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Low-cost GNSS sensors for monitoring applications

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Abstract
Among several instruments and techniques that can be used for monitoring purposes, GNSS technology has undergone a fast evolution and provides a large choice of solutions. Despite the best performances can be achieved by using double frequency geodetic receivers, capable to maintain high precisions even for wide-scale monitoring, in the recent years, several interesting solutions were presented in the low-cost market. In this work, a monitoring system based on a couple of low-cost GNSS receivers has been developed and tested in the field (Ponte Motta in Cavezzo - Modena, Italy). The two receivers were positioned about 50 m from each other and data were acquired at 1-Hz frequency. The position solutions were calculated both in post processing, through two different free and open-source software packages, and using an embedded RTK processor. The analysis aims to assess on one hand the capability of the system to perform the monitoring of slow displacements with the best possible precision, and, on the other hand, the performances of the real-time solutions that can be used for early warning purposes. The precisions evidenced by the tests show that such low-cost instrumentation can be used for many monitoring purposes, especially considering the cost that is about a tenth of geodetic instruments.

Keywords GNSS · Monitoring · Low-cost

Introduction

The interest in land and structures monitoring systems has increased over recent years, especially for early warning applications. The capability to perform continuously operating monitoring of landslides or structures such as bridges, dams, or skyscrapers should constitute a fundamental element to prevent potential emergency situations and save lives, especially in seismic areas like Italy, riddled with many ancient structures.

In some situations, it may not be possible to set up a continuously operating system; therefore, the system could be powered only for a certain time, enough to reach the minimum required precision for the monitoring.

The GNSS technology has proved to be one of the most flexible and effective tools for monitoring purposes (Hudnut and Behr 1998; Celebi and Sanli 2002; Squarzoni et al. 2005). Usually, to achieve very high precision measurement, geodetic receivers are used. These instruments allow precisions at the centimeter level, or even less, in static mode and very long observation time spans.

Nevertheless, despite the decreasing cost of such instruments, geodetic class equipment is still quite expensive if compared with other sensors used for structural engineering, such as inclinometers, extensimeters, and so on. However, in recent years, a new class of low-cost GNSS receivers has become available on the market which is able to perform centimeter-level positioning. Consequently, many experiments were carried out by the scientific community in order to evaluate their real performances (Takasu and Yasuda 2009; Wiśniewski et al. 2013; Cina and Piras 2015; Caldera et al. 2016).

There are two main advantages in using low-cost GNSS equipment; first is that it permits deployment in dangerous areas (e.g., landslides, extreme weather phenomena, etc.) reducing the economic cost of its possible loss or damage. Second is that its low-cost permits greater sampling in areas of interest. The presence of more monitoring stations permits to survey not only a single structure or area, but to provide a more complete description of the whole situation.

The purpose of this paper is to demonstrate the use of data from a low-cost u-blox GNSS receiver for multiple applications. In particular, we investigated the performances of

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relative positioning varying the considered time spans from 1 Hz solution up to a daily solution and passing through different intermediate steps. While 1 Hz solutions one could be particularly interesting for early warning systems, the others are much more interesting in monitoring slow and low-entity movements, because of the higher precision.

To achieve these objectives, various tests were performed using variable data collection time spans, which impacts achievable precisions and is of particular interest.

The achievable precisions were evaluated depending on various time spans through a differenced approach and considering a baseline of about 50 m, installed on a masonry bridge crossing the Secchia river. The two receivers were located respectively on the center line and on the abutment. Two free and open-source software packages were then used to post process the raw data, whose solutions were then compared with the one obtained as the average of the RTK embedded modules of the receivers. This approach also permitted to assess the impact of the different data processing phases on the final results.

The relationship among accuracy and time span could be used to determine the exact time span which provides the required precision. This point is important if the monitoring system cannot be continuously operating (for many reasons, e.g., lack of a steady power source due to the impossibility to install solar panels), and the main purpose is to evaluate the magnitude of the smallest detectable movement.

The case study is presented in the first section, with some details regarding the assembling of the monitoring prototype and its implementation. Then, the obtained results are reported and divided into two main parts, respectively, the kinematic 1 Hz solutions and the static ones with different increasing time spans. A detailed analysis on the kinematic solution was performed too, in order to reduce some patterns appearing in the solutions, through the setting of an empirical sequential filtering.

The processing of the static solutions regarding the increasing time spans was performed using the software packages RTKLIB (2.4.3 b8 version) and goGPS (0.4.3 version).

For each described section, a method introduction and the corresponding obtained results are discussed.

Implementations of the monitoring system and case study

The first objective of the research was to set up a monitoring system capable to acquire and send GNSS data 24 h per day even in areas where neither power line nor internet line are available. This is a fundamental aspect in order to maintain the functionality of the system especially in case of catastrophic events that may isolate some areas. Therefore, the hardware of the monitoring package consists of three parts: the power supply, the GNSS instrumentation, and the data communication system.

As for the power supply system, a completely autonomous prototype was implemented in order to provide the necessary voltage in any operational situation (one for both instruments). The power supply system then consists of a solar panel, a charge regulator, and a battery with the proper ampere-rating. Everything was designed in order to supply enough power even in poor lighting seasons or periods.

The GNSS instrumentation consists of a couple of low-cost single frequency u-blox receivers C94-M8P, each paired with a single frequency antenna Trimble Bullet 360. These receivers also include a UHF radio module for the rover-master autonomous connection. The cost of the two receivers and two GNSS antennas is about 800 euros.

The remote communication system consists of a Raspberry Pi 3 coupled with a 4G Dongle internet key. Moreover, an external hard disk was set up in order to allow the local storage of raw data. These components cost about 200 euros.

A summary of the components that form the monitoring system is shown in Fig. 1, together with their approximate cost (summer 2017). In this analysis, the cost of the PC used for data processing is not considered. The test site for the first experiments on the field is Ponte Motta in Cavezzo (Modena, Italy), a 94-m bridge built in 1888 constituted by five 16-m long spans, shown in Fig. 2. The bridge is one of the few crossing the Secchia river in the northern area of Modena (Italy), a periodically flooded zone with great water flow rates (Nones 2018). These extraordinary water flows may generate high loads on the bridge piers. Moreover, the Emilia Romagna earthquake of 2012 caused severe structural damages, thus reinforcing works were carried out during 2017, through the realization of micro-pile supports and steel bars under the arches. Nevertheless, in the absence of extraordinary events, no significant movements can be expected for this rigid structure.

Figure 3 illustrates the installation and layout of the system. The experimentation started in September 2017 and from that moment GNSS data from both GPS and GLONASS constellations were acquired with a 1-Hz frequency. The dataset used during the tests for the data analysis consists of two subsets acquired in different periods, both constituted by 31 days of GNSS observations. A direct comparison between the post-processing solutions and the one obtained from the embedded RTK module was not possible, since when the system is enabled in RTK mode it does not allow raw data to be recorded. Despite the aforementioned problem, the considered datasets are almost comparable, since they were acquired on the same test field, in two closed periods of the same length (December 2017, January 2018).

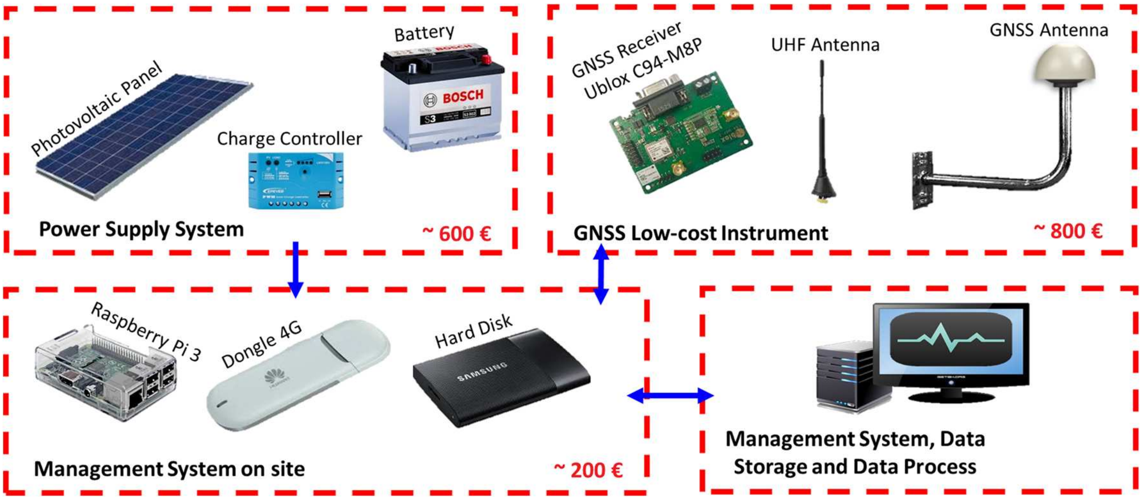


Fig. 1 Main elements composing the monitoring system and their approximate costs

Data processing

In this paragraph, the three different GNSS data processing modes used for the tests are introduced. The post-processing solution was obtained using two different open-source software packages, goGPS and RTKLIB.

The goGPS software package is an open source one, developed in the Matlab environment by Milan Polytechnic (IT) together with Osaka University (JP) (Realini and Reguzzoni 2013; Herrera et al. 2016). The software is designed for the GNSS positioning both for post-processing and real-time applications (only using NTRIP protocol). goGPS can be used through a graphical interface or can work batch processing through further Matlab scripts. For the test, the batch mode was preferred since it can be automated, resulting faster than the graphical interface.

The RTKLIB open-source software package was developed by Tomoji Takasu of Tokyo University of Marine Science and Technology (JP) (Takasu 2007; Takasu et al. 2007; Takasu and Yasuda 2009). It consists of a library of functions and several executable files. In this case too, the program can be launched both via a graphical interface or executing the single CUI APs (the executables) through a terminal or inside scripts.

Both software packages were used for static processing of L1 GNSS observables adopting standard parameters suggested by the developers. In Table 1, a list of the parameters used for each software package is reported where is evident that almost all parameters and considered models are the same.

Eventually, the u-blox embedded RTK module of the C94-M8P (Firmware 3.01 HPG 1.40) receivers was used. It allows to calculate real-time solutions, which are directly available at the serial port of the rover receiver, the corrections sent through the UHF module from the master receiver. In this case, it is not possible to set or modify any parameter of the module and no further elaborations are needed. The RTK embedded solutions are used in section 4 (1 Hz solution for early warning application) and in the "Assessment of the precision as function of observing-session time span" section (simulating a static solution as an average of the RTK solution for every considered time span).

Treatment of kinematic solutions for early warning purposes

This section explains the treatment of kinematic GNSS solutions with the aim to assess the performance of a possible early warning system with certainly lower precisions, but with the advantage of being able to recognize a movement in a timely manner. It is known that the GNSS system is generally

Fig. 2 The test site: "Motta di Cavezzo" bridge (Modena, Italy)

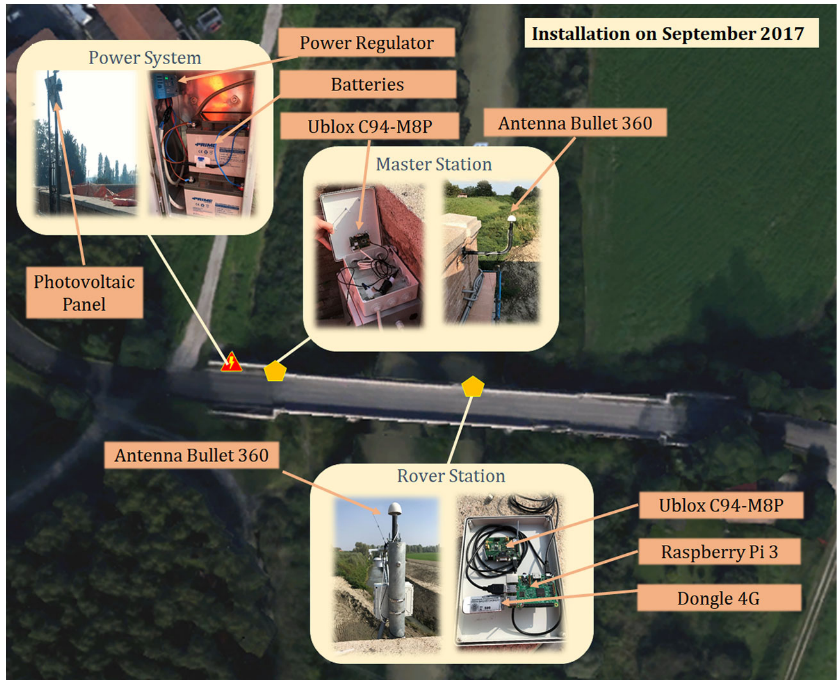


Fig. 3 Layout of the GNSS monitoring system installed on the bridge

affected by biases whose create patterns in real-time solutions (Fig. 4), depending on the position and on the boundary conditions. For this reason, it is possible to model them to reduce their effect. The considered dataset consists of 31 days 1 Hz solutions produced from u-blox C94-M8P module through the RTK approach (January 2018). The time series of such kinematic solutions were firstly observed and seemed to confirm the presence of a repeating pattern like the one evidenced in Gandolfi et al. 2015.

The autocorrelation function (Cliff and Ord 1973) was applied on the time series in order to evidence the period characterizing the pattern (Fig. 5). It was estimated as 86,164 s, which is the length of a sidereal day. Therefore, clarified that some systematic effects do not depend on a real movement, but probably derive from repeating boundary conditions, they can be modeled to reduce their impact. This work shows one of the possible approaches to reduce these effects, which has the advantage of not having to reconstruct a reference signal with a mathematical function.

Starting from the data obtained through the autocorrelation function, the repetition period of the pattern, the 1-Hz time series was split in sidereal days as shown in Fig. 6.

The correlation between them is quite clear and could be due to some sideral patterns in the GNSS boundary conditions such as multipath, satellites geometry, etc.Other interpretations, such as structural movements due to thermal effects, should have a daily period featured by a much more regular pattern and daily frequency signal that is not present here. The signal in this time series, with a sidereal daily recursion, presents restricted pattern in some particular windows time of the day (Fig. 7).

If we define x as a generic sidereal day, the RTK solutions of this day can be filtered removing a model estimated by considering n preceding days. For each sidereal day k ($k = 1$

Table 1 Main parameters used for each software package for static processing of L1 GNSS observables

Parameter	RTKLIB	goGPS
Version	2.4.3 b8	0.4.3
Constellations	GPS and GLONASS	GPS and GLONASS
Elevation mask	10°	10°
Ionosphere correction	Klobuchar	Klobuchar
Troposphere correction	Saastamoinen	Saastamoinen
Satellite ephemeris	Broadcast	Broadcast
Integer ambiguity resolution	Fix and hold algorithm (using LAMBDA method to fix)	LAMBDA 3.0—Integer rounding
Dynamic model	Kinematic	Variable

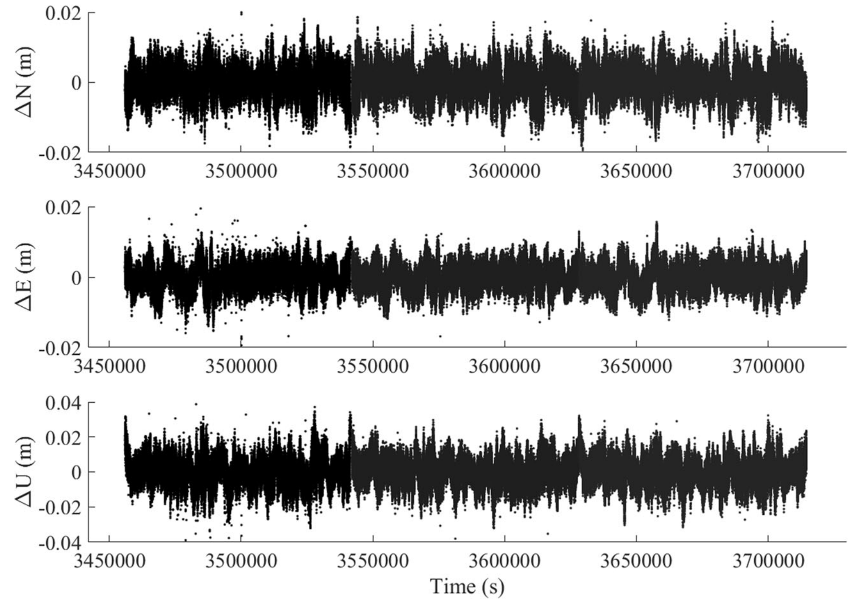


Fig. 4 Three days 1-Hz time series produced from u-blox C94-M8P RTK embedded module

… n), the solutions are filtered using a moving average set to a span of 100 s. The filter for the day x is computed as the average of the values found in the models of the time series for the n prior days. Finally, as shown in Fig. 8, the solution of the day x can be calculated as the difference between the RTK solutions and the value of the filter for the corresponding epoch.

The number n of sidereal days considered in the definition of the filtering models can vary and a specific test to define this parameter was performed. In particular, values of n from 1 to 9 were considered and the improvements in the repeatability of the filtered solutions were evaluated in terms of RMS.

Results

For each day from 10th to 31th of the considered period in the test, the RMS of the 1 Hz RTK filtered solutions using daily models was estimated. Figure 9 shows one of the daily time series analyzed as described, overlapped with the obtained filter.

At last, the comparison between the original time series and the filtered one (obtained differencing the original time series and the filter) is reported in Fig. 10.

The mean values of these daily RMS are reported in Fig. 11 depending on the number of days used in the estimation of the filtering models. Results are shown for the three coordinate components and considering a three-dimensional error.

Figure 11 shows the RMS of the raw solution and the filtered ones (above) and the improvements in the RMS of the solutions in terms of percentages relatively to the unfiltered RTK ones (below). The use of an estimated filtering model based only on the previous day leads to little improvements in the RMS, which are less than 10% for all components. Differently, using three or more previous days, the application of filtering models leads to reductions in terms of RMS up to 25%.

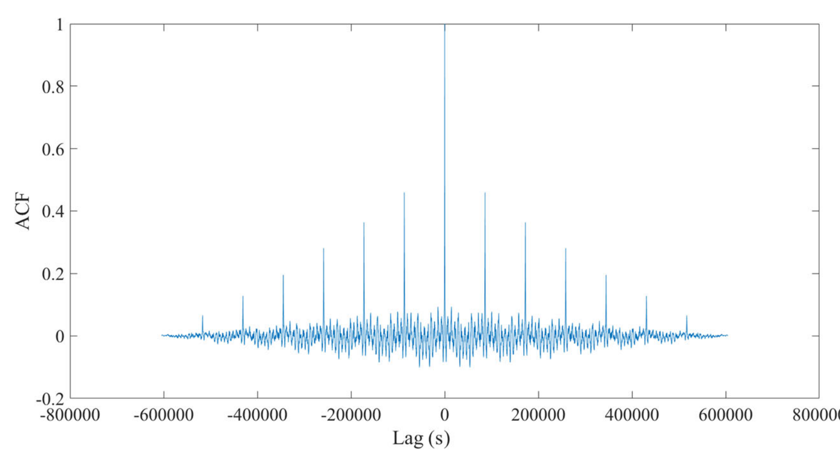


Fig. 5 Peaks corresponding to the sidereal days evidenced through the autocorrelation function

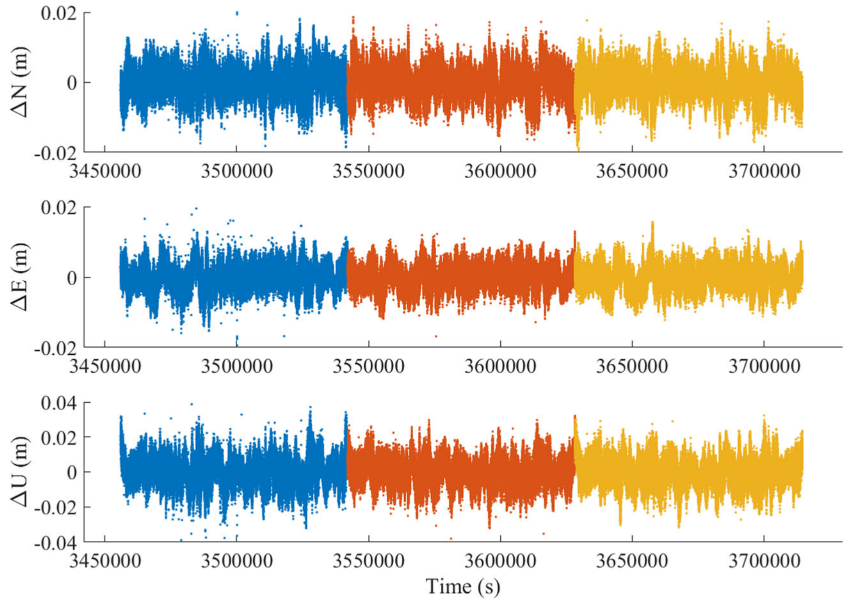


Fig. 6 One-hertz time series of 3 days; every color represents a different day

For this specific application on the Ponte Motta bridge, the best results were obtained considering 4 days in the estimation of the models. Nevertheless, this aspect should be tuned depending on the monitored site.

With the purpose of observing smaller and smaller movements, the reduction of the scattering in the time series through the application of filters like the one described above is a fundamental focus. It could even be possible to use more processing strategies to further reduce the system sensitivity, such a low pass filter (LPF), e.g., based on the calculation of moving averages. By this way, the sensitivity would be highly dependent on the dimension of the span used to determine the moving average, but on the other hand, it would permit to detect movements or displacements only after a delay equal to the span dimension itself and not in real time. Frequency domain-based methods have the same problem of the described LPF.

Since the main purpose was exclusively to assess the real-time achievable precisions and not the a-posteriori ones, such aspects were not investigated during the work.

Assessment of the precision as a function of observing-session time span

This section refers to a test performed using static processing with the aim to evaluate the best precision of the monitoring system at the varying of the observation time span. The goal is

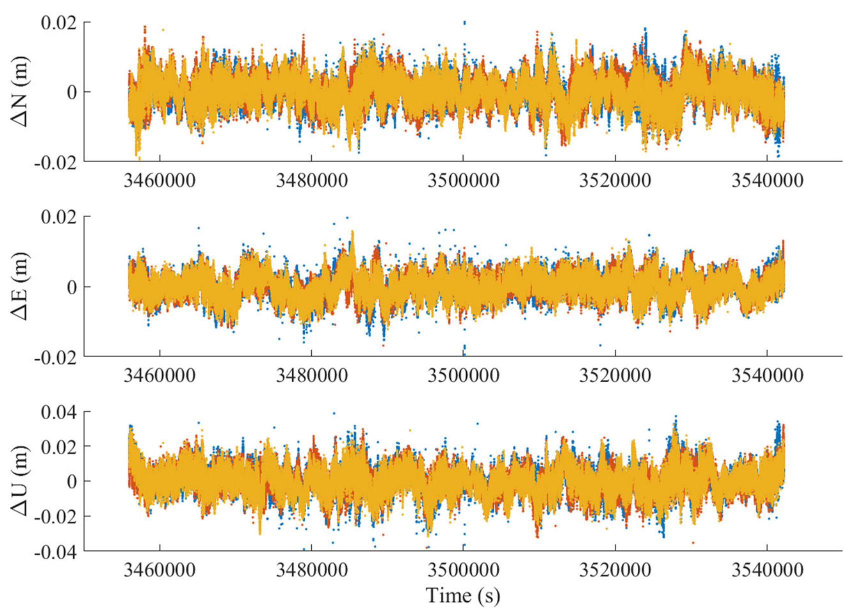


Fig. 7 Overlap of the 3 days 1-Hz time series

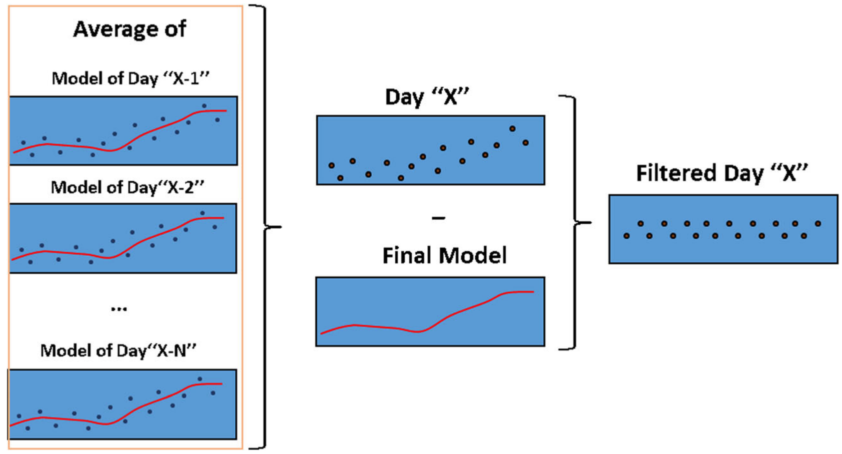


Fig. 8 From the left: daily model (weighted moving average), final model (average of the previous *n* daily models), and filtered solution (RTK solution without the previously determined model)

to understand how the system could work in reduced time windows and how much the repeatability of the result improves by decreasing the time spans with respect to a daily solution, in order to determine the statistically identifiable movements.

The 1 Hz GNSS data acquired by both receivers were converted from u-blox binary format to *RINEX* standard format. With the aim of simulating separate independent observing-sessions shorter than 24 h, each *RINEX* file was split into several ones having different time spans and data sampling (Gandolfi et al. 2016).

Several tests were performed for each considered time span to assess the data sampling impact on the solutions. These tests resulted in no particular advantages in incrementing the sampling time if the time windows are quite long. Then, the most suitable data sampling for each time window was chosen and used to split the *RINEX* files.

The splitting process was performed on 31 daily files through the TEQC software package (Estey and Meertens 1999) obtaining, from each considered *RINEX*, the products below:

- 1 file containing 24 h observations with 30 s of data sampling;
- 2 files containing 12 h observations with 30 s of data sampling;
- 4 files containing 6 h observations with 5 s of data sampling;
- 8 files containing 3 h observations with 5 s of data sampling;
- 12 files containing 2 h observations with 5 s of data sampling;
- 24 files containing 1 h observations with 1 s of data sampling.

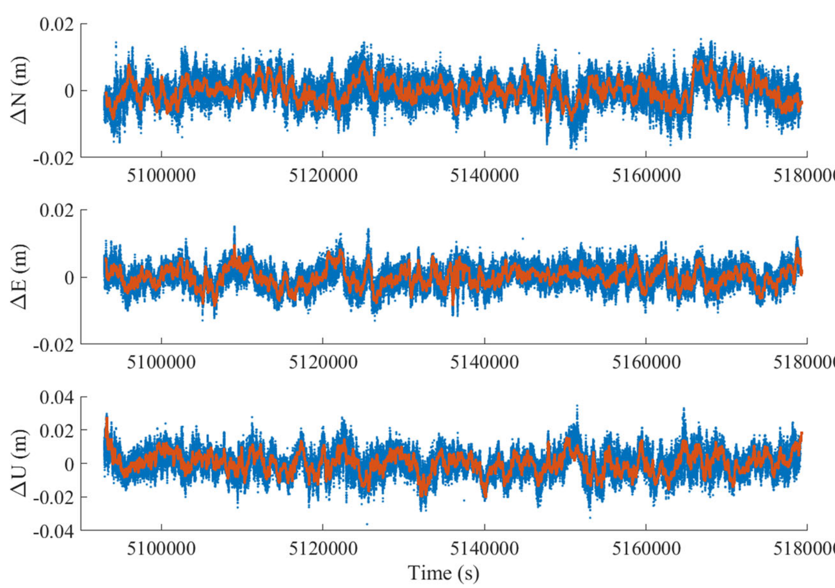


Fig. 9 Overlapping of one of the 1-Hz raw time series and the corresponding 4-day filter

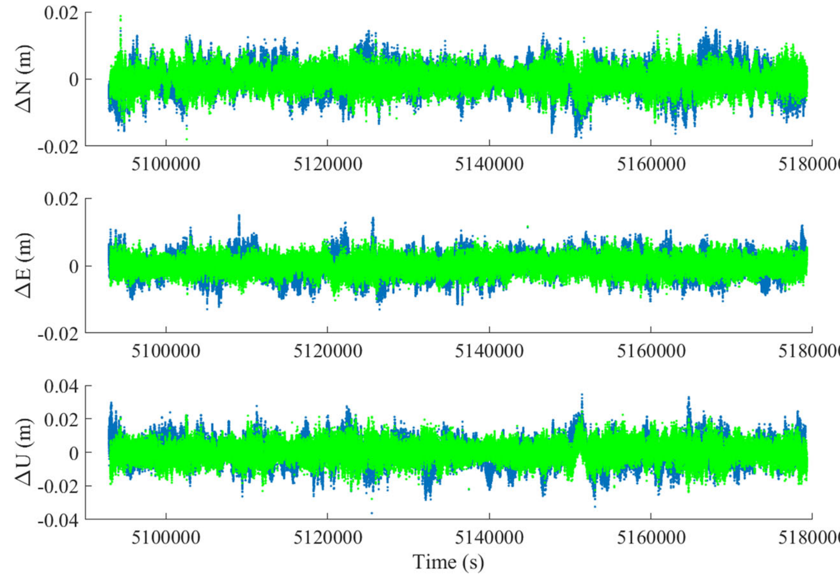


Fig. 10 Overlapping of one of the 1-Hz raw time series and the corresponding the filtered one

Each *RINEX* file was then processed using both the open-source software packages abovementioned.

The position solutions were arranged in time series, one set for each of the considered time spans, all expressed in a local topocentric reference system to separate northing, easting, and vertical (NEU) components. In order to eliminate potential outliers that could affect the evaluation of the precision, expressed in terms of RMS σ, a statistical approach was used, relying on a 3σ criteria as follows:

1. The linear regression line of each time series is computed together with the RMS of the related residuals;
2. The highest residual is compared with the 3σ value and the related solution is considered an outlier if the residual exceeds the threshold. In such a case, the solution is removed from all the three NEU components;
3. The first two steps are reiterated until no further outliers in the time series are detected. The last RMS values for each NEU component are then assumed as the parameters representing the precision of the solutions.

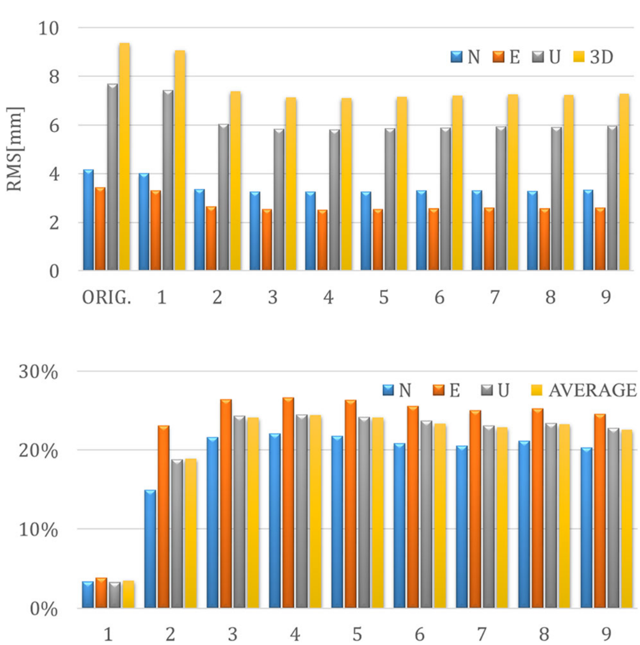


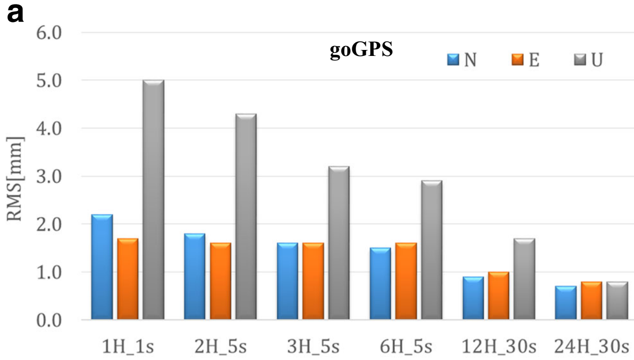
Fig. 11 RMS of the RTK filtered solutions depending on the number of days considered for the filtering model estimation (above) and relative improvement with respect to the original time series (below)

The same scheme and post-processing were used for the solutions estimated through the RTK embedded module too, but each solution was calculated as the average value of the coordinates obtained within the considered time span. For instance, the "1 hour" solutions are the mean values of 3600 acquired 1 Hz RTK coordinates in each considered hour, and so forth for the longer time spans. Therefore, the comparison between the post-processed solutions, which are calculated autonomously, and the RTK solutions should consider the fact that the latter are not affected by the convergence time necessary to fix the ambiguities.

Results

For each of the observing-session time spans listed in section 5, the RMS of the related time series were computed. Results obtaining through post processing with goGPS and RTKLIB are shown in Fig. 12.

First of all, the precisions are always within 2 mm in terms of RMS for the horizontal components, even acquiring 1 hour of observations. The RMS for the vertical component is within 5 mm for the shorter observing-sessions but decrease to lower values for the daily solutions. As for the two software packages used to estimate the post-processed solutions, no significant differences are evident considering the observing-a



b

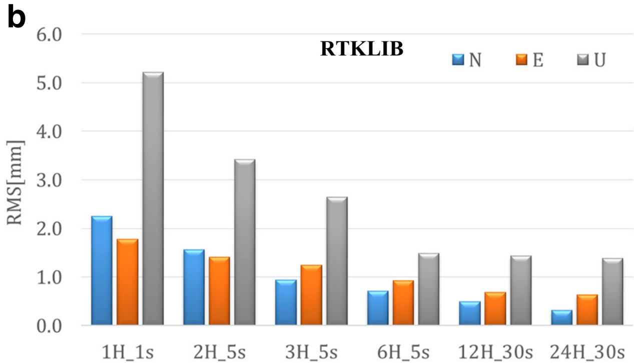


Fig. 12 RMS of NEU components of each time series obtained with the described post-processing methods. Respectively, goGPS (**a**) and RTKLIB (**b**) solutions are reported

session shorter than 6 h. Differently, in the case of *RINEX* files including 6 h of observations or more, the RTKLIB software provides better solutions on the northing component with respect to goGPS. Conversely, considering the vertical component and daily files, goGPS provides less scattered solutions.

As for the solutions of Fig. 13 calculated through the embedded RTK module, these are more precise than the post-processed ones, considering the shorter observing-sessions.

Such behavior is an expected fact, since it has to be considered that each solution requires for a convergence time necessary to reach the phase ambiguities fixing, that is more impacting on shorter observing-sessions. In the RTK solution, unless the occurrence of cycle slips, the ambiguity fixing is maintained over time, thus impacting only once in terms of convergence time. Otherwise, for the post-processed solutions, a new ambiguity fixing is necessary for each *RINEX* file. Nevertheless, considering the northing component, the RTK solutions are the most precise even considering daily observations.

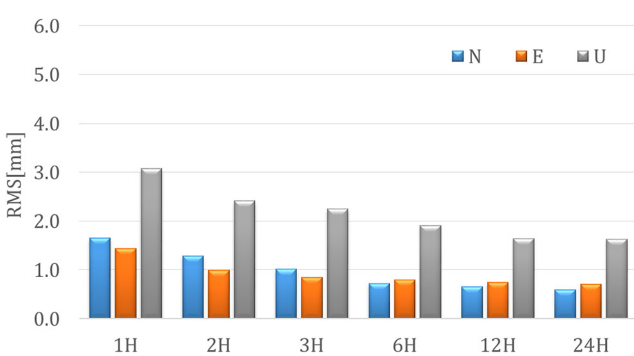


Fig. 13 RMS of NEU components of each time series obtained with the described methods using the u-blox embedded RTK module

Conclusions

Basing on low-cost GNSS instrumentation, a monitoring system was assembled with the aim to provide data to a remote analysis center 24 h per day. The whole system costs about 1000 euros and can be coupled with an autonomous power supply system spending further 600 euros.

The performances of the monitoring system were tested on a masonry bridge located in Ponte Motta that can be considered a stable benchmark. GNSS data were acquired at 1-Hz frequency, both in terms of phase observables and RTK solutions provided by the software embedded in the u-blox C94-M8P receiver chosen for the test. The distance between master and rover receivers is about 50 m and should be mentioned that a Trimble L1 antenna was included in the system pack instead of the patch one provided by u-blox.

The RTK module has proven to provide real-time solutions with a 4 mm RMS for the horizontal components and 8 mm for the vertical one. These results are representative of the system sensitivity with respect to quick displacements that should be detected in nearly real time for early warning application purposes.

Moreover, the performances of the real-time monitoring system can be improved in terms of sensitivity by applying ad hoc filtering models based on the solutions of previous days. This way, a reduction up to 25% in the RMS of the coordinates estimated at 1-Hz frequency was obtained.

Considering daily observations, the precision of the system in terms of RMS of the solutions is less than 1 mm for the horizontal components and 1–1.5 mm for the height. The RMS is increasing for shorter observing-sessions but remains within 2 mm in the horizontal component even using 1 h of observations. The vertical component has about 5 mm of RMS for 1-h long observations.

A comparison with the two free software packages RTKLIB and goGPS has shown better results for the first one, especially considering the northing component, whereas goGPS provides higher precision only for the vertical component when 24 h of observables are used.

The test using post-processed solutions calculated on independent blocks of observations is important in the case that the start and stop mode is chosen for the slow displacements monitoring. This modality can be required in case of limitations in the power supply.

In conclusion, despite the geodetic class double frequency instrumentation should still be considered the only one reliable for long distances between the receivers, the low-cost monitoring system here presented seems to provide very competitive performances, suitable, for example, for the monitoring of structures. For this study, we have considered just a very short baseline and concentrate the test in the accuracy vs software package and windows time span, but considering the quality of the obtained results, some more tests should be addressed on the impact of the baseline length on the accuracy and the repeatability.

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