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Expressing the NOANET GNSS network to the Hellenic Geodetic Reference System of 1987 (HGRS1987): A synergy between Geodesy and Geodynamics

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Abstract

In the present study we describe an algorithm which allows the expression of the coordinates of the NOANET (National Observatory of Athens Continuous Operating Reference Station Network) to the official Hellenic geodetic reference system (HGRS87). The algorithm calculates the estimated velocities of ten NOANET stations. The main idea is to transform the coordinates (as well as the velocities) from the International Terrestrial Reference Frame 2008 (ITRF2008) to the HGRS1987. This is realised by (a) the use of the 3D time-dependent transformation model and (b) using the transformation tool provided by the Greek Cadastral and Mapping Agency. The final products are the computed projection coordinates (X, Y) and the orthometric heights of the ten stations. The consistency between the computed and official HGRS1987 coordinates is in general better than 10 cm for the projection coordinates, while for the estimation of the heights, the accuracy remains uncertain. The reason for the uncertainty of the heights is the fact that they depend on a model of geometric geoidal heights which is not yet assessed.

Keywords: *geodetic reference frame, velocities, NOANET, GNSS, coordinate transformation*

Περίληψη

Στην παρούσα εργασία παρουσιάζεται ένας αλγόριθμος για τον υπολογισμό των προβολικών συντεταγμένων και των ορθομετρικών υψομέτρων του δικτύου NOANET του Εθνικού Αστεροσκοπείου Αθηνών ως προς Ελληνικό Γεωδαιτικό Σύστημα αναφοράς του 1987 σε συνδυασμό με την Εγκάρσια Μερκατορική προβολή (ΕΓΣΑ87/TM87). Τούτο επιτυγχάνεται μέσω χρήσης (α) του Μοντέλου του 3Δ χρονικά μεταβαλλόμενου μετασχηματισμού ομοιότητας (β) του μοντέλου μετασχηματισμού όπως υπολογίζεται μέσω της εφαρμογής της Α.Ε Εθνικό Κτηματολόγιο και Χαρτογράφηση με το όνομα HEPOS_TRANSFORMATION_TOOLS. Η συμβατότητα των υπολογισμένων προβολικών συντεταγμένων σε σχέση με τις επίσημες, είναι γενικά καλύτερη των 10 cm. Για τα εκτιμώμενα υψόμετρα, δεν υπάρχει καμία ένδειξη ακρίβειας, από την στιγμή που υπολογίζονται με την χρήση ενός γεωμετρικού γεωειδούς και υπάρχει αποποίηση ευθύνης από το λογισμικό HEPOS_TRANSFORMATION_TOOLS.

Λέξεις κλειδιά: *γεωδαιτικό πλαίσιο αναφοράς, ταχύτητες, NOANET, GNSS, μετασχηματισμοί συντεταγμένων*

1. Introduction

The Continuous Operating Reference Stations (CORS) of Global Navigation Satellite Systems (GNSS) network of the National Observatory of Athens (NOA) known as the NOANET was initially established for the needs of the monitoring of the crustal deformation of the Greek area (Ganas et al. 2008; Ganas et al. 2011; Ganas et al. 2013; Chousianitis et al. 2013a; Chousianitis et al. 2013b). The network's reference frame was realized by 18 European IGS stations, using the GAMIT software (Herring et al. 2005). For more, details, see Chousianitis et al. (2013b). It consists of eighteen CORS stations nationwide (Figure 1). Station NOA1 located in Attica is also included in the European Permanent Network (EPN, www.epn.oma.be). However, NOA1 was bot included to the realization of the frame. We must mention that the NOA has an open data policy and the GNSS data are publicly available. The GNSS data have been used in several studies, published by many researchers and research agencies.

The solution of the NOANET is described by Chousianitis et al. (2013b). For ten out of the eighteen stations, there is an official solution, where the coordinates are referred to the International Terrestrial Reference Frame of 2008 (ITRF2008, Altamimi et al. 2011) and the 3D velocities are referred to the so called "stable Europe" (or more specifically with respect to the Eurasian plate). The officially released coordinates and velocities could be obtained from the following internet site: http://www.gein.noa.gr/services/GPS/noa_gps.html . There is no explanation why eight stations are not included to the officially released solution (both for coordinates and velocities).

The aim of this report is to present a rigorous methodology transforming the NOANET to the Hellenic Geodetic Reference System of 1987 (HGRS1987). The transformation is applied using the time-dependent transformations, described in detail by Altamimi (2002). The HGRS87 is a 2D non-geocentric traditional local reference system which was established more than 30 years ago and it was formally adopted by the Hellenic Mapping and Cadastral Organization in 1987. The HGRS87, despite its outdated character, remains fully operational as the official coordinate system of the Hellenic cadastral system. The implementation of GNSS permanent networks, such as NOANET, creates the need of transforming global geocentric coordinates to the local HGRS87 realization. Following that need, when the Hellenic Positioning System (HEPOS) was initialized, a Terrestrial Reference System was implemented for the Hellenic region as the official reference system of HEPOS, called Hellenic Terrestrial Reference System of 2007 (HTSR07, Katsambalos et al. 2010).

The HTRS07 is a densification of the European Terrestrial Reference System of 1989 (ETRS89, Gubler et al. 1992) and the coordinates refer to the European Terrestrial Reference Frame of 2005 at the epoch of 2007.5 The coordinates with respect to the HTRS07 could be transformed to the official HGRS1987 coordinates (computed coordinates), using the algorithm given by (Katsambalos et al. 2010). The rms (root mean square) for the projection coordinates differences (official versus computed) is 8.3 cm nationwide (Katsambalos et al. 2010). This algorithm could be also useful for geodetic, geophysical and engineering surveys and studies in Greece.

General Note

The term reference system has a general meaning in Geodesy, including a set of particular conventions and conditions regarding the 3D position and the velocities, respectively. On the other hand, the term reference frame describes a particular realization of the reference system (in a given epoch and for a particular set of stations). In order to avoid any confusion for now on we will call the aforementioned reference system realizations as (a) the HGRS1987 reference frame and (b) the HTRS07 reference frame, respectively.

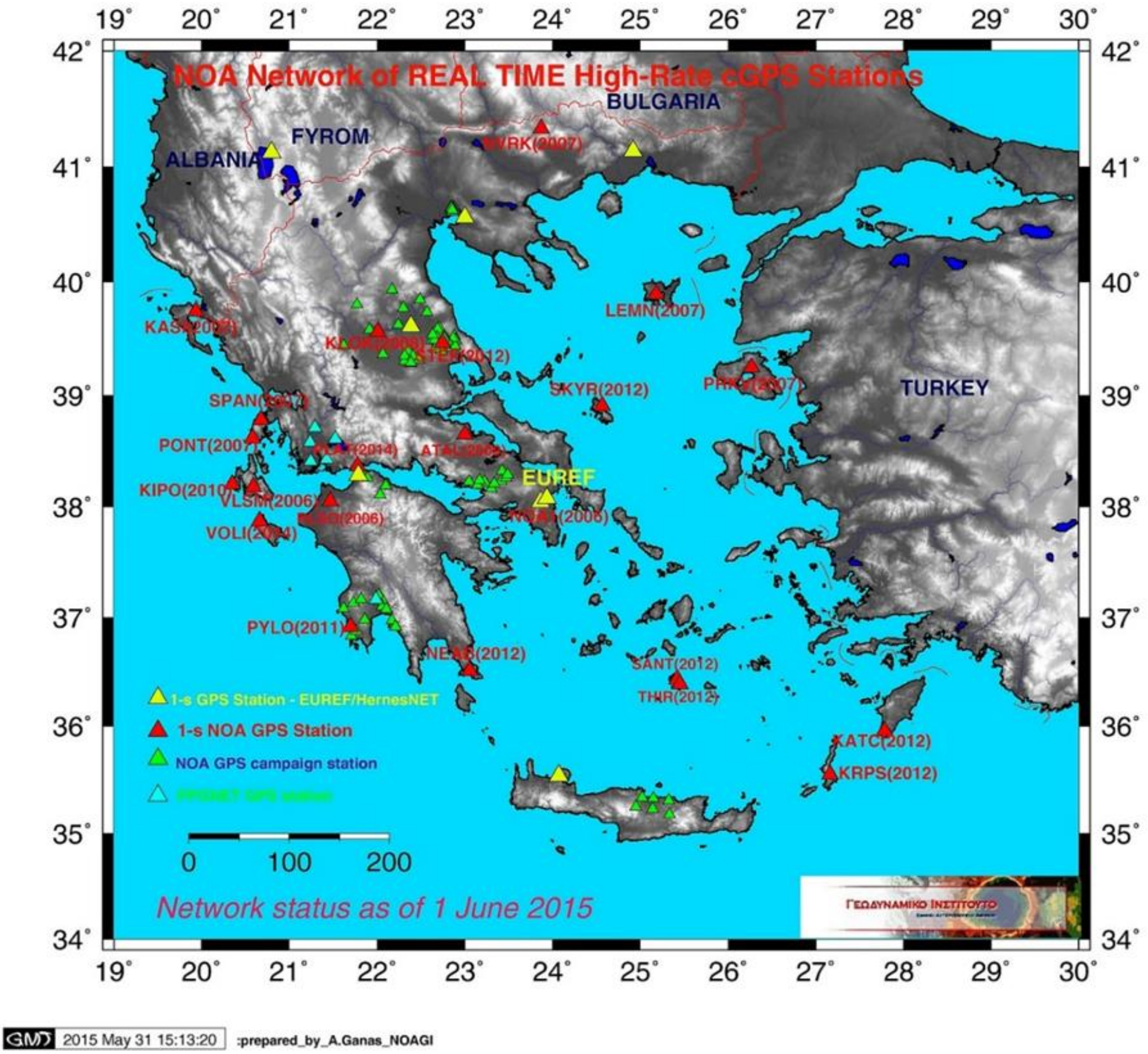

Fig.1: The NOANET (source: http://www.gein.noa.gr)

2. Methodology for expressing the ITRF2008 coordinates to HGRS1987 reference frame

We shall describe the methodology for the transformation of NOANET to HGRS1987 reference frame. The steps for the computations are:

I. converting the topocentric to geocentric velocities (with respect to the stable Europe), using the well-known formula, stationtwise (e.g. Cai et al. 2011):

$$\mathbf{v}_{XYZ} = \mathbf{R}^{-1}\mathbf{v}_{enu} \qquad (1a)$$

$$\begin{bmatrix} v_X \\ v_Y \\ v_Z \end{bmatrix} = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\sin\varphi\cos\lambda & -\sin\varphi\sin\lambda & \cos\varphi \\ \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\lambda \end{bmatrix}^{-1} \begin{bmatrix} v_e \\ v_n \\ v_u \end{bmatrix} \qquad (1b)$$

where $\mathbf{v_X}$, $\mathbf{v_Y}$, $\mathbf{v_Z}$ are the geocentric velocities, $\mathbf{v_e}$, $\mathbf{v_n}$, $\mathbf{v_u}$ the topocentric velocities and **φ, λ** the geodetic latitude and longitude, respectively. We use the officially released topocentric velocities (www.gein.noa.gr). The up-velocity component was assumed zero for all the stations (there is no information at the website).

II. Estimating the geocentric velocities with respect to the ITRF2008, as follows (Boucher and Altamimi, 2007), pointwise:

$$\mathbf{v}_i^{ITRF2008} = \mathbf{v}_i^{europe} - \mathbf{\Omega}^{ITRF2008}\mathbf{x}_i^{ITRF2008} \qquad (2a)$$

or more explicitly:

$$\begin{bmatrix} v_{X_i}^{ITRF2008} \\ v_{Y_i}^{ITRF2008} \\ v_{Z_i}^{ITRF2008} \end{bmatrix} = \begin{bmatrix} v_{X_i}^{europe} \\ v_{Y_i}^{europe} \\ v_{Z_i}^{europe} \end{bmatrix} - \begin{bmatrix} 0 & \omega_Z & -\omega_Y \\ -\omega_Z & 0 & \omega_X \\ \omega_Y & -\omega_X & 0 \end{bmatrix} \begin{bmatrix} X_i^{ITRF2008} \\ Y_i^{ITRF2008} \\ Z_i^{ITRF2008} \end{bmatrix} \qquad (2b)$$

where $v_{X_i}^{ITRF2008}$, $v_{Y_i}^{ITRF2008}$, $v_{Z_i}^{ITRF2008}$ the 3D velocities and the coordinates with respect to the ITRF2008 per point i, the velocities with respect to the stable Europe and is the 3X3 matrix that contains the angular velocities of the Eurasian plate with respect to the ITRF2008 plate tectonic model (Altamimi et al. 2012). The angular velocities with respect to each axis are:

$$\omega_X = -0.085 \pm 0.011\, mas/a \quad , \omega_Y = \text{-}0.533 \pm 0.007\, mas/a \quad , \omega_Z = 0.774 \pm 0.012\, mas/a$$

III. Transformation of the ITRF2008 coordinates and velocities to the HTRS07 reference frame (using the formulations, described in detail Altamimi et al. (2002), Soler and Snay (2004). The core of this step is the time-dependent transformation (Altamimi et al. 2002) between coordinates and velocities among different ITRF versions (see http://itrf.ign.fr/trans_para.php). In addition, Boucher and Altamimi (2007) provide all the necessary mathematical formulations regarding the transformation between the ITRF and the ETRF2005 (epoch 2007.5). Initially, the coordinates and the velocities with respect to the ITRF2008 are transformed to ITRF2005 and finally the latter ones to the ETRF2005 (epoch 2007.5). We should notice that the ETRF2005 is a defunct reference frame. The transformation scheme relies on the transformation from the ITRF2005 to the ETRF2005 (see e.g. Doukas et al. 2017).

IV. Transformation of the HTRS07-derived coordinates to the HGRS1987 reference frame coordinates, using the official tool of the National Agency for the Cadastre and Cartography, called HEPOS_TRANFORMATION_TOOL (www.hepos.gr). The algorithm for the coordinate transformation between the HTRS07 reference frame and the HGRS87 reference frame is described in detail by Katsambalos et al. (2010). Figure 2 summarizes the methodology.

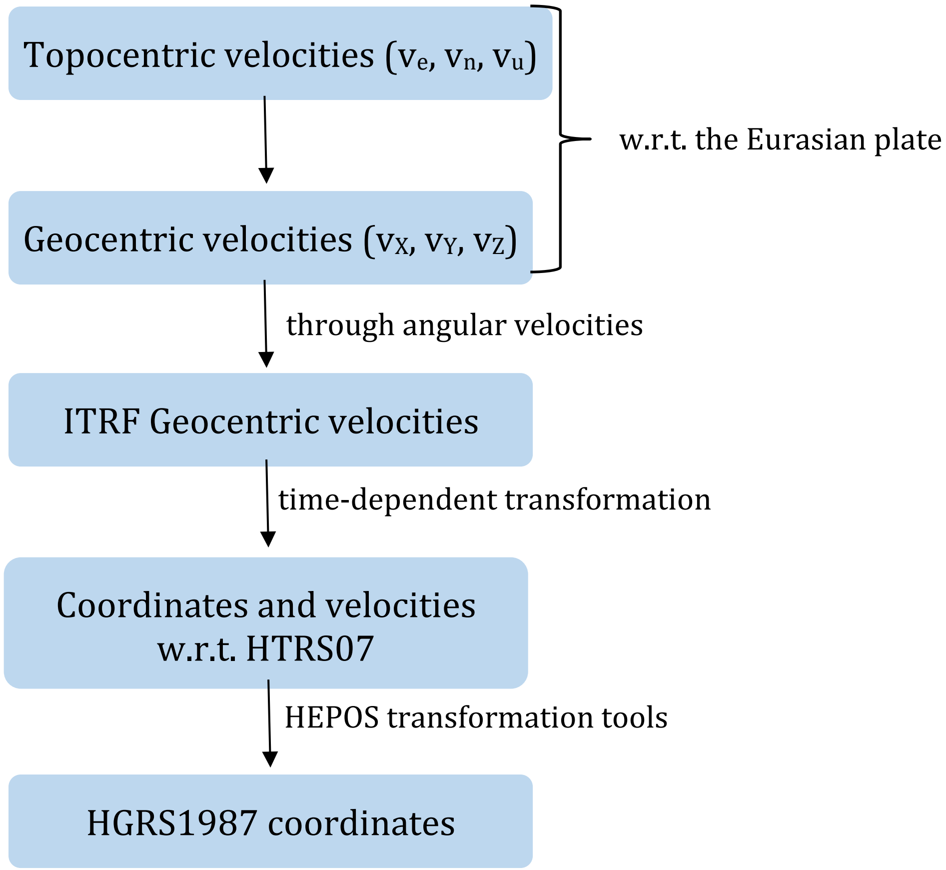

Fig.2: The flow of the transformations of the NOANET 3D coordinates referenced to ITRF2008 to HGRS1987 reference frame.

3. Data and results

Table 1 presents the initial coordinates and velocities of NOANET (www.gein.noa.gr/gps.html) as published by Chousianitis et al., (2013b). There are ten (10) stations which have complete information regarding the position and the velocity (out of eighteen). Figure 3 depicts the NOANET velocities.

Table 1: Coordinates and velocities of the NOANET stations. The coordinates refer to the ITRF2005 (estimated at a certain epoch). Source: Chousianitis et al. 2013b.

Station	**X (m)**	**Y (m)**	**Z (m)**	**epoch (year)**	**V_E (mm/a)**	**V_N (mm/a)**
ATAL	4591113.837	1948751.167	3962396.681	2010.081	12.06	-5.29
KASI	4616572.582	1674415.556	4056441.293	2009.664	19.49	14.10
KLOK	4564747.022	1845610.774	4040935.116	2009.710	20.74	5.78
LEMN	4434466.076	2084864.374	4069305.463	2009.809	6.56	-1.37
NOA1	4599643.319	2034827.976	3909890.749	2011.210	7.16	-11.94
PONT	4671272.658	1754437.059	3959389.395	2011.999	-3.46	-7.2
PRKV	4435581.306	2188830.489	4013585.908	2009.732	4.64	-0.14
RLSO	4679938.994	1840151.157	3910407.703	2010.391	8.86	-8.58
SPAN	4658312.235	1757780.670	3973702.588	2009.796	20.69	4.01
VLSM	4699991.611	1765547.717	3921162.215	2010.338	17.20	3.67

Table **2** shows the coordinates and the velocities with respect to the ETRF2005, epoch 2007, while Table **3** summarizes the final coordinates of the NOANET stations with respect to the HGRS1987 reference frame.

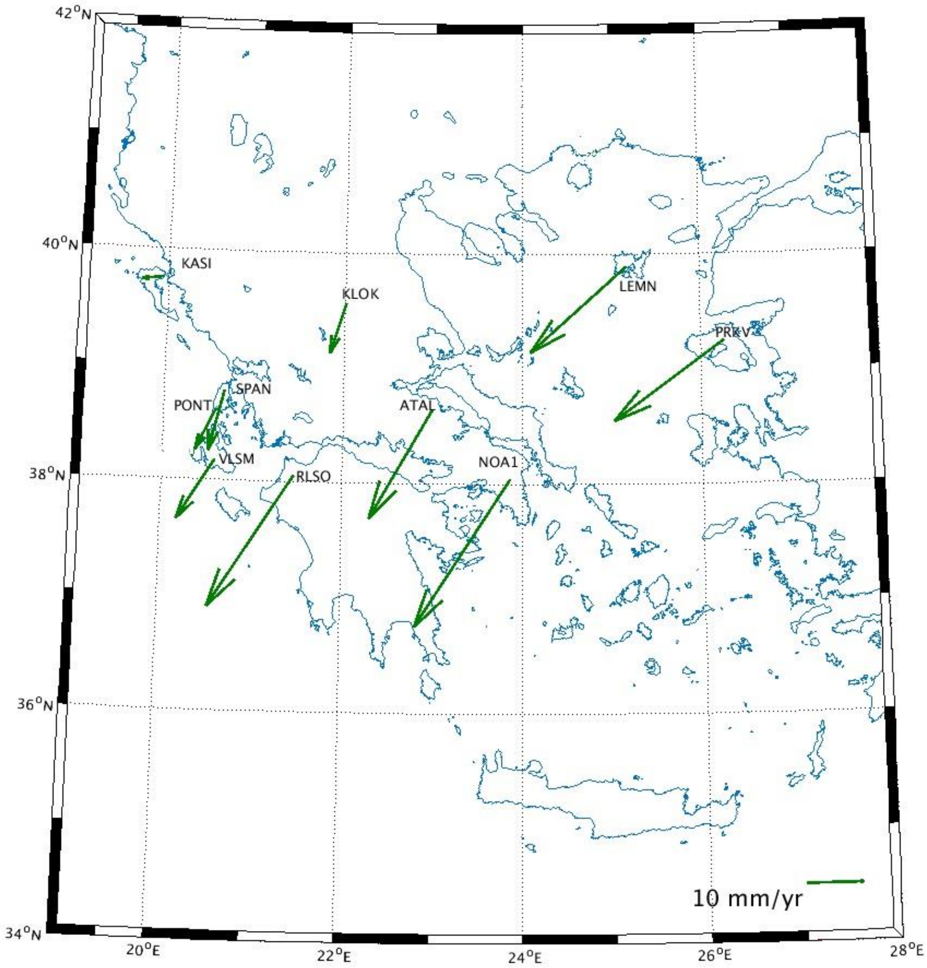

Fig.3: The NOANET velocities of the ten stations with respect to the stable Eurasian plate. The vectors correspond to the velocities (V_N, V_E) of Table 2.

Table 2: 3D coordinates (with respect to ETRF2005, epoch 2007.5) and velocities (with respect to the stable Europe) of the NOANET stations.

Station	X (m)	Y (m)	Z (m)	V_X (mm/a)	V_Y (mm/a)	V_Z (mm/a)	V_N (mm/a)	V_E (mm/a)
ATAL	4591114.237	1948750.860	3962396.417	16.08	-5.63	-15.35	-19.15	-10.99
KASI	4616572.975	1674415.270	4056441.067	0.95	-3.79	-0.90	-0.50	-3.69
KLOK	4564747.434	1845610.460	4040934.865	5.44	-1.44	-6.31	-8.76	-2.71
LEMN	4434466.472	2084864.073	4069305.219	15.26	-10.58	-10.89	-14.88	-16.95
NOA1	4599643.719	2034827.662	3909890.539	20.34	-9.79	-20.53	-25.73	-16.77
PONT	4671273.048	1754436.757	3959389.129	5.19	-2.09	-6.66	-7.20	-3.46
PRKV	4435581.697	2188830.187	4013585.668	15.84	-13.46	-11.30	-13.79	-19.41
RLSO	4679939.379	1840150.841	3910407.471	17.11	-6.93	-17.30	-23.08	-14.62
SPAN	4658312.590	1757780.315	3973702.339	6.29	-1.53	-9.16	-10.57	-2.56
VLSM	4699992.015	1765547.414	3921161.949	7.24	-4.50	-7.84	-10.48	-6.42

Table 3: Coordinates of the NOANET stations with respect to the HGRS1987 reference frame. It consists of the projection coordinates (Easting and Northing for the Transverse Mercator projection as used in Greece -one zone, central meridian λ=24-) and the orthometric height H derived from a specific geoid model for Greece.

Station	E (m)	N (m)	H (m)
ATAL	412779.700	4278464.724	98.050
KASI	151571.982	4407222.990	77.150
KLOK	329279.135	4381044.503	103.240
LEMN	600775.467	4416729.831	66.823
NOA1	487920.455	4210757.574	500.410
PONT	202534.358	4279743.243	23.543
PRKV	695311.845	4346200.970	130.022
RLSO	277411.619	4214756.879	107.983
SPAN	210892.729	4297476.537	424.982
VLSM	201019.102	4230648.288	411.406

Regarding the accuracy of the transformation, it is rather difficult to give a rigorous answer. For the map coordinates as we mentioned before, there is a nation-wide rms of the residuals at the level of **±8.3 cm**. Here, the term residuals refer to the differences between the official projection coordinates and the one estimated from the transformation procedure. Nevertheless, the level of agreement of the transformed coordinates compared to the official solution shows significant variability across the country. For example, for Attica the accuracy of the transformation is **±3-4 cm**, while for Epirus or Eastern Macedonia is worse than **±10 cm**. Hence, the consistency between the official HGRS1987 reference frame and the HGRS1987 computed from the HTRS07 reference frame remains questionable, though better than 10 cm (Katsambalos et al. 2010).

One can also see that we present information regarding the orthometric heights. We should point out that the heights estimated through the HEPOS transformation tool are not assessed and validated. They are computed using interpolated geometric geoidal heights of unknown accuracy. The software has also a particular disclaimer for the height component accuracy. The geometric geoidal heights are computed from the well-known formula (Heiskanen and Moritz 1967, pointwise) for approximately 2200 benchmarks, nationwide:

$$N_i = h_i - H_i \tag{3}$$

where N are the geoidal heights, h and H are the geometric and orthometric heights for each one of 2200 benchmarks, respectively. The geometric heights refer to the HTRS07 reference frame. Using the information of these 2200 points, the software interpolates the geoidal height for any arbitrary point. Details for the interpolation model are not given. Finally, using the Equation 3, one can compute the orthometric height for any arbitrary point.

The aforementioned procedure offers four particular services to the geodetic practice in Greece:

1. It transforms the NOANET network to the HGRS1987. This gives the opportunity to monitor the transformation between the modern Terrestrial Reference Frames (TRFs) and the HGRS1987. The velocities of the NONET stations play crucial role, since they are the tool for the time-dependent transformation.

2. It provides to the reader/user a rigorous algorithm for the treatment of similar problems in the daily geodetic/surveying practice, especially in areas of intense geodynamic behaviour (e.g. Crete, Ionian islands, see e.g. Papadimitriou 2006).

3. In the case of precise height determination of the NOANET stations (using spirit levelling; e.g. Heiskanen and Moritz 1967) the described transformation process

can be considered as a validation tool for the heights computed from the official software HEPOS transformation tool. If the NOANET stations heights are determined through spirit leveling, one can validate the full 3D information referring to the HTRS07 reference frame (projection coordinates and orthometric heights). Thus, the NOANET stations can stand as the external validation points for assessing the 3D consistency between the official HGRS1987 reference frame and the computed one.

4. Since the NOA implements an open data policy, the user (e.g. Surveyor Engineer) can directly refer all his work to the HGRS1987 reference frame. Now this can only be applied to the static measurements. Nevertheless, if there is the possibility for real time services, the user can exploit the NOANET for the so-called Real Time Kinematic GNSS (e.g. Wanninger, 2002).

5. The NOANET stations could be implicitly or explicitly used in any effort in the direction of the establishment of a new reference frame in Greece. They could directly be used as a part of a greater CORS network all over the country, which will realize the fundamental GNSS network of the new frame. Alternatively, they could be exploited as an external source of the reference frame accuracy.

4. Conclusions and further work

In the present study we described a methodology for transforming the NOANET stations coordinates to the HGRS87, which is the official geodetic reference system for Greece. The core of our methodology was the use of time-dependent transformations in which the rigorous velocity estimation plays crucial role. The described algorithm can be applied for similar problems, facilitating the daily practice for a wide range of users. In addition, the proposed strategy could also offer valuable services regarding various subjects, especially for the validation of the geodetic networks in Greece. The need of reliable velocities of the Hellenic area reveals the neuralgic role of the Geodynamics.

The knowledge of the geophysical behaviour of the area gives the robustness that we need for the geodetic applications. On the other hand, the geophysical behaviour of the stations is significantly improved using precise geodetic measurements and rigorous analysis. The correlation between these two fields (Geodynamics and Geodesy) is of great importance, especially for areas like Greece. By these means, NOANET could serve as a validation network for the assessment between the official Greek geodetic reference system and other modern terrestrial reference frames. However, due to well documented problems of the HGRS1987 reference frame, the validation has a limitation of **8-10 cm** in terms of its reliability. Additionally, the described methodology gives a kind of orthometric height estimation for the stations. Nevertheless, their quality is not explicitly investigated.

The open data policy of NOA can minimize the cost for many geodetic, surveying and cartographic studies in the Greek area. The expansion of the NOANET (with more stations and better distribution) and the option of using the GNSS data in real time mode (except for static surveys) can significantly improve the geodetic practice in Greece.

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