A methodology investigation for a semi-kinematic datum realization in Greece combining geodetic and geological data

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ABSTRACT

Greece is one of the most active geodynamic areas in the world with variety of type faults and geomorphological features, (e.g. North Anatolian Trough, Cephalonia Transform Fault etc.) which effects to Terrestrial Reference Frame (TRF) realization. Last years, the need of a new modern geodetic reference frame become more and more obvious, in order to replace the Greek Geodetic Reference System 1987 (GGRS'87) which is the official national geodetic datum. The GGRS'87 is a static TRF and have been implemented with classical geodetic techniques in trigonometric benchmarks (BMs). In addition, the measurements have been executed in a long period of about five decades ago. The main scope of the present study is on one side to show up the influence of the earthquake events in a modern TRFs such as, the International Terrestrial Reference Frame 2014 (ITRF2014) and on the other side to provide a methodology which treats this issue in a semi-kinematic datum, exploit the GNSS permanent networks. We proposed a modern approach that combining geodetic and geological techniques in order to improve the estimation of deformation field after strong earthquake events using observations as obtained from GNSS stations and dislocation modeling following the theoretical Okada approach. An essential parameter, in order to do the back-wise analysis in a semi-kinematic datum, is the geodetic velocity estimation which derived from a daily GPS/GNSS time series analysis. The GPS/GNSS data processing was carried out with GAMIT/GLOBK software package following all the recommendations of IGS. For coordinate time-series analysis (covering a time span of more than 16 years) we use firstly, a simply linear trend with the assumption that all error sources characterized as a white noise. Secondly, we apply an automatic robust estimator Median Interannual Difference Adjusted for Skewness (MIDAS) which is resistant to common problems (e.g. discontinuities, outliers, seasonality). Analyzing the post-seismic displacements for three greater seismic events in the Greek area (Samothrace, Lefkada and Cephalonia) of the period of 2012 – 2016 in a network of 47 cGPS sites, we found that have an impact of 33.5 cm on 3D position estimation for the Lefkada seismic event. According to the proposed methodology, which considers the EQ offsets in GNSS position time series, the improvement in 3D position is treated on sub-centimeter level.

I. INTRODUCTION

A. *Advances from GNSS technology*

The Global Navigation Satellite Systems (GNSS) is a very important tool to observe the geodynamic processes on Earth's crust, such as plate tectonic motions, volcanic activity monitoring, post-glacial rebound. GNSS consists of multi satellite constellations of **Global Positioning System** (GPS) which created by U.S. Department of Defense, the Russian **GLObal NAvigation Satellite System** (GLONASS), also the European GNSS as called **Galileo** and finally the Chinese **BeiDou Navigation Satellite System** (BDS).

In the last decades, GNSS has seen a significant improvement on the precision of the measurements, giving the opportunity to study geophysical signals, through the analysis of daily coordinates monitoring or high rate GNSS observations. However, along with increase of precision, the cost of GNSS receivers decreases with the time. Thus, large GNSS permanent networks (i.e. IGS, EPN) over the Globe are established, leading to the availability of a denser and more accurate velocity field (Fotiou and Pikridas 2012). The IAG Reference Frame Sub-commission for Europe (EUREF), in Wroclaw annual Symposium at 2017 (Resolution 2), recognizing that national, dense velocity fields are now available in several areas of Europe and considering the demand to derive a dense European velocity field which is compatible with nationally implemented velocity fields (Brockmann et al. 2017).

B. *Seismicity over Greek area*

In this study, the most characteristic geomorphological features of the Greek territory and the strongest earthquakes (EQ) events which occurred in a period between 2012 – 2016 as depicted in Figure 1., are present. According to EQ catalog which provided by the Institute of Geodynamics of National

Observatory of Athens (www.gein.noa.gr), the number of the strong EQ events with magnitude more than 6 M_w for the study period is total 4.

With chronological order, the most intense EQ events was occurred: i) on Cephalonia Island at the January of 2014 with magnitude 6.1 M_w, ii) in the Northeastern region of Aegean Sea, on the Samothrace Island with magnitude 6.9 M_w, iii) on Lefkada Island at the Ionian Sea with magnitude 6.5 M_w. For these three EQ events we have estimate the displacements using the observations from the relative GNSS permanent networks. In Table 1 detail information, about the related EQs and the nearest to epicenter GNSS station, is provided.

Table 1. Details about EQ events and the nearest GNSS stations

Location of EQ epicentre			GNSS station	Distance from EQ [km]
Region	Long.	Lat.		
Cephalonia	20.41	38.19	VLSM	34
Samothrace	25.40	40.29	LEMN	47
Lefkada	20.45	38.76	PONT, SPAN	20, 19

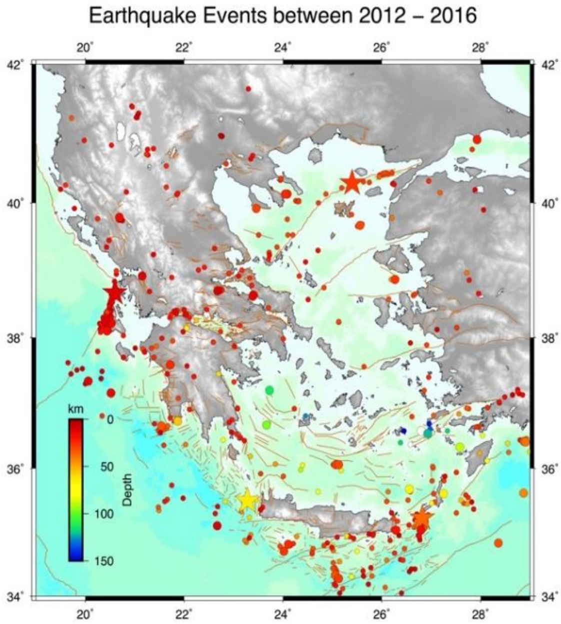

Figure 1. Seismicity of Greece 2012-2016 and the active faults contained in NOAFaults database (Ganas et al. 2013)

II. METHODOLOGY

A. *The concept*

The main idea for the new/modern semi kinematic datum in Greece based on a novel approach, which takes into account the geodetic velocity field and the deformation field due to strong earthquake events. Since the last years, many studies focused on the implementation of a new Greek geodetic reference frame, propose different methodologies to overcome the effect of the strong geodynamic activity of Greece. The last years, a plethora of studies exploit the GNSS technique, for geodetic velocity estimation over the South-East Mediterranean region and especially in Greece (e.g. McClusky et al. 2000; Hollenstein et al. 2008; Floyd et al. 2010; Bitharis et al. 2016). Chatzinikos et al. (2015) propose the implementation of a semi-kinematic datum, based on seven stable crustal blocks, which are describes the geophysical structure of Earth's crust. Bitharis et al. (2017) show up the impact of inhomogeneous Greek velocity field with emphasis to kinetic energy, proposing an Optimal Reference Frame (ORF) which based on a criterion of minimizing the relative angular momentum implies the realization of a reference frame whose total kinetic energy is minimal (Dermanis 2001).

A semi-kinematic datum generally defined in a specific reference epoch, given the possibility to transform the kinematic point coordinates from each measurement epochs to the reference epoch, using the geodetic velocities. On previous study (Bitharis, Papadopoulos, et al. 2018), we emphasized the necessity of a geodetic velocity in order to process regional GNSS networks and therefore to establish a modern semi-kinematic reference frame in Greece.

The mathematical formula of our proposed methodology described by the following equation:

$$\mathbf{X}^{o}_{t_i} = \mathbf{X}^{\alpha}_{t_j} + \dot{\mathbf{X}}_{t_i - t_j} + \mathbf{Eq}^{n}_{t_i - t_j} \tag{1}$$

where $\mathbf{X}^{o}_{t_i}$ is the vector of adjusted coordinates at the reference epoch t_i, which the semi-kinematic datum is fixed. $\mathbf{X}^{\alpha}_{t_j}$ denote the vector of a-priori coordinates at t_j epoch. Also, with $\dot{\mathbf{X}}_{t_i - t_j}$ in the vector of geodetic velocities as estimated. Finally, with $\mathbf{Eq}^{n}_{t_i - t_j} = \left[\mathrm{eq}^{n}_{x} \quad \mathrm{eq}^{n}_{y} \quad \mathrm{eq}^{n}_{z}\right]_{t_i - t_j}$ we describe the strong earthquake displacements in 3D geocentric cartesian coordinate system of each n point.

Also, Equation 1, can be formed in detail in matrix equations as:

$$\begin{bmatrix} \mathrm{X}^n \\ \mathrm{Y}^n \\ \mathrm{Z}^n \end{bmatrix}^{o}_{t_i} = \begin{bmatrix} \mathrm{X}^n \\ \mathrm{Y}^n \\ \mathrm{Z}^n \end{bmatrix}^{a}_{t_j} + \begin{bmatrix} \mathrm{Vx}^n \\ \mathrm{Vy}^n \\ \mathrm{Vz}^n \end{bmatrix} + \begin{bmatrix} \mathrm{eq}^n_x \\ \mathrm{eq}^n_y \\ \mathrm{eq}^n_z \end{bmatrix}_{t_i - t_j} \tag{2}$$

Especially, in the present study, we are lead to the assumption that the reference epoch of the semi-kinematic datum is the 2012.01. The coordinates of 47 selected GNSS stations (see; Figure 2) in epoch 2016.01 were transformed to the reference epoch using the estimated geodetic velocities. This selection was done with the criterion of common GNSS stations in these two different epochs.

B. *GNSS data analysis*

The GNSS data process was performed using GAMIT (**G**NSS **a**t **MIT**), which is a fully operated scientific software package, oriented to crustal deformation studies (Herring et al. 2010). Our analysis was extended in a long-time period covering 16 years (2001-2016) of continuously GPS (daily) data for more than 220 European Continuously Operating Reference Stations (CORS). Should be mentioned that the majority of GNSS stations was primary established for Network Real Time Kinematic (NRTK) applications. The most GNSS sites are located in areas with strong geodynamic activity such as Ionian Sea and Corinth Rift, are suitable for geodynamic investigation purposes. The monument foundation in the most sites is a roof, following the recommendations of EPN/EUREF. In our local network 5 Greek EPN stains are included (AUT1, NOA1 LARM, PAT0 and TUC2).

As a first step, the quality check of GNSS 30-sec RINEX files was performed. Next, we estimate daily loosely constrained solutions of site positions, where orbital and Earth Orientation Parameters (EOP) were held fixed to IGS final and IERS Bulletin A values with weights. The weighting strategy is dictated by the network scale and the a-priori Earth rotation tables, thus the EOPs are constrained as recommended for a continental scale analysis (Herring et al. 2010). The whole GNSS network was separated in 6 individual sub-networks using more than 24 common IGS stations for each sub-network.

Additionally, about GNSS analysis strategy, we follow the recommendations of IGS/EUREF analysis centers, Zenith Total Delay (ZTD) adjusted every 2-hour interval using Vienna Mapping Function 1 (VMF1) (Boehm et al. 2006). Concerning the Solid Earth Tides, the IERS2003 conventions were followed. In addition, the FES2004 ocean loading model (Lyard et al. 2006) and the Atmospheric Pressure Loading corrections (Tregoning & van Dam 2005) were applied.

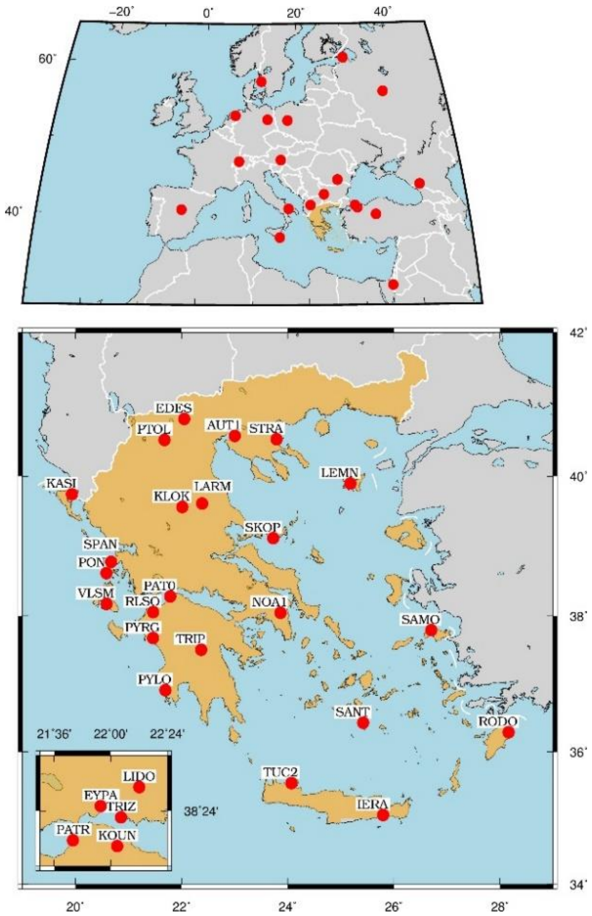

Figure 2. The spatial distribution of Greek GNSS Network (below) and core IGS Network (above).

On the second step, all the individual sessions of the six local sub-networks were combined, using a seven-parameter Helmert transformation to estimate site coordinates in ITRF2014 (Altamimi et al. 2016) from individual daily solution.

The estimation of the geodetic velocities is a very important step in our study, due to key-role who plays on our proposed methodology. Also, it is mandatory to clean/remove the outliers from daily coordinate time-series, in order to reflect the geophysical signals and the geodynamic processes of the Earth's crust. Thus, we follow two different approaches for the geodetic velocity estimation, comparing them to choose the most suitable for our case. Initially, a simple linear model was fitted on the daily coordinated time-series. Correspondingly, we apply a robust trend estimator MIDAS approach (Blewitt et al. 2016) which developed to make trend estimates resistance to step discontinuities in time-series.

C. *Timeseries Coordinates of LEMN, PONT, SPAN, VLSM stations.*

In our analysis, we estimate the post-seismic displacements using the daily coordinate timeseries, which is a very useful tool for natural geohazards monitoring, providing a comprehensive view of GNSS station trajectories.

On Figure 3, we represent the daily (raw) coordinate timeseries of the nearest GNSS stations to each EQ event that we study (see; Table 1). We choose to represent only a small time-span window of the timeseries, because we prefer to focus on the time when the earthquake event was occurred.

The estimated post-seismic displacements for the selected GNSS sites for the three EQ events are given in Table 2. These values calculated using average differences of a weekly coordinates for a period of one month before and after the EQ event. We choose to calculate the displacements using the coordinates of a month period after the events due to post-seismic relaxation, which is a phenomenon caused from large EQs ($M_w \geq 5.5$) and can be described as a time-dependent redistribution of displacement (Feigl & Thatcher 2006). The most recent realization of ITRF (Altamimi et al. 2016), including parametric fitting models (*Log)arithmic, (Exp)onential, Log+Exp, and Exp+Exp* in coordinate time series to reduce the impact of large EQs.

The highest offsets in GNSS timeseries was founded in PONT station, which located on the hanging-wall of the fault. The co-seismic displacements on topocentric coordinate system, calculated as 38 cm to the south and 21 cm to the west for PONT. The second permanent station SPAN moved almost to the same direction, with smaller values 6 cm to the south and 7 cm to the west. Our results are confirmed in previous studies (Ganas et al. 2016).

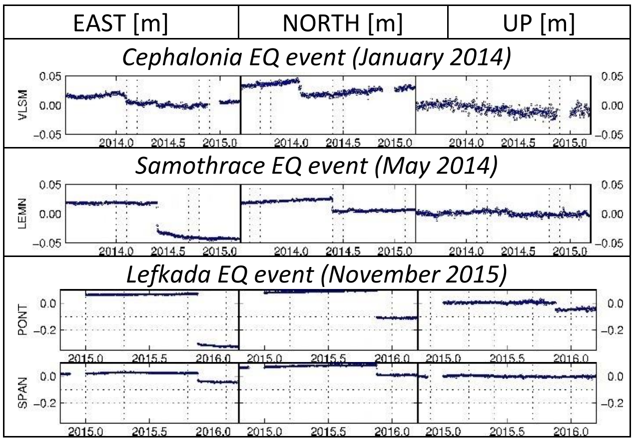

Figure 3. Daily raw coordinate timeseries of the nearest GNSS stations. VLSM (Cephalonia), LEMN(Lemnos) and PONT, SPAN (Lefkada).

The geodetic offsets/displacements that detected for timeseries analysis they have compared with those from a theoretical model, so-called Okada approach (Okada 1985), which provides analytical solutions for deformations due to shear and tensile faults in an elastic half space. Especially, for the two EQs which occurred in the Ionian Sea (i.e. Cephalonia and Lefkada) a detail view given by (Bitharis, Pikridas, et al. 2018). Additionally, on previous study by Sboras et al. 2015, it was found that the comparison between modelled and observed ground deformation was fully compatible for Samothrace EQ. Co-seismic deformation modelling helps to detect discontinuities in GNSS time series (Métivier et al. 2014)

Table 2. The estimated displacements using GNSS time-series, in geocentric cartesian reference system as expressed in ITRF2014 (units: m)

GNSS stations	eq_x	eq_y	eq_z
VLSM	0.017	-0.024	-0.012
LEMN	0.033	-0.009	-0.045
PONT	0.255	-0.126	-0.334
SPAN	0.061	-0.055	-0.047

D. *Assessment of geodetic velocities with different fitting models*

On current subsection we considered to perform the analysis of the geodetic velocity estimation, with simple linear model, assume that the errors are characterized as a white noise, and on the other side using a MIDAS which is a more sophisticated approach. The results of two different approaches are shown on Figure 4. According to the results, we can detect that the differences appeared in the intense geodynamic activity such as: Ionian Sea, Lemnos Island and Santorini volcano. In Figure 5, we shown the histogram of geodetic velocities differences between Linear Model and MIDAS trend estimator. The differences are very closed in the most sites, with values smaller than a 2 mm/yr on the horizontal component for the 80% of the GNSS sites and 0.5 mm/yr for the 70% of the network on the vertical component respectively. Nevertheless, we have significant differences in the GNSS stations which are located in Ionian Sea (e.g. PONT, SPAN and VLSM) and on Northeastern Aegean Sea (LEMN and SAMO). We can assume, that these different results are due to the strong earthquake events (see; Table 1) which effects on the daily GNSS coordinates timeseries (see; Figure 3). Especially, about GNSS station PONT, which is located on the south region of Lefkadas Island, we have the grater differences, in both velocity magnitude and azimuth/angle.

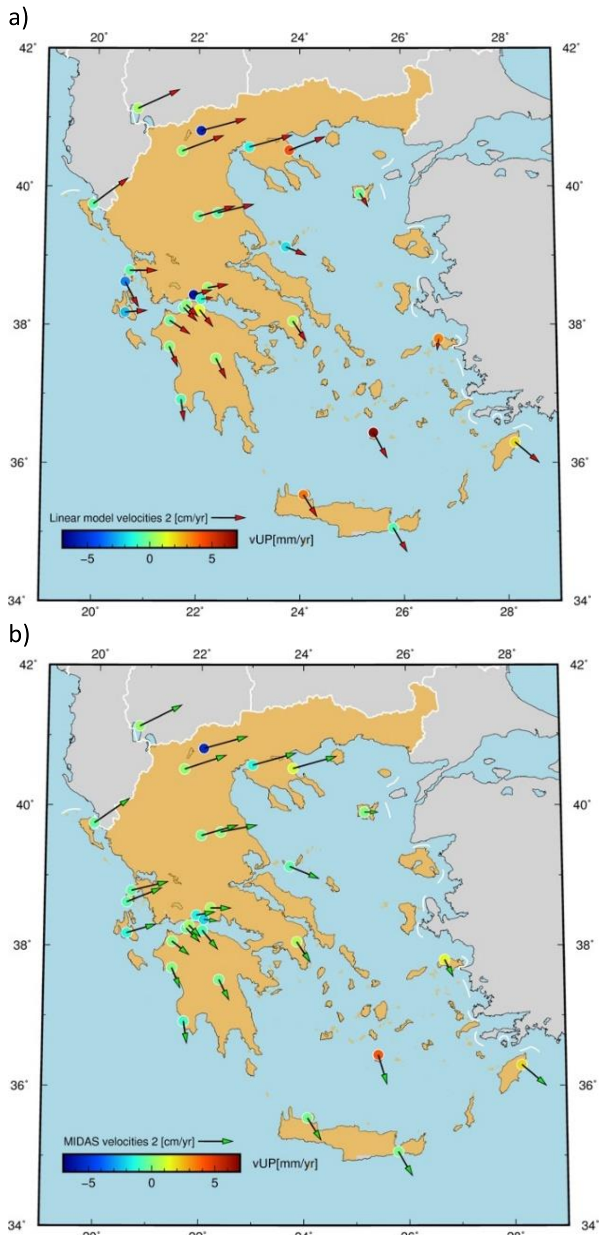

Figure 4. Geodetic velocities over Greece applying: a) Simple Linear trend model (red vectors), b) MIDAS trend estimator (green vectors). Color bar depicts the vertical component.

Concerning to vertical velocities, we have a small yearly temporal variation, due to the missing of intense geophysical phenomena, such as postglacial rebound, as confirmed in previous studies (Bitharis, Ampatzidis, Pikridas, Fotiou, et al. 2017). According to the results obtained by the comparison between the two different approaches, we appreciate that the vertical velocity (vUp) estimation using MIDAS, provides a smoother pattern on the vertical component. This can be explained by the fact that the linear model is more sensitive overcame the GNSS timeseries offset/gaps and generally the discontinuities.

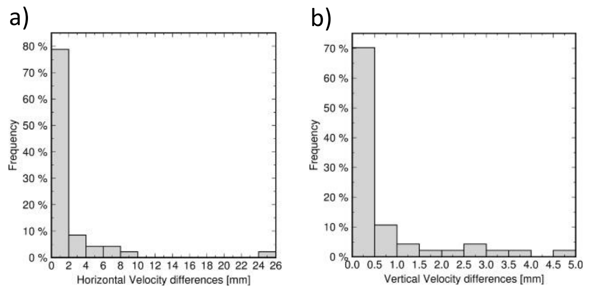

Figure 5. Histogram of geodetic velocities differences between Liner Model and MIDAS trend estimator, at Horizontal (a) and Vertical (b) component.

III. Results and discussion

We proposed a methodology of a semi-kinematic datum which can maintain and improve the geodetic infrastructure which is the prerequisite a for long-term sustainability of a Greek Reference Frame. Including a correction term of EQ offsets on a backward analysis using a time depended transformation model as formed in Equation 1, we ensure a most consistent GNSS network in a specific reference epoch.

The necessity of a datum modernization, was reflected in Figure 6, where the differences between adjusted - observed coordinates at reference epoch of the semi-kinematic datum are illustrated. The time-depended transformation was carried out following four different approaches:

1) *Linear fitting model*
2) *Linear fitting model with EQ correction term*
3) *MIDAS approach*
4) *MIDAS approach with EQ correction term*

If we assume that the daily coordinates time-variation, follow a linear trend, having estimates of this velocity with absolute accuracy, and we have no effects from error sources (e.g. EQ offsets, equipment changes, antenna replacements), the differences between adjusted - observed coordinates at any reference epoch should be completely the same. The largest differences have been detected in the Ionia Sea and the wider area of Northeast Aegean Sea, as expected due to strong EQ events. These results, using a linear fitting model (1) are illustrated in Figure 6 for the horizontal component. The mathematical expression is given by the following equations:

$$\Delta\mathbf{X} = \mathbf{X}^{o}_{t_i} - \mathbf{X}^{\alpha}_{t_i} \qquad (3)$$

Where, $\Delta\mathbf{X}$ is the vector of coordinate differences, between adjusted $\mathbf{X}^{o}_{t_i}$ and observed $\mathbf{X}^{\alpha}_{t_i}$ coordinates at reference epoch $t_i = 2012.01$, as transformed using the four different velocity methodologies.

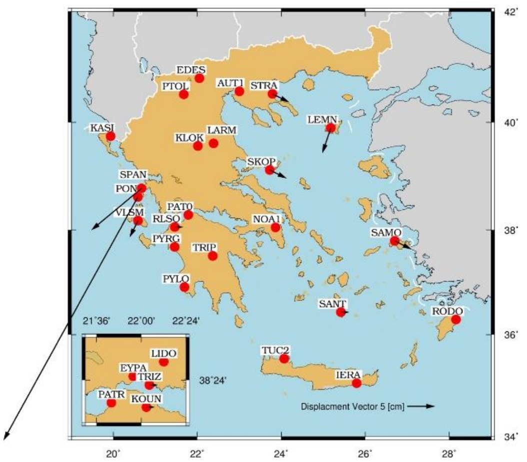

Figure 6. Differences between adjusted - observed coordinates at reference epoch of semi-kinematic datum using geodetic velocities of linear model.

Table 3, lists the statistical quantities between the four different approaches as mentioned. According to the results, we found that the EQ correction term which denoted as $\mathbf{Eq}^{n}_{t_i-t_j}$, reduce significant the differences between adjusted and observed coordinates at reference epoch 2012.01. Thus, the mean differences using the correction term reduced more than 62% from 2.1 ±6.4 cm to 0.8 ±0.6 cm for MIDAS and 35% from 4.8 ±1.4 cm to 1.5 ±0.4 cm for simple linear model respectively. Should be note, that an interesting quantity is the standard deviation (STD), which used to quantify the amount of variation/dispersion of the coordinate difference in our case.

Table 3. 3D statistics of different models between adjusted - observed coordinates (epoch 2012.01) applying correction term $\mathbf{Eq}^{n}_{t_i-t_j}$ and without $\varnothing$

Statistics (units: cm)	MIDAS		Linear model	
	$\varnothing$	$\mathbf{Eq}^{n}_{t_i-t_j}$	$\varnothing$	$\mathbf{Eq}^{n}_{t_i-t_j}$
MIN	0.1	0.1	0.2	0.2
MAX	44.2	3.8	33.5	10.4
MEAN	2.1	0.8	1.7	1.1
STD	6.4	0.6	4.8	1.5
1-α=95%	1.8	0.2	1.4	0.4

The largest values of 3D differences (MAX) in the case that we ignore the EQ term ($\varnothing$), are founded in the GNSS stations which are close to EQ events (see; Table 2) as expected. One of the advantage of our methodology is that can minimize these remarkable values. Especially, the seven GNSS sites with the largest 3D differences are depicted in Figure 7 for the four approaches.

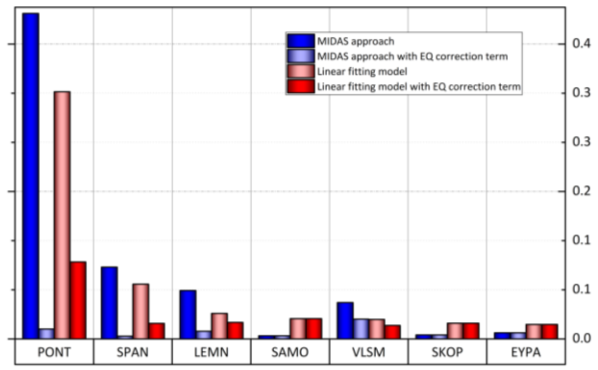

Figure 7. 3D Differences between MIDAS and Linear model approach applying correction term and without.

Summarizing, the MIDAS approach with EQ correction term provides the most reliable results in compare with the remain approaches, in special cases, that we have strong offsets on GNSS timeseries due to EQ activity or discontinuities. However, the linear fitting model with EQ correction term gives acceptable results in the case that coordinates following a linear time-variation. Consequently, in areas with active geodynamic behavior such as: Greece, Italy, New Zealand, Japan, the MIDAS approach with EQ including correction term could be the proper.

The proposed methodology, provides consistent results on discrete points, where a GNSS station has been established, but it not possible to have knowledge in the wider/neighbor area. To overcome this weakness, we develop a methodology where we can combine the theoretical displacements from Okada model, with the observed displacements, as estimated by GNSS analysis. This synthetic methodology, gives the advantage that could provide a continuous deformation field based on GNSS data and geological model, consider the fault/EQ parameters. Essentially, we correct the theoretical displacements to the observed, using some experimental transformation models e.g. 3D affine, Helmert transformations formulas. To evaluate our methodology, we use real data from an extra GNSS site in Lefkada Island, with very encourage results. On this experiment, the differences on the coordinate before and after the EQ using the synthetic methodology reduced from 5 cm to 1 cm in the 3D position.

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