Deformation detection through the realization of reference frames

Nestoras Papadopoulos[1], Melissinos Paraskevas[2], Katsafados Ioannis[3], Nikolaidis Georgios[4], Anagnwstou Eyaggelos[5]

[1] HMGS/Geodesy and Topography Branch, (nespap@gmail.com)
[2] HMGS/Geodesy and Topography Branch, (melipara1@yahoo.gr)
[3] HMGS/Geodesy and Topography Branch, (john.katsafados@gmail.com)
[4] HMGS/Geodesy and Topography Branch, (geonklds@gmail.com)
[5] HMGS/Support Division, (vagelis_anagnostou@yahoo.com)

Keywords: *deformation; reference system; GGRS87; ITRF2008; HMGS; GPS; GNSS*

Abstract

Hellenic Military Geographical Service (HMGS) has established and measured various networks in Greece which constitute the geodetic infrastructure of the country. One of them is the triangulation network consisting of about 26.000 pillars all over Greece. Angle and distance measurements that held by HMGS through the years have been used after adjustment for the state reference frame which materializes the current Hellenic Geodetic Reference System of 1987 (HGRS87). The aforementioned System is a static one and is in use since 1989 after the decision of the State Geodetic and Geophysical Committee. Through the years especially in the era of satellite systems many GNSS networks have been established. The latest such network materialized by HMGS is ongoing and covers until now more than the 2/3 of the country. It is referenced by IGS permanent stations and consists a local realization of ITRF2008. Firstly, this gives the opportunity to calculate a transformation between the two systems and a statistical analysis of the residuals leads to intermediate conclusions. After that and in conjunction with existing past transformations, tectonic deformations and their directions are concluded. Moreover past GPS observations on the same pillars in compare to the newer ones give also a sense of tectonic changes. Greece is one of the most tectonic active countries in Europe and the adoption of contemporary dynamic or semi-dynamic coordinate system is a necessity as it should incorporates a deformation model like 3d velocities on the realization frame. The detection of geodynamic changes is a continuous need and should be taken into consideration per each epoch.

I. INTRODUCTION

A. *Scientific Background*

The Hellenic plate boundary region, located in the collision zone between the Nubian/Arabian and Eurasian lithospheric plates, is characterized by a complex field of crustal motion, deformation and high seismic activity. It is presently one of the seismo-tectonically most active areas of Europe.

During the last 40 years, continuous and campaign-type GPS measurements have been used to determine the crustal motion and deformation in the area of Greece (e.g. Kahle et al., 1993; Müller, 1996; Kahle et al., 1998; Cocard et al., 1999; Briole et al., 2000; Kahle et al., 2000; Peter, 2001; Ch. Hollenstein, et al. 2007; Bitharis et al 2016 etc).

Deep seismicity under the sea of Crete is related to the subduction of the northward moving (relative to Eurasia) African oceanic lithosphere, whereas shallow seismicity throughout the Aegean Sea and Greek mainland is related to the southwestward (again relative to Eurasia) extension of the Aegean continental lithosphere driven by a combination of gravitational spreading of the Anatolian continental lithosphere from the east (Papazachos 1990). All that process affects to ground deformation with a variety of velocities at Greek territory.

Despite all that process, the official coordinate system: the Hellenic Geodetic Reference System of 1987 (HGRS87) which was adopted in 1990 is a static reference system and it is very old to support geodetic purposes.

The scientific purpose of the present study is twofold. First to point out the necessity for a new geodetic system and second to certify numerically deformation around rifts. In order to do this, three different data sets were compared.

B. *Area of interest*

HMGS held surveys all over the Greek territory using GPS and classical methods. From 2014 HMGS started GPS surveys on triangulation points in order to establish the new HMRF (Hellenic Military Reference Frame). Until summer of 2018 there was measured 346 stations mostly in the continental part of Greece from Thrace to Northern Peloponnese. ($37.2^o<\phi<41.2^o$, $19.3^o<\lambda<26.7^o$) and the islands Chios and Rhodes. GPS measurements will continue in the following years to the rest of Greek Region. In this study the above area was selected.

II. MATERIALS AND METHODS

A. *Hellenic Geodetic Reference System 1987*

The official geodetic reference system, called the 'Hellenic Geodetic Reference System of 1987-HGRS1987', was reported at 1989 (Takos, 1989) and adopted in 1990 (Veis 1995). It is mainly realized by classical measurements (angles, azimuths and distances), where the involved mentioned measurements can exceed up to 50 years in age. HMGS carried out measurements (angles and distances) to first order network from 1964 to 1979. Second third and fourth order network was established at following years from 1975 to 1989 (mostly from 1982 to 1989). First and second order network were adjusted separately. From the adjusted values of the higher order networks third and fourth order networks were adjusted together. In addition, data from TRANSIT (Doppler) and GPS observations were assimilated in thirty (30) carefully selected stations in 1986. From these measurements and the adjusted results of almost 26.000 triangulation points a new data frame was established. GRS80 ellipsoid was used oriented in parallel to ITRF1989 in order to specify a nongeocentric datum that is tied to the coordinates of the basic geodetic station at the Dionysos Satellite Observatory (DSO) northeast of Athens. As projection method Transverse Mercator was selected with central meridian of $\lambda=24^o$. The initial uncertainty calculated and it was estimated as 0.1 ppm, (Hellenic Mapping and Cadastral Organization 1987).

Alongside the translation vector to ITRF 1989 was calculated from Veis 1995 with estimated accuracy of $\pm 2 * 10^{-7}$. This corresponds to a translation vector from HGRS87 to ITRF89 as [DX DY DZ] = [-199.695 +74.815 +246.045].

B. *HELLENIC GPS NETWORK 2002 (HEGNET2002)*

In 2000 HMGS started establishing a new GPS network which consists of

- 28 basic station
- 201 triangulation points
- 9 tide gauges
- 5 SLR stations (WEGENER project)

All sites contain at least 12 hour observations that took place in 2000 and 2001. Dionysos permanent GPS station was used as a reference point and the process was performed using the BERNESE v4.2 software. For the adjustment the Colombus v.3.2 software was used. Final coordinates refer to ITRF1996 at the epoch of 2000.0. Calculations were completed at May 2003. The accuracy of HEGNET2002 estimated at about 1cm. This network was a first trial for a GPS network in the Greek territory.

C. *Hellenic Military Reference Frame*

At 2014 HMGS decided to establish a new network of GPS and gravity surveys simultaneously in Greek territory. Until summer of 2018, 346 triangulation and levelling points were surveyed. Most of the aforementioned points were triangulation pillars which had already been surveyed for the national coordinate system the HGRS87 (Hellenic Geodetic Reference System 1987) using classic methods (Takos, 1989) many decades ago and also many of them had been remeasured in the past (2000-2001) using GPS for the HEGNET2002 (Anagnostou et al., 2007) and processed using Bernese software (Dach et al, 2007).

In these yearly campaigns for the HMRF network GPS stations were divided into two classes. Class A stations had many hours of observations (at least 6 hours) and were referenced directly from 13 IGS stations. In the processing there were used also daily observation of permanent GNSS stations in order to densify the processed bases. Class B stations with less observations were referenced from Class A stations. The IGS stations formatting the reference network were closer and around Greece stations. These were BUCU, RAMO, NOT1, VILL, MAS1, KIT3, MATE, POTS, WSRT, GRAZ, SOFI, YEBE and ISTA (fig. 2).

For the Class A stations the GAMIT/GLOBK (Herring et al, 2018) software was used. Also grids for the ocean tide loading (FES2004), the atmospheric delay corrections (Vienna Mapping Functions 1) and non-tidal atmospheric loading corrections (for each year referenced to the earth center of mass) were used. The most recent earth orientation parameters and precise orbits were used as well. The selected reference system is the IGS08. Class B stations processed using a commercial software, Trimble Total Control (TTC), using precise orbits and clock corrections. Total accuracy of the network is estimated under 2cm.

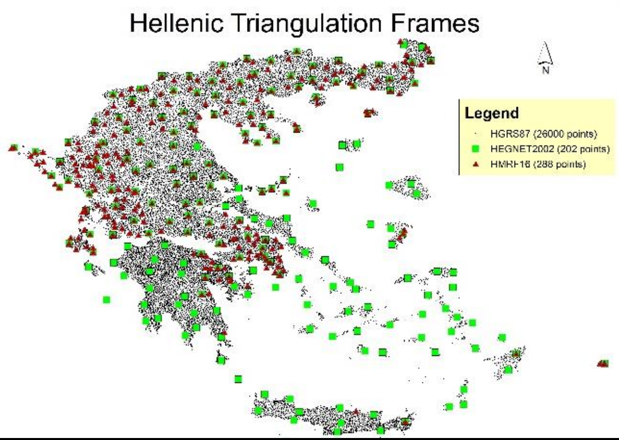

Figure 1. 25702 Triangulation points of HGRS87 depicted as black small dots, 201 Triangulation points of HEGNET2002 depicted as green square, 328 triangulation points of HMRF depicted as red triangle.

D. *GPS data processing*

In course of preparation to HMRF many processing strategies, models, algorithms and software were tested by HMGS. One of the stages was an effort undertaken to combine GPS

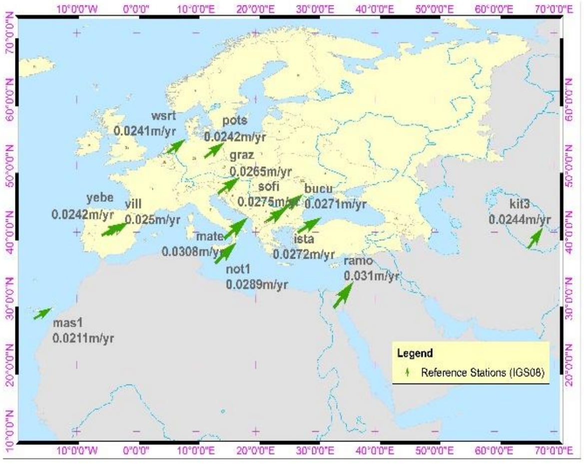

Figure 2. Reference IGS stations of HMRF used in this study. Labels and arrows present the velocities of each station, calculated by IGS.

solutions from two different software (BERNESE 5.0, GAMIT 10.6, 10.7) and find an answer to a question how algorithms influence the final results. GAMIT/GLOBK software was finally selected. Firstly GAMIT software used to process all baselines in a loose solution. Grids for modeling atmosphere and ocean loading was used in the processing. Ambiguity resolution was fixed through double differences and wide-lane and narrow-lane frequency combinations formatted. Afterwards the GLOBK software through a Kalman filter stabilized all the stations to the IGS08 frame. Using GLOBK took into consideration standard errors of the reference stations. This means that it moves the whole network in a manner that it best fits, always inside the ambiguity of each of the reference stations.

Table 1. Processing strategy followed during the project

Processing – Adjustment strategy	Day by day processing-RELAX method (gamit), year by year adjustment using Kalman filter (globk)
Reference Stations	13 IGS permanent GNSS stations (fig. 2)
Ocean Tide Loading	FES2004
Atmospheric Delay Corrections	Vienna Mapping Functions 1
Non-Tidal Atmospheric Corrections	Atmdisp referenced to the center of earth mass for each year
Orbits	IGS precise orbits
Data Windowing	10^{o} elevation mask
Ambiguity resolution	Double differences, wide-lane & narrow-lane combinations

E. *TECTONICS*

In order to recognize deformation areas in Greek region it is useful to associate calculated displacements with active faults. The recognized movement depends on the base of what is kept stable. In most researches movements presented from stable Europe, or stable world.

It is already known that the region of Greece is one of the most rapidly deforming parts of the continents globally, as evidenced from geological (e.g. Jolivet et al., 2015), seismological (e.g. Tiberi et al., 2000; Kassaras et al., 2009; Karakonstantis, 2017) and geodetic observations (e.g. Chousianitis et al., 2015), with velocity differences ranging 20–40 mm/yr (Floyd et al., 2010). Deformation rates become larger along the Hellenic arc, exceeding 200 nstrain/yr (Kreemer et al., 2003, 2014) due to the active subduction of the eastern Mediterranean lithosphere beneath the Aegean continental plate and along the North Aegean Trench, as a result of the westwards propagation of the North Anatolian Fault (McClusky et al., 2000). The active oceanic subduction progressively becomes continental convergence in north-western Greece and Albania (McKenzie, 1978). Intraplate brittle deformation is also complex, clustered along seismogenic zones with variable kinematic rates (Chousianitis et al., 2015)

All that movements and many more are included to the Greek Database of Seismogenic Sources (GreDaSS) (Caputo R. and Pavlides S. et al., 2013).(fig3)

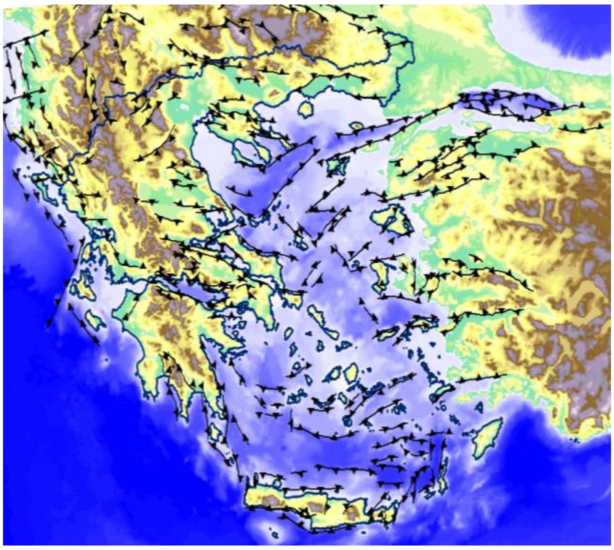

Figure 3. Active faults in Greek region from GreDaSS (downloaded on 16/03/2019), over topography-vathmetry map of HMGS.

F. *ACCURACY*

Accuracy is essential to deal with in order to decide if the measured difference results correspond to displacement or they are less than the error of positioning.

Class "A" stations were surveyed using forced placement of the antenna on the pillar since it was screwed in a bolt built inside each pillar. For class "B" stations the antenna was placed on a levelling tribrach which was fixed on a small (less than 4cm high), metal tripod. So centering of the antenna to the marking of the pillar is estimated to have accuracy better than 1cm. Also network accuracy for the HEGNET2002 and the HMRF is about 1cm and 2cm respectively.

As far as it concerns HGRS87 coordinates, they have a theoretical accuracy of 3cm as it was calculated from the adjustment of the network. Also, transformation to ITRF89 has an error of 30cm, using the translation vector according to Veis, 1994.

Combining all the above we are lead to total accuracy. In order to compare HEGNET and HMRF we must calculate the error for each network. Antenna positioning error (sd_ant) is about 1cm and gps processing error (sd_gps) is about 2cm for both networks in the IGS08 frame. So total error for each network (sd_HEGNET and sd_HMRF) is calculated from the square root of the summation of the squares of sd_ant and sd_gps which means that it is 2.24cm according to equations 1 and 2. For the comparison of the two networks (sd_comp1) we must take into account both of them which means the square root of the summation of the squares of the two network errors that is 3.16cm. So combining the two networks if a displacement conclusion is more than 3.16cm it is assumed to be real displacement otherwise we cannot conclude if there is or there isn't a displacement.

In order to compare HGRS87 and HMRF coordinates it must be calculated total error for the HGRS87. Adjustment of the network has an estimated error (sd_adj) of 3cm and transformation error (sd_trans) is about 0.30m. Calculating the square root of the summations of the squares of sd_aj and sd_trans we conclude to total error (sd_HGRS) of 30.15cm. For the comparison of the two network the total accuracy (sd_comp2) is about 30.23cm. So any difference in position above sd_comp2 is assumed to be real displacement.

$$sd\_comp = \sqrt{{sd_i}^2 + sd_j 2^2} \quad (1)$$

where i and j can be sd_HEGNET or sd_HMRF or sd_HGRS and include all parameters that cause uncertainty to each data frame according the following equations:

$$sd_{hegnet,\ or}\ sd_{HMRF} = \sqrt{\mathrm{sd\_gps}^2 + \mathrm{sd\_adjustment}^2} \quad (2)$$

$$sd_{HGRS87} = \sqrt{\mathrm{sd\_tranformation}^2 + \mathrm{sd\_adjustment}^2} \quad (3)$$

III. RESULTS

A. *COMPARISON HMRF vs HEGNET*

In order to take accurate results all measurements of HEGNET was recalculated with GAMIT/GLOBK at the epoch of survey and final coordinates calculated with the same process as those of HMRF.

A complete (re-)processing of all campaign type measurements was carried out, using the GAMIT/GLOBK software version 10.6 and 10.7 (Herring et al, 2018). 13 mainly European IGS stations formatted the reference network (Fig. 2) and also EUREF sites were included in the data analysis in order to densify the network and format smaller baselines containing 24h observations. The whole processing was done in one reference frame, the IGS08, using velocities and ambiguities of the reference stations, IGS precise orbits and earth rotation parameters. Final results concluded at an average accuracy of position about 2cm.

After calculating coordinates (X, Y, Z) for both HMRF and HEGNET at the survey epoch, they were transformed to the same topocentric system (E, N, U). Then the displacement vector (DE, DN, DU) was calculated for each point alongside with the epoch difference. An average displacement (DS) of 36.6cm is concluded, mostly in the horizontal plane (DHor=34.8cm) in an average difference of epochs (Depoch) of about 16 years as shown in table 2.

Table 2. Statistics of displacement (DE, DN, DU, DHor in meters, Depoch in decimal years)

	Average	Std	Min	Max
DE	0.083	0.121	-0.196	0.273
DN	0.314	0.099	0.058	0.469
DU	0.032	0.100	-0.344	0.306
DS	0.366	0.084	0.176	0.523
DHor	0.348	0.093	0.118	0.519
Depoch	15.993	1.191	13.210	18.092

Taking into consideration the variance of epoch differences, from the total displacement a mean annual rate calculated for each point. This yearly displacement is an estimation because it is measured from two distinct epochs and not through a time series which is the best method for velocity calculation. This annual displacement is shown in Fig. 4

From the results it is shown that horizontal displacements take place in Greek region and there are subareas with the same behavior.

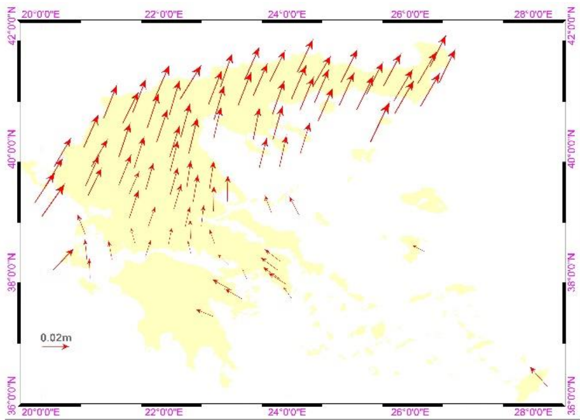

Figure 4. Mean annual displacements on triangulation point measured at 2001-2002 and 2014-2018, referenced to IGS08.

B. *COMPARISON HGRS87 vs HMRF*

HGRS87 is parallel orinented to ITRF89 and the transformation vector from one system to the other as was calculated by Veis, 1994 and Veis, 1995 is:

$$DX=-199.695m \quad DY= 74.815m \quad DZ=246.045m \tag{4}$$

Using the translation vector (Veis, 1994) the HGRS87 coordinates are transformed to ITRF89 ones.

After that, using the transformation from ITRF89 to ITRF2008 (Boucher and Altamimi, 2011) without rates of change of the parameters it was concluded to ITRF2008 coordinates which are assumed to be identical to IGS08. Some mm that reflect to the difference from the antenna calibrations between IGS08 and ITRF2008 were ignored. After the above calculations coordinate data were collected in the same coordinate system (IGS08) for 328 common points from HGRS87 and HMRF. The remaining difference is the displacement due to the difference of the epochs. Comparing the aforementioned results by subtracting ITRF2008 coordinates (transformed from HGRS87) from HMRF coordinates an average displacement of about 1.3m was concluded. Standard error for the comparison calculated up to 0.30m at Section II paragraph F so most of the coordinate difference is assumed to be displacement. Part of these differences including those that are lower than 0.3m could also be considered as inconsistency between datums. Statistics from the above comparison are depicted on Table 3.

Table 3. Statistics from difference between ITRF2008 coordinates transformed from HGRS87 and HMRF coordinates (all in meters).

	DX	DY	DZ	DS
Average	-0.93	0.42	0.40	1.31
Std	0.50	0.79	0.55	0.80
Min	-2.00	-5.62	-0.90	0.18
Max	0.75	1.41	3.30	6.32

Also comparison of transformed geocentric coordinate to topocentric ones (E, N, U) occur the same results, as expected. But with planar coordinates and horizontal displacement vector the above become more intuitive. Those are depicted in Fig. 5.

Taking a closer look to the map of Fig. 5, the reader can conclude that it resembles to the map of velocity field in Greece (Bitharis et al, 2016). There are some inconsistencies because measurements for HGRS87 started over 50 years ago. Also some vector as those in Kastellorizo which have the biggest displacements of 5-6m shows that HGRS87 coordinates there, were calculated more locally because of the big distance from the mainland and has its own HGRS87 realization after Papadopoulos, 2015.

From data above it can be concluded that HGRS87 cannot support geodetic purposes to the whole Greek region. High tectonic activity, three decades since the adoption of HGRS87, over four or five decades since the first surveys were held and the total dominance of gps usage leads to the selection of a new semi-kinematic coordinate system. Also the location of Greece itself, that means near or above tectonic plate boundary, indicates the need of a new semi-kinematic datum (Stanaway, 2014).

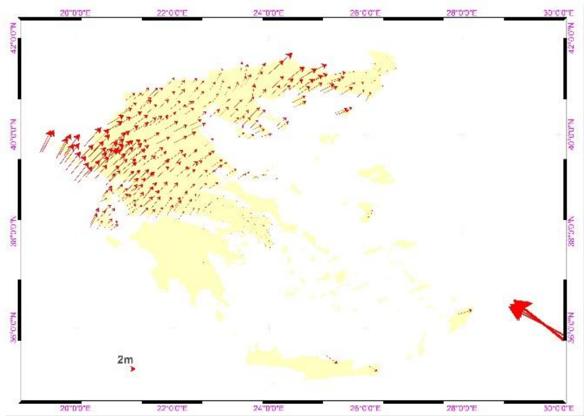

Figure 5. Horizontal displacements on triangulation point of HGRS87, transformed to IGS08 and measurements of 2014-2018 (HMRF). All stations refer to stable world (do not follow the velocities of the station of the IGS)

Adoption of semi-kinematic datum means that crustal deformation is modelled and this model is an integral part of the datum definition. Surveys made will refer to the latest realization of the kinematic ITRF or ETRF reference frame and using station velocities the survey will be propagated back to the fixed reference epoch of the semi-kinematic datum. In that way all measurements and surveys will be comparable, gps users will make survey to the present epoch and the selected datum will be fixed in time.

From data above is also obvious that trajectory vectors at the same stations are different from 1987 to 2002 and from 2002 to 2018, so if a kinematic datum is adopted station velocities should be reviewed periodically at each geological block.

C. *VELOCITIES ON TECTONICS*

Interesting results occur at local areas around faults. Keeping stable some stations, measured displacements to near points can confirm the activity of faults of Gre.DA.S.S.

Class "A" stations of HMRF selected to be the stable reference points because they were the reference points for surveying class "B" stations. Then for each class "B" point calculated E, N for itself and for the corresponding stable station in a topocentric coordinate system for both HGRS87 and HMRF. After that for each class "B" point DE, DN (Stable - class "B") calculated in both HGRS and HMRF. Lastly DDE (DE_HMRF – DE_HGRS87) and DDN (DN_HMRF – DN_HGRS87) was calculated and total horizontal displacement was exported (DD_Hor).

In that way displacement vectors of 197 points referred to 104 near points were extracted as shown in Fig. 6. Overlaying the major faults of the Greek area it can be concluded that this relative displacements occur mostly when a baseline is intersected by a fault.

In order to evaluate the aforementioned results each area must be studied carefully including (or concluding to) more local faults.

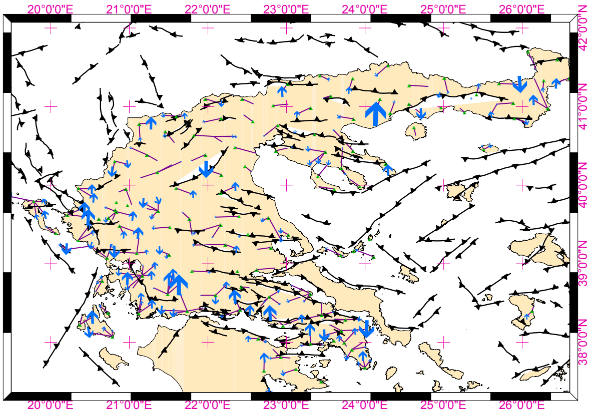

Figure 6. Measured relative displacements on triangulation points of HGRS87 and HMRF in conjunction to faults by GreDaSS database.

D. *CASE STUDY Kefallonia*

Kefallonia island is one of the most studied areas in Greece. Numerous papers are published about it (Sakkas et al. 2015; Boncori et al. 2015; Lagios et al. 2007; Yannick et al. 2000). The horizontal trajectories of this area relatively to Eurasia show a consistent pattern with the overall motion of the west end of the Hellenic West Arc as described from previous studies (Cocard et al., 1999; Kahle et al., 2000; Hollenstein et al., 2006, Lagios et al., 2007).

Useful results for the tectonic regime of Kefallonia can be studied by DGPS analysis for the period 2001 to 2017 and classical measurements during 70s. In order to detect local tectonic motions, different stations was selected as fixed points in order to establish a local network tied to IGS08 which indicates displacements from the HGRS87 era of measurements to HMRF observations using the methodology described in the previous paragraph:

1) Selected as fixed station triangulation point 123074 in Ithaki island, it can be observed that west part of kefallonia is moving faster that the rest island and the total deformation observed up to 5.3m (!) since more than 40 years. The moving pattern of the area agree with other studies (Cocard et al., 1999, Hollestein et al., 2006) and shows that the border of Boundary between Pre-Apulian and Ionian geologic units, causes different velocities to the blocks (fig. 7).

2) Selecting as fixed station triangulation point 3035 in southeast part of kefallonia island, it can be observed that west part of kefallonia is moving faster and counterbalancing than the rest island and the total deformation observed is up to 1.9m, in almost 40 years. That means that stations which are placed western of

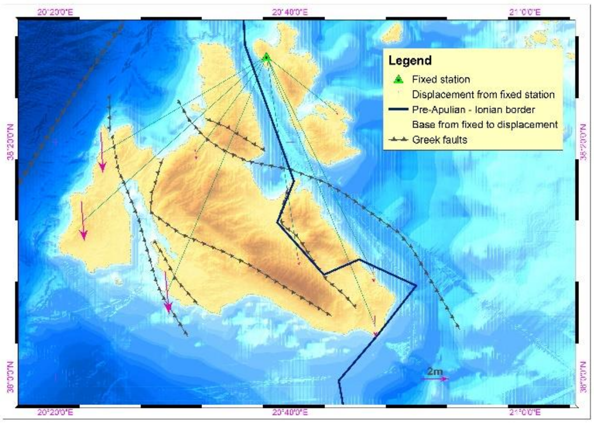

Figure 7. Measured relative displacements on triangulation points of Kefallonia in relation to Ithaki (point 123074).

the border between the pre-Apulian and Ionian geologic part present much more displacements than the other areas in the island. These trajectories show also a clock-wise rotation of Kefallonia in respect of the center of the island, which already mentioned (Lagios 2007, Cocard et al., 1999) (fig. 8).

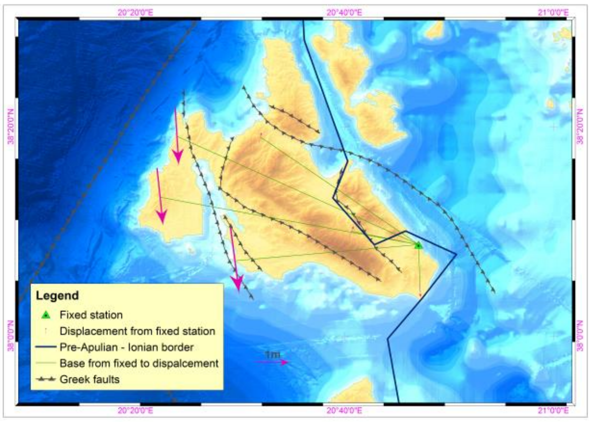

Figure 8. Measured relative displacements on triangulation points of Kefallonia in relation to the southeast part of Kefallonia (point 3035).

3) Selected as fixed station triangulation point 145060 in continental Greece about 80km faraway of the coast, it can be observed that horizontal trajectories in Kefallonia agree to the general pattern of the area (western Greece, Akarnania block). Southern and western stations are moving faster than northern and eastern ones so kefallonia (average displacement 7.5m) is moving faster that Ithaki (average displacement 5.8m) and Lefkada (average displacement 4.8m) and the three islands are moving faster than Akarnania block (average displacement 3.4m) (fig. 9). So there are at least four separate blocks in this area as suggested by Haslinger et al. 1999 and corroborated by the GPS results of Cocard et al. 1999 and confirmed from Hollestein et al., 2008.

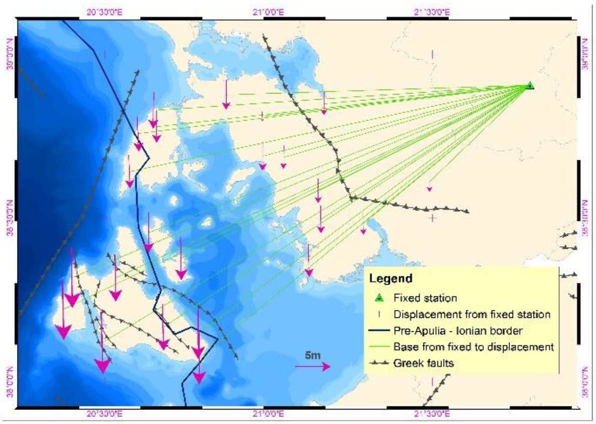

Figure 9. Measured relative displacements on triangulation points of Kefallonia, Lefkada, Ithaki and Akrnania block in relation to central Greece (point 145060).

4) Selected as reference station triangulation point 110024 in continental Greece, at the southeast part of Akarnania Block, it can be observed that stations at Lefkada island were almost stable (the maximum displacements for 40 years is up to 0.59m), while Kefallonia island present a differential movement from 2 to 4.2m. From this trajectories it is obvious that kefallonia island is moving in different way than Akarnania Block and Lefkada island. That means that Kefallonia consists a separate block from Akarnania and Lefkada, which already mentioned at Ch. Hollenstein et al., 2008 (fig. 10).

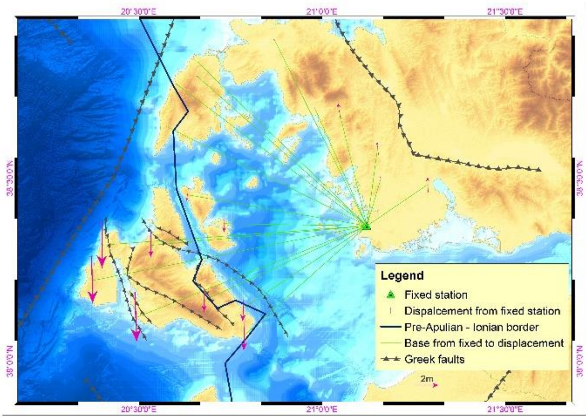

Figure 10. Measured relative displacements on triangulation points of Kefallonia, Lefkada, Ithaki and Akrnania block relative to the south of Akarnania block (point 110024).

Beside the above results that come from the comparison between HGRS87 and HMRF and the crustal motion referred to a fixed point inside or outside Kefallonia it also essential to examine the absolute displacement of some points. This can be done by comparing the common points of HEGNET and HMRF. It is obvious that the border between the Pre-Apulian and the Ionian geological units divides the region in two different motion models. . The Ionian one (east unit) moves rather to the north with total displacement of 22-24 cm in about 16 years. The Pre-Apulian (west unit) is displaced faster and in north-east direction making up 36cm in about 16 years (fig. 10). This agrees with total regression of the pre Apulian zone that was underlined at Briole et al., 2015, Lagios et al., 2012).

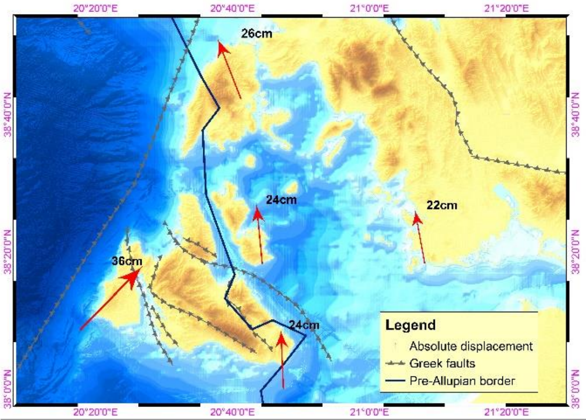

Figure 10. Measured absolute displacements on triangulation points of Kefallonia, Lefkada, Ithaki and Akrnania block in 16.3 years.

IV. CONCLUSIONS

A complete analysis of almost 15 years of campaign-type data on GPS sites in Greece has been performed. It is presented a combined GPS solution in a global reference frame, which meets high demands in terms of consistency, accuracy, reliability and resolution. This was reached by several important steps, such as referring to a strictly consistent reference frame, rigorously selected reference stations, introducing network constraints and the survey itself by selecting the sites, making gps measurements, forcing and fixing the exact point of measurement etc. The above resulted in 94 common sites from the realization of HEGNET2002 and HMRF, nevertheless referenced to the same frame in different epochs.

The GPS results ascertain and refine previous geodetic, geological and seismological findings in detail and reveal new kinematic constraints, which allow improved insights in the crustal motion and deformation of the regions studied.

The overall results for the studied area clearly show the different (known and supposed) kinematic regimes That reside in this region. A displacement of about 10cm-50cm with an average of 35cm exist in the Greek territory in a 16-year time span. Statistics (table 2) and the variance of vector directions (fig. 4) reveal the diversity of crustal deformation.

Looking back in time since the present national coordinate system was surveyed and established and comparing it to modern surveys some facts are revealed. Transforming HGRS87 coordinates to ITRF2008 ones for 328 points concludes to a mean difference of about 1.3m±0.8m between them and the present situation. This fact leads to two conclusions. The first one is that HGRS87 is well established since the surveys it comes from were held in a 2-decade time variance and the transformation to a modern reference frame is consistent since a deformation model wasn't applied for each surveyed site. The second one is that there is high tectonic activity in Greece resulting to deformations that can be reached up to 6.3m in the time passed between the surveys of the aforementioned reference systems. Nevertheless the consistency of HGRS87 and the good fitting using a translation vector refer to the establishment period of it. Nowadays deformation models via velocity field and the dominance of gps equipment lead to the need of an adoption of a new semi-kinematic reference frame in order to achieve geodetic accuracy and play the role of the geodetic infrastructure for Greece. Also station velocities should be reviewed periodically due to variation of block movements. Combining it with geophysical properties (gravity) in order to include the dynamic variation in potential and conclude to more accurate heights would be the best strategy.

Examining the 197 local vectors of deformation shows that the deformation model is affected differently for each region in Greece. This method certifies the existence of active faults and reveal areas of newer possible ones. Also an essence of deformation velocity and direction of it is concluded. Although deformation is obvious in many areas geological surveys are essential in order to have a combined analysis that leads to more precise results.

In a preliminary such case study at the area around Kefallonia island, clockwise rotation around the centre of Kefallonia was confirmed. The existence of Akarnania Block with different movement in reference with the rest continental Greece, was also confirmed. Finally places around the boundary of Pre- Apullian and Ionian geologic units was found to have differential movements.

Remaining work for next years is to measure the rest of Greek region in order to complete HMRF. Discussion of a new semi kinematic coordinate system must begin with all the competent Services (HMGS, NTUA, AUTH etc). Carefully study of each displacement referenced to every base point can support numerically the activeness of faults included in GreDaSS.Also the exploitation of raw measurements that was included in the adjustment of HGRS87 can reveal more detail information about local movements in the Greek territory.

V. ACKNOWLEDGEMENTS

The authors would like to acknowledge the HMGS and its Commander himself for the support, the data that was granted and the assigned work that lead to that paper. Also we would like to thank NTUA and Professor Vasillios Gikas personally for the opportunity of presenting the work that has been done.

References

Anagnostou E., (2007). National Report of Greece to EUREF, EUREF Symposium Proceedings, 6-9 June 2007, London, UK.

Beutler, G., Bock, H., Brockmann, E., Dach, R., Fridez, P., Gurtner, W.,Hugentobler, U., Ineichen, D., Johnson, J.Meindl, M., Mervart, L.,Rothacher, M., Schaer, S., Springer, T., Weber, R., (2001). In: Hugentobler,U., Schaer, S., Fridez, P. (Eds.), Bernese GPS Software Version 4.2. Astronomical Institute, University of Berne, Switzerland.

Bitharis S., Fotiou A., Pikridas C., Rossikopoulos D., (2016). A New Velocity Field of Greece Based on Seven Years (2008–2014) Continuously Operating GPS Station Data. In: Freymueller J.T., Sánchez L. (eds) International Symposium on Earth and Environmental Sciences for Future Generations. International Association of Geodesy Symposia, vol 147. Springer, Cham Link.

Boucer C., Altamimi Z., (2011). Memo v.8: Specifications for reference frame fixing in the analysis of a EUREF GPS campaign.

Briole P., Rigo A., Lyon-Caen H., et al., (2000). Active deformation of the Corinth rift, Greece: Results from repeated Global Positioning System surveys between 1990 and 1995. J Geophys Res 105:25605. doi: 10.1029/2000JB900148.

Caputo R., and Pavlides S., (2013). The Greek Database of Seismogenic Sources (GreDaSS), version 2.0.0: A compilation of potential seismogenic sources (Mw > 5.5) in the Aegean Region.http://gredass.unife.it/, doi: 10.15160/unife/gredass/0200.

Chousianitis K., Ganas A., Evangelidis C., (2015). Strain and rotation rate patterns of mainland Greece from continuous GPS data and comparison between seismic and geodetic moment release. https://doi.org/10.1002/2014JB011762.

Cocard M., Kahle H.G., Peter Y., et al., (1999). New constraints on the rapid crustal motion of the Aegean region: Recent results inferred from GPS measurements (1993-1998) across the West Hellenic Arc, Greece. Earth Planet Sci Lett 172: 39 – 47. doi:10.1016/S0012-821X(99)00185-5.

Dach R., Hugentobler U., Fridez P., Meindl M., (2007). "Bernese GPS Software Version 5.0."Astronomical Institute, University of Bern, Switzerland.

Floyd M. a., Billiris H., Paradissis D., et al., (2010). A new velocity field for Greece: Implications for the kinematics and dynamics of the Aegean. J Geophys Res. Solid Earth 115:1–25. doi: 10.1029/2009JB007040.

Forsberg F., Liu J. B., Burns P. N., Merton D. A., Goldberg B. B., (1994). Artifacts in ultrasonic contrast agent studies. https://doi.org/10.7863/jum.1994.13.5.357.

Jolivet Laurent, Armel Menant, Pietro Sternai, Aurélien Rabillard, Laurent Arbaret, et al., (2015). The geological signature of a slab tear below the Aegean. Tectonophysics, Elsevier, 2015, 659, pp. 166-182. <10.1016/j.tecto.2015.08.004>. <insu-01187096>

Herring T. A., King R. W., Floyd M. A., McClusky S. C., (2018). Introduction to GAMIT/GLOBK.Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts, Institute of Technology.

Hollenstein C., Müller M.D., Geiger A., Kahle H.G., (2008). Crustal motion and deformation in Greece from a decade of GPS measurements, 1993–2003. Tectonophysics 449 (1–4):17–40. doi:10.1016/j.tecto.2007.12.006.

Kahle H.-G., Müller M.V., Mueller S., Veis G., Billiris H., Paradissis D., Drewes H., Kaniuth K., Stuber K., Tremel H., Zerbini S., Corrado G., Verrone G., (1993). Monitoring West Hellenic Arc Tectonics and Calabrian Arc Tectonics "WATH A CAT" using the Global Positioning System. In: Smith, D., Turcotte, D. (Eds.), Contributions of Space Geodesy to Geodynamics: Crustal Dynamics, volume 23 of AGU Geodynamics Series, pp. 417–429.

Kahle H.-G., Straub C., Reilinger R., McClusky S., King R.W., Hurst K., Veis G., Kastens K., Cross P., (1998). The strain rate field in the eastern Mediterranean region, estimated by repeated GPS measurments. Tectonophysics 294, 237–252.

Kahle H.-G., Cocard M., Peter Y., Geiger A., Reilinger R., Barka A., Veis G., (2000). GPS-derived strain rate field within the boundary zones of the Eurasian, African and Arabian Plates. J. Geophys. Res. 105 (B10), 23353–23370.

Karakonstantis A., Papadimitriou P., (2017). Local earthquake tomography in the broader area of western Corinth gulf. Bulletin of the Geological Society of Greece 50 (3), 1143-1152.

Kassaras I., Louis F., Makropoulos K., Magganas A. and Hatzfeld D., (2009). Elastic-Anelastic Properties of the Aegean Lithosphere-Asthenosphere Inferred from Long Period Rayleigh Waves, in "The Lithosphere: Geochemistry, Geology and Geophysics", Eds. J. E. Anderson and R. W. Coates, ISBN: 978-1-60456-903-2, Nova Publishers, N.Y., USA, pp. 383.

Kreemer C, Holt W.E. and Hains A.J., (2003). An integrated global model of present-day plate motions and plate boundary deformation, Geophys.J.Int, 154, 8-34.

Kreemer C., Blewitt G., Klein E.C., (2014). A geodetic plate motion and global strain rate model. Geochemistry Geophys Geosystems 15:3849–3889. doi: 10.1002/2014GC005407.

McClusky S., Balassanian S., Barka A., Demir C., Ergintav S., Georgiev I., Gurkan O., Hamburger M., Hurst K., Kahle H., Kastens K., Kekelidze G., King R., Kotzev V., Lenk O., Mahmoud S., Mishin A., Nadariya M., Ouzounis A., Paradissis D., Peter Y., Prilepin M., Reilinger R., Sanli I., Seeger H., Tealeb A., Toksöz M.N., Veis G., (2000). Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. J Geophys Res 105(B3):5695. doi:10.1029/1999JB900351.

McKenzie D., (1978). Active tectonics of the Alpine—Himalayan belt: the Aegean Sea and surrounding regions. Geophysical Journal of the Royal Astronomical Society 55, 217–254.

Müller M.V., (1996). Satellite geodesy and geodynamics: Current deformation along the West Hellenic Arc. PhD thesis, Eidgenössische Technische Hochschule ETH Zürich. Mitteilungen Nr. 57, Institut für Geodäsie und Photogrammetrie.

Papadopoulos N., (2015). Processing of satellite observations in Megisti island using GAMIT/GLOBK, Master diploma thesis, NTUA,School of Rural and Survey Engineering.

Papadopoulos N., Technical report on the coordinate calculation of the triangulation network in Megisti island in an international coordinate system and the calculation of a local transformation between WGS84 and HGRS87.

Papazachos B.C., (1990). Seismicity of the Aegean and the surrounding area, Tectonophysics, 178,287-308.

Peter Y., (2001). Present-day crustal dynamics in the Adriatic–Aegean plate boundary zone inferred from continuous GPS-measurements. Mitteilungen Nr. 71. Institut für Geodäsie und Photogrammetrie, ETH Zürich.

Stanaway R., (2014). Regional and national reference frames. Reference Frames in Practical Manual, Commission 5 Working Group 5.2 Reference Frame, FIG Publication No 64.

Takos I., (1989). New adjustment of Greek geodetic networks. Journal of the Hellenic Military Geographic Service, Issue No. 36, pp.15–30 (in Greek).

Tiberi C., Lyon-Caen H., Hatzfeld D., Achauer U., Karagianni E., Kiratzi A., Louvari E., Panagiotopoulos D., Kassaras I., Kaviris G., Makropoulos K. AND P. Papadimitriou, (2000). Crustal and upper mantle structure beneath the Corinth rift (Greece) from a teleseismic toHellenic Journal of Geosciences, vol. 45, 193-208 207 Project 33 N:17 2/14/11 9:14 PM Page 207 mography study. J. Geophys. Res., 105, No B12, 28159-28171. Tselentis, G.-A. (1997). Contemporary Seismology. Publ. Papasotiriou, Athens (in Greek).

Tscherning C.C., Forsberg R., Knudsen P., (1992). "The GRAVSOFT package for geoid determination." Edited by Petr Holota. 1. Continental Workshop on the Geoid in Europe: Towards a Precise Pan-european Reference Geoid for the Nineties. Prague: Research institute of geodesy, topography and cartography. 327-334.

Veis G., (1994). Reference Systems and the realizations of HGRS87 in: Digital Cartography, Photogrammetry, Remote Sensing and Cutting Edge Technologies, Technical Chamber of Greece.

Veis G., (1995). Technika Chronika, Technical Chamber of Greece.