Experimental Study on Low-Cost Satellite-Based Geodetic Monitoring over Short Baselines

Stefano Caldera[1]; Eugenio Realini[2]; Riccardo Barzaghi[3]; Mirko Reguzzoni[4]; and Fernando Sansò[5]

Abstract: The use of geodetic techniques, in particular of the global positioning system (GPS), or other global navigation satellite systems (GNSS), for monitoring different kinds of deformations is a common practice. This is typically performed by setting a network of geodetic GPS/GNSS receivers, allowing accuracies in the order of millimeters. The use of lower-cost devices has been recently studied, showing that good results can be achieved. In this paper, the impact of the software used for the data analysis is also investigated to verify whether a fully low-cost monitoring system, i.e., both hardware and software, can be set up. This is done by performing a series of relative positioning experi-ments in which data are processed by different software packages. The main result is that by using a low-cost u-blox EVK-6T GPS receiver and analyzing its data with free and open-source software, movements of the order of a few millimeters can be detected when a short baseline with daily solutions is used.

Author keywords: Global navigation satellite systems (GNSS); Deformations; Low-cost receivers; u-blox receiver; Free and open-source GNSS software; Bernese; Leica Geo Office (LGO) Combined; goGPS.

Introduction

Human society, in its turbulent development, is meeting increasing threats and difficulties related to the ominous behavior (or reaction) of its environment, be it natural or built. Natural hazards and those related to large structure and infrastructure failures create the need for punctual and prompt risk monitoring to mitigate effects in terms of life safety and economic protection. A large part of such risks is revealed by a precursory change of geometry, or deformation, such as mentioning the motion of a landslide or the deformation of a large structure, like a dam, a bridge, and so on. In such cases, the continuous determination of the position of *N* points in time, such as a geodetic monitoring system, is one of the possible effective approaches used to control the risk and, when necessary, to give a prompt alarm, when certain probability thresholds are exceeded.

The establishment of a permanent global navigation satellite system (GNSS) network is certainly one way to perform such monitoring, as witnessed by a large amount of literature of both a scientific and technical nature (Roberts et al. 2004; Chan et al. 2006; Meng et al. 2007; Watson et al. 2007; Borghi et al. 2009; Kaloop and Li 2009; Fastellini et al. 2011; Wang 2011; Yi et al. 2013). A small network of permanent GNSS stations, 10 km or less of diameter, which covers many cases, can provide coordinates accurate to millimeters for such stations, with, e.g., 1-day latency. However, one limiting factor of this approach is the cost of such a system based on geodetic receivers. This restricts the possibility of its application to institutions that can afford it and reduces the number of permanent stations that can be built, with a correspondent decrease in the efficiency of the monitoring system. In recent years, however, the attention of the GNSS community has been drawn to the possible application of low-cost GNSS receivers, which for such small networks might be capable of producing useful results (Heunecke et al. 2011; Buchli et al. 2012; Benoit et al. 2014; Cina and Piras 2014). For this reason, the authors of this paper have started studying the problem to show that the approach can be very advantageous from an economic standpoint when low-cost receivers are used and an inexpensive (or even free) open-source software package is applied to build an authentic *low-cost monitoring system*.

The paper reports the results of an experiment in which two very short baselines of different lengths (70 m and about 3 km) were monitored with u-blox GPS receivers for 36 days. Data were processed with different software applications in different modes to understand the potential of the system and to compare the performances of some scientific, commercial, and open-source software packages. Furthermore, considering that single-frequency observations along with an unrefined ionospheric model were used, experiments were performed on several bases up to 30 km to evaluate the degradation of the accuracy of the baseline estimation with respect to the baseline length.

[1]Researcher, Geomatics Research and Development srl, Via Cavour 2, 22074 Lomazzo, Italy.

[2]Researcher, Geomatics Research and Development srl, Via Cavour 2, 22074 Lomazzo, Italy (corresponding author). E-mail: eugenio.realini@g-red.eu

[3]Full Professor, Dept. of Civil and Environmental Engineering, Politecnico di Milano, P.za L. da Vinci 32, 20133 Milano, Italy.

[4]Assistant Professor, Dept. of Civil and Environmental Engineering, Politecnico di Milano, P.za L. da Vinci 32, 20133 Milano, Italy.

[5]Professor Emeritus, Dept. of Civil and Environmental Engineering, Politecnico di Milano, P.za L. da Vinci 32, 20133 Milano, Italy.

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Very Short Baseline Experiment: Hardware, Configuration, and Software

The hardware used in the experiment consisted of two permanent GPS stations, also called continuously operating reference stations, which were well established and analyzed over a long time span, and a u-blox receiver, which simulated the monitoring station (marker name, UBLX). More precisely, the pre-existing reference stations were

- MILA, which uses a TOPCON Odyssey E receiver with TPSCR3_GGD CONE antenna (both from TOPCON

Corporation, Tokyo), located at the premises of Politecnico di Milano, Leonardo Campus; and

- PROV, which uses a TOPCON Legacy E receiver, with JAVAD RegAnt antenna (JAVAD GNSS, Inc., San Jose, CA), located at the premises of the Provincia di Milano.

The UBLX receiver was placed at Politecnico di Milano, about 70 m from the MILA station and 2.8 km from the PROV station. The apparatus used was an EVK-6T receiver, which is an evaluation kit for the LEA-6T module, with its standard ANN-MS patch antenna (u-blox AG, Thalwil, Switzerland) [Fig. 1(a)]. Using such

Fig. 1. (a) u-blox EVK-6T with its ANN-MS antenna (image by Eugenio Realini); (b) Trimble Bullet III antenna (image by Stefano Caldera)

Fig. 2. Locations of the receivers involved in the very short baseline experiment (©Mapbox, Data ODbL ©OpenStreetMap contributors)

a low-performance antenna was done to keep the cost of the hardware used in the experiment as low as possible; a higher quality antenna could be used as well, for example, one equipped with a small dome for avoiding snow accumulation (this kind of antenna exists on the market at costs lower than \$100) [Fig. 1(b)]. The cost of a u-blox evaluation kit providing raw data (typically the models ending with T), including the ANN-MS antenna, is about \$300. For this experiment, a notebook was used to power the receiver and to provide storage for logging the raw data. The location of the receivers is shown in Fig. 2. The UBLX antenna was fixed on a small iron platform (about 15×15 cm^2) by its own magnetic base. The platform was in turn fastened to the top of a pole, which was rigidly attached to the corner of a railing. The system did not allow for significant and permanent movements with respect to the target of this study. With strong winds, storms, etc., the antenna may have had oscillations, but they were of short duration and could not affect the daily solutions computed in this work.

Three different software applications were used in the experiment, *Bernese GPS 5.2* software (Dach et al. 2007), *Leica Geo Office (LGO) 8.0*, and *goGPS v0.4.2*. *Bernese GPS* is well known in the scientific community; the interested reader can find more details in Dach et al. (2007) and in the software manual [Astronomical Institute (2007)]. The results derived by such software will be considered as the truth in the following sections. The *LGO* software is a well-known commercial software by the Leica Geosystems Company. Like *Bernese GPS*, *LGO* adjusts single bases by phase double differences. The *goGPS* software (Realini and Reguzzoni 2013; Herrera et al. 2015) was originally a navigation software developed at Politecnico di Milano in Italy (Geomatics Laboratory of the Como Campus) for teaching purposes. Both the *MATLAB* and *Java* versions of the software have now been offered to the international community under free and open-source software (FOSS) licenses, such as GPLv3 and LGPLv3, respectively. Therefore, the software has evolved in time with contributions from the geodetic community, including some of the authors of this paper. The *goGPS* software can now adjust stationary bases by double differences using the Kalman approach (Kalman 1960). It is worth pointing out that the *goGPS* results in Realini and Reguzzoni (2013), reported to be in the meter to submeter level, are related to kinematic positioning. This involves several limitations with respect to the expected accuracy, compared with the static daily positioning performed in this paper. The main difference between kinematic and static positioning lies in the redundancy of the system to be solved. Additionally, several improvements were made to *goGPS* algorithms since the experiments reported in Realini and Reguzzoni (2013), which contributed to the performances reported in this paper. The most important

Fig. 3. IGb08 adjustment network: triangles = IGS stations; circles = EPN stations; squares = experiment permanent stations (©Mapbox, Data ODbL ©OpenStreetMap contributors)

improvements are the implementation of a precise time synchronization between rover receiver and reference station (i.e., interpolating observations on a common reference time) and an outlier detection and removal method, based on the leave-one-out technique (Biagi and Caldera 2013), and applied to code and phase double differenced observations. Note that, according to the original target, other FOSS software has also been used, such as *RTKLIB 2.4.2* (Takasu and Yasuda 2009). The results for the MILA-UBLX baseline showed repeatability at a decimeter level (in particular, 11 cm in EAST, 4.7 cm in NORTH, and 16.7 cm in UP); therefore, it was decided to exclude this software from the subsequent tests. For the sake of completeness, included in the Appendix are the configuration parameters for all the software used in this work, including *RTKLIB*.

Very Short Baseline Experiment: Data Analysis

First, the data of the reference stations over a time span of 77 days [from date of year (DOY) 21/2014 to 97/2014] were used to frame them into the international IGb08 reference frame (Rebischung et al. 2012; Rebischung 2013). The software used for this was *Bernese*, applying international guidelines for regional network densification (Ferland et al. 2002; Kouba 2003; Petit and Luzum 2010), constraining the common stations GRAS, GRAZ, MEDI, PADO, PFA2, TORI, WTZR, and ZIMM to official International GNSS Service (IGS) solutions. In addition, five stations belonging to the EUREF Permanent GNSS Network (EPN) have been included in the network (Fig. 3). Automatic network adjustment and data analyses were managed by the RegNet tool (Biagi and Caldera 2011). Then 37 days of data from the experiment were analyzed (from DOY 60/2014 to 96/2014), with daily solutions computed for each of the baselines using the three software applications.

The results in terms of (E, N, U) coordinates (with respect to the mean values of the UBLX coordinates estimated with MILA reference station and *Bernese*) are plotted in Figs. 4 and 5 for the two baselines and the three software applications, when the 1-Hz observations were adjusted (missing values for *LGO* in Fig. 5 are caused by the software failing to provide a valid solution for those DOYs). Because the main issue is deformation monitoring, the presence of possible systematic biases in the estimated coordinates is secondary; therefore, it is not important to analyze how close the solutions are to zero in Figs. 4 and 5. The index of interest is instead the stability of the daily solutions over time, i.e., the so-called repeatability; this is simply the standard deviation of the estimated coordinates over the period under test. Note that the solutions are all single frequency (i.e., L1 only). All of the three software applications were used with the following options: no refined estimate of the troposphere, i.e., Saastamoinen model only (Saastamoinen 1972), and no refined estimate of the ionosphere, i.e., Klobuchar model only (Klobuchar 1987) for *LGO* and *goGPS*, whereas *Bernese* implements the model described in Geckle and Feen (1982), and the integer ambiguity resolution is enabled. Because of the very short baseline, possible mismodeling in the atmospheric effects has a very limited impact on the solution. More refined models or a network adjustment could be used when longer baselines are considered. As for the integer phase ambiguity resolution, *goGPS* applies the *LAMBDA* method (Teunissen 1995; Verhagen and Li 2012). Because *Bernese* does not provide *LAMBDA* as an option, the *SIGMA* method (Dach et al. 2007) was chosen instead. Finally, all the presented results were obtained by using broadcast ephemerides. An additional adjustment was also performed with *Bernese* with precise ephemerides, verifying that no sensible difference existed in the solution, especially for the shorter baselines, which are of greater interest for local monitoring problems.

The numerical results in terms of mean components of the baselines and their standard deviation (repeatability) are reported in Tables 1 and 2. It should be noted that the reported standard

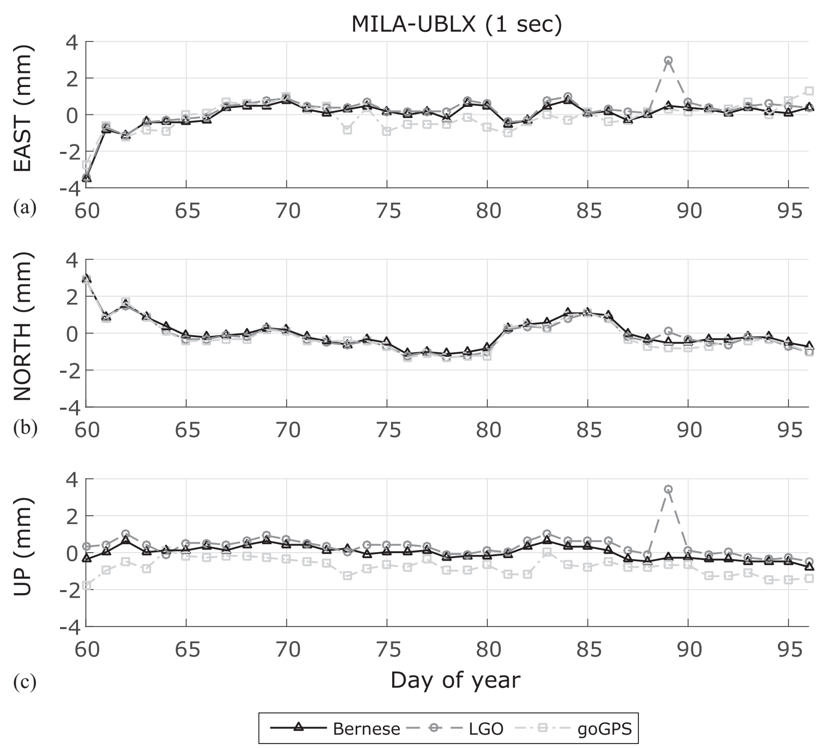

Fig. 4. Differences with respect to the mean values of UBLX coordinates estimated with MILA base station and *Bernese* [baseline: MILA-UBLX (70 m), rate: 1 s]: (a) the daily E adjusted values; (b) the daily N adjusted values; (c) the daily U adjusted values

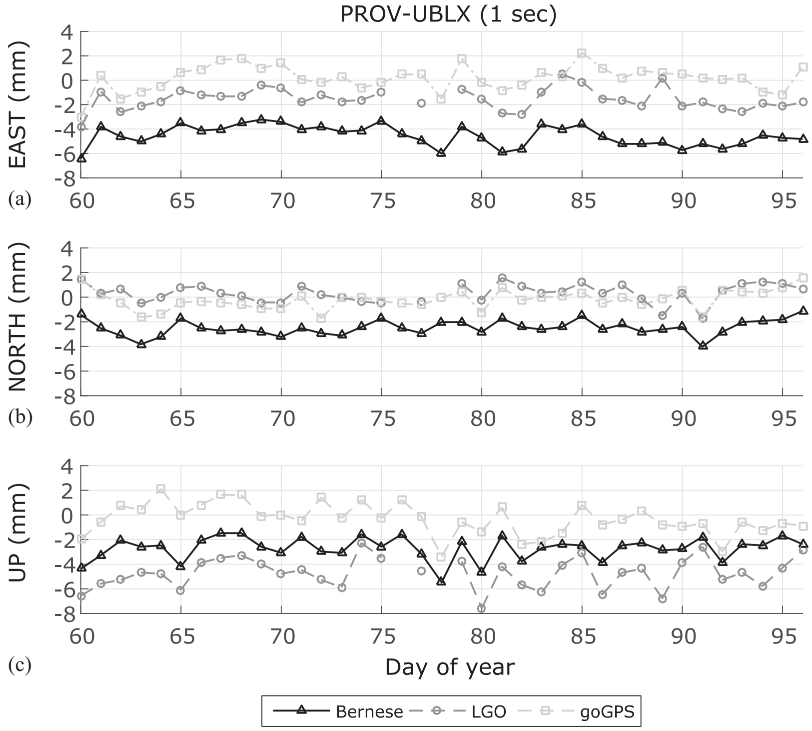

Fig. 5. Differences with respect to the mean values of UBLX coordinates estimated with MILA base station and *Bernese* [baseline: PROV-UBLX (2.8 km), rate: 1 s]: (a) the daily E adjusted values; (b) the daily N adjusted values; (c) the daily U adjusted values (Note: *goGPS* solution seems to be the most robust against biases in the estimated coordinates, i.e. the closest to zero differences)

Table 1. Baseline MILA-UBLX (70 m)

	Baseline components (m)			Repeatability (mm)		
Software	EAST	NORTH	UP	σE	σN	σU
Bernese	−44.1604	−45.2588	6.1114	0.7	0.8	0.4
LGO	−44.1602	−45.2589	6.1117	0.9	0.8	0.6
goGPS	−44.1605	−45.2590	6.1106	0.7	0.9	0.5

Note: Rate: 1 s. Mean and standard deviation of the 37 daily baseline components estimated by the three software applications.

Table 2. Baseline PROV-UBLX (2.8 km)

	Baseline components (m)			Repeatability (mm)		
Software	EAST	NORTH	UP	σE	σN	σU
Bernese	2068.9699	1901.0493	3.0984	0.8	0.6	1.0
LGO	2068.9729	1901.0521	3.0964	0.9	0.8	1.3
goGPS	2068.9746	1901.0516	3.1008	1.1	0.8	1.3

Note: Rate: 1 s. Mean and standard deviation of the 37 daily baseline components estimated by the three software applications.

deviations are just sample estimates based on the daily coordinates with respect to their empirical means and not the formal figures resulting from the least-squares adjustment, which are known to be always too optimistic because of imperfect knowledge of the stochastic model of the errors (e.g., Beutler et al. 1987; Han and Rizos 1995).

Furthermore, the same data stream has been decimated with time lags of 5 s (200 mHz), 15 s (66 mHz), and 30 s (33 mHz) and reprocessed in the same way. This was done to study the loss of accuracy by increasing the time lag between data, because this is a sensible parameter when the practical problem of electric supply and data transmission is tackled. It should be noted that setting the u-blox sampling rate to time lags higher than 1 s (instead of decimating 1-Hz observations) introduced synchronization problems with respect to the standard sampling rate used by reference stations, in the sense that the receiver did not always start the sampling at 0 s (e.g., 0, 15, 30, 45 s) and sometimes started at 1 s (e.g., 1, 16, 31, 46 s).

The results are reported in Tables 3 and 4. Some comments are as follows:

- For the repeatability, which is a prominent index when control problems are faced, it can be seen that the standard deviations of 1-Hz solutions are quite consistent for the two bases (of lengths 70 and 2.8 km respectively), comparing one software with the other. In particular, *LGO* and *goGPS* solutions are basically equivalent and only marginally worse than that of the *Bernese* software. Nearly the same thing happens for the other time lags.
- The decrease of data from 1 to 30 s lags does not affect significantly the repeatability of daily solutions.
- The stability of the mean components of the bases estimated with different time lags over the 37-day period is quite strong, with some advantage from the *Bernese* software and *goGPS* over *LGO* solutions.
- Ninety-nine percent confidence intervals around the mean are generally below the ±2-mm values, which makes the approach useful for the mentioned monitoring problems.

Short Baselines Experiment

To evaluate the performance degradation when increasing the length of the baselines, the computations were repeated by

Table 3. Baseline MILA-UBLX (70 m)

Software	Rate (s)	Baseline components (m) EAST	NORTH	UP	Repeatability (mm) σE	σN	σU
Bernese	1	−44.1604	−45.2589	6.1113	0.8	0.9	0.4
	5	−44.1604	−45.2589	6.1113	0.7	0.8	0.4
	15	−44.1604	−45.2589	6.1114	0.7	0.8	0.3
	30	−44.1604	−45.2589	6.1114	0.7	0.8	0.3
LGO	1	−44.1602	−45.2589	6.1117	0.9	0.8	0.6
	5	−44.1603	−45.2585	6.1115	0.9	0.9	0.7
	15	−44.1627	−45.2575	6.1049	0.9	0.8	1.1
	30	−44.1626	−45.2576	6.1052	0.9	0.8	1.2
goGPS	1	−44.1605	−45.2590	6.1106	0.7	0.9	0.5
	5	−44.1605	−45.2590	6.1107	0.8	0.9	0.5
	15	−44.1605	−45.2591	6.1108	0.8	0.9	0.5
	30	v44.1605	−45.2590	6.1109	0.9	0.9	0.5

Note: Mean and standard deviation of the 37 daily baseline components estimated by the three software applications with different data sampling.

Table 4. Baseline PROV-UBLX (2.8 km)

Software	Rate (s)	Baseline components (m) EAST	NORTH	UP	Repeatability (mm) σE	σN	σU
Bernese	1	2068.9699	1901.0493	3.0984	0.8	0.6	1.0
	5	2068.9698	1901.0494	3.0981	0.8	0.6	0.9
	15	2068.9698	1901.0494	3.0980	0.9	0.6	1.0
	30	2068.9697	1901.0494	3.0979	0.8	0.6	0.9
LGO	1	2068.9729	1901.0521	3.0964	0.9	0.8	1.3
	5	2068.9721	1901.0531	3.0952	1.0	0.9	1.4
	15	2068.9721	1901.0531	3.0947	0.9	0.8	1.1
	30	2068.9746	1901.0518	3.1016	0.9	0.8	0.7
goGPS	1	2068.9746	1901.0516	3.1008	1.1	0.8	1.3
	5	2068.9747	1901.0516	3.1008	1.0	0.8	1.3
	15	2068.9748	1901.0516	3.1008	0.9	0.8	1.3
	30	2068.9749	1901.0516	3.1010	1.0	0.8	1.2

Note: Mean and standard deviation of the 37 daily baseline components estimated by the three software applications with different data sampling.

differentiating with respect to three additional permanent stations farther than the ones used before (Fig. 6). The practical target of this test is to verify whether the proposed system can work, even in a scenario without a dense network of permanent stations, and without the need to install an ad hoc geodetic master station. The test was based on the same procedure described in the previous section, but processing data with a 30-s sampling rate using *goGPS* software. In particular, the repeatability is reported in Table 5 and plotted in Fig. 7 for the sake of comparison. The increase of the baseline length up to 30 km leads to a significant decrease in the performances, which was largely expected and also happens when using standard geodetic receivers. However, it has to be noted that the repeatability remains at the centimeter level, which still enables the possibility of monitoring deformations, depending on the required accuracy in performing such a task. In this sense the graphs shown in Fig. 7 can be used as a *transfer function* between the required repeatability and the minimum system requirement in terms of distance of the closest

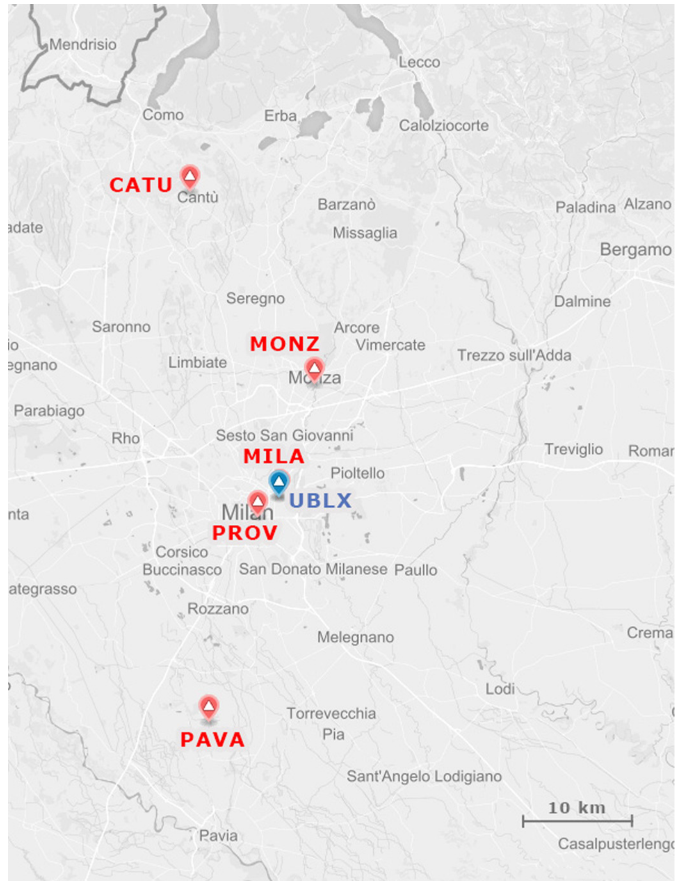

Fig. 6. Location of the receivers involved in the short baseline experiment (©Mapbox, Data ODbL ©OpenStreetMap contributors)

Table 5. Standard Deviation of the 37 Daily Baseline Components Estimated by *goGPS* Software (Rate 30 s) with Different Baseline Lengths

Baselines	Length (m)	Repeatability (mm) σE	σN	σU
MILA-UBLX	64	0.9	0.9	0.5
PROV-UBLX	2811	1.0	0.8	1.2
MONZ-UBLX	11355	4.2	2.9	4.1
PAVA-UBLX	22668	3.8	6.8	7.3
CATU-UBLX	30527	8.5	8.5	11.6

reference station. These graphs hold for the conditions under which this experiment has been performed, but they cannot be straightforwardly generalized for every condition and with any baseline. In particular, an incorrect ambiguity fixing could lead to much worse results in terms of repeatability, thus making the *continuous* transfer functions of Fig. 7 unrealistic. The increasing chances on an incorrect ambiguity fix when increasing the baseline length can be somehow measured by the increasing number of unresolved ambiguities by the *LAMBDA* method, as reported in Fig. 7.

Conclusions and Perspectives

Because deformation monitoring means identifying changes of baselines in time, the main index providing the level of sensitivity

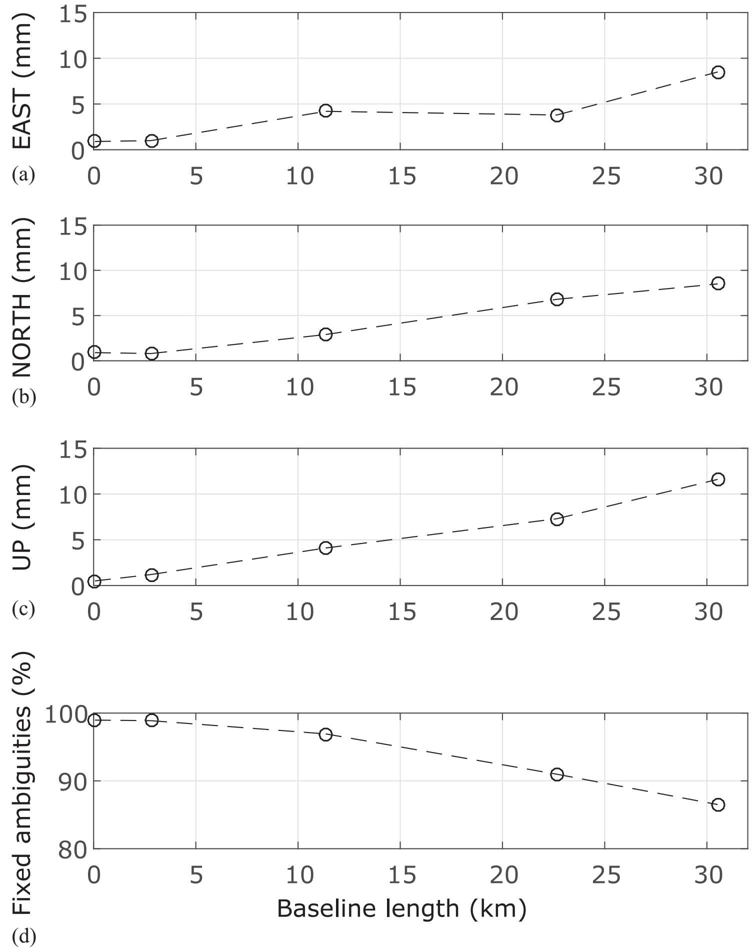

Fig. 7. (a–c): standard deviations of the 37 daily baseline components estimated by *goGPS* software (rate: 30 s) with different baseline lengths; (d) percentage of ambiguities resolved by the *LAMBDA* method

Table 6. SI (in mm) by Software and Baseline Length (Rate: 30 s)

Software	64 m	2.8 km	11 km	23 km	31 km
Bernese	1.1	1.3	4.7	7.1	9.8
LGO	1.7	1.4	5.7	11.5	14.7
goGPS	1.4	1.8	6.5	10.7	16.7

of a control system based on a low-cost GPS is called repeatability, namely the RMS of the residuals of daily components of the bases with respect to their mean values. To summarize the results, if a compound index such as $\mathrm{SI} = \sqrt{\sigma^2(E) + \sigma^2(N) + \sigma^2(U)}$, where SI = stability index, is taken for data at a 30-s lag, which is important for applications, the values are those reported in Table 6. This proves the possibility of detecting three-dimensional (3D) shifts from 2 to 3 mm, or more, depending on the length of the control baseline, and makes the implementation of a low-cost monitoring system possible and useful in most cases. Here, low-cost is the consequence of the use of a low-cost apparatus (in the order of hundreds of dollars) and of FOSS. Indeed, from the experiment to a routine application, some important steps have to be taken:

- A monitoring box (MB) has to be built that is capable of supplying electricity to the measuring apparatus, to protect it in adverse environmental conditions, and to transmit the data to a control center. Such a system has already been built in an experimental configuration in a joint venture by the two Italian companies GReD (Lomazzo, Italy) and Proteco (Genova, Italy).
- A center with automatic software processing has to be established to provide daily results (with suitable diagnostic indexes) to the user.

This will increase the cost of a routine service; however, the price compared to current solutions would be cut by at least a factor of approximately five. Indeed the experiments will have to continue in at least three directions including:

- Testing the MB in more realistic conditions in the field (change of temperatures, bad weather, multipath, etc.) and using existing different low-cost antennas;
- Studying the effect of substituting the reference station with another low-cost receiver or a virtual reference station (VRS); and
- Studying the possible improvements achievable by using low-cost multiconstellation receivers, such as tracking GPS, GLONASS, BeiDou, and Galileo.

This last step is crucial, because adjusting many data along different lines of sight, more spread out in the sky plot, has a very positive effect on the position dilution of precision (PDOP), and opens the possibility that even better figures in the repeatability could be achieved in the future.

Appendix. Software Configuration Parameters

The following table provides the configuration parameters for all the GNSS processing software packages used in this work.

Parameter	*Bernese*	*LGO*	*goGPS*	*RTKLIB*
Processing mode	Batch	Batch	Kalman filter	Kalman filter
Frequencies	L1	L1	L1	L1
Constellations	GPS	GPS	GPS	GPS
Ephemeris	Broadcast	Broadcast	Broadcast	Broadcast
Ionosphere	Default	Klobuchar	Klobuchar	Klobuchar
Troposphere	Saastamoinen	Saastamoinen	Saastamoinen	Saastamoinen
Elevation cutoff	15°	15°	15°	15°
Code error standard deviation	Auto	Auto	30 cm	30 cm
Phase error standard deviation	Auto	Auto	3 mm	3 mm
Ambiguity resolution	*SIGMA*	Auto	*LAMBDA*	*LAMBDA*
Cycle slip threshold	Auto	Auto	0.5 cycles	10 cm
PCO/PCV file	I08.ATX	I08.ATX	I08.ATX	I08.ATX

Note: *Default* in the case of *Bernese* means that a simple ionospheric model (Geckle and Feen 1982) is applied to code observations, whereas no ionospheric model is specified for phase double differences. ATX = extension for files in the ANTEX (ANTenna EXchange) format; PCO/PCV = phase center offset/phase center variation.

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