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Konstantinos Katsampalos
Christopher Kotsakis
Michail Gianniou

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Hellenic terrestrial reference system 2007 (HTRS07): a regional realization of ETRS89 over Greece in support of HEPOS

KONSTANTINOS KATSAMPALOS – CHRISTOPHER KOTSAKIS
Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Greece

MICHAIL GIANNIOU
Ktimatologio S.A., Hellenic Cadastre, Athens, Greece

Summary. – An overview of a regional realization of ETRS89 over the area of Greece is presented in this paper. The underlying project is related to the recent establishment of the Hellenic Positioning System (HEPOS), a GPS-based spatial positioning service using a network of 98 continuously operating reference stations located in Greece and operated by KTIMATOLOGIO S.A. The data analysis procedure that was followed for the least-squares adjustment of the HEPOS network is described, along with the adopted methodology for the datum definition and its alignment with the ETRS89/ETRF05 reference frame. The paper presents also a combined transformation model that was concurrently developed for the connection between the official Hellenic Geodetic Reference System 1987 (HGRS87) and the Hellenic Terrestrial Reference System 2007 (HTRS07), where the latter identifies the ETRS89/ETRF05-based frame that underlies the operation of HEPOS. The results obtained from the evaluation of the aforementioned model, at 2430 geodetic benchmarks throughout Greece, revealed an accuracy level that is better than 10 cm in terms of the rms value for the total horizontal transformation error.

1. – INTRODUCTION

The Hellenic Positioning System (HEPOS) is a national GPS-based service for surveying and geomatics applications in Greece, which supports real-time and post-processing 3D spatial positioning up to mm-level accuracy. Established by KTIMATOLOGIO S.A. during a two-year project (2006-08) that was co-funded by the Hellenic State and the EU, HEPOS consists of 98 continuously operating GPS reference stations which cover the entire area of Greece, including its mainland part and all major islands (see fig. 1).

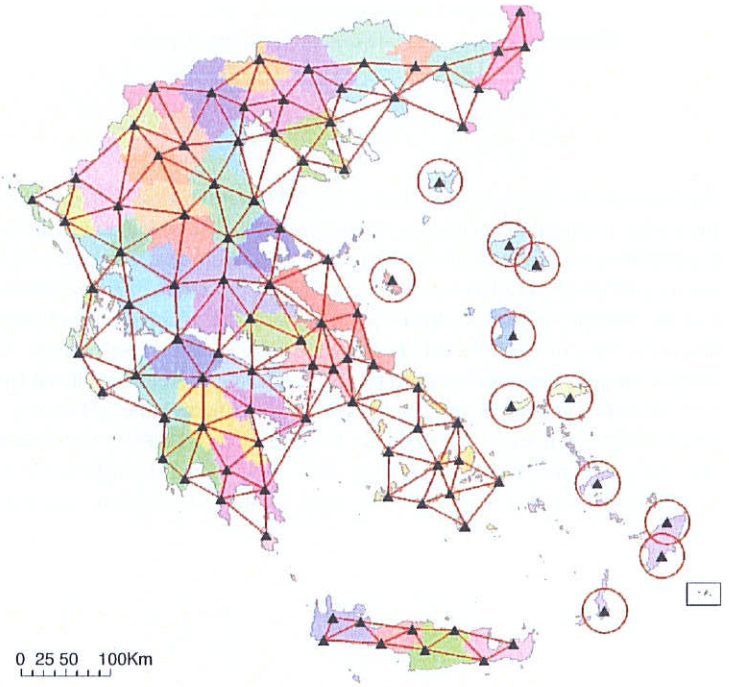

Fig. 1 – The HEPOS network (98 stations).

Based on the results of a weighted least-squares adjustment using 17 days of continuous GPS observations that were collected over the HEPOS network in the fall of 2007, the 3D Cartesian coordinates at its 98 permanent reference stations have been determined with respect to the European Terrestrial Reference System (ETRS89). These spatial coordinates provide, for the first time, a nation-wide

realization of ETRS89 in Greece, which is henceforth called the *Hellenic Terrestrial Reference System 2007* (HTRS07). Note that the three EUREF/EPN stations operating in Greece at that time, namely TUC2 in Crete (since 2004), AUT1 in Thessaloniki (since 2005) and NOA1 in Athens (since 2006), were also included in the adjustment of the HEPOS network, along with 11 additional reference stations of the EUREF permanent GNSS network. More details about the HEPOS network adjustment and the realization aspects of HTRS07 are given in sections 4 and 5 of the present paper, respectively.

Within the frame of the HEPOS project, a coordinate transformation model has also been determined between HTRS07 and the official Hellenic Geodetic Reference System of 1987 (HGRS87) based on the known coordinates for 2470 geodetic benchmarks of the national triangulation network. These benchmarks represent almost 10% of the entire Hellenic triangulation network and they were re-surveyed through a national GPS campaign over a six-month period in 2007. The performance of the derived model for the HTRS07-HGRS87 coordinate transformation is better than 10 cm (in terms of its estimated rms value for the total horizontal transformation error throughout the Hellenic area), which is considered more than sufficient for most HEPOS-based cadastral surveying projects that need to be tied to the official HGRS87 spatial reference frame. The development of this coordinate transformation model and the results obtained from its evaluation are presented in detail in Sect. 6.

Note that in terms of regional geodynamic effects on the HEPOS network, some preliminary results obtained during its first year of operation by Katsampalos et al. (2008) indicated the presence of 1-2 cm/yr relative horizontal velocities (with respect to the EUREF/EPN station AUT1 located in Thessaloniki) at a number of selected HEPOS stations over the mid-western part of Greece.

2. – HEPOS PROJECT

HEPOS was developed by KTIMATOLOGIO S.A., a state-owned agency that is responsible for the operation of the Hellenic Cadastre. The scope of the underlying project was twofold: firstly, there was the aim to define a modern and precise geodetic reference frame for Greece in accordance with the EUREF guidelines and the INSPIRE directive, and secondly there was the need to establish the necessary infrastructure for fast, inexpensive, efficient and accurate GPS-based spatial positioning in support of cadastral surveys and other types of surveying and mapping applications throughout the country. The system had been in limited use since the beginning of 2008 for the production of Very Large Scale Ortho-photomaps (VLSO) of the entire Hellenic area, in support of the on-going modernization efforts for the Hellenic cadastral infrastructure. Since May 25, 2009, HEPOS has been fully released

to the general public and the surveying/geomatics community (see http://www.hepos.gr).

In general, the HEPOS system supports various real-time network-based GPS positioning techniques (VRS, FKP, MAC), as well as post-processing geodetic positioning up to mm-level accuracy. However, 11 of the total 98 HEPOS reference stations, which are located in several islands across the eastern part of the Aegean Sea (see Figure 1), offer currently only single-base solutions. More operational and technical details about the HEPOS system can be found in Gianniou et al. (2009).

3. – GEODYNAMICAL CONDITIONS IN THE HELLENIC AREA

It is well documented in the geodetic literature that the geodynamical activity over the Hellenic area, as depicted from various GPS-derived velocity fields and crustal deformation patterns, differs significantly from that of the «stable part» of Europe (e.g. Hollenstein et al. 2006, Kahle et al. 1995, McClusky et al. 2000, Nyst and Thatcher 2004). For example, the old DION satellite tracking station that is located at the Dionysos Observatory nearby Athens presents a 3.1 cm/yr SW-motion, which is clearly visible in the ETRF05 velocity field given in Altamimi (2007). In another study by Hollenstein et al. (2006) a similar SW-motion of about 3 cm/yr (with respect to the Eurasian plate) was inferred over a continuous GPS network that had been established in the southern-western part of the country. Overall, the residual velocity field in the area of Greece, with respect to a Eurasian-fixed reference frame, is almost two orders of magnitude stronger than the existing intra-plate velocity field in central Europe. Furthermore, the complexity of the crustal deformation processes in Greece due to short/long-term seismicity, active faulting, fault geomorphology, continental plate tectonics and regional micro-plate tectonics (Nyst and Thatcher 2004) suggests a rather spatially inhomogeneous velocity field, a fact that imposes considerable challenges for the realization and long-term stability of a spatial coordinate reference frame over the Hellenic area.

The aforementioned behaviour has been validated using the official data published by EUREF for the three Hellenic EPN stations that were operating in 2007, namely AUT1, NOA1 and TUC2. Based on their weekly position estimates obtained from the EUREF/EPN website (see http://www.epncb.oma.be/), the horizontal trajectories of these stations were computed with respect to ETRF05 over the time period 2005.0–2008.8. From these trajectories, the following mean horizontal velocities were derived: 1.03 cm/yr (AUT1), 2.80 cm/yr (NOA1), and 3.00 cm/yr (TUC2). Fig. 2 shows the computed trajectories (coloured dots) as well as the theoretical trajectories resulting from the officially published EUREF/EPN velocities (grey dots).

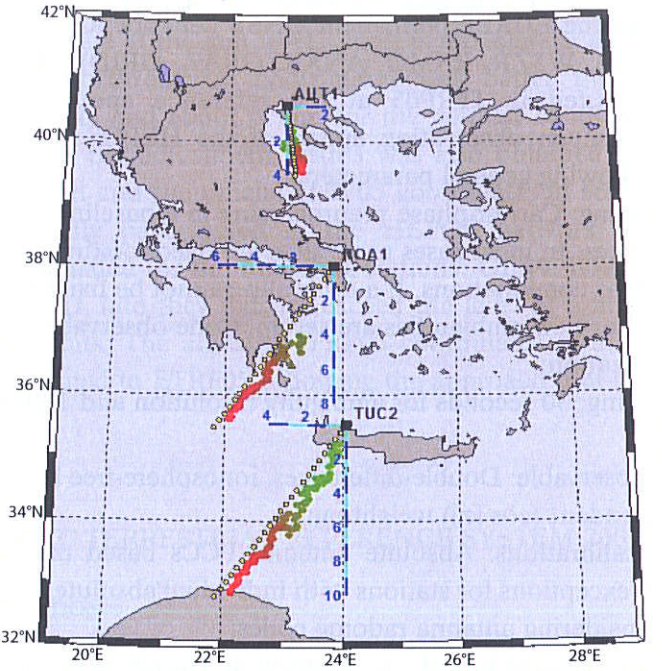

Fig. 2 – ETRF05 horizontal trajectories at the three EUREF/EPN stations in Greece over the time period 2005.0 (green dots) – 2008.8 (red dots). The scale of the local horizontal axes at each station is given in cm. Note that the NOA1 station started its operation in 2006.

Note that apart from the differences in the magnitude of the horizontal velocity vectors at the three Hellenic EUREF/EPN stations, AUT1 shows a completely different direction of horizontal crustal motion (see fig. 2). These results agree well with the current knowledge on the Hellenic velocity field, according to which the northern part of the country moves less than the southern part with respect to a Eurasian-fixed stable reference frame, at a minimum rate of 1 cm/yr.

4. – HEPOS NETWORK ADJUSTMENT

The HEPOS network has been adjusted with the use of 17 days of continuous GPS observations that were collected over its 98 permanent reference stations. Two data sets, spanning a two-week period (October 7-20, 2007) and a three-day period (November 17-19, 2007), were combined into a single weighted least-squares solution using the Bernese software program (ver. 4.2). The three EUREF/EPN stations located in Greece at the time of HEPOS development, namely AUT1, NOA1 and TUC2, were also included in the network adjustment, along with 11 additional

reference stations of the EUREF permanent GNSS network (GLSV, JOZE, MATE, NICO, NOT1, TRAB, WTZR, RAMO, ANKR, GRAZ, ORID). The final adjusted solution was computed in ITRF05 at the reference epoch 2007.79 (which corresponds to the mean observation epoch of the HEPOS network) and it is described by the following general parameters:

– pre-processing: Carrier-phase preprocessing in a baseline by baseline mode using triple-differences. In most cases cycle slips are fixed looking simultaneously at different L1/L2 linear combinations. If a cycle slip cannot be fixed reliably, bad data points are removed or new ambiguities are set up. Code observables were used only for clock synchronization;

– data sampling: 30 seconds for ambiguity resolution and 180 seconds for the final processing;

– modeled observable: Double-differences, ionosphere-free linear combination with elevation-dependent (cos [z]) weighting;

– antenna calibrations: Absolute antenna PCCs based on IGS05 absolute calibration model (exceptions for stations with individual absolute calibrations listed in epnc_05.atx) considering antenna radome codes;

– troposphere: Estimation of zenith delay at 1-hour interval at each station using the wet-Niell model;

– ionosphere: Regional ionospheric model computation (only for OIF ambiguity resolution);

– ambiguity resolution: Use of the quasi-ionosphere-free (QIF) strategy with regional TEC information (elevation cut-off angle: 10 degrees);

– orbits-ERPs: IGS final orbit and ERP information;

– planetary Ephemeris: DE200;

– ocean loading: Onsala Space Observatory's FES2005 model;

– atmospheric loading: No atmospheric loading corrections are taken into account;

– tidal model: Solid earth tidal displacements are modelled according to the IERS 1996 conventions;

– rejection criteria: Daily RINEX observation files containing less than 10% of possible observations are ignored. The threshold value concerning data screening is 2.5 mm, specifically for a normalized or L1 zero-difference zenith residual. Station where baseline data exceeding the overall sigma level of 5 mm is excluded.

The datum definition in the HEPOS network adjustment was implemented through minimal constraints at a single reference station. In particular, the EUREF/EPN station located in Thessaloniki (AUT1) was kept fixed to its ITRF05/2007.79 coordinates, which were derived from its official ITRF05/2000.0 coordinates/velocities that were available through the EUREF website.

The a-posteriori standard deviations for the final adjusted ITRF05 coordinates of all HEPOS stations were at the mm level, whereas the average daily repeatability in the corresponding north/east/up coordinates was better than 2 mm for the horizontal components and about 5 mm for the vertical component. An external quality assessment of the adjustment results was also obtained by the differences between the estimated and the official ITRF05 coordinates at several EUREF/EPN stations that originally participated in the HEPOS network adjustment. Such differences were evaluated for the following stations: GLSV, JOZE, MATE, NOT1, WTZR, GRAZ, ORID, and they did not exceed the level of 6 mm in all Cartesian coordinate components. The adjusted ITRF05 coordinates of all HEPOS stations were finally transformed to ETRF05 following the approach that is described in the next section.

5. – THE HELLENIC TERRESTRIAL REFERENCE SYSTEM 2007

5.1. - Datum definition

In compliance with the EU Inspire Directive (15/5/2007), the Hellenic Terrestrial Reference System 2007 (HTRS07) is a realization of ETRS89 at the HEPOS reference stations. This realization is based on the estimated 3D Cartesian coordinates of the 98 continuously operating HEPOS stations with respect to the ETRF05 frame for the time epoch 2007.5.

According to the EUREF specifications, the computation of a GPS campaign in ETRS89 should follow the procedure described in the memo *Specifications for reference frame fixing in the analysis of a EUREF GPS campaign (version 7)* by Boucher and Altamimi (2008) – abbreviated thereafter as the *B/A memo*. At the time of the HEPOS network adjustment and the HTRS07 realization, an older version of the *B/A memo* was available (version 6 from 2007) recommending that the analysis of a EUREF GPS campaign in ETRS89 should consist of the following three steps:

- Step 1: process GPS data in ITRS at current epoch, using a recent ITRF;
- Step 2: convert in ETRS89 at current epoch;
- Step 3: express in ETRS89 at epoch 1989.0.

Due to the complex geodynamic conditions over the area of Greece (see Sect. 3) and the lack of a reliable crustal velocity model for the entire country, it was decided not to execute step 3 for the establishment of HTRS07. It should be noted that the current version of the *B/A memo* (version 7) does not recommend anymore the implementation of step 3, and thus the transformed ETRFxx coordinates from step 2 should not be propagated by means of whatever intraplate velocities to any other epoch than the central epoch of the used observations (Boucher and Altamimi 2008).

From the implementation of step 1, which has been outlined in the previous section, the adjusted ITRF05 coordinates for all HEPOS stations at the mean epoch 2007.79 were available. As already mentioned in Sect. 4, the EUREF/EPN station AUT1 was solely fixed for the datum definition during the HEPOS network adjustment in ITRF05. This choice was based on the geodynamic considerations that were discussed in Sect. 3 and the rationale that a single high-quality Hellenic permanent reference station, as stable as possible with respect to the Eurasian tectonic plate, should be associated with the subsequent HTRS07 realization.

Next, the computation of the ETRF05 coordinates (at the same mean epoch 2007.79) for all HEPOS reference stations, including the three Hellenic EUREF/EPN stations that participated in the HEPOS network adjustment, was performed according to the procedure described in step 2 of the *B/A memo*. The comparison of the resulting coordinates for the three Hellenic EUREF/EPN stations with their official ETRF05/2007.79 coordinates (obtained from the EUREF website using their ETRF05/2000.0 coordinates and velocities) showed the following systematic differences:

AUT1
$\Delta X = 2$ mm, $\Delta Y = 6$ mm, $\Delta Z = 1$ mm,

NOA1
$\Delta X = 1$ mm, $\Delta Y = 8$ mm, $\Delta Z = 1$ mm,

TUC2
$\Delta X = 9$ mm, $\Delta Y = 6$ mm, $\Delta Z = 1$ mm.

Given the formal accuracy of the estimated coordinates at the above stations as obtained from the original HEPOS network adjustment in ITRF05 (see Sect. 4), these discrepancies should be considered significant and they partially reflect the inherent weakness of the *B/A memo* (step 2) when applied in areas having different geodynamical characteristics than the stable part of the Eurasian tectonic plate. In particular, the systematic offset in the ΔX component for TUC2 (located in Crete) signifies that the southern part of the HEPOS network will not comply with the official EUREF shift and rotation rate parameters employed for the ITRF*xx* → ETRF*xx* transformation.

To ensure an «optimal» ETRS89 realization in the HEPOS network over the entire Hellenic area, the following alternative approach was finally adopted for the ITRF05 → ETRF05 transformation:

– Determination of the 3D Cartesian coordinates of the station AUT1 with respect to ITRF05/2007.79 and ETRF05/2007.5 based on its official ITRF05/2000.0 and ETRF05/2000.0 coordinates/velocities provided by EUREF. Note that the selected epoch 2007.5 for the ETRF coordinates corresponds to the mean epoch of

the national GPS campaign at the 2470 HGRS87 benchmarks which were used for deriving the official transformation model between HTRS07 and HGRS87 (see Sect. 6).

– Computation of the translation components ΔX, ΔY and ΔZ between ITRF05/2007.79 and ETRF05/2007.5 based solely on the respective «official» 3D Cartesian coordinates of AUT1 obtained from the previous step.

– Use of the above translation parameters for implementing the transformation of all HEPOS stations from ITRF05/2007.79 to ETRF05/2007.5.

The foregoing realization scheme corresponds to a more or less empirical approach, which is nonetheless consistent with a basic principle specified by the EUREF/TWG for ETRS89 realization in European spatial reference systems. Specifically, as described in the introductory section of the current *B/A memo*, any new frame validated by the TWG would have minimum systematic shift with regard to the EUREF89 frame, but should stick to its own scale especially if it is significantly more accurate than the scale underlying EUREF89. Our «AUT1-based» approach for the ETRS89 realization in the HEPOS network preserves the scale information of the original GPS measurements, in contrast to B/A memo's methodology (step 2) which would introduce regional systematic distortions due to geodynamical effects that were previously outlined.

In the following, we briefly present the numerical results obtained through the three aforementioned steps for the HTRS07 realization. The official *ETRF05/2000.0* coordinates for AUT1 which were available by EUREF at the time of GPS data processing in the HEPOS network (December 2007) are

$$\begin{aligned} X &= 4466283.737 \pm 0.003 \text{ m} \\ Y &= 1896166.625 \pm 0.002 \text{ m} \\ Z &= 4126096.618 \pm 0.003 \text{ m} \end{aligned} \tag{1}$$

Taking into account the ETRF05 velocities provided by EUREF for AUT1 at that time, the following coordinates were then computed with respect to ETRF05/2007.5:

$$\begin{aligned} X &= 4466283.774 \text{ m} \\ Y &= 1896166.650 \text{ m} \\ Z &= 4126096.559 \text{ m} \end{aligned} \tag{2}$$

The official ITRF05/2000.0 coordinates for AUT1 that were also available through the EUREF website are given below:

$$\begin{aligned} X &= 4466283.488 \pm 0.003 \text{ m} \\ Y &= 1896166.775 \pm 0.002 \text{ m} \\ Z &= 4126096.773 \pm 0.003 \text{ m} \end{aligned} \tag{3}$$

Taking into account the corresponding ITRF05 velocities provided also by EUREF, the following ITRF05/2007.79 coordinates were obtained for AUT1:

$$\begin{aligned} X &= 4466283.390 \text{ m} \\ Y &= 1896166.941 \text{ m} \\ Z &= 4126096.795 \text{ m} \end{aligned} \tag{4}$$

From the differences between the ETRF05 (epoch 2007.5) coordinates given in (2) and the respective ITRF05 (epoch 2007.79) coordinates given in (4), the corresponding 3D Cartesian shifts were determined at AUT1: $\Delta X = 0.384$ m, $\Delta Y = -0.291$ m, $\Delta Z = -0.236$ m. These shift parameters were adopted for the transformation of all HEPOS reference stations from ITRF05/2007.79 to ETRF05/2007.5 and they provide the basis for the current HTRS07 realization.

One year after the ETRS89 realization in the HEPOS network, an updated version of the *B/A memo* (version 7) was issued recommending «not to use the ETRF05 and rather to adopt the ETRF00 as a conventional frame of the ETRS89 system». Note that if the official ETRF00/2000.0 (instead of ETRF05/2000.0) coordinates/velocities of AUT1 had been used for the implementation of the previous procedure, the following ETRF00/2007.5 coordinates would have been obtained for AUT1:

$$\begin{aligned} X &= 4466283.762 \text{ m} \\ Y &= 1896166.635 \text{ m} \\ Z &= 4126096.545 \text{ m} \end{aligned} \tag{5}$$

Comparing the respective coordinates given in (2) and (5), it can be inferred that the HTRS07 system has a 3D spatial offset of about 2.4 cm with respect to ETRF00 which is the currently endorsed frame by EUREF for the realization of ETRS89 in Europe.

5.2. - TM07: Map projection system for HTRS07

For the support of cadastral, mapping and other GPS surveying applications in Greece with respect to HTRS07, a Transverse Mercator (TM) map projection with a single meridian zone is endorsed according to the following parameters:

central meridian (CM): $\lambda_0 = 24°$ East
scale factor along CM: $k_0 = 0.9996$
latitude of origin: $\varphi_0 = 0°$
false easting: $E_0 = 500000.000$ m
false northing: $N_0 = -2000000.000$ m

A different meridian zone is used only for the island of Kastelorizo ($\lambda \approx 29.6°$ East) where the TM projection, with respect to the HTRS07 system, is applied as follows:

central meridian (CM): $\lambda_0 = 30°$ East
scale factor along CM: $k_0 = 1.0000$
latitude of origin: $\varphi_0 = 0°$
false easting: $E_0 = 500000.000$ m
false northing: $N_0 = -2000000.000$ m

Note that the GRS80 reference ellipsoid is officially adopted for the conversion between Cartesian coordinates (X, Y, Z) and curvilinear geodetic coordinates (φ, λ, h) within the HTRS07 system.

6. – TRANSFORMATION MODEL BETWEEN HGRS87 AND HTRS07

A key objective within the HEPOS project was the development of a coordinate transformation model between the HGRS87 reference system (which is still the official geodetic datum in Greece) and the HTRS07 reference system that underlies the operation of HEPOS.

HGRS87 is a traditional non-geocentric local horizontal datum that was established several years ago by the Hellenic Military Geographic Service, and it is realized by the known curvilinear geodetic coordinates (φ, λ) with respect to the GRS80 ellipsoid at almost 24000 geodetic benchmarks throughout the country (Takos 1989). The map projection system associated with HGRS87 is a single-zone TM projection with the same parameters as in the HTRS07 case (see previous section) except for the value of the false northing parameter which is set to zero. A different TM meridian zone, with respect to HGRS87, is used only for the island of Kastelorizo based on the parameters $\lambda_0 = 27°$ E, $k_0 = 0.9996$, $\varphi_0 = 0°$, $E_0 = 0.0$ m and $N_0 = 0.0$ m. Height information at the HGRS87 benchmarks is available in terms of their known orthometric heights that have been determined by local ties (using spirit or trigonometric leveling surveys) with neighboring benchmarks of the Hellenic vertical reference frame.

In order to derive a precise transformation model between the aforementioned reference systems, a six-month project was carried out by KTIMATOLOGIO S.A. in 2007 to facilitate the determination of the spatial position at 2470 HGRS87 benchmarks (almost 10% of the national triangulation network) with respect to particular ITRF and ETRF frames. An example of the distribution of the re-surveyed HGRS87 geodetic benchmarks within the 1 : 50 000 TM mapping sheets is shown in fig. 3. Based on this extended network of «common points», a two-step transformation procedure has been

developed that allows the mutual transformation between HGRS87 and HTRS07, everywhere in Greece, with an average accuracy level that is better than 10 cm.

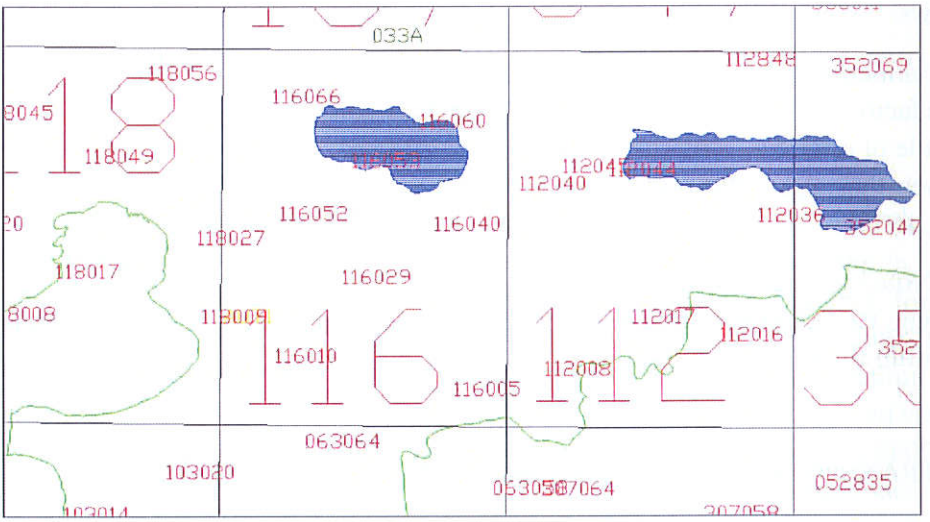

Fig. 3 – Typical distribution of re-surveyed HGRS87 geodetic benchmarks within the 1 : 50 000 TM mapping sheets.

According to the specifications issued by KTIMATOLOGIO S.A. for the national GPS campaign at the 2470 HGRS87 geodetic benchmarks, the data sampling rate was 15 seconds, the elevation mask was 15 degrees and the minimum observation time was set to 1 hour. Twelve Trimble 5700-5800 receivers with Zephyr or R8 internal antennas were used for the data collection. The 1-hour minimum duration time had to be extended under poor DOP or difficult signal reception conditions. It is considered that under normal conditions, this observation period is sufficient for achieving 1-2 cm accuracy in the horizontal position and slightly lower accuracy in the height component. It was further required that each HGRS87 benchmark had to be measured from a primary and a secondary GPS reference station, with the corresponding baseline lengths limited to approximately 40 km. GPS data from all three Hellenic EUREF/EPN stations were used for estimating the 3D Cartesian geocentric coordinates of the primary reference stations (located approximately at the centre of each 1 : 50 000 TM mapping sheet) based on individual weighted least-squares adjustments by fixing AUT1 to its official ITRF00/2007.236 coordinates (note that ITRF05 coordinates were not available at the time of these computations). The estimated positions for the other EUREF/EPN stations (NOA1, TUC2) were always compared to the corresponding official coordinates issued by EUREF and the resulting residuals were consistently within the 1-cm level. The computed coordinates of the 2470 HGRS87 benchmarks with respect to ITRF00/2007.236 were finally transformed to the HTRS07 system (i.e. ETRF05/2007.5) using a similar procedure to the one described in Sect. 5.

Transformation strategy

From the total number of 2470 re-surveyed HGRS87 benchmarks, 4 of them were located in the small island of Kastelorizo ($\lambda \approx 29.6°$ East) for which a separate 3D-shift model has only been determined to realize the HGRS87-HTRS07 coordinate transformation.

The development of a two-step coordinate transformation model HGRS87-HTRS07 for the main area of Greece, including its mainland part and all of its islands (except Kastelorizo), was based on the rest 2466 geodetic benchmarks. From these points, 36 were suspected for blunders and they were removed from the subsequent analysis, 2199 were used within the adjustment procedure for determining the transformation model parameters (see fig. 4), and the remaining 231 points were reserved for the external validation of the performance of the derived transformation model (see fig. 5).

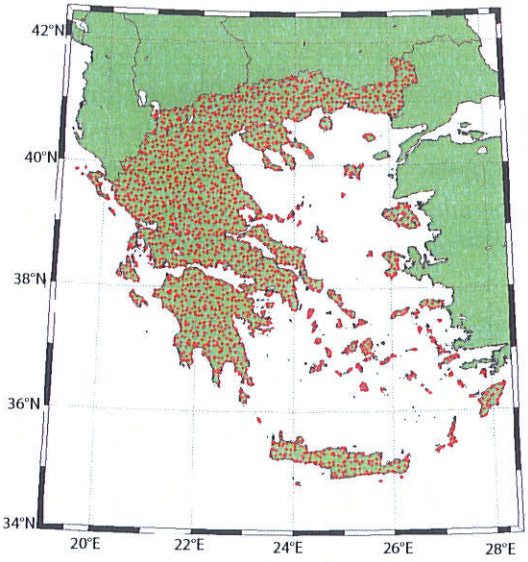

Fig. 4 – The network of 2199 HGRS87 geodetic benchmarks that were used for the development of the HTRS07-HGRS87 transformation.

As a first step, the 3D linearized Helmert-type similarity transformation was used to determine the seven basic parameters (3 shifts, 3 rotations, 1 scale factor) relating the HTRS07 and HGRS87 reference systems:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \begin{bmatrix} (1+\delta s) & \varepsilon_z & -\varepsilon_y \\ -\varepsilon_z & (1+\delta s) & \varepsilon_x \\ \varepsilon_y & -\varepsilon_x & (1+\delta s) \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \tag{6}$$

The least-squares inversion of the previous model requires the knowledge of the 3D Cartesian coordinates with respect to HGRS87, which is generally problematic due to the lack of known ellipsoidal heights at the HGRS87 benchmarks.

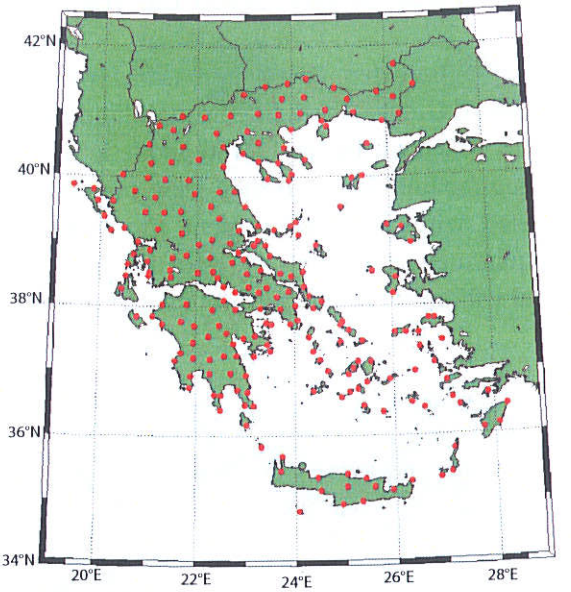

Fig. 5 – The network of 231 HGRS87 geodetic benchmarks that were used for the external evaluation of the HTRS07-HGRS87 transformation.

To overcome this problem, we chose to avoid the combined use of the available orthometric heights with an external geoid model, and instead we followed a different approach involving the direct transformation of the «observed» HTRS07 ellipsoidal heights to the HGRS87 system based on a simple 3D shift model. The three shift parameters of this preliminary transformation were computed through a least-squares adjustment of the standard Molodensky transformation formulae using as input data the horizontal coordinate differences φ'-φ and λ'-λ in the corresponding systems with respect to the GRS80 reference ellipsoid.

After the foregoing determination of approximate HGRS87 ellipsoidal heights and the subsequent computation of the 3D Cartesian coordinates with respect to HGRS87, a least-squares adjustment with the 7-parameter model given in (6) was performed and its final results are presented in table 1. Note that the values of the seven parameters shown in this table are given in the sense of the HTRS07 → HGRS87 transformation.

Table 1 – Parameters of the 3D similarity transformation from HTRS07 to HGRS87

Transformation parameter	Value
t_x	203.437 m
t_y	–73.461 m
t_z	–243.594 m
ε_x	–0.170 arcsec
ε_y	–0.060 arcsec
ε_z	–0.151 arcsec
δ_z	–0.294 ppm

As it can be seen from the statistics of the adjusted residuals after the 3D similarity transformation (see table 2), the average horizontal transformation error between HGRS87 and HTRS07 is larger than 60 cm, with extreme horizontal residuals that can reach more than 2.5 m. This is mainly due to the significant regional distortions and other systematic errors within the original HGRS87 coordinates, a typical problem that occurs in most local geodetic datums that were established in previous decades through classic geodetic techniques and non-rigorous data adjustment procedures. The spatial behaviour of the horizontal residuals after the 3D similarity transformation is depicted in figures 6 and 7.

Table 2 – Statistics of the magnitude of the horizontal residula vectors after the 3D similarity trasformation between HGRS87 and HTRS07 (values in m)

Network	Max	Min	μ	rms
2199 computation points	2.34	0.01	0.55	0.63
231 external evaluation points	2.59	0.02	0.58	0.68

To facilitate a more accurate transformation scheme between HTRS07 and HGRS87, an additional modeling step is required to take into account the inherent distortions in the HGRS87 horizontal coordinates. For this purpose, a pair of gridded mapping coordinate corrections (δE and δN) was determined based on the spatial modeling of the systematic part of the horizontal residuals after the 3D similarity transformation. The correction grids (also called shift-grids by many authors) were computed based on a biharmonic spline interpolation algorithm that is described in Sandwell (1987), with a 2×2 km resolution over the entire Hellenic territory; note that only the island of Kastelorizo is excluded.

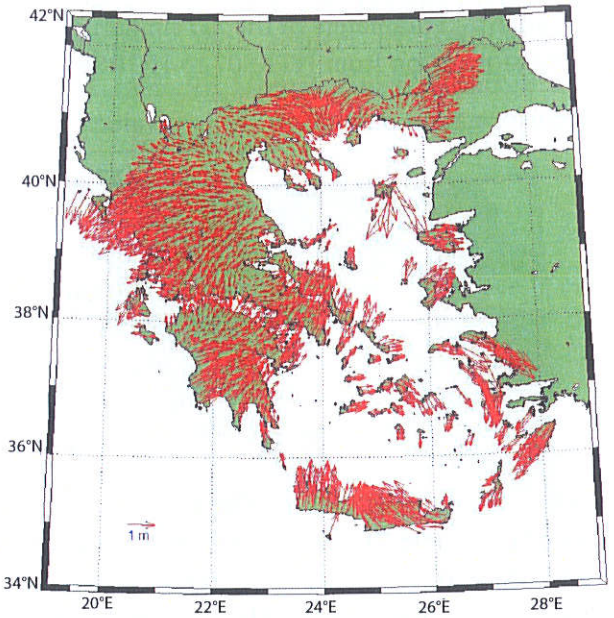

Fig. 6 – Horizontal residual vectors after the 3D similarity transformation between HTRS07 and HGRS87, at the 2199 computation points.

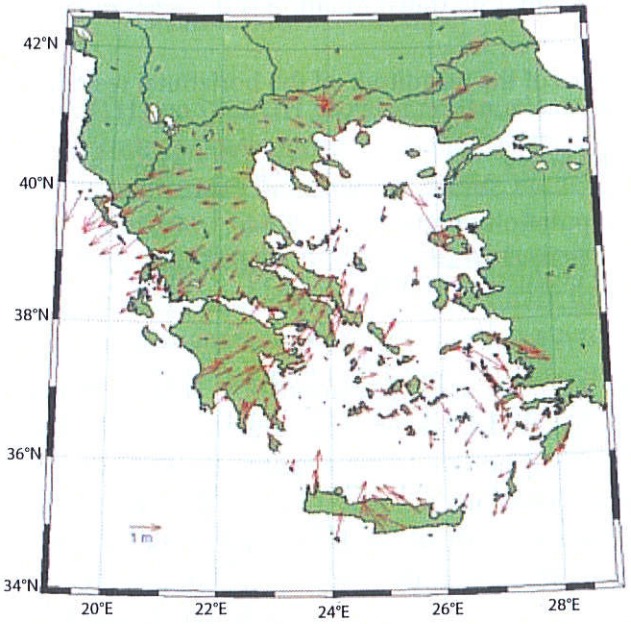

Fig. 7 – Horizontal residual vectors after the 3D similarity transformation between HTRS07 and HGRS87, at the 231 external evaluation points.

Table 3 – Statistics of the magnitude of the horizontal residual vectors after the implementation of the two-step transformation between HGRS87 and HTRS07 (values in m)

Network	Max	Min	μ	rms
2199 computation points	0.05	0.00	0.01	0.01
231 external evaluation points	0.24	0.01	0.07	0.08

The final transformation model between HTRS07 and HGRS87 is thus comprised of a 3D similarity transformation (with its associated parameters given in table 1), in conjunction with additive corrections to the resulting horizontal (planar) coordinates that are computed via 2D spatial interpolation from the available correction grids. From the statistics of the horizontal residuals obtained after this two-step procedure (see table 3), it is evident that the total transformation between HTRS07 and HGRS87 can be realized with an average accuracy level of about 8 cm throughout Greece, with maximum residuals that can reach up to 24 cm. It should be emphasized that this accuracy level corresponds to the vectorial horizontal component of the transformed spatial positions.

Note that the determination of absolute or relative orthometric heights from GPS measurements using the HEPOS system requires a different geoid-aided transformation procedure that will be developed in the near future.

Software development

The combined transformation model between HTRS07 and HGRS87 is accessible to all HEPOS users in various ways. More specifically, the following options are currently available:

– implementation of the transformation model in post-processing using a standalone software package that was developed by the Department of Geodesy and Surveying in the Aristotle University of Thessaloniki (AUTH) and it is freely available through the official HEPOS website (see www.hepos.gr), along with the required correction grid files. The software package supports single-point coordinate transformation, as well as coordinate transformation for large groups of data points using an appropriate input file of known coordinates in either of the two reference systems.

– implementation of the transformation model either in real-time or in post-processing using commercial software that is provided by several geomatics sector

companies in Greece. So far, most of the authorized GPS/GNSS dealers in Greece have already implemented the foregoing two-step transformation model into their controller's firmware and/or their office post-processing software.

7. – FUTURE WORK

As a first step for future research activities, all data collected and the results obtained from the national GPS campaign at the 2470 HGRS87 geodetic benchmarks will be used for a detailed evaluation of the recent high-resolution EGM08-based global geoid model over the Hellenic area; some preliminary results have already been presented by Kotsakis et al. (2008). Concurrently, we plan the development of a new regional geoid model for Greece that can be used in GPS-aided leveling surveys in conjunction with the HEPOS system. Also, given the strong tectonic activity over Greece, the determination of a crustal velocity model based on continuous GPS data recorded at the HEPOS stations is an additional research topic that should be prioritized in the upcoming years. Last but not least, it should be mentioned that certain actions by the responsible national mapping and cadastral authorities need to be initiated for the gradual replacement of the old (and rather problematic) HGRS87 geodetic datum with the new (HEPOS-based) HTRS07 spatial reference system, in accordance with the requirements imposed by the INSPIRE directive.

8. – ACKNOWLEDGMENTS

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REFERENCES

Z. ALTAMIMI (2007), *ITRF2005 and consequences for ETRF2005*. Presented at the EUREF Annual Symposium, London.

C. BOUCHER, Z. ALTAMIMI (2008), *Memo: Specifications for reference frame fixing in the analysis of a EUREF GPS campaign*. Version 7, 24/10/2008.

M. GIANNIOU, K. KATSAMPALOS, C. KOTSAKIS (2009), *Real-time Positioning in ETRS89 using the Hellenic Positioning System*. Presented at the EUREF Annual Symposium, May 27-30 2009, Florence, Italy.

C. HOLLENSTEIN, A. GEIGER, H.-G. KAHLE, G. VEIS (2006), *CGPS time-series and trajectories of crustal motion along the West Hellenic Arc*. Geophys. J. Int., 164, pp. 182-191.

H.-G. KAHLE, M.V. MULLER, A. GEIGER, G. DANUSER, S. MUELLER, G. VEIS, H. BILLIRIS, D. PARADISSIS (1995), The strain field in northwestern Greece and the Ionian islands: results inferred from GPS measurements. Tectonophysics, 249, pp. 41-52.

K. KATSAMPALOS, C. KOTSAKIS, V. VLAHAKIS, A. GANILAS, G. PAPOUDAS (2008), *Coordinate temporal variations and preliminary velocity estimates using HEPOS data (in Greek)*. Presented at the workshop «HEPOS and modern geodetic reference systems: theory, realization, future prospects and applications». September 25-26, Thessaloniki, Greece.

C. KOTSAKIS, K. KATSAMPALOS, D. AMPATZIDIS, M. GIANNIOU (2008), *Evaluation of EGM08 using GPS and leveling heights in Greece*. To appear in the Proceedings of the IAG International Symposium on Gravity, Geoid and Earth Observation GGEO, June 23-27, Chania, Greece.

S. MCCLUSKY, S. BALASSANIAN, A. BARKA, C. DEMIR, S. ERGINTAV, I. GEORGIEV, O. GURKAN, M. HAMBURGER, K. HURST, H. KAHLE, K. KASTENS, G. KEKELIDZE, R. KING, V. KOTZEV, O. LENK, S. MAHMOUD, A. MISHIN, M. NADARIYA, A. OUZOUNIS, D. PARADISSIS, Y. PETER, M. PRILEPIN, R. REILINGER, I. SANLI, H. SEEGER, A. TEALEB, M.N. TOKSOZ, G. VEIS (2000), *Global positioning system constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus*. J. Geophys. Res., 105(B3), 5695-5719.

M. NYST, W. THATCHER (2004), *New constraints on the active tectonic deformation of the Aegean*. J. Geophys. Res., 109, B11406, doi: 10.1029/2003JB002830.

D.T. SANDWELL (1987), *Biharmonic spline interpolation of GEOS-3 and SEASAT altimeter data*. Geophys. Res. Lett., no. 2, pp. 139-142.

I. TAKOS (1989), *New adjustment of the Hellenic triangulation network (in Greek)*. Bulletin of the Hellenic Military Geographic Service, no.136, pp. 19-93.