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Datum definition for geodetic vertical velocity field derived from GNSS observations: a case study in western and southern Turkey

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ABSTRACT This study aims to determine the datum definition for the geodetic vertical velocity field derived from temporary and continuous GNSS observations. The observations have been analysed to investigate how the effect of vertical velocity for GNSS stations depends on the reference station selection. For this purpose, a network consisting of 26 GNSS stations has been designed. The GNSS observations have been processed using Bernese GNSS software v5.2 according to the different strategies. The strategies have been generated from ten different datum definitions of one to ten continuous GNSS stations within the IGS network in the Eurasia region, which is thought to be the least affected by tectonic movements. The vertical velocities of our solution derived from four reference stations concur within 0.4 mm/yr with those of the IGS/EUREF/NGL solution. It has been determined that the vertical velocities obtained based on the four reference stations proposed within the scope of the study are equal to the vertical velocities obtained from the ten stations distributed over the European region. The usability of these outcomes has been investigated in the studies to be carried out on Turkey's west and south coasts.

Key words: GNSS, time series, datum definition, vertical velocity.

1. Introduction

Geodetic vertical velocities are now widely used in many areas such as cadastral uses, sea level changes, glacial thickness, tectonic movements, deformations caused by disasters such as earthquakes/landslides, monitoring engineering structures, and determining the maximum height that the tsunami can reach and damage (Bock *et al*., 1985; Blewitt, 1993; Biagi *et al*., 2011). The space geodetic techniques such as the Global Navigation Satellite System (GNSS) have allowed highly accurate measurements of the geodetic vertical velocities.

The global GNSS networks covering the world are sometimes insufficient in determining the crustal movements in a region. The lack of a permanent GNSS station in the study area forces scientists to undertake GNSS measurement campaigns in the field. Some measures should be taken in order to prevent the temporary measurements from being affected by conditions that may reduce the measurement quality, such as seasonal effects, groundwater withdrawals, solar maximum and minimum (Eckl *et al*., 2001; Blewitt and Lavallée, 2003; Wang and Liou, 2006; Doğan *et al*., 2014; Duman and Sanli, 2019; Saracoglu and Sanli, 2020; Yavaşoğlu *et al*., 2020). Especially in determining vertical displacement, these effects should be eliminated or minimised.

The GNSS processing method, or selecting suitable reference stations, has been considered the foremost quality factor in determining the vertical movements/velocities (Doğan, 2007;

Firuzbadi and King, 2012; Duman and Sanli, 2019; Saraçoğlu and Sanli, 2020). For example, if research is conducted in an area affected by plate movements, choosing reference stations in the region with minor plate movement is recommended.

GNSS session duration has been a significant factor in obtaining the highest quality data in the GNSS observations (Gregorius *et al*., 1999). Although the continuous GNSS stations are one step ahead in this regard, GNSS measurement campaigns should be made when needed. Many studies on this subject have determined that a minimum of 8-10 hours of GNSS measurement time is needed to increase the quality of the measurement (Eckl *et al*., 2001; Doğan, 2007; Sanli and Engin, 2009; Alkan *et al*., 2015; Şafak *et al*., 2020). In addition, it is recommended to measure the vertical velocities for at least three years for a GNSS station to eliminate seasonal effects (Blewitt and Lavallée, 2003; Ozturk and Sanli, 2011; Santamatria-Gomez *et al*., 2011).

Another concept in determining vertical velocities from GNSS is accuracy analysis. Many studies have shown that base distance, latitude, longitude and ellipsoidal height, all affect the vertical component accuracy and, thus, the vertical velocities (Doğan, 2007; Sanli and Kurumahmut, 2011; Firuzbadi and King, 2012). Accuracy analysis on GPS stations whose ellipsoidal heights varied between 50 and 1631 m has been carried out by Sanli and Kurumahmut (2011). They determined that the difference in altitude affected the GPS position (Sanli and Kurumahmut, 2011). Firuzabadi and King (2012) investigated the precision of position estimates from static observation as a function of the duration of the observing session and the number and distribution of reference stations (Firuzabadi and King, 2012). Seasonal variations, base distance, and measurement time have been shown to affect GPS position accuracy (Doğan, 2007).

This study aims to investigate the effects of reference station selection on geodetic vertical velocities obtained by processing data from permanent GNSS stations and temporary GNSS sites in a reference frame datum. To this end, we analyse GNSS data acquired by the International GNSS Service [IGS (IGS, 2021)], Turkish National Sea Level Monitoring System [TUDES (TUDES, 2022)], and Turkish Continuously Operating Reference Stations [TUSAGA-AKTIF (TUSAGA-AKTIF, 2022)] networks. The calculated geodetic vertical velocity from the continuous GNSS station is compared with the actual velocity determined by IGS/EUREF/NGL. When we focus on the absolute value of the difference between those calculated in this study and those published by IGS/EUREF/NGL, the differences are statistically insignificant with a 95% confidence level. Hence, the general framework of the study is to determine the ideal evaluation strategy for determining the geodetic vertical velocity with GNSS. The results of a carefully implemented GNSS analysis are presented using different strategies adapted to determine accurate vertical station velocities. The novelty of the present study is that vertical velocities estimated from four reference stations (GRAZ, BUCU, ZECK, POLV) and ten reference stations could be considered equal using continuous GNSS station observations or campaign GNSS data on the western and southern coasts of Turkey. Thus, the GNSS data processing that takes a long time can be shortened (approximately 50% time savings), and the problems of appropriate geometry design in the data evaluation can be eliminated.

2. Methodology and data analysis

2.1. Study area and approach

Precise point positioning (PPP) may impact a favourable solution for providing static and kinematic geodetic point positioning. With the combination of precision satellite orbits and clocks, PPP can give cm-level precision (Zumberge *et al*., 1997). On the other hand, by GNSS measurements based on a global GNSS reference network, orbits can be estimated simultaneously with coordinates, and, then, a datum definition can be composed (Dong *et al*., 1998). The second choice was followed in this study, and the data were analysed based on reference stations. GNSS data between 2004 to 2018 were used in the frame of the IGS, TUDES, and TUSAGA-AKTIF networks. The ellipsoidal heights of the continuous GNSS stations vary between 32 and 1947 m (Fig. 1). Also, temporary GNSS data from sites near Turkish tide gauges are used. To maximise the number of the sites with a common-data period, we only used data from 2010 to 2018 (Fig. 1). Information about the temporary GNSS measurements is shown in Table 1. The campaigns of GNSS measurements are carried out in May or September, when the K-P index is under four, and solar activity seems ideal on the dates planned. Suppose the base distance between the reference station and the measurement stations is from a few to thousands of kilometres [some nearby IGS stations e.g. IZMI, ISTA, MERS, ANKR, TUBI are not used as references because they are affected by tectonic movements in the region (Doğan *et al*., 2006)]. In such case, the existing errors in satellite orbits and global networks are not too significant. However, in the regional networks created, it is essential to eliminate these errors in terms of datum definition (Firuzabadi and King, 2012).

The GNSS data were processed using BERNESE GNSS software v5.2 (Dach *et al*., 2015). IGS final precise ephemeris and Earth rotation parameters were used in processing. Cycle slip detection and repair were analysed for L1 and L2 phase data at triple and double-difference levels. We used the ionosphere-free linear combination for the final baseline solution using the solved L1/L2 phase integer ambiguity resolution. We estimated the tropospheric refraction and the tropospheric zenith delay at two-hour intervals. The GNSS data processing details are described in Table 2.

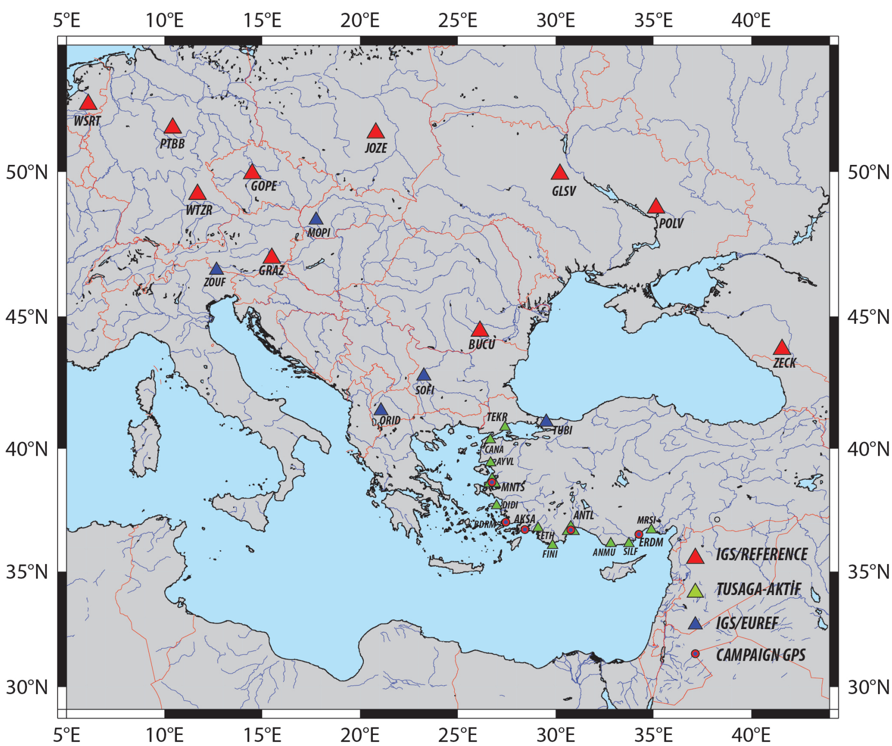

Fig. 1 - GNSS network.

Table 1 - Information of the GNSS processing campaign.

Year	2001-2003-2005-2007-2009	2008-2010-2011-2012	2013-2014-2017	2016-2018
Number of stations	4-3-6-4-4	3-5-5-5	6-6-1	5-3
Receiver	Trimble 4700	Ashtech Z-X	Leica GS15	Topcon TPSGR3
Antenna	TRM29659.00	ASH701975.01A	LEIGS15	TPSGR3
Observation time	8-12 hours	8-12 hours	8-12 hours	8-12 hours

Table 2 - The GNSS data processing strategy used in this study.

Parameter	Description
GNSS software	Bernese v5.2 (Dach *et al.*, 2015) for GNSS observations processing
Data	Double differenced phase and code pseudo-range observations
Sessions and sampling	24-hour sessions for continuous stations and 8-10-hour sessions for temporary site with 30 s sampling interval
Elevation cut-off angle	10°
Ionosphere refraction	Ionosphere free linear combination L3 (first-order eliminated)
Troposphere refraction	A priori zenith delays from the Saastamoinen (1972) model, using a standard atmosphere, mapped with the Vienna Mapping Function [VMF1 (Böhm *et al.*, 2006)]
Antenna PCV	IGS absolute phase centre corrections (IGS, 2021)
Earth orientation	IERS
Earth and polar tide	IERS2010 (Petit and Luzum, 2010)
Ocean tide loading	FES2004 (Lyard *et al.*, 2006)
Orbits	IGS final products
Reference frame	ITRF2014 datum (Altamimi *et al.*, 2016)

To determine whether the precision of the positioning of a site is affected by the choice of reference station, we first computed a series of solutions, testing by using ten different datum strategies and determined GNSS data processing time for one day (Table 3).

Table 3 - GNSS data processing strategies.

	Reference station										
Strategy	GRAZ	BUCU	POLV	ZECK	GLSV	JOZE	GOPE	WTRZ	PTBB	WSRT	Processing time
1	•	•	•	•	•	•	•	•	•	•	14 min
2	•	•	•	•	•	•	•	•	•		13 min
3	•	•	•	•	•	•	•	•			12 min
4	•	•	•	•	•	•	•				10 min
5	•	•	•	•	•	•					9 min
6	•	•	•	•	•						8 min
7	•	•	•	•							6 min
8	•	•	•								5 min
9	•	•									< 5 min
10	•										< 5 min

The anchoring of GNSS networks to a reference system is a problem at seven degrees of freedom, including three translations, three rotations, and one scale factor. Seven unknowns must be estimated; therefore, at least three reference sites (3´3 known coordinates) must be used. Some of these parameters would be neglected if less than three reference stations were used. For instance, only translations can be estimated with the choice of one reference station. In this sense, strategies (S1, S2, ... S10) shown in Table 3 were created, and GNSS data processing was made according to these strategies. Some of these parameters have been neglected since not all three translations, three rotations, and one scale factor can be determined in S9 and S10 (S10 is a solution using only scale factor and S9 gives a solution with scale and three transitions factors).

Some information for the 21 continuous GNSS stations used for time series analysis is shown in Table 4. The continuous GNSS data have been obtained from four different data providers. While the data belonging to IGS, EUREF, and TUDES networks were available between the 2004 and 2018 periods, TUSAGA-AKTIF data were available between 2010 and 2018. There is a 35% data gap in the data within TUDES, whereas, within IGS, EUREF, and TUSAGA-AKTIF networks, data gaps are less than 10%. The resulting data samples (processed GNSS data) are approximately 2500-5000. In the temporary GNSS data, at least ten years for the time series, at least five temporary measurements have been carried out, and we selected the stations with repeated measurements for 3-6 days. Since they are generally measured in the same season, this part is not considered to be exposed to seasonal effects.

Table 4 - Continuous GNSS data information.

			Continuous GNSS data information (after processing)		
Station	**Data sample**	**Data span (year)**	**Data gaps (%)**	**Ellipsoidal height**	**Data centre**
ANMU	2484	6.8	6.9	39.6	TUSAGA-AKTIF
ANTA	3249	8.9	36.4	32.7	TUDES
ANTL	2524	6.9	5.4	88.7	TUSAGA-AKTIF
AYVL	2356	6.5	11.7	54.2	TUSAGA-AKTIF
BUCU	5071	13.9	0.8	143.2	IGS
CANA	2488	6.8	6.8	141.2	TUSAGA-AKTIF
DIDI	2415	6.6	9.5	79.3	TUSAGA-AKTIF
FETH	2408	6.6	9.8	37.3	TUSAGA-AKTIF
FINI	2509	6.9	6.0	36.3	TUSAGA-AKTIF
GRAZ	5080	13.9	0.6	538.3	IGS
MNTS	3228	8.8	36.8	59.2	TUDES
MOPI	4662	12.8	8.8	579.0	EUREF
MRSI	2421	6.6	9.3	40.5	TUSAGA-AKTIF
ORID	4864	13.3	4.8	773.0	IGS
POLV	5050	13.8	1.2	178.4	IGS
SILF	2500	6.8	6.3	52.8	TUSAGA-AKTIF
SOFI	4853	13.3	5.0	1119.5	IGS
TEKR	2543	7.0	4.7	48.8	TUSAGA-AKTIF
TUBI	5009	13.7	2.0	220.3	IGS
ZECK	4122	11.3	19.3	1166.3	IGS
ZOUF	4851	13.3	5.1	1946.5	IGS

2.2. Time series processing method

We apply time-series analysis to obtain reliable velocity estimates and their uncertainties for each station based on their daily position estimates. After processing the GNSS data for all stations, the phase of creating time series and determining velocities was then started. Many studies have suggested the linear time series model (Lyard *et al*., 2006; Petit and Luzum, 2010; Altamimi *et al*., 2016). The primary purpose of time series creation for VLM is to see the general trend in the created network, determine the local velocity in the region, and compare them with other methods. In this study, the model used was proposed by Dach *et al*. (2015), as shown in Eq. 1 (Dach *et al*., 2015). This model also uses the FODITS module in Bernese GNSS software v5.2.

$$\begin{aligned} y(t_i) = & d_o + v_0(t_i - t_0) + \\ & \sum_{k=1}^{n_d} d_k \eta_{d,k}(t_i) + \sum_{k=1}^{n_s} s_k \eta_{s,k}(t_i) + \\ & \sum_{k=1}^{n_v} v_k \left(t_i - t_{v,k}\right) . \eta_{v,k}(t_i) + \\ & \sum_{k=1}^{n_p} a_k \, sin\left(\omega_k t_i - t_{v,k}\right) + b_k \, cos\left(\omega_k t_i - t_{v,k}\right) . \eta_{p,k}(t_i) \end{aligned} \quad (1)$$

where d_o is offset, drift is v_0 $(t_i - t_0)$ at an epoch t_0, discontinuities is $d_k \eta_{d,k}$ (t_i), outliers is $s_k \eta_{s,k}$ (t_i), velocity changes v_k $(t_i - t_{v,k})$. $\eta_{v,k}$ (t_i) and periodic function parameterised as an ω_k, a_k and b_k.

GNSS data processing has been carried out with ten different strategies shown in Table 3. Then, time series were created using the FODITS module, and vertical velocities were calculated with the algorithm shown in Fig. 2. The seasonal signals have also been removed for all data.

Figs. 3 and 4 show the time series at two sample GNSS permanent stations (TUBI and ORID). Note that up components have been de-trended and residual values of up components for GNSS stations have been determined. The residuals of up coordinates and their histograms for TUBI and ORID stations are shown in Figs. 3 and 4, respectively. The residuals of up coordinates have a mean near zero, the maximum positive is 10.46 mm, and the minimum is -10.41 mm. The standard deviation of the mean is greater than 3 mm.

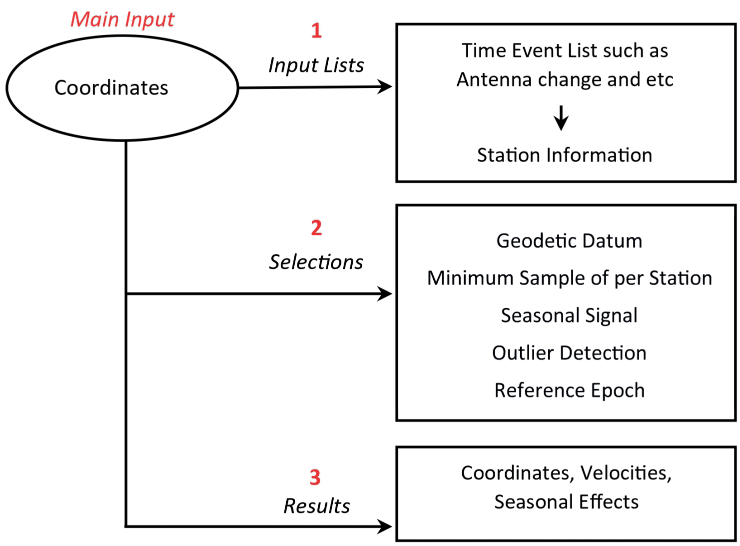

Fig. 2 - FODITS algorithm.

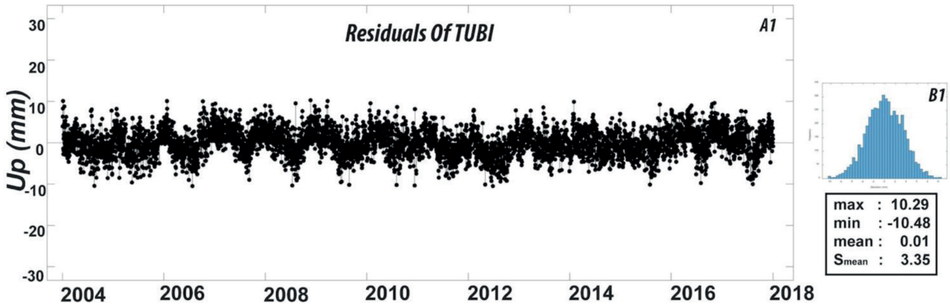

Fig. 3 - Residuals of up coordinate time series for TUBI station.

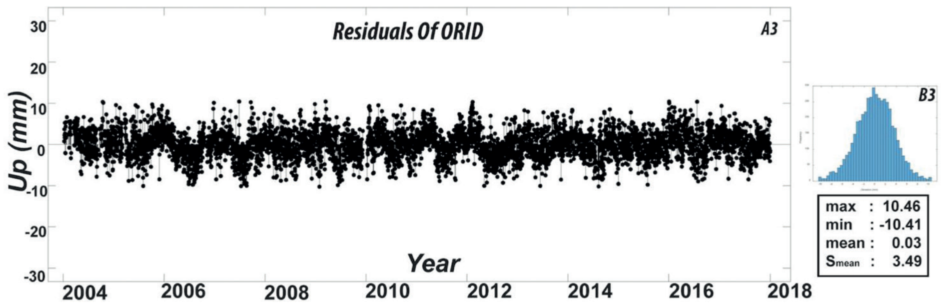

Fig. 4 - Residuals of up coordinate time series for ORID station.

An example of up coordinate time series from temporary AKSZ and BDRM GNSS sites is shown in Fig. 5. AKSZ and BDRM sites have a positive trend for up coordinates concerning the first observation in 2007. The changes of up components are about 15 and 30 mm between the 2007 and 2018 periods, respectively.

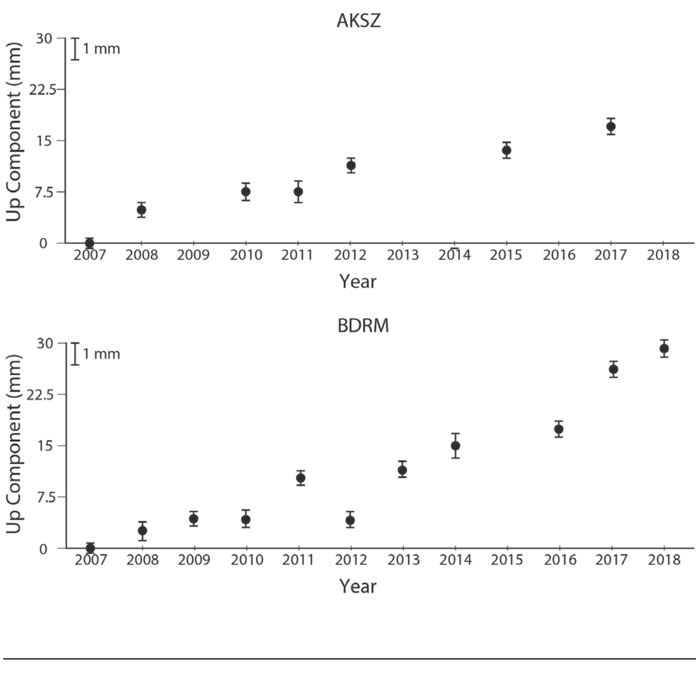

Fig. 5 - Time series for the sites of AKSZ and BDRM.

3. Results and discussion

The vertical velocity values and standard deviations have been computed for GNSS stations using ten different datum strategies in Table 3. An example of vertical velocity values from the ORID station is shown in Fig. 6. As shown in the figure, the vertical velocity estimated for the first datum strategy (S1) is less than 1 mm/yr. The vertical velocity differences between datum strategies S1 and S10 are less than 3 mm/yr, and the velocity for S10 is larger than the other datum strategies. Vertical velocity changes fit well with the first datum strategy (S1), starting from 2 to 8, but not with strategies S9 and S10.

We consider the ITRF solution as actual velocity since this solution is based on a long continuous daily time series of GNSS data (Firuzbadi and King, 2012). We estimated the first datum strategy (S1) solution for ORID stations to be approximately 0.9 mm/yr in vertical velocity (almost the same as those published by IGS, EUREF or NGL). The estimated velocity values using strategies S9 and S10 cannot be considered realistic. Fig. 6 includes an example of the velocities calculated with S1 and the vertical velocities published by NGL are quite close to each other. Moreover, Table 5 shows whether the differences between the vertical velocities published by NGL and S7, S8, and S9 are statistically significant or not (http://geodesy.unr.edu/NGLStationPages/GlobalStationList/, accessed March 2022).

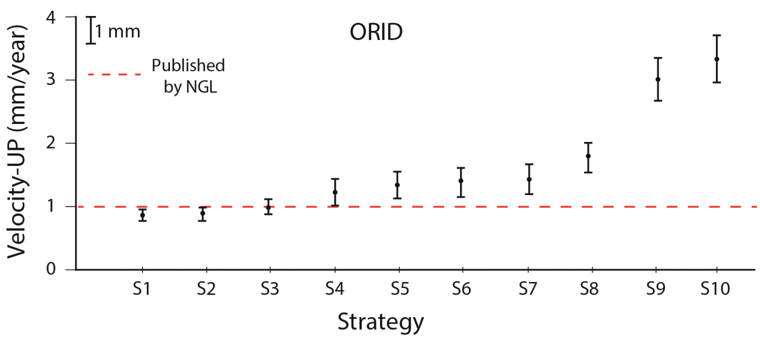

Fig. 6 - Vertical velocity values of ORID station for different strategies (Table 3). The error bars indicate one standard deviation.

The differences are statistically insignificant from zero at the 95% confidence level (T-Test and boundary value is 1.96), and the result coincides with the NGL solution. In Table-5, it was determined that the differences between S7 and NGL were statistically insignificant, and it was assumed that these two vertical velocity values were equal to each other. However, when focusing

Table 5 - Differences between this study and published data.

Station	Vup values				Differences (numerical) and T-test values					
	S7 (mm/yr)	S8 (mm/yr)	S9 (mm/yr)	NGL (mm/yr)	S7-NGL (mm/yr)	T test	S8-NGL (mm/yr)	T test	S9-NGL (mm/yr)	T test
TUBI	-0.9 ± 0.4	-1.1 ± 0.6	-0.3 ± 0.8	-1.3 ± 0.6	0.4 ± 0.7	1.1	0.2 ± 0.6	0.6	1.0 ± 0.9	2.8
MOPI	-0.4 ± 0.5	-0.9 ± 0.4	-1.5 ± 0.9	-0.2 ± 0.8	0.2 ± 0.9	0.3	0.7 ± 0.9	1.1	1.3 ± 1.2	2.0
ORID	1.2 ± 0.7	1.7 ± 1.0	2.2 ± 1.2	1.0 ± 0.6	0.2 ± 0.8	0.6	0.6 ± 1.2	1.7	1.2 ± 1.3	3.3
SOFI	-0.1 ± 0.6	-0.9 ± 0.5	-1.3 ± 0.9	-0.4 ± 0.5	0.3 ± 0.7	1.2	0.5 ± 0.7	2.0	0.9 ± 1.0	3.6
ZOUF	1.5 ± 0.6	1.8 ± 1.0	2.6 ± 1.4	1.0 ± 0.5	0.5 ± 0.7	1.9	0.8 ± 1.1	3.2	1.6 ± 1.5	6.4

on the differences between S8 and NGL, it was determined that some of the differences were statistically significant, and some were insignificant. All the differences between S9 and NGL were statistically significant and cannot be considered equal. The differences between the S10 and the NGL are significant as they are larger than the S9 have, therefore, not been included in Table 5.

In addition, the sub-combinations of the reference stations S7 have been taken into account, as the vertical velocities obtained from S1 and S7 are considered statistically equal to each other. These sub-combinations consisting of GRAZ (G), BUCU (B), POLV (P) GNSS station and ZECK (Z) are named GBPZ (S7), GBP, GBZ, GPZ, BPZ. Double and single combinations of S7 are not taken into account. In this sub-combination of S7, it has been observed that the velocity values are close to each other, but the standard deviations are larger in triple combinations. GNSS processing using three reference stations can generally give a solution with enough quality. However, while using three reference stations, the solution must be carried out based on two or fewer reference stations in case of possible software-related problems (data adequacy on that day, etc.). So, four stations as a reference will make the results more reliable. An example of vertical velocity from the ORID station with sub-combinations of S7 is shown in Fig. 7.

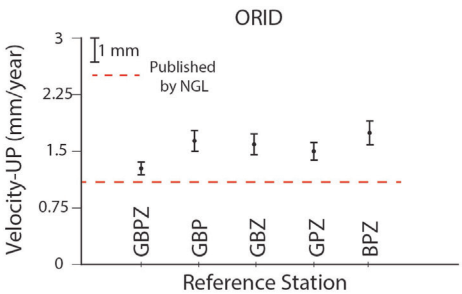

Fig. 7 - Vertical velocity values of ORID station for sub-combinations of S7.

Since the test demonstrates that the difference between S7 and published velocity is minimal, all the data have been processed according to ten different strategies, and the vertical velocities and standard deviations have been determined. Figs. 8 and 9 show the differences between the velocity field determined using the S1 strategy minus the velocity components obtained using other strategies. As shown in Figs. 8 and 9, a notable velocity difference was observed for S9 and S10 strategies. The differences between the S10 strategy are more significant than the other strategies. As shown in Figs. 8 and 9, the velocity differences for all the stations are statistically insignificant from S1 to S7 and smaller than other strategies.

After determining the point-wise GNSS vertical velocities, according to each strategy, the velocity fields changed to the ten strategies used for the SW coast of Turkey, Marmara, Aegean, and Mediterranean regions were also examined. It is predicted that the vertical velocity fields can have similar values from S1 to S7. However, the standard deviations can be larger in S7 and there can be statistically significant changes in the velocity fields from S8 to S10 compared to other strategies. In this context, velocity fields were created from the average method (Davies and Blewitt, 2000; Lavallee, 2000; Booker *et al.*, 2014). For this solution, the point-wise Eurasia-fixed GNSS velocities were used based on suggestions in previous studies (Duman and Şanlı, 2022; Vardic *et al.*, 2022).

Table 6 shows the vertical velocity fields and differences obtained with S1, S7, S8, and S9. According to the results, the regional vertical velocities obtained from S1-S7 can be considered statistically equal to each other, but they cannot be considered statistically equal with the vertical velocities obtained from S1-S8 and S1-S9.

Table 6 - Vertical velocity field in coasts of Turkey, Mediterranean, Aegean, and Mediterranean.

Region	Vertical velocity fields				Differences (numerical) and T-test values					
	S1 (mm/yr)	S7 (mm/yr)	S8 (mm/yr)	S9 (mm/yr)	S1-S7 (mm/yr)	T test	S1-S8 (mm/yr)	T test	S1-S9 (mm/yr)	T test
Coast of Turkey	1.1 ± 1.0	1.4 ± 2.2	2.1 ± 3.0	3.2 ± 4.7	0.3 ± 2.4	0.3	1.0 ± 3.2	1.0	2.1 ± 4.8	2.1
Marmara	1.1 ± 0.5	1.5 ± 1.0	2.1 ± 1.3	2.3 ± 2.7	0.4 ± 1.1	1.6	1.0 ± 1.4	4.0	1.2 ± 2.7	4.8
Aegean	1.4 ± 0.9	1.5 ± 2.1	2.0 ± 3.2	2.8 ± 3.4	0.1 ± 2.3	0.1	0.6 ± 3.3	0.6	1.8 ± 3.5	2.2
Mediterranean	0.6 ± 0.3	0.7 ± 0.7	1.1 ± 1.9	1.3 ± 1.9	0.1 ± 0.8	1.1	0.5 ± 1.9	5.6	0.7 ± 1.9	8.9

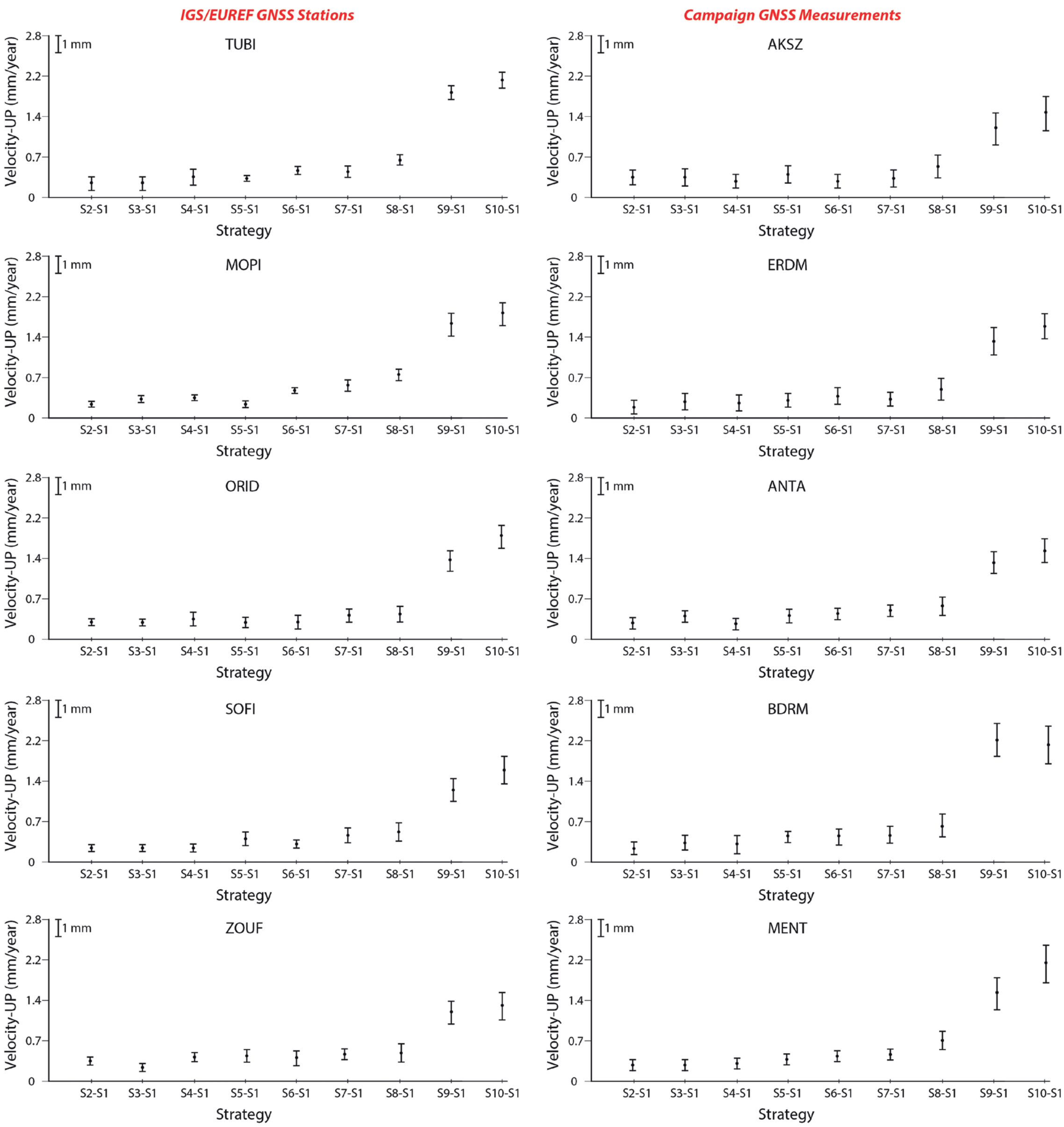

Fig. 8 - Differences and standard deviations between S1 and other strategies.

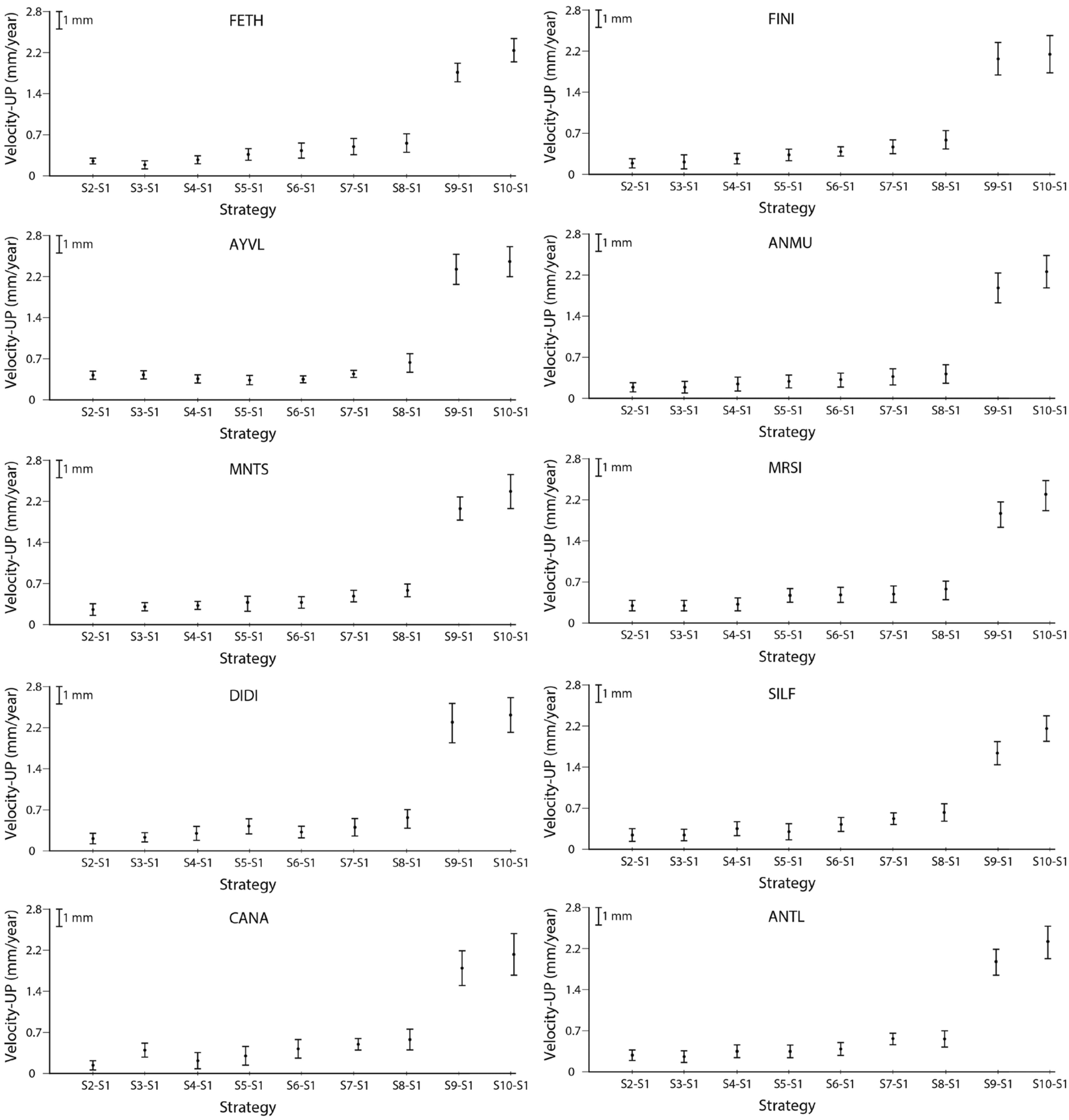

Fig. 9 - More differences and standard deviations between S1 and other strategies.

Fig. 10 indicates the vertical velocity derived from S7 for permanent and temporary GNSS stations. A significant relative motion was observed for GNSS stations in the campaign. The vertical velocities for AKSA and BODR sites located on the same side of the Aegean Sea are estimated by an average of 2.4 ± 0.5 mm/yr. The relative velocity vectors easily recognize that the region is active with significant deformation patterns. Also, based on the vertical velocity vectors indicated in Fig. 8, a significant relative motion has been found in the continuous GNSS stations (except for MNTS, TUBI, and SOFI stations). Further, the CANA GNSS station has a much bigger vertical velocity than the others.

Focusing on Fig. 10, some GNSS stations have an uplift, others subsidence. These movements are thought to be due to local and tectonic effects. For example, an earthquake (epicentre is Bodrum

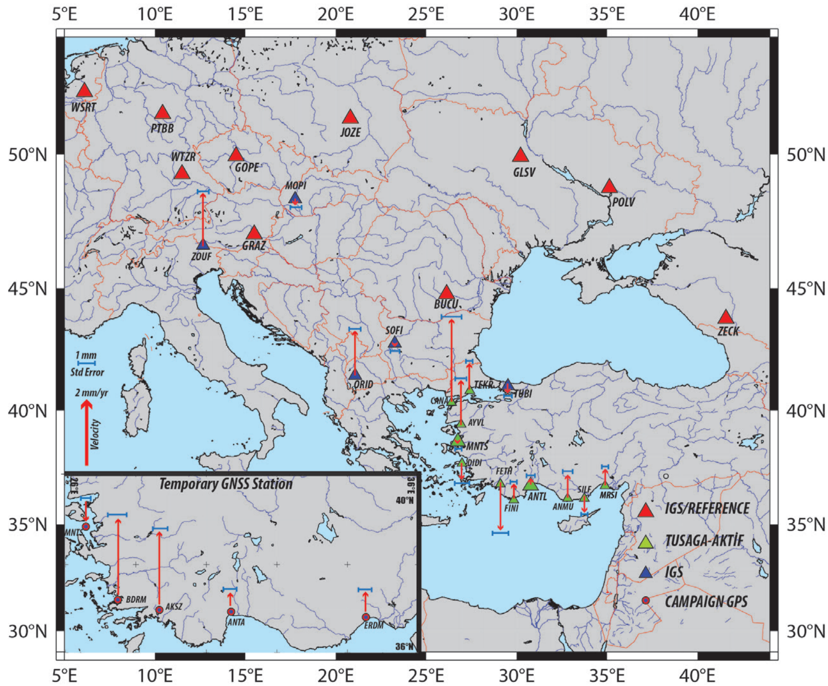

Fig. 10 - Vertical velocities of the continuous GNSS stations and their uncertainties.

and magnitude is 6.6 M_w) occurred in 2017, with an uplift of around 5 cm in the Bodrum region (Konca *et al.*, 2019). Regarding the MNTS station, since this station is also a tide gauge station, it has been concluded that the subsidence observed is due to sea-level changes (Erkoç *et al.*, 2022).

4. Conclusions

The primary purpose of the work discussed in this paper was to determine how the changes of an estimated vertical velocity variation among continuous stations or temporary sites depends on the number of reference stations.

The differences were determined between the vertical velocity obtained using ten reference stations (S1 strategy) minus the vertical velocity obtained using other strategies. The results clearly indicated a notable velocity difference for one and two reference stations (S9 and S10 strategies). However, the velocity differences are statistically insignificant when using three or more reference stations (S1, … S8 strategies), and they are smaller than other strategies.

The results indicated that the lowest differences were obtained for four or more reference stations and the highest differences for the two or one reference station. Also, the vertical velocity from the differences between this study and the published velocity was determined for 5 IGS stations. The differences are statistically insignificant from zero at the 95% confidence level (1.96), and the result coincides with the published velocities.

The most important output of the study is the reference station strategy (S7), which includes a minimum of four references and is suggested to be used in studies conducted in the western and southern coastal regions of Turkey. With the proposed strategy, vertical velocity values based on ten references spread across Europe can be reached with the S7. The differences are statistically insignificant. Using the S7 strategy fixed to reference stations of GRAZ, BUCU, ZECK, and POLV, results in suitable geometry can be obtained. It is not only available in the study area but can also give better results in the Balkan area and in central and south-eastern Europe because the suggested strategy's reference stations in the present study cover the area. Moreover, approximately 14 years (~5100 days) of data can be analysed in 54 days if processed in about ten stations. Thanks to the recommended reference stations, it can be evaluated in 23 days, with about a 50% reduction in time.

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