# Low-Cost GNSS Receivers Reliability Using Centipede RTK Network for Land Surveying

Muhammad Ali Sammuneh[a], Mojtaba Eslahi[b], Rani EL Meouche[c] and Elham Farazdaghi[d]
*Institut de Recherche en Construction (IRC), ESTP Paris, 94230 Cachan, France*

Keywords: GNSS, Land Surveying, RTK, Centipede-RTK, Low-Cost GNSS.

Abstract: The question of using low-cost Multiband Global Navigation Satellite System GNSS receivers and antennas in land surveying is real and important. In France, mainly a collaborative Real Time Kinematic (RTK) network called Centipede covers the country providing the corrections open access in real time to the users. Furthermore, the low-cost interface application and software called SW Maps connect the Low-cost GNSS receiver to the Centipede-RTK network using a smartphone. The cost of surveying projects using all these elements is certainly economical. The main question here is the reliability of this package to perform continuous, stable, and reliable RTK land surveying. We test this capability by examining the differences in the RTK position of known control points with a series of measurements over different mount points. The results show that we can use this package for land surveying only with necessary validation and control by experimental users, as the indicators of Centipede RTK accuracy via the SW Maps interface are not representative.

## 1 INTRODUCTION

Low GNSS cost concept is attractive economically and it can offer an alternative to accomplish some kinds of engineering projects. Nevertheless, the main question is to examine the reliability of this package (Low-cost dual frequency receiver, low-cost antenna, open access Centipede-RTK network in France and free Android GIS application SW Maps on smartphone) to achieve land surveying in RTK in a continues, stable and reliable way. We explore this possibility by examining the differences in RTK position of known control points with a series of measurements over different mount points.

We start with the necessary definitions of technical terms and their abbreviations to ensure a good understanding of this work. A GNSS, or Global Navigation Satellite System, is a generic name for a group of artificial satellites consisting mainly of constellations from the United States (GPS), Russia (GLONASS), Europe (Galileo), and the China (Beidou) that transmit position and timing data from their high orbits (Teunissen and Montenbruck, 2017). NTRIP (Network and Transport of RTCM via Internet Protocol) is a protocol for transmitting Real Time Kinematic (RTK) corrections over the Internet to Global Navigation Satellite System (GNSS) receivers. RTK, on the other hand is a technique for improving the accuracy of GNSS positioning using information from (GNSS-RTK base or a mount point) a fixed reference station whose position is well known (GNSS Science Support Centre fosters collaboration across scientific communities through the provision of GNSS science-based products and services., 2021). Typical nominal accuracy for RTK systems is 1 cm horizontally and 2 cm vertically (Seeber, 2003).

Centipede RTK is a network of shared, open-access GNSS RTK bases. The Centipede project aims to create a network of open RTK bases available to anyone in the coverage area. Public institutions, individuals, and private stakeholders (farmers or other public partners) extend the network. The objective of the project is to provide complete coverage of the metropolitan area. The French public research institute working for the coherent and sustainable development of agriculture, food and the

[a] https://orcid.org/0009-0008-4977-7386
[b] https://orcid.org/0000-0001-5005-1867
[c] https://orcid.org/0000-0001-5063-6638
[d] https://orcid.org/0000-0001-9935-1553



Sammuneh, M. A., Eslahi, M., El Meouche, R. and Farazdaghi, E.
Low-Cost GNSS Receivers Reliability Using Centipede RTK Network for Land Surveying.
DOI: 10.5220/0013444800003935

In *Proceedings of the 11th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2025)*, pages 211-218
ISBN: 978-989-758-741-2; ISSN: 2184-500X

environment (INRAE) (“INRAE: research for Agriculture, Food and Environment,” n.d.), financially supports the project and since its launch in 2019, it has benefited from shared resources between research institutes, public bodies, farmers, and private companies (“Le Reseau Centipede RTK,” n.d.). SW Maps is a free Android GIS and mobile mapping application for collecting, presenting, and sharing geographic information (“SW Maps - GIS & Data Collector – Applications - Google Play,” n.d.). It allows users to perform high-precision GPS surveys using external RTK-compatible Bluetooth or USB serial receivers. It can be used with low-cost GNSS receivers and requires a USB-C male to USB-A male cable to work with an Android phone.

The current research presents studies on low-cost receivers and antennas that address their accuracy or stability. In addition, publications related to the Centipede collaborative network discuss the accuracy of this network using high-quality geodetic GNSS receivers and antennas. Nowadays several researches have been done on low-cost GNSS. In fact, we recently have access to low-cost GNSS receivers and low-cost antennas (LCRA). In addition, free smartphone applications serve as an interface to connect LCRA to the Centipede mount point (Sammuneh et al., 2023). We found it interesting to explore the possibility of securing land surveying in an economical and trustworthy manner. Our work differs from others in that we gather all the low-cost concepts and tools (receivers, antennas, correction network, interface, and software); and tried to answer this simple question: Could we trust the RTK results of LCRA within the Centipede network for reliable land surveying ?

There is an increasing number of studies on the accuracy of low-cost GNSS receivers and dual-frequency receivers (Jackson et al., 2018). A recent review, found that “Low-cost GNSS receivers generally exhibit lower observation quality compared to geodetic GNSS receivers in both open sky and urban conditions” and “Sub-centimeter accuracy can be achieved in the static relative method while a few centimeter accuracy is possible in RTK when open sky conditions are guaranteed (Stopar et al., 2024). However, for longer baselines and areas with obstructed views of the sky, low-cost GNSS receivers still can’t achieve the same positioning quality as geodetic GNSS receivers”. Studies on the performance of low-cost dual-frequency GNSS receivers and antennas for surveying in urban areas are the main subject of recent research (Hamza et al., 2023, 2021b, 2021a, 2020). There are many studies on the accuracy of RTK using LCRA in different scenarios, including open-sky environments. (Bellone et al., 2016; Broekman and Gräbe, 2021; Cina and Piras, 2015). Semler et al. (2019) showed that 1 cm spatial accuracy is possible in open sky conditions using LCRA (Semler et al., 2019). Other researches discuss the limits of baseline distances, giving a limit of up to 20 km for short baselines, since beyond this distance the quality of positioning deteriorates due to ionospheric distortion (Caldera et al., 2016; Tsakiri et al., 2017). Moreover, when testing the kinematic performance of RTK in a non-urban area with a long baseline of about 30 km, the RTK solutions showed good concordance with the post-processed data, with less than 5% of the differences exceeding 3 cm in the planimetric component and 10 cm in the vertical component (Sanna et al., 2022).

However, Centipede is a network of mount points, each of which sends its own RTK corrections to the user but it is not NRTK. The Centipede website states that “This technology can be used, for example, to carry out naturalistic surveys (flora, fauna) with a high degree of localization accuracy, to carry out aerial photographic surveys (using drones) and to automate the driving of agricultural vehicles” (“Le Reseau Centipede RTK,” n.d.).

Thus, now the Centipede RTK databases are archived in RINEX (Receiver Independent Exchange Format) in the RENAG databases, which is a serious guarantee of durability for the network's data. Conversely, the Centipede databases are used for RENAG's daily analyses (“Le Reseau Centipede RTK,” n.d.).

## 2 MATERIALS AND METHODS

In our project, we use the Leica GNSS receivers & antenna, u-blox dual-frequency GNSS chip ZED-F9P Survey GNSS low-cost receiver (“ZED-F9P module,” 2023) and Calibrated Survey GNSS Multiband antenna (IP67) (“Calibrated Survey GNSS Tripleband + L-band antenna (IP67),” n.d.), SW maps android application, and smartphone. We use the GNSS calculations online service network of the IGN website to manage the Rinex files and to calculate control points coordinate (“Calculs GNSS Réseau en ligne | RGP,” n.d.). The centipede website is used to show the actual situation of the mount points.

In our case, we used two main modes:
Static mode: Relative positioning to the phase in deferred time. The precision is of the order of

centimetres or even millimetres for high-quality receivers (Teunissen and Montenbruck, 2017).
RTK mode: Relative phase positioning in real-time. The precision is of the order of 5 cm. The data is sent via internet (Teunissen and Montenbruck, 2017).

The method of this study aims to have serial estimations of the coordinates of well-known Control points in RTK based on different mounting points going from the nearest one to 60 km distance. We start by using static mode with 3 hours of GNSS observation using a high quality receiver and antenna to generate a RINEX observation file with 30-sec frequencies. We then wait for 2 weeks to obtain the precise orbit file to calculate the final coordinates of the reference point REF1 ("Calculs GNSS Réseau en ligne | RGP," n.d.). Once the REF1 coordinates are fixed, we start using a Low-cost GNSS receiver and antenna to connect to the Centipede network via smartphone using the SW maps application. We start by creating a GIS project in SW Maps and allow only RTK fix quality features to be stored.

We examine the possibility of connecting the Centipede mount points and getting RTK fix quality from them by recording 3-4 minutes of RTK observations, with 5 seconds frequency for each mount point, within 60 km distance from our reference point. Then we collect the data related to each functional mount point within 30 minutes and 5 seconds frequency .After analysis, we focus on three mount points for the next data collection for one day with ten series of 30 minutes and 5 seconds frequency for each one of the three mount points to investigate their continuity, stability, and reliability. We examine three levels of planimetric accuracy, less than 5 cm, from 5 to 10 cm, and over 10 cm.

# 3 LOW-COST RELIABLE GNSS RECEIVERS DUE TO THE CENTIPEDE RTK NETWORK

## 3.1 Reference Point

We choose a reference point with an open sky view to make our measurements using (the signal) GNSS constellations without multipath effects. We call this point "REF1". We collect the observations using a LEICA GS10 dual frequency receiver and LEIAS10 Leica antenna ("Leica Viva GS10 et GS25 – Récepteurs GNSS de haute précision," n.d.). The measurements are made in static mode with 30 seconds frequency for 3 hours to generate the RINEX file of REF1. We use the IGN online site calculation service to obtain the final position coordinates ("Calculs GNSS Réseau en ligne | RGP," n.d.). The calculations use Bernese GNSS software. It calculates vectors from 12 permanent GNSS stations (RGP) and REF1, using the precise orbits to determine the final coordinates of REF1. The estimated accuracy given by the calculation report is (North: 9 mm, East: 10 mm, Height: 23 mm), with final coordinates in UTM 31 N (E = 450714.314 m, N = 5404846.437 m).

## 3.2 Centipede Mount Points

In this section, we will mainly use the U-blox dual-frequency GNSS chip ZED-F9P Survey GNSS low-cost receiver & Calibrated Survey GNSS Multiband antenna connected to a smartphone by SW Map Android GIS application. In this part, we will discuss the possibility of contacting the mounting points of Centipede via the application within 60 km distance from the reference station REF1 to verify the *connectivity* and to ensure a fixed ambiguity solution (RTK Fixed). Then we will examine the *stability* of the observations for each mount point by observing the differences in behaviour over time (changes). Finally, we will concentrate on three stable mount points to test the accuracy for ten sets of measurements covering 6 hours of RTK observation to ensure the *reliability* of the mount station's diffused corrections.

### 3.2.1 Connectivity

The Centipede network covers the French territories but there are some gaps. For the practical use of this network and as we aim to propose a strategy, we will examine the connectivity and the differences in the plan components for near and far points within the limit of 60 km. The connection is made through the NTRIP settings in SW-Maps, and then we can indicate the type of solution (DGPS or RTK Fix), PDOP, HDOP, VDOP, satellite in view, satellite in use, the horizontal and vertical accuracy. However, the accuracy is given in meters. This does not help to ensure the user the accuracy needed for his work in land surveying. We are looking for an indicator that shows the level of accuracy in cm. However, we will verify in section 3.2.4, whether this indicator change has any impact on the results.

As mentioned in Table 1, we have mainly 14 mount points and we found that 12 mount points can be contacted giving RTK Fix solution except the GRIG mount point which gave DGPS RTK solution and is discarded from the test set. Table 1. 14 Centipede-RTK network mount points within 60 km of the reference point.

Table 1: 14 Centipede-RTK network mount points within 60 km of the reference point.

| Mount Point | Distance from Reference Point (KM) | Connectivity ǀ RTK Fixed solution |
|---|---|---|
| RICE | 8 | Yes ǀ Yes |
| STME | 9 | No |
| OUIL | 19 | Yes ǀ Yes |
| ENSG | 20 | Yes ǀ Yes |
| ENSG2 | 20 | Yes ǀ Yes |
| LAUR | 20 | Yes ǀ Yes |
| LNE1 | 25 | No |
| CDFX | 28 | Yes ǀ Yes |
| HBC77 | 40 | Yes ǀ Yes |
| GRIG | 41 | Yes ǀ No |
| BARB | 48 | Yes ǀ Yes |
| COND | 49 | Yes ǀ Yes |
| SGC | 51 | Yes ǀ Yes |
| GPTR | 60 | Yes ǀ Yes |

### 3.2.2 Planimetric Differences

In this work, we will focus only on horizontal or planimetric results. To estimate the accuracy of the measurements, we assume that the coordinates of reference REF1 are accurate and precise. Therefore, the 2D horizontal or planimetric differences $dP$ are considered as the accuracy levels to be discussed. It is given by difference of the components east $dE$ and north $dN$ of the observed coordinates $Obs(E, N, U)$ from the reference point $Ref(E, N, U)$:

$$dE = E_{Ref} - E_{Obs} \quad (1)$$

$$dN = N_{Ref} - N_{Obs} \quad (2)$$

$$dP = \sqrt{dE^2 + dN^2} \quad (3)$$

We keep the term difference when talking about accuracy because it is more representative in our case with only one reference point. As Figure 1 shows, the 2D planimetric differences give an idea of the connectivity of the mount points, but also alert the results concerning the OUIL station for example. We expect the distant mount points to give high differences like COND-50KM which gives for some observations a 2D difference level of 20 cm. The OUIL station is 19 km away from our reference point and it shows a steady level of 15 cm 2D planimetric differences that exceed all the other mount points within 60 KM of distance. Mount points show except (OUIL and COND) in Figure 1, 2D planimetric differences reaching a maximum level of 7 cm for the RTK fix solution.

We see that for some mount points the behaviour is not stable giving a 5 cm level of difference and suddenly jumping to a 20 cm level COND-50 KM while. BARB-48 KM gives differences less than 5 cm level, but it changes for every 5 sec observation. Therefore, we need to verify the stability of the 2D planimetric differences with time for these eleven mount points over a longer observation period. It is quite interesting that the mount stations @50km and @60km show differences of about 5 to 7 cm. Nevertheless, our sets of measurements in this section are intended to verify the connectivity.

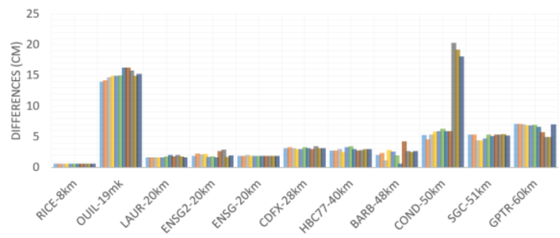


Figure 1: The difference in 2D Planimetric coordinates of 11 mount points of Centipede Network within one minute per station with 5 seconds frequency.

### 3.2.3 Stability

We collect observations for each mount point within five minutes with a five-second frequency. This choice is made to collect data within the period that the satellite configuration is likely to gives the same positioning dilution of the precision PDOP for each data set, and to preserve the same metrology conditions for the troposphere and ionosphere. Figure 2 shows the difference in 2D planimetric coordinates of 11 mount points of Centipede Network within five minutes per station with 5 seconds frequency.

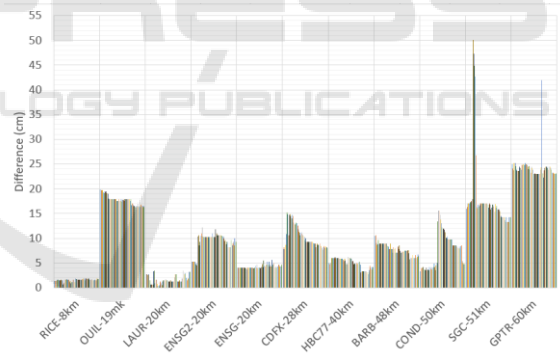


Figure 2: Difference in 2D Planimetric coordinates of 11 mount points of Centipede Network within five minutes per station with 5 seconds frequency.

The poor accuracy of the OUIL mount point is again shown and it means that the corrections sent by this point are not good enough to be used for 2D topographic surveying with a 5 cm accuracy level. This confirms our suspicion about Centipede mount points and the need to verify their reliability before any surveying. Still talking about OUIL, the changes go from 20 to 16 cm which means that the rate of change is 4 cm within five minutes. Another interesting result comes from a distance of 20 km between two mount points on the same building, ENSG (Ecole national des sciences geographies), called ENSG and ENSG2. The first provides a level of 4 cm difference while ENSG2 indicates 10 cm.

Therefore, one should use the first mount point rather than the second if they have the same distance from our reference point. The indicators in the SW-Maps interface are the same for both mount points. Beyond 20 km distance, the differences are quite above 5 cm level. HBC77@40km distance shows some exceptions to be below 5 cm level for some times. Remembering the results in (Sanna et al., 2022) about the performance of RTK in a non-urban area with a long baseline of about 30 km, the RTK solutions have shown a good concordance with post-processed data, with less than 5% of differences surpassing 3 cm in the planimetric component. Meanwhile, the BARB@48km mount point has a 6-10 cm level. COND@50km has quite troubling behaviour by giving less than a 5 cm level for the first two minutes and then suddenly it reaches a 15 cm level of difference. The difference then decreases slightly over time, but remains above the 5 cm level.

Therefore, the stability of this mount point again shows its chaotic behaviour. SEG@51km has more than a 15 cm difference level and sometimes some pics reach 50 cm. GPTR@60km has a stable 20 cm level of difference with one pic reaching 40 cm. In (Caldera et al., 2016; Tsakiri et al., 2017) a limit of 20 km for short baselines is given because more than this distance, the quality of positioning deteriorates due to the ionospheric bias. We focus on three mount points stations RICE@8km, LAUR@20km, and ENSG@20 km. As Figure 3 illustrates ENSG@20km has a mainly 5 cm level of difference within five minutes. RICE@8km is better than the 2 cm level, however, LAUR@20km is still below than the 3.5 cm level but with fluctuating behaviour.

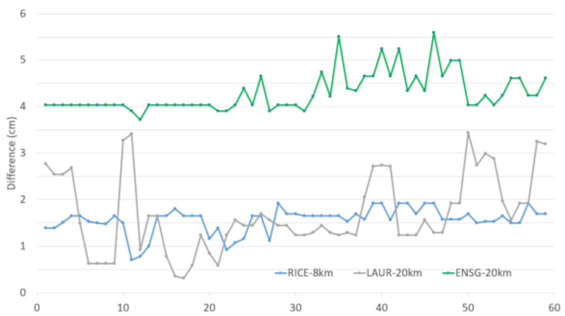


Figure 3: Difference in 2D Planimetric coordinates of three mount points of Centipede Network within five minutes per station with 5 seconds frequency.

### 3.2.4 Reliability

We need to extend the research for one day to study the behaviour of these three “short baselines” over time. We have ten sets of observations for each mount point. The observations are 5 minutes for RICE and then 5 minutes for LAURE and finally 5 minutes for ENSG within a 20 minute time span. We wait 20-30 minutes to restart the observations of the next set. We will consider nine sets to show the behaviour of the LAUR@20km mount point. Figure 4 shows sub-ten-centimeter level differences of all LAUR mount point sets. We can distinguish four sets with differences below the 5 cm level (3, 5, 6, and 8). The RTK measurements are for 5 minutes with 5 seconds frequency, which means that for these four sets the surveying work reaches the required level of 5 cm maximum of accuracy. Nevertheless, the other sets except set 2 go beyond the five centimeters level but below the seven centimeters level. Set 2 shows instability and the difference level reaches 10 cm.

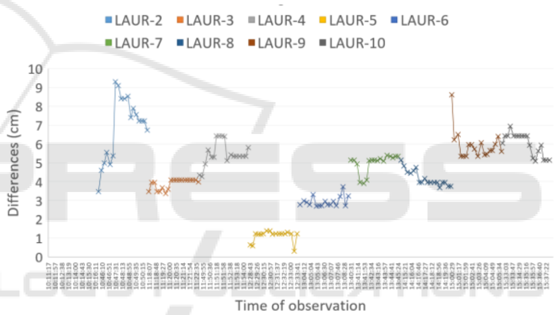


Figure 4: 2D planimetric differences of nine sets of observations based on LAUR mount point.

The LAUR mount point shows good results (<5cm) and bad results; therefore one can use it to periodically verify his measurements by comparing them with known points around his work. These conclusions of results are with 20 km distance from LAUR mount point. It is worth future research work to verify for <10 km distance whether the differences for all sets go lower than the five cm level of difference. LAUR mount point could be used for topographic or surveying works within a 20 km distance, with strict periodic verifications and controls on the site.

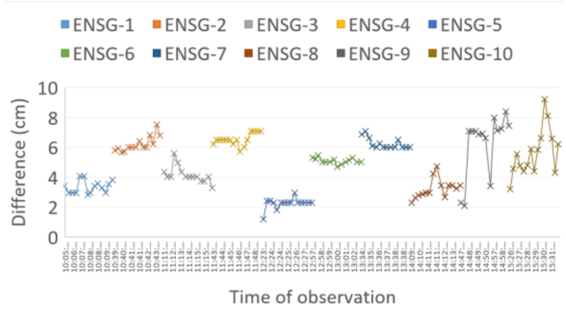


Figure 5: 2D planimetric differences of nine sets of observations based on ENSG mount point.

Figure 5 shows the differences with sub-nine-centimeter levels of all ENSG@20km mount point sets. We can distinguish four sets (1, 3, 5 and 8). Sets 5 and 8 reappear again to have good results like as in the LAUR case. The values of sets (2, 4, 6, and 7) are lower than the seven-centimeter difference level. Sets 9&10 shows chaotic behavior with differences varying between 2 and 9 cm difference level. We can give the same conclusion as for the LAUR mount point. Both have a 20 km distance from the reference point. We can use them as alternative mount points if the RICE mount point is disabled.

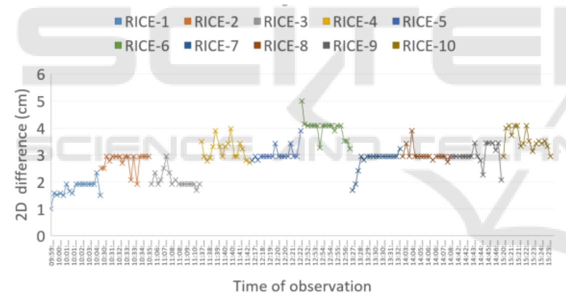


Figure 6: 2D planimetric differences of 10 sets of observations based on RICE mount point.

Figure 6 shows the differences with sub-five centimeter levels of all RICE@9km mount point sets. The measurement differences are stable within one centimeter for each set. These results confirm the preliminary results and ensure the continuity, stability, and reliability of this mount point for use in topographic or surveying works within a 9 km distance.

## 4 DISCUSSION

Knowing that topographic works in France are subject to the decree of September 16, 2003. The accuracy classes Land surveying needs to respect an accuracy level depending on the objective of the project and the scale of the plan ("Arrêté du 16 septembre 2003 portant sur les classes de précision applicables aux catégories de travaux topographiques réalisés par l'Etat, les collectivités locales et leurs établissements publics ou exécutés pour leur compte - Légifrance," n.d.). It gives 10 cm accuracy class for cadastral map scale of 1/500 and 20 cm for 1/1000 to 1/2000. With this discussion, we can confirm that the RICE Centipede mount point within 10 km tends to provide a five cm accuracy level. On the other hand, the 20km mount points (LAUR and ENSG) offer a 10 cm accuracy level. Therefore, the accuracy of RTK positioning presented in this work indicates that it is possible to use it in land surveying with 1/500 – 1/1000 and 1/2000 map scale factor.

15 cm with no confirmed stability (SGC and GPTR). If the accuracy level is fixed to be 10 cm level, one should not use mount points with distances over 48 km. Nevertheless, this criterion of distance is to be reconsidered after the OUIL mount point at 19 km distance has an accuracy level above 16 cm. Furthermore, we detect for a set of observations using the LAUR@19km mount point we see a huge leap in accuracy. The problem is that there are no indicators in real-time to alert the user of such a sudden out-of-accuracy range and thus out of use. We can point to the case of two mount points ENSG and ENSG2, where both are in the same place so the same distance from the user. However, they give different levels of accuracy for broadcast corrections (ENSG-5 cm and ENSG2-10cm). Hence, there is doubt about the quality of broadcast corrections without any kind of warnings sent to users in real-time.

After all, the user can use Centipede RTK network with Low-cost GNSS receivers and SW Maps application, but the user needs to control his work. To do so we suggest having some control points in the surveying area. These control points could be the result of high accuracy GNSS receiver for example. Then periodically compare the Centipede-RTK coordinates with the control point coordinates to eliminate the out-of-use problem and verify the consistency of the accuracy level. Finally, in the case of land surveying with a map scale of 1/200 to 1/500, we cannot trust the use of LCRA dependent on Centipede-RTK without verification with control points, because the user has no reliable indication of accuracy in real time. Nevertheless, it is a good alternative to be used for small-scale maps starting from 1/1000.

## 5 CONCLUSIONS

We test the feasibility of using a low-cost GNSS receiver and antenna for land surveying based on corrections broadcast from a collaborative network of RTK mount points in France. The interface is SW Maps, a free GIS Android application for smartphones. We conclude that the nearest centipede mount point does not mean that it is the best one to use. The indicators of accuracy are not representative in real-time using the SW Map smartphone application and the mount points of the collaborative free RTK network (Centipede). The corrections sent by Centipede mount points may change dramatically without any warning message for users in real-time. The use of low-cost GNSS receivers/antennas with the Centipede-RTK network connected via SW Maps GIS free smartphone application should be controlled and verified to ensure the reliability of the corrections used for land surveying.

For Future work, we intend to automatically record the data without the user intervention in the SW Map to generate temporal series for long-term measurement. Test the differences near ENSG, ENSG2, LAUR, and OUIL mount points within less than 10 km to examine the results of our work. Use the corrections of Centipede using a high-quality receiver-antenna and compare at the same time with low-cost GNSS receiver-antenna results for the same conditions to examine if there are notable differences. Explore the possibility of using Centipede corrections as an alternative solution in RTK mode for high-quality receivers when the paid network broadcast is lost. Finally, explore the archive of Centipede RTK databases in RINEX format newly available in the RENAG databases.

## REFERENCES


Arrêté du 16 septembre 2003 portant sur les classes de précision applicables aux catégories de travaux topographiques réalisés par l'Etat, les collectivités locales et leurs établissements publics ou exécutés pour leur compte - Légifrance [WWW Document], n.d. URL https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000000794936 (accessed 2.18.25).

Bellone, T., Dabove, P., Manzino, A.M., Taglioretti, C., 2016. Real-time monitoring for fast deformations using GNSS low-cost receivers. Geomatics, Natural Hazards and Risk 7, 458–470. https://doi.org/10.1080/19475705.2014.966867

Broekman, A., Gräbe, P.J., 2021. A low-cost, mobile real-time kinematic geolocation service for engineering and research applications. HardwareX 10, e00203. https://doi.org/10.1016/j.ohx.2021.e00203

Calculs GNSS Réseau en ligne | RGP [WWW Document], n.d. URL https://rgp.ign.fr/SERVICES/calcul_online.php (accessed 9.8.22).

Caldera, S., Realini, E., Barzaghi, R., Reguzzoni, M., Sansò, F., 2016. Experimental study on low-cost satellite-based geodetic monitoring over short baselines. Journal of Surveying Engineering 142, 04015016.

Calibrated Survey GNSS Tripleband + L-band antenna (IP67) [WWW Document], n.d. Geo-matching. URL https://geo-matching.com/products/calibrated-survey-gnss-tripleband-l-band-antenna-ip67 (accessed 2.18.25).

Cina, A., Piras, M., 2015. Performance of low-cost GNSS receiver for landslides monitoring: test and results. Geomatics, Natural Hazards and Risk 6, 497–514. https://doi.org/10.1080/19475705.2014.889046

GNSS Science Support Centre fosters collaboration across scientific communities through the provision of GNSS science-based products and services., 2021. GSSC Home [WWW Document]. URL https://gssc.esa.int/ (accessed 2.19.25).

Hamza, V., Stopar, B., Ambrožič, T., Sterle, O., 2021a. Performance Evaluation of Low-Cost Multi-Frequency GNSS Receivers and Antennas for Displacement Detection. Applied Sciences 11, 6666. https://doi.org/10.3390/app11146666

Hamza, V., Stopar, B., Ambrožič, T., Turk, G., Sterle, O., 2020. Testing Multi-Frequency Low-Cost GNSS Receivers for Geodetic Monitoring Purposes. Sensors 20, 4375. https://doi.org/10.3390/s20164375

Hamza, V., Stopar, B., Sterle, O., 2021b. Testing the Performance of Multi-Frequency Low-Cost GNSS Receivers and Antennas. Sensors 21, 2029. https://doi.org/10.3390/s21062029

Hamza, V., Stopar, B., Sterle, O., Pavlovčič-Prešeren, P., 2023. Low-Cost Dual-Frequency GNSS Receivers and Antennas for Surveying in Urban Areas. Sensors 23, 2861. https://doi.org/10.3390/s23052861

INRAE: research for Agriculture, Food and Environment [WWW Document], n.d. URL https://www.inrae.fr/en (accessed 2.18.25).

Jackson, J., Saborio, R., Anas Ghazanfar, S., Gebre-Egziabher, D., Davis, B., University of Minnesota. Department of Aerospace Engineering and Mechanics, 2018. Evaluation of Low-Cost, Centimeter-Level Accuracy OEM GNSS Receivers (No. MN/RC 2018-10).

Le Reseau Centipede RTK [WWW Document], n.d. Centipede RTK. URL https://docs.centipede.fr/ (accessed 2.18.25).

Leica Viva GS10 et GS25 – Récepteurs GNSS de haute précision [WWW Document], n.d. URL https://leica-geosystems.com/fr-fr/products/gnss-systems/receivers/leica-viva-gs10-gs25 (accessed 2.18.25).

Sammuneh, M.A., El Meouche, R., Eslahi, M., Farazdaghi, E., 2023. Low-Cost Global Navigation Satellite System

(Low-Cost GNSS) for Mobile Geographic Information System (GIS), in: Ben Ahmed, M., Boudhir, A.A., Santos, D., Dionisio, R., Benaya, N. (Eds.), Innovations in Smart Cities Applications Volume 6. Springer International Publishing, Cham, pp. 105–117.
Sanna, G., Pisanu, T., Garau, S., 2022. Behavior of Low-Cost Receivers in Base-Rover Configuration with Geodetic-Grade Antennas. Sensors 22, 2779. https://doi.org/10.3390/s22072779
Seeber, G., 2003. Satellite Geodesy. Walter de Gruyter.
Semler, Q., Mangin, L., Moussaoui, A., Semin, E., 2019. DEVELOPMENT OF A LOW-COST CENTIMETRIC GNSS POSITIONING SOLUTION FOR ANDROID APPLICATIONS. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-2/W17, 309–314. https://doi.org/10.5194/isprs-archives-XLII-2-W17-309-2019
Stopar, B., Sterle, O., Pavlovčič-Prešeren, P., Hamza, V., 2024. Observations and positioning quality of low-cost GNSS receivers: a review. GPS Solut 28, 149. https://doi.org/10.1007/s10291-024-01686-8
SW Maps - GIS & Data Collector – Applications - Google Play [WWW Document], n.d. URL https://play.google.com/store/apps/details?id=np.com.softwel.swmaps&hl=fr (accessed 2.18.25).
Teunissen, P.J., Montenbruck, O. (Eds.), 2017. Springer handbook of global navigation satellite systems. Springer International Publishing, Switzerland.
Tsakiri, M., Sioulis, A., Piniotis, G., 2017. Compliance of low-cost, single-frequency GNSS receivers to standards consistent with ISO for control surveying. International Journal of Metrology and Quality Engineering 8, 11.
ZED-F9P module [WWW Document], 2023. u-blox. URL https://www.u-blox.com/en/product/zed-f9p-module (accessed 2.18.25).