outside the greenhouse can help to give an idea of the difficulty and how feasible it is to use the carrier phase measurements.

Another important quality check parameter is multipath, in locations where there are reflective surfaces the GNSS signals from the satellites may be reflected. This can mean that the user antenna receives both direct and reflected signals from the satellites, and the measurements will, therefore, be contaminated by the reflected signals and contain errors. These errors will then affect positioning performance. And finally, SNR this provides a measure of how strong the satellite signal is compared to background noise and is important because a clear signal with high SNR is easier to track and less likely to be contaminated by multipath and other errors. Comparing the SNR values indoors and outdoors gives an idea of the impact of the greenhouse on the signal.

These metrics are used to compare the data from the multifrequency receiver for Test 1 (static open sky), Test 2 (static inside greenhouse).

Figure 3. Outdoor and inside greenhouse GNSS antenna locations

The following table summarizes the quality check test results.

Table 1. Quality Check Comparison

Cycle Slip			
Test Scenario\GNSS Constellation	L1 GPS	E5a Galileo	E5 AltBOCGalileo
Test 1 Outdoor Open Sky	20	5	3
Test 2 Greenhouse	4709	5	3
RMS Multipath (m)			
Test 1 Outdoor Open Sky	0.399	0.268	0.166
Test 2 Greenhouse	0.7158	0.639	0.499
Average SNR (dB)			
Test 1 Outdoor Open Sky	43.10	42.42	42.49
Test 2 Greenhouse	43.05	42.05	42.05
Average Number of Tracked Satellites			
	GPS		GALILEO
Test 1 Outdoor Open Sky	8.37		5.03
Test 2 Greenhouse	8.25		5.00

Results show that outdoors there is good satellite visibility for both GPS and Galileo. However, in indoors, the number of tracked satellites is lower but not by a large amount, indicating that the greenhouse structure does not fully block the satellite signals. This is important as it means that a positioning solution will still be possible indoors. It can be seen that in the outdoor case the average SNR for GPS L1 is slightly higher than for Galileo signals, but both are good. When moving indoors, there is some reduction in SNR for both GPS and Galileo signals, but it is not a very large reduction.

If we consider multipath, we can see that even outdoors there is a certain level of multipath error. The indoor tests show much larger levels of multipath though. This means that range errors are larger indoors and will likely affect the quality of the position solution. One interesting and encouraging point is that the Galileo signals have lower multipath errors than the GPS signals – both outdoors and indoors.

Finally, if we look at the registered number of cycle slips, the impact of the greenhouse can be appreciated, with more cycle slips in the indoor scenarios, and also shows the benefit of Galileo E5 AltBOC, with far few cycle slips reported than for GPS L1 signals.

In addition to looking at the signal quality in these static tests, the GNSS data has been processed to observe the effect of different frequencies and constellations on the position solution. NSL in-house software MSP3 has been used to produce precise point positioning (PPP). To be noted that the same RINEX data has been used to compute position using PPP, which has been used to compute the estimated accurate position. In this way we have two solutions; one which is generated by NRCan and one which is generated by NSL in house software. In order to check the accuracy of MSP3 generated PPP solution NRCAan generated position is used as a reference position.

For both the outdoor and indoor data, the position results from each epoch are compared against a reference position to compute errors and generate statistics. However, for indoor test we used the average position of the results as the reference coordinate to calculate position accuracy. This limitation means that the absolute accuracy values may not be entirely correct for the indoor tests, but the precision and convergence time results are still useful.

The following tables summarizes the position solution results (PPP and single point code) obtained from different combinations of constellations and signals. We obtain precise and orbit product from CDDIS MGEX product.

Table 2. Summary of Horizontal Position Accuracy (m) by single point code for static tests using RTKlib

Constellations	Signals	Horizontal Error Percentile							
		Test 1. Outdoor				Test 2. Greenhouse			
		50 %	68 %	95 %	99 %	50 %	68 %	95 %	99 %
GPS	L1	0.43	0.60	1.28	2.60	1.63	2.32	6.1	6.76
GPS+GAL	L1	0.41	0.55	1.14	2.34	1.82	2.58	5.57	6.29
GPS+GAL+GLO	L1	0.52	0.64	1.18	2.42	1.75	2.48	4.90	5.55

Table 3. Summary of Horizontal Position Accuracy (meters) by PPP for static tests using MSP3

Constellations	Signals	Horizontal Error Percentile							
		Test 1. Outdoor				Test 2. Greenhouse			
		50 %	68 %	95 %	99 %	50 %	68 %	95 %	99 %
GPS	L1/L2	0.15	0.17	0.22	0.23	0.69	0.79	1	1.21
GPS+GAL	L1/L2/E5a	0.05	0.06	0.11	0.13	0.31	0.38	0.56	0.56
GPS+GAL	L1/L2/E5 AltBOC	0.05	0.06	0.10	0.13	0.15	0.23	0.3	0.32
GPS+GAL+GLO	L1/L2/E5a	0.40	0.41	0.44	0.45	0.48	0.57	0.76	0.76

Statistical results show the advantages of PPP over a single point code solution. It also shows that the use of Galileo AltBOC signal not only improves the position solution by providing the 95 % accuracy of 10 cm but also shows an advantage in inside the green house.

In addition to accuracy of the solution, convergence time is also important. For the envisaged operations it is no good having a very accurate solution if it takes several hours of initialization before that best solution can be reached. It is well known that PPP solutions can take some time to converge, but the indoors performance is not something that has been widely studied. To show the convergence, the time series of position errors for each test are shown.

It appears from these results that indoors PPP solutions do converge to a stable solution in a timeframe similar to outdoors, but the positions errors are higher after convergence, i.e. the final solution is not as accurate in the greenhouse scenario.

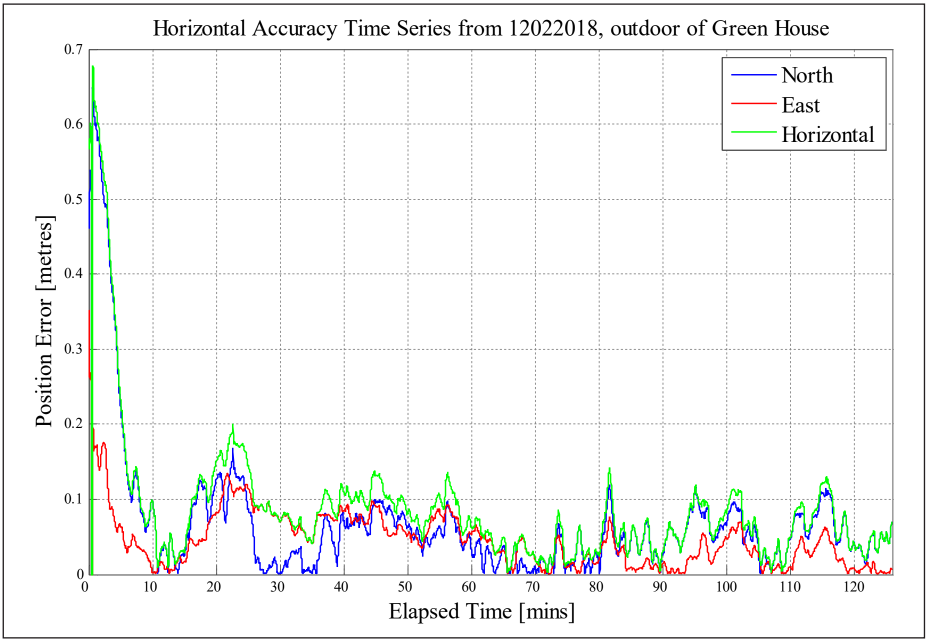

Figure 4. Horizontal accuracy produced by MSP3 using PPP, outside the greenhouse.

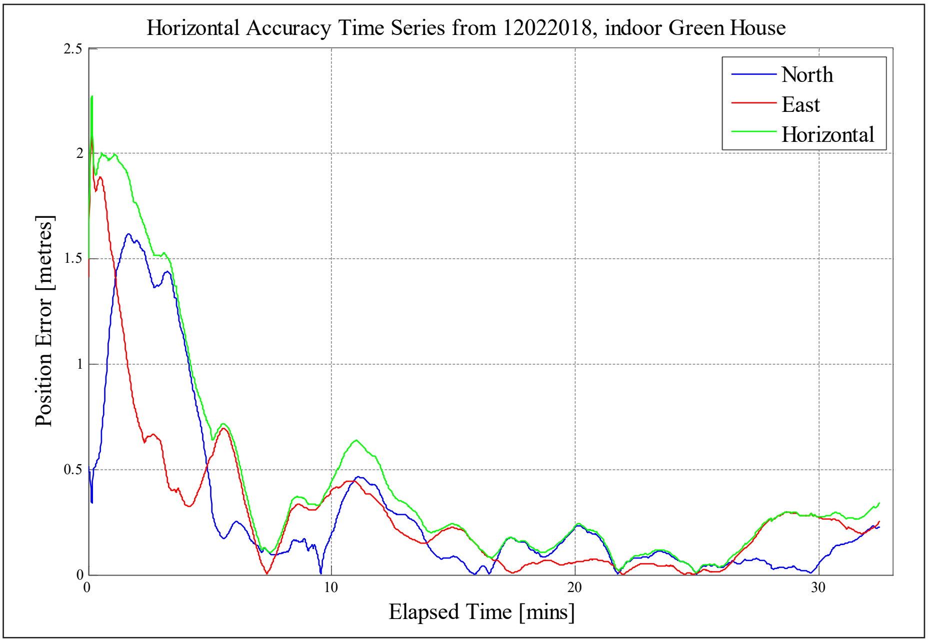

Figure 5. Horizontal accuracy produced by MSP3 using PPP, inside the greenhouse.

7. DYNAMIC INSIDE THE GREENHOUSE

For the dynamic tests, data from various sensors have been used:

- The core GNSS results are generated by processing multi-constellation, multi-frequency observations from the GNSS receiver mounted onboard the robot.
- In order to compare the PPK with PPP solution, a local base station (single frequency GNSS receiver) has been installed outside the greenhouse, with a known position. The onboard GNSS receiver is used as a rover for the PPK solution.

For this data collection no 'true' reference positions are available, and so the analysis is limited to inspection of the trajectory defined by the position solutions to see how well it describes the path of the robot during each test.

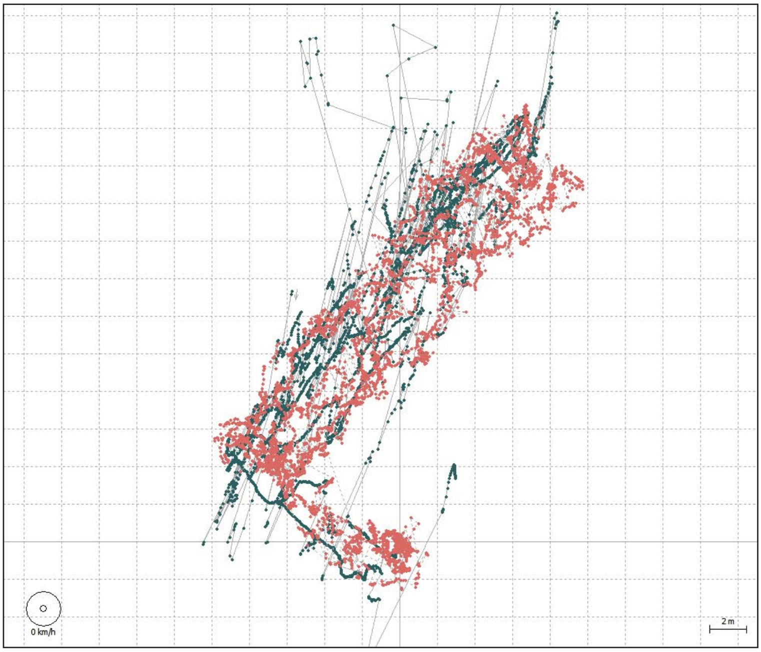

Figure 6. Scatter plot of GPS+GAL Code Solution (red) and GPS+GAL PPP (green) Solution for Test 3

In this test, the robot moved inside the green house along some of the side corridors and then returned to the start point. We can see again from the GPS+GAL code solution from RTKlib (red dots) the general movement of the robot. However, there is a lot of scattering in the results, and it cannot be deduced the exact track on which the robot moved. The RTKlib GPS+GAL L1/L2/E5a solution (blue line) again shows some smooth parts but many jumps, and it is difficult to tell from that the robot route.

For the MSP3 GPS+GAL L1/L2/E5AltBOC solution, the trajectory is much smoother, and the route down the different side corridors is clear to see.

Figure 7. Google Earth plot of GPS+GAL L1/L2/E5AltBOC PPP Solution from MSP3 for Test 3 Dynamic

In this test corresponding to test 3, the dynamic, base station is also logging GNSS data, which further use in producing position solution using PPK via RTKLib. In the following figure, the red trajectory shows the position solution produced by PPK while blue trajectory is produced by PPP solution using MSP3.

It can be seen that both solutions show a common trajectory; however, PPP solution produces a very smooth solution, while sometimes PPK solution distracts from the trajectory and shows some jump. We can clearly see the advantage of using PPP over PPK.

Figure 8. Comparison of GPS+GAL L1/L2/E5AltBOC PPP Solutions from MSP3 (Blue) to the PPK (Red) for Test 3. Dynamic

8. CONCLUSION

From these results we can make the following conclusions: Various quality parameters have been measured at GPS L1, Galileo E5a and Galileo AltBOC frequency in order to assess the impact of the greenhouse roof. The number of tracked satellites is slightly lower when moving indoors, as well as the SNR for both GPS and Galileo signals, but the greenhouse structure does not fully block the satellite signals. This means that a positioning solution is still possible indoors.

The indoor tests show much larger levels of multipath than outdoors. This means that range errors are larger indoors and will likely affect the quality of the position solution. One interesting and encouraging point is that the Galileo signals have lower multipath errors than the GPS signals, both outdoors and indoors. This is most noticeable for Galileo E5 AltBOC signals and demonstrates the advantage of this signal and the potential for using it in GreenPatrol. Tests also show the benefit of Galileo E5 AltBOC, with far few cycle slips reported than for GPS L1 signals inside the greenhouse.

Overall, therefore, we can see that, although tracking conditions are more difficult in the greenhouse, they are not insurmountable for providing a GNSS solution, and the performance of Galileo E5 AltBOC is especially encouraging as it shows the best performance indoors.

It can be seen that the Galileo E5 AltBOC signal offers clear advantages over the other signals in terms of better signal quality and better positioning performance and so the use of a receiver that can provide these measurements is highly recommended.

In terms of the type of solution, PPP has shown excellent performance outdoors, and the indoor tests (particularly the dynamic ones) are highly encouraging in terms of the performance that can be achieved. Test results confirmed that PPP also shows equivalent performance with respect to PPK. In a remote environment like Greenhouse where the possibility of nearest base station is rarer, PPP shows a significant alternative to PPK and shows better position performance.

FINANCIAL SUPPORT. The presented results have been achieved within the GREENPATROL project (http://greenpatrol-robot.eu). The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776324.

References

Berns, K. and von Puttkamer, E. (2009). *Autonomous Land Vehicles*. Wiesbaden: Vieweg Teubner.

Ebrahimi, M. A., Khoshtaghaza, M., Minaee, S. & Jamshidi, B. (2017) Vision-based pest detection based on SVM classification method. *Computers and Electronics in Agriculture*. pp. 52–58.

Guo, J., Li, X., Li, Z., Hu, L., Yang, G., Zhao, C., Fairbairn., Watson, D. and Ge, M. (2018). Multi-GNSS precise point positioning for precise agriculture. *Precision Agriculture.* 19. pp. 895–911.

Hu A. P., Thomas, S., Jennings, B. and Mcmurray, G. (2014). Development and Testing of a Low-Cost Multi-Function Robotic Arm for Agriculture. *American Society of Agricultural and Biological Engineers Annual International Meeting (ASABE 2014)*. Montreal. pp. 4565–4574.

Huddar, S. R., Gowri, S., Keerthana, K., Vasanthi, S. and Rupanagudi, S. R. (2012). Novel algorithm for segmentation and automatic identification of pests on plants using image processing. Third International Conference on Computing, Communication and Networking Technologies (ICCCNT'12), Coimbatore. pp. 1–5.

Perez-Ruiz, M. and Upadhyaya, S. K. (2012). GNSS in Precision Agricultural Operations. In: Elbahhar, F. & Rivenq, A. (eds.) *New Approach of Indoor and Outdoor Localization Systems*. London: Intech Open. pp. 3–26.

Shivaramaiah, N. and Dempster, A. (2009). The Galileo E5 AltBOC: Understanding the Signal Structure, *International Global Navigation Satellite Systems Society IGNSS Symposium*. Qld. pp. 1–13.

Titterton, D. and Weston, J. D. (2004). *Strapdown Inertial Navigation Technology*. Reston: AIAA.

Toho, H., Bock, H., Schueler, T., Junker, S. and Kiroe, A. (2012). Exploiting the Galileo E5 Wideband Signal for Improved Single-Frequency Precise Positioning, *Inside GNSS*. pp. 64–73.

Ueka, Y. and Arima, S. (2015). Development of Multi-Operation Robot for Productivity Enhancement of Intelligent Greenhouses: For Construction of Integrated Pest Management Technology for Intelligent Greenhouses. *Environmental Control in Biology*. 53(2). pp. 63–70.

Xia, C., Chon, T. S., Ren, Z. and Lee, J. M. (2015). Automatic identification and counting of small size pests in greenhouse conditions with low computational cost. *Ecological informatics*. pp. 139–146.