










15 Years of the Italian GNSS Geodetic Reference Frame (RDN): Preliminary Analysis and Considerations

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Abstract. In 2011, the IGMI (Istituto Geografico Militare Italiano) defined the new Italian geodetic reference, materialized by the Rete Dinamica Nazionale (RDN), a cluster of 99 GNSS permanent stations located in Italy and, few of them, in neighbouring areas. RDN also includes some IGS and EPN sites, so that it constitutes a densification of those two networks. The official coordinates of the 99 GNSS stations were initially obtained by computing a limited period of 28 days starting from the end of 2007 and aligned to the datum ETRS89-ETRF2000 at epoch 2008.0. After years of continuously acquired data, other studies published the stations' coordinates together with the associated velocities. This paper presents the updated results of the velocity trends considering the whole dataset now available, consisting of 15 years of data. The analysis considered only the 77 stations that worked consistently for at least five years. The workflow starts with the archive organization and pre-analysis, followed by the geodetic computation using the Precise Point Positioning approach implemented in the GIPSYX software. After the post-processing of the solutions, which included the alignment to the ETRF2000 frame and the analysis of discontinuities, the mean velocities have been computed. The latter were compared to those estimated in a previous work basing on 8 years long dataset. The comparison shows the overall agreement between the linear trends, but also highlights the importance of considering the whole dataset nowadays available to assess the behaviour of those few sites who underwent velocity changes over time.

Keywords: Italian reference network · RDN · Italian velocity field · Precise point positioning · GNSS

1 Introduction

In the last decades, the use of GNSS permanent stations has become a standard in the definition of geodetic reference frames, such as the global ITRF and the European ETRS through the IGS (International GNSS service) (<https://igs.org>) and EPN (European Permanent Network) (<https://epncb.eu>) networks respectively. This way allows a continuous monitoring of the positions, with the advantage of being able to update the coordinates

in case of natural movements, also ensuring the possibility of aligning local data using GNSS measurements. CORS (Continuously Operating Reference Station) networks are nowadays used in several technical and scientific contexts, such as the monitoring of crustal movements, landslides, and subsidence, and as a support for surveying activities in real-time.

In Italy, several stations have been installed and maintained by scientific institutes and agencies such as ASI (Italian Space Agency), INGV (National Institute of Geophysics and Vulcanology) and Universities or commercial companies. As established by the Ministerial Decree [1], in 2011 the new Italian geodetic reference frame has been materialized by the Rete Dinamica Nazionale (RDN) and aligned on the new official national datum ETRS89-ETRF2000 (2008.0). The IGMI (Istituto Geografico Militare Italiano) decided to define this GNSS network as a densification of the EPN (European Permanent Network) on a national scale. It was done by selecting already existing permanent stations, without taking charge of their direct management. EUREF (Reference Frame sub-commission for Europe) has recognized the RDN as an EPN class B densification network, including most of the stations located in our territory and meeting the European standards for geodetic reference systems [2–4].

The first release of RDN was composed by 99 GNSS tracking stations, homogeneously distributed on the Italian territory every 3.000 km², continuously acquiring and transmitting GNSS data to a Data Processing Centre situated at IGMI [1, 5]. RDN also included some stations belonging to the IGS and EPN networks, some of those located outside the Italian borders [1]. In 2011 the IGMI published an Official Note with the network's official coordinates, obtained by computing the first 28 consecutive days starting from the end of 2007. The dataset of RDN acquisitions is freely and publicly available on the Istituto Geografico Militare repository (<ftp://37.207.194.154/>), accessible from the official site (<http://www.igmi.org/rdn/>). This repository also included data from permanent stations which are not formally included in the RDN.

The definition of a dynamic geodetic frame is generally obtained through the precise computation of the stations coordinates at a given epoch and their variations over time, i.e. the average velocity parameters. These data allow to understand the local dynamics and trends which affect each specific site, also being able to update the positions considering a uniform movement over time. Despite the formal definition of the Italian reference, which fixes the coordinates at 2008.0 epoch, the dynamic nature of RDN enables to periodically update the stations coordinates taking into account the natural changes of the crustal surface [6]. The knowledge of the positions and the velocity associated to each station is obtained through refined computation processes which are usually carried out starting on huge amount of data [7, 8]. In 2018, the stations coordinates and the associated velocities obtained using the 2008.0–2016.0 dataset have been published by Barbarella et al. 2018 [3].

This paper aims to present the updated results of the velocity trends considering the whole available dataset, now consisting in fifteen years of data. The analysis follows different steps, starting from the archive organization and pre-analysis, the geodetic computation using the Precise Point Positioning [9, 10] approach, and finally the post-processing of the time-series and the velocity computation. Furthermore, discontinuities in the time-series have been evaluated. Finally, a comparison between the velocities

estimated with this last computation and those already published in previous works, based on shorter dataset, is provided.

2 Dataset

The analysed dataset considered for this publication has been selected basing on the list of 99 GNSS stations officially included in the Ministerial Decree 2011. In 2013 about the 20% of the official RDN stations was found to be not correctly working due to several problems [11]. We found the number of stations still working at the time to be 77. Note that one station was found to be not coherent with the one reported in [3], where 78 stations were considered, therefore it was not considered in the following analysis. The spatial distribution of the selected RDN stations is presented in Fig. 1, where different symbols are used to show stations belonging to IGS and EPN networks.

All the available observations with a time span ranging from the end of 2007 to the end of 2021 have been downloaded from the official IGMI repository. Any lack of data detected in the archive have been filled by downloading additional RINEX data from other public repositories (EUREF - igs.bkg.bund.de, INGV - gpsfree.gm.ingv.it). The dataset is made of daily files in RINEX format with 30 s sample rate.

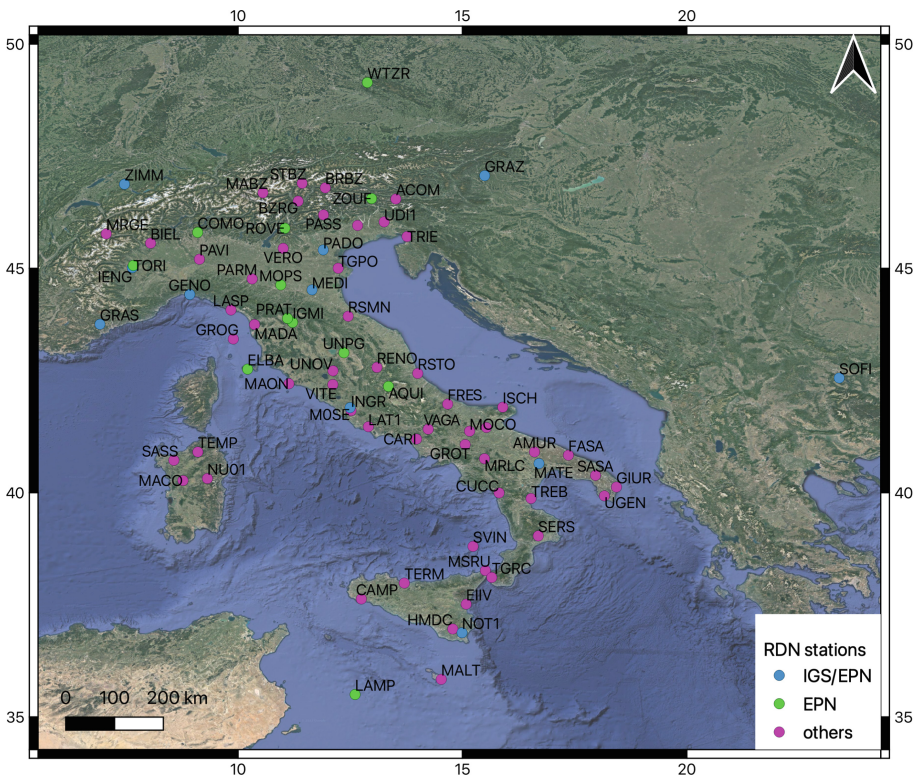


Fig. 1. Spatial distribution of the 77 RDN stations: blue dots refer to stations belonging to both IGS and EPN networks, whereas green dots show EPN sites. Pink dots refer to other stations. (Color figure online)

3 Methods

3.1 Archive Analysis

As already known by previous works [12, 13], the RDN archive does not fulfil the international standards for GNSS data sharing yet, both in terms of files metadata (RINEX headers) and log files. Therefore, the first operational phase consisted of the organization of the dataset to make it homogeneous in order to simplify the following automated elaboration procedures. Moreover, the archive analysis underlined some significant inaccuracy that had to be solved:

- different file formats (compression type, daily/hourly RINEX), RINEX version, and file-name structures;
- RINEX data related to GNSS permanent stations not included in the official RDN network;
- no reporting of instrumental changes or replacements in metadata;
- incomplete maintenance of some stations, with very poor data consistency.

3.2 Processing Using GIPSYX 1.7

The processing of re-organized and complete archive was carried out using the PPP approach implemented in the GIPSYX 1.7 software package [<https://gipsy.jpl.nasa.gov>], exploiting only GPS data. This method has proved to enable comparable precision and accuracy with those obtained by differential approaches. Moreover, the PPP approach does not require the contemporary acquisition from more than one receiver, making more flexible the data processing of large networks. GIPSYX follows an undifferenced approach, which allows elaborating each station independently from the others, allowing the reprocessing of a single station in case of mistakes [7, 14, 15]. The other great advantage of the PPP is related to the direct alignment of the coordinates onto a global reference frame and the independence from any kind of geodetic infrastructure on the ground [16].

As for the processing parameters, the Vienna Mapping Function was used as tropospheric model and the cut-off angle was set equal to 10° . IGS absolute corrections for antennas calibrations were applied through `igs14.atx` files. As for the satellite orbits, JPL (Jet Propulsion Laboratory) fiducial products were used, thus allowing direct alignment of the coordinates to the IGB14 (<https://lists.igs.org/pipermail/igsmail/2020/007917.html>), which is a consistent update of the ITRF2014. ITRS2014 coordinates were then expressed in the ETRS89 by applying the transformation parameters published by Z. Altamimi in Table 3 within the technical note [17], leading to the ETRF2000 frame.

3.3 Post-processing

Having available for each station the time-series of the solutions aligned to the ETRF2000 reference frame, these have been analyzed following different steps:

- transformation of the solutions, expressed in geocentric coordinates, to local topocentric coordinate systems (North, East, Up), together with the propagation of the covariance matrix;
- splitting of the time series basing on discontinuities due to instrumental changes (receiver/antenna) and known from already available metadata;
- visual analysis to check additional discontinuities due to earthquakes or possible local phenomena;
- calculation of the regression lines for each part of the time-series using weighted least squares approach;
- outlier rejection considering a 3σ threshold: outlier solutions have been rejected in all three components even if only one of them had values exceeding the threshold;
- discontinuities resolution after solving the jumps between the consecutive parts of the series, by implementing 1) the Heaviside step function [18], or 2) calculating independent slopes for different time-series spans in the case of steady velocity changes over time;
- computation of the regression lines of the recomposed time series and related slopes. These values are representative of the mean velocity for each station over the whole analysed period (thereafter expressed in mm/years).

4 Result and Discussion

Following the above described steps, the mean velocity in the analyzed period for each of the selected stations has been computed. Figure 2 shows the spatial distribution of the velocities for the planimetric components referred to the ETRF reference frame.

Table 1 reports the velocities of the selected RDN stations considering fifteen years of data. Velocities are expressed in the local topocentric components, North, East and Up, together with the related uncertainties, and all the values are expressed in mm/year. These velocities (Table 1) can be used for different purposes such as geodesy and geodynamics analysis. For example, they can be considered when estimating the crustal deformations affecting the Italian territory and its motion relative to the stable part of the Eurasian plate.

The computed trends are also shown in Fig. 2, which highlight the heterogeneous velocity field in the Italian peninsula, as already observed by Barbarella et al. 2018 [3]. Different clusters of vectors can be observed, mainly related to tectonic boundaries between the Eurasian and African plates. Position rates up to 5 mm/y can be observed in the south and eastern part of Italy, whereas the Alps, Sardinia, and the north-western regions, which are strongly linked to the stable part of Eurasian plate, show almost no residual ETRS89 velocities [19].

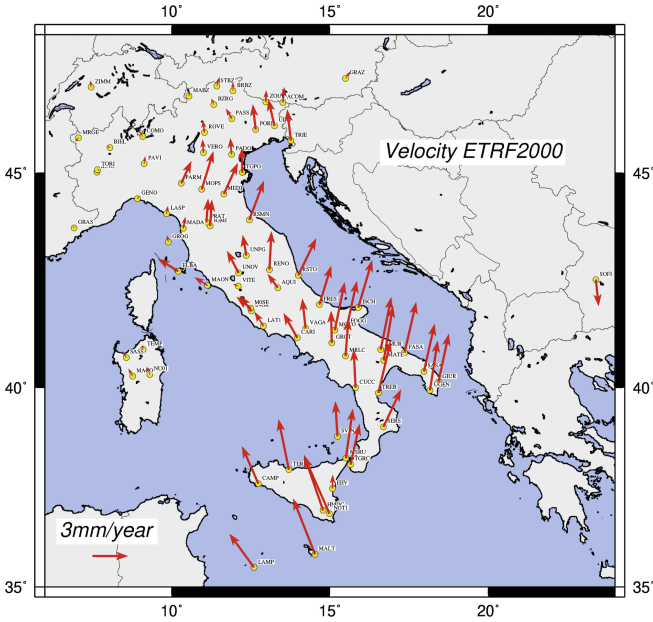


Fig. 2. Velocity vectors map in ETRF estimated in the timespan ranging from 2007–2021 for the 77 RDN stations.

Table 1. Velocities of the RDN stations expressed in the local topocentric components (North, East, Up) and the related uncertainties. Values are expressed in mm/year.

SITE	V_N	V_E	V_U	σV_N	σV_E	σV_U	SITE	V_N	V_E	V_U	σV_N	σV_E	σV_U
ACOM	1,3	0,1	1,0	0,003	0,004	0,012	MRGE	-0,3	-0,2	1,5	0,005	0,004	0,015
AMUR	4,4	0,9	-0,4	0,003	0,003	0,010	MRLC	3,2	0,3	0,7	0,015	0,011	0,018
AQUI	1,2	-0,9	-0,8	0,007	0,008	0,013	MSRU	4,1	0,6	-0,2	0,004	0,004	0,014
BIEL	0,1	-0,2	0,6	0,004	0,003	0,012	NOT1	4,8	-2,1	-1,3	0,005	0,006	0,016
BRBZ	0,7	0,0	1,1	0,005	0,004	0,016	NU01	0,7	-0,3	-0,3	0,020	0,019	0,047
BZRG	0,5	-0,2	1,2	0,006	0,004	0,013	PADO	1,4	-0,1	-0,7	0,008	0,004	0,011
CAMP	3,1	-1,4	0,3	0,013	0,012	0,048	PARM	1,8	0,8	-0,9	0,005	0,003	0,020
CARI	2,1	-1,2	-0,2	0,019	0,013	0,046	PASS	0,8	-0,5	0,4	0,006	0,006	0,016
COMO	0,4	-0,3	-0,3	0,004	0,006	0,010	PAVI	0,6	0,1	-0,8	0,003	0,006	0,009
CUCC	3,2	-0,2	-0,1	0,006	0,013	0,024	PORD	2,1	-0,3	-1,0	0,006	0,004	0,016
EIIV	1,2	0,0	1,0	0,015	0,007	0,016	PRAT	2,0	0,1	-0,2	0,004	0,005	0,014
ELBA	1,1	-1,7	-0,6	0,006	0,007	0,018	RENO	3,2	0,2	0,3	0,019	0,015	0,063
FASA	4,2	1,0	-1,0	0,016	0,020	0,102	ROVE	1,0	-0,1	0,5	0,004	0,004	0,017
FOGG	3,8	0,9	-0,1	0,004	0,004	0,012	RSMN	3,3	1,2	0,6	0,004	0,004	0,013

(continued)

Table 1. (continued)

SITE	V _N	V _E	V _U	σV _N	σV _E	σV _U	SITE	V _N	V _E	V _U	σV _N	σV _E	σV _U
FRES	3,2	1,0	-0,7	0,005	0,005	0,015	RSTO	3,1	1,5	-1,0	0,005	0,004	0,010
GENO	0,2	0,2	-0,4	0,004	0,003	0,012	SASA	4,0	0,9	-1,0	0,009	0,014	0,033
GIUR	4,1	0,9	-1,3	0,003	0,003	0,012	SASS	0,5	-0,3	0,4	0,003	0,003	0,012
GRAS	0,2	-0,1	-0,3	0,004	0,003	0,009	SERS	3,1	1,5	0,3	0,004	0,004	0,014
GRAZ	0,6	0,4	-0,4	0,003	0,003	0,011	SOFI	-2,2	0,2	-0,7	0,004	0,004	0,016
GROG	0,6	-0,1	-0,2	0,005	0,005	0,017	STBZ	0,8	0,2	1,1	0,006	0,005	0,018
GROT	2,7	-0,1	0,9	0,003	0,003	0,011	SVIN	2,9	-0,2	0,2	0,007	0,007	0,019
HMDC	4,6	-1,6	-1,2	0,005	0,008	0,018	TEMP	0,4	-0,1	-0,1	0,005	0,007	0,017
IENG	-0,1	0,2	-0,1	0,004	0,003	0,010	TERM	4,2	-0,9	0,9	0,024	0,018	0,069
IGMI	2,2	0,2	-0,6	0,007	0,003	0,013	TGPO	2,1	0,0	-5,2	0,007	0,005	0,015
INGR	1,3	-1,0	-0,4	0,003	0,005	0,010	TGRC	3,4	0,8	0,5	0,013	0,012	0,044
ISCH	4,0	1,2	-0,5	0,003	0,003	0,012	TORI	0,0	0,2	0,4	0,004	0,004	0,012
LAMP	2,8	-2,1	-1,2	0,006	0,007	0,012	TREB	4,4	1,0	0,8	0,013	0,016	0,043
LASP	0,6	0,1	-0,5	0,003	0,003	0,010	TRIE	2,6	-0,3	-0,7	0,003	0,005	0,011
LATI	1,2	-0,7	1,1	0,004	0,006	0,017	UDII	2,2	-0,5	-0,5	0,003	0,003	0,011
M0SE	1,0	-1,2	-0,5	0,003	0,003	0,011	UGEN	4,2	0,7	-0,9	0,004	0,003	0,011
MABZ	0,4	0,1	1,9	0,006	0,005	0,019	UNOV	1,9	-1,0	0,5	0,018	0,019	0,065
MACO	0,6	-0,4	0,7	0,011	0,009	0,040	UNPG	1,7	-0,3	-0,7	0,004	0,005	0,012
MADA	0,9	0,2	-0,9	0,004	0,004	0,017	VAGA	2,5	-0,3	0,6	0,019	0,011	0,014
MALT	4,7	-1,8	-0,6	0,005	0,005	0,019	VERO	1,1	-0,1	0,3	0,006	0,005	0,011
MAON	0,7	-1,1	-0,8	0,004	0,003	0,013	VITE	0,2	-0,5	-1,4	0,013	0,020	0,050
MATE	4,6	0,8	0,1	0,003	0,003	0,010	WTZR	0,4	0,0	-0,7	0,004	0,004	0,013
MEDI	2,6	1,2	-2,0	0,005	0,006	0,013	ZIMM	0,5	-0,1	0,6	0,003	0,003	0,010
MOCO	4,0	0,8	-0,2	0,004	0,004	0,013	ZOUF	1,0	0,0	0,7	0,003	0,003	0,010
MOPS	3,2	1,0	-1,8	0,003	0,004	0,013							

Considering the availability of a common dataset computed by Barbarella et al. 2018 [3], relating to a shorter period (2008.0–2016.0), a comparison between the velocities published in that work and those estimated in this study has been performed. Note that positive differences result when our values are higher than Barbarella et al. 2018 ones. Obtained Since similar processing methodologies were used, the main differences between the two datasets lay in the time span increased of 6 years. The vectors in Fig. 3 show the velocity differences for each analyzed site between the two considered datasets. It can be observed that most of the differences are quite negligible having magnitudes in the order of few tenths of mm/y. Only a few stations show higher differences, up to a couple of mm/y. Their spatial distribution does not evidence any systematic effects related to specific areas.

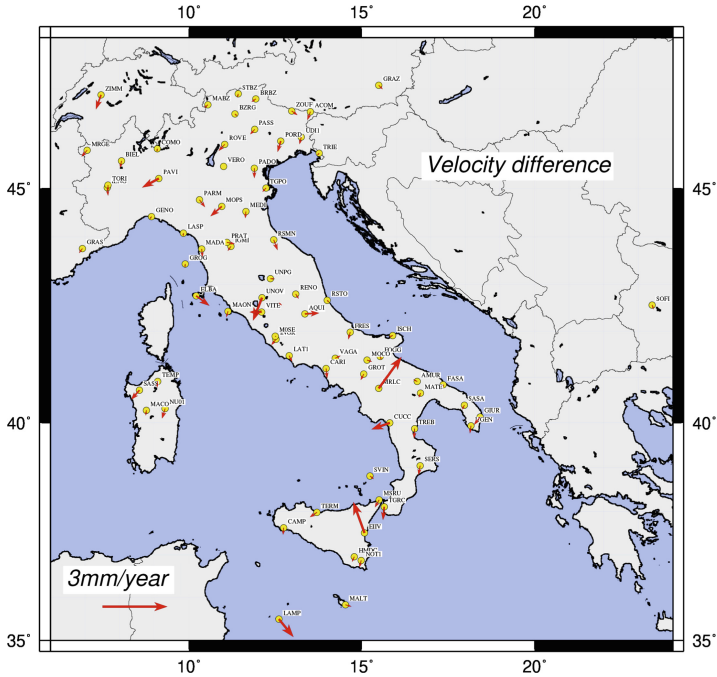


Fig. 3. Vectors of the velocity differences between Barbarella et al. 2018 dataset and the 15-years dataset, for the 77 RDN stations. Positive values mean that Barbarella et al. 2018 velocities are lower than the current dataset ones.

Figure 4 shows the histogram of the residual velocities between the two considered datasets, relating to the three topocentric directions Northing, Easting and Up.

Considering the plan components, only 3 sites have velocity differences higher than 1 mm/y, while most of the differences are less than 0.4 mm/y for the North component and less than 0.2 mm/y for the East one. Residuals along the Northing direction are slightly biased (-0.2 mm/y), suggesting that a reduction of the overall velocity field might have occurred in the last years. This fact should be verified using further data and studied together with geological observations and considerations.

Differences along the Up component are generally higher: 11 sites have residual rates greater than 1 mm/y, while the other sites are characterized by differences lower than 0.5 mm/y.

The highest values of the velocity differences can be due to several factors, primary related to changes in the geomorphology of the site occurred in the period 2016–2022. The geomorphology of the area may affect the velocity depending on the occurrence of local phenomena such as landslides or earthquakes, that may no longer make valid the hypothesis of linearity of the velocity field. This can be evidenced by analysing a significantly longer time span. Figure 5 highlights the differences in the consistency of the two considered datasets in terms of total number of RINEX files analyzed for each station.

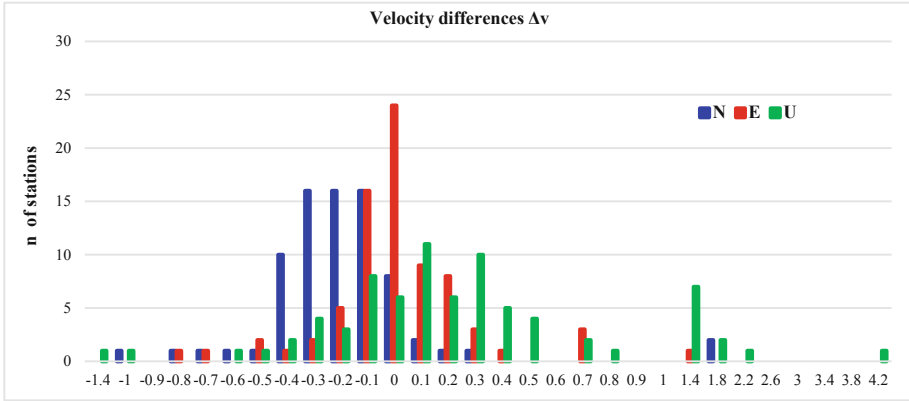


Fig. 4. Histogram of the velocity differences, for the three components of the local topocentric system. X-axis relates to the difference values, y-axis relates to the number of stations for each class of differences. Values are expressed in mm/year. Positive values mean that Barbarella et al. 2018 velocities are lower than the current dataset ones.

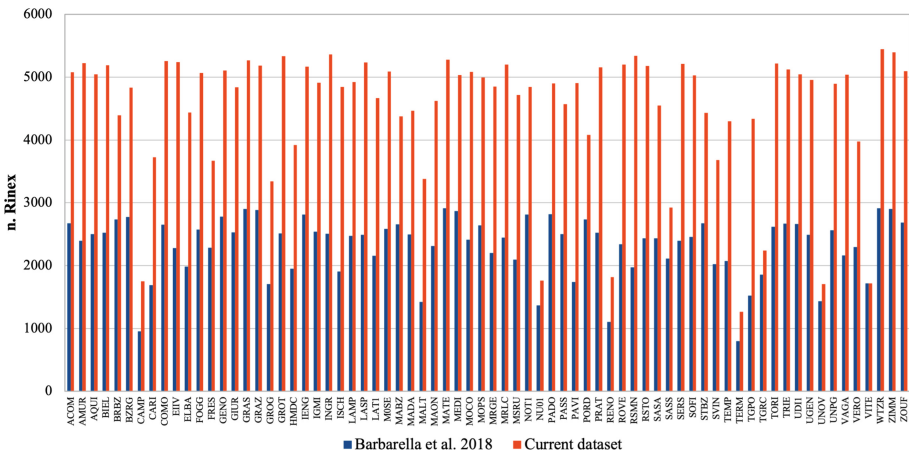


Fig. 5. Consistency histogram of the two considered datasets, in terms of total number of RINEX files analyzed for each selected station. Blue bars refer to Barbarella et al. 2018 [3], red bars refer to the current dataset. (Color figure online)

Figure 6 provides an example of time series who led to different mean velocities, showing data related to MRLC station. Considering the period after 2016 the velocities have changed enough to affect the whole trends. This becomes appreciable only considering the whole time span while it was not evident from the dataset considered in the previous work.

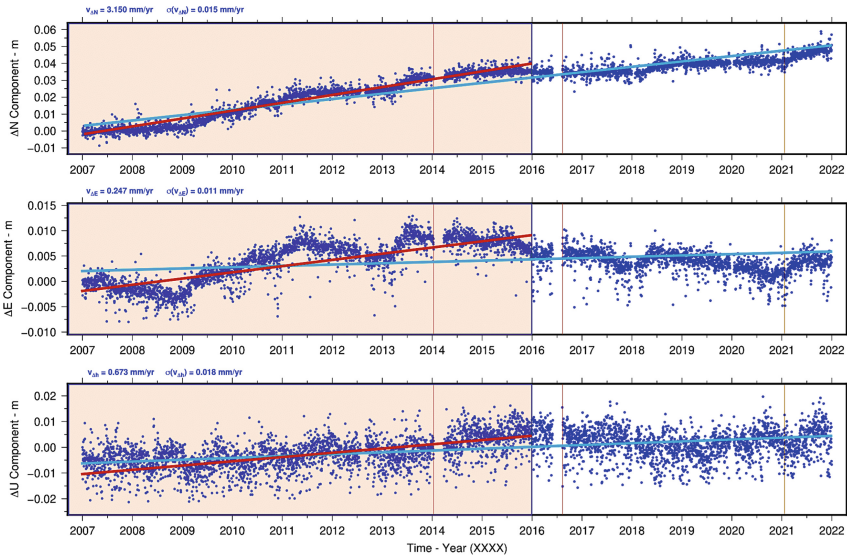


Fig. 6. Example of the MRLC station time series expressed in the three topocentric components. The periods analyzed in Barbarella et al. 2018 is highlighted with a shady background. The regression lines considering the two different time spans, for each component, are showed: red line for the shorter period, blue line for fifteen years dataset. (Color figure online)

5 Conclusion

Starting from the 15 years of GNSS data provided by the RDN stations, in this work the velocity field of the Italian reference network has been calculated and updated with respect to what already published. A previous work already estimated, by following similar data processing, the velocity field relying on a 8 years time-span. The comparison between the two sets of linear trends highlighted the good stability already reached by the frame in 2016 due to the long-term acquisitions. Nevertheless, some stations shown linear trends significantly different from those previously estimated, so evidencing the needs of considering also newly acquired data. These trend variations should be studied to assess whether they depend on local or regional phenomena. Moreover, being the Italian peninsula affected by relevant residual displacements with respect to the Eurasian tectonic plate, after such a long period from the definition of the Italian formal reference, within the geodetic community should rise the need to update the reference coordinates of the RDN network. This ought to be done considering the linear trends evidenced in this paper, also taking care of the fact that jump discontinuities are present in the dataset and, in some cases, the velocity ratios vary over time for the same site. In other words, it might be the time to follow up the international standards for reference frames management as done for the IGS and EPN reference networks. Finally, also the repository used for the RDN data sharing should be integrated with log-files containing stations metadata and all the information for proper use of the GNSS files.

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