EFFECT OF THE TRANSFORMATION BETWEEN GLOBAL AND NATIONAL GEODETIC REFERENCE SYSTEMS ON GCPS AND CPS ACCURACY

Vassilios D. Andritsanos, Michail Gianniou and Dimitra I. Vassilaki

Technological Educational Institute of Athens, Department of Civil Engineering and Surveying & Geoinformatics Engineering, 12210 Athens, Greece; vdandrit@teiath.gr, mgianniou@teiath.gr, dimitra.vassilaki@gmail.com

ABSTRACT

The 3D-2D projective transformation between the 3D object space and the 2D reference system of satellite images is computed through the georeferencing process. Ground Control Points (GCPs) are normally used for the georeferencing of the images (indirect georeferencing). Orbital metadata that accompany state-of-the-art satellite images may be used either alone (direct georeferening) or in conjuction with GCPs (integrated georefencing). In all cases Check Points (CPs) are used in order to evaluate the accuracy of the georeferencing. The accuracy of high resolution photogrammetric products in integrated georefencing is thus influenced by i) the accuracy of the GCPs, ii) the accuracy of the orbital metadata and iii) the accuracy of the transformation between the geodetic reference system of the GCPs (usually the national system) and the global reference frame (used for the orbital metadata). This study focuses on the fact that Ground Control Points (GCPs) and Check Points (CPs) are mostly measured in the national reference systems while orbital data is available in a global reference system such as WGS84/ITRS. Usually, one country-wide set of transformation parameters is being used to transform from the national system to WGS84/ITRS. However, the internal accuracy of national geodetic networks established by conventional triangulation methods several decades ago is in many cases limited to few meters. Thus, a country-wide similarity transformation between national and global system cannot offer sufficient accuracy. This study outlines the geodetic background of transformations between national and global reference systems and it presents expected transformation errors for several countries, based on published data concerning the internal accuracy of national trigonometric networks. Furthermore, data from Greece is analyzed to show the impact of the coordinate transformation on the accuracy of GCPs and CPs. More specifically, a number of points are identified on high resolution satellite optical and SAR images and then they are measured in-situ with GPS technology. For the transformation between global and national coordinate system different approaches have been tested. Comparative evaluation and discussion of the results is performed.

INTRODUCTION

The use of satellite images for 3D object representation is feasible today with impressive accuracy. The accuracy has been augmented due to the progress in camera technology and to the evolution of the geodetic positioning. The link between geodesy, photogrammetry and satellite imagery is the knowledge of the position of characteristic points on the ground, which also appear on the satellite images. These well known Ground Control Points (GCPs) are used for the effective recovery of 3D-2D projective transformation between the 3D object space and the 2D reference system of the satellite images in a process called georeferencing. The efficient reduction of the number of GCPs can be achieved by a concept of overlapping images, called aero-triangulation (AT) (Skaloud, 1999). The introduction of Global Navigation Satellite Systems (GNSS) and especially Global Positioning System (GPS) in early nineties boosted the fast and accurate determination of the GCPs. By coupling the information of the origin of the image in space with the concept of overlapping imagery and at least three GCPs for each image block the remaining parameters of

the exterior orientation can be estimated and the images can be georeferenced (Skaloud, 1999). Within this approach the exterior orientation of each image is treated as unknown and estimated in a bundle adjustment process. This is the only way to determine the sensor position and orientation if no additional orientation systems are used during the flight and only rough estimations of the exterior orientation of the imaging sensor are known. Using the so-called indirect method of image orientation, the six unknown orientation parameters are estimated from a number of ground control points and their corresponding image coordinates (Cramer et al., 2000). Ground coordinate system allows the determination of the positions of points in the object space coordinate system which is defined by the ellipsoid parameters, the datum definition and a cartographic projection. The ground coordinate system can be a national reference system or a regional coordinate system (Yildiz and Oturanc, 2014). With the availability of integrated GPS/inertial systems the direct measurement of the full exterior orientation of any sensor during data recording became possible (direct georeferencing). This direct measurement of the orientation parameters is the fundamental difference between the modern and the traditional indirect approach. Using appropriate GPS and inertial systems and processing their data in an optimal filtering approach, the orientation parameters are determined with very high absolute accuracy. Although GCPs (and their reduction) is not a major issue any more in direct georeferencing – ground control information is only necessary to solve for the datum parameters in principle – the process still suffers from a large amount of interactive editing and control (Cramer et al., 2000). The integrated georeferencing can be defined as the combination of the direct and the indirect method comes with all their advantages and drawbacks (Liebold and Maas, 2014). The accuracy of the georeferencing process (direct, indirect or integrated) is estimated using characteristic CPs in images with known coordinates on the ground. In common practice, GCPs and CPs are mostly determined in the national reference systems while orbital data is available in a global reference system such as WGS84/ITRS. Usually, one set of transformation parameters is being used to transform from the national system to WGS84/ITRS. However, the internal accuracy of national geodetic networks established by conventional triangulation methods several decades ago is in many cases limited to meters than centimeters. Thus, a country-wide similarity transformation between national and global system cannot offer sufficient accuracy. In addition, the usual final product of the georeferencing procedure, an ortho-photo map, has to be referenced to the national datum in order to remain consistent with other mapping products. Some comments on the relation between national and international reference system are presented in the theoretical section and a case study in Greece is evaluated.

THEORETICAL BACKGROUND

Classical transformation between national and international reference systems

The geodetic link in image georeferencing is focused on the coordinates used in GCPs and in CPs. These coordinates are usually referenced to the national datum. The definition of the national datum and the method of its realization are major geodetic tasks. The definition of a national datum is a subject of either a classical astrogeodetic definition (Bomford, 1980; Torge, 2001), or a hybrid satellite-ground definition based on common points' adjustment, or, finally, a satellite based definition with relation to a solution of the International Terrestrial Reference System (ITRS). The realization of a classical national system is made by reference benchmarks of known coordinates. These coordinates are used by the surveying community of the country and are referenced to the official map projection used.

However, the internal accuracy of national geodetic networks established by conventional triangulation methods several decades ago is in many cases limited to meters. Thus, a country-wide similarity transformation between national and global system cannot offer sufficient accuracy. The well-known model of 7-parameter similarity transformation provides the relation between local and global geocentric Cartesian coordinates (Torge, 2001):

$$\mathbf{r}^G = \mathbf{r}_o + (1 + m)\mathbf{R}^L\mathbf{r}^L \tag{1}$$

where $\mathbf{r}^G$ and $\mathbf{r}^L$ are the position vectors in the global (international) and local (national) system and the $\mathbf{r}_o$ vector contains the coordinates of the origin of the local system with respect to the global one. Under the assumption of small difference in the scale between the two systems and small deviations from parallelism of their axes, small scale correction m is close to zero and the rotation matrix $\mathbf{R}^L$ is composed of three small Eulerian angles:

$$\mathbf{R}^L = \begin{bmatrix} 1 & \varepsilon_Z^L & -\varepsilon_Y^L \\ -\varepsilon_Z^L & 1 & \varepsilon_X^L \\ \varepsilon_Y^L & -\varepsilon_X^L & 1 \end{bmatrix} \tag{2}$$

The 2D and 1D geodetic separation of the three dimensional position can be expressed by the 4-parameter similarity transformation on the projection plane and the 1D polynomial fit for the height component (see next section). The mathematical model of the 2D similarity transformation is (Fotiou, 2007):

$$\begin{bmatrix} x^a \\ y^a \end{bmatrix} = m \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x^b \\ y^b \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix}, \tag{3}$$

where $\begin{bmatrix} x^a & y^a \end{bmatrix}^\mathrm{T}$ and $\begin{bmatrix} x^b & y^b \end{bmatrix}^\mathrm{T}$ are the coordinates of a point with respect to the projection reference systems α and b, respectively, m is the scale component, θ is the rotation angle counterclockwise and $\begin{bmatrix} t_x & t_y \end{bmatrix}^\mathrm{T}$ the 2D translation component.

In the case of conventional national systems, the nationwide transformation parameters are often known with a limited accuracy due to the internal distortion of the national system as a result of the limited accuracy of classical triangulations. In geodynamically active counties like Greece, geological phenomena can cause additional distortions due to accumulated deformations. The distortions of a national network can be identified using contemporary satellite measurements on geodetic benchmarks. The residuals of a 7-parameter transformation of equation (1) can depict the above mentioned distortions. The residuals of a transformation between HTRS07 (Hellenic Terrestrial Reference System 2007) which is the satellite based reference system of HEPOS (Katsampalos et al., 2010) and the Greek national system GGRS87 (Greek Geodetic Reference System 1987) are presented in Figure 1(a) (Gianniou et al., 2009). Studies performed in other national networks in Europe showed similar results. The deformations in France (Kasser and Breton, 2003), Germany (Jäger et al., 2006) and Finland (Ruotsalainen, 2003) are depicted in Figures 1 (b) – 1(d), respectively.


(a) (b) (c) (d)
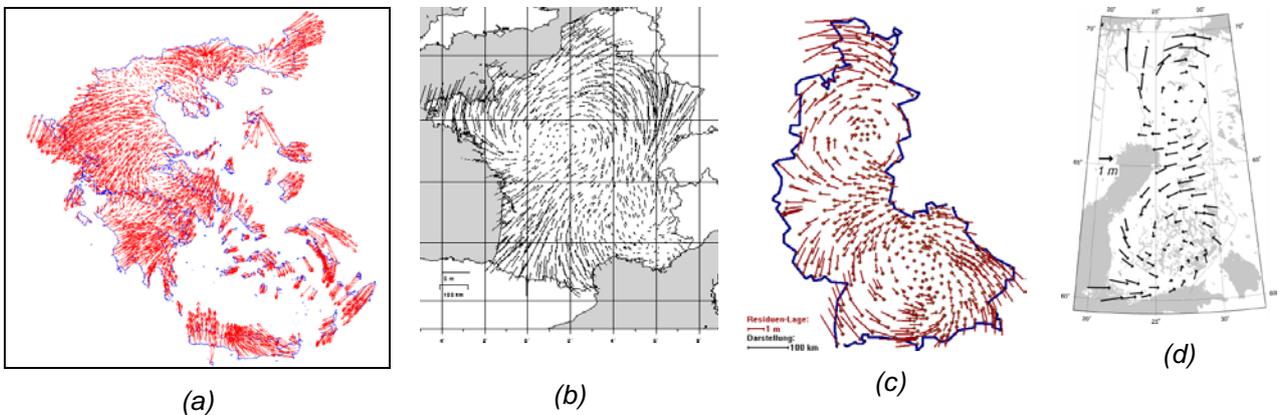
Figure 1: Distortions of conventional national network in Greece (a) and other European countries (b – France, c – Germany (DHDN network), d – Finland).

The distortions between a national reference system and an international satellite based system are propagated into the final coordinates of the GCPs. The erroneous character of the GCP coordinates affects the final mapping product of the satellite images. In order to overcome this problem, different schemes can be proposed:

- Estimation of local 7-parameter similarity transformation using a number of common points (at least 3) in the area under study.

- Transition to projective coordinates using a simplified 4 parameter similarity transformation model on the plane and a number of common points (at least 2).

For the above transformation procedures proper height information can play an important role if the application area is large.

The height problem

As mentioned before, satellite based observations utilize Cartesian 3D coordinates in a well-defined geodetic system. The triplet of the geodetic Cartesian coordinates has to be connected to the projection plane of the final product. Strictly speaking, the Cartesian coordinates and their transformation to the geodetic-ellipsoidal ones, do not contain physical characteristics of Earth's gravity field. These coordinates describe the location of a specific point with respect to a mathematical model of the Earth's surface. In order to achieve the physical connection which is necessary in height determination one has to introduce the concept of the geoid (Hofmann – Wellenhof and Moritz, 2005; Torge, 2001). The geoid height N (or undulation) connects the ellipsoidal height h (distance from a mathematical model) and the orthometric height H (distance from the equipotential surface of the geoid) according to the well-known equation:

$$h = H + N \tag{4}$$

Geoid heights can be obtained using spherical harmonic coefficients estimated from a spectral combination of satellite and ground data (global models – EGM2008, see Pavlis et al., 2008 and EIGEN-6C4, see Förste at al., 2014), using local geoid models computed from gravity and topography data (e.g., Andritsanos et al., 2004; Andritsanos, 2000) or using geoid maps. In case that information of ellipsoidal, orthometric and geoid height is simultaneously available, equation (4) contains a residual part due to inconsistencies on each height definition, realization of the vertical datum and measurement limitations. The major problem of equation (4) is the definition of the orthometric height which depends on the realization of the national vertical system. As it is well known, European vertical systems are connected to specific tide gauges using numerous sea level observations (at least 18.6 years). The estimation of a mean sea level for each country is the base of its vertical datum definition. Nevertheless, mean sea level is not an equipotential surface in general due to the presence of sea surface topography. In order to overcome these inconsistencies various transformation models based on the following equation are proposed (Fotopoulos, 2003; Kotsakis and Sideris, 1999):

$$h - H - N = \mathbf{a}^T \hat{\mathbf{x}} + v \tag{5}$$

where $\mathbf{a}^T \hat{\mathbf{x}}$ is the mathematical expression of the parametric transformation model used and represents from a geometric point of view a corrector surface between different height systems. This surface can be constructed by the coefficients of a plane (in small areas)

$$\mathbf{a}^T \hat{\mathbf{x}} = \begin{bmatrix} x & y & 1 \end{bmatrix} \cdot \begin{bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{bmatrix} = \hat{a}x + \hat{b}y + \hat{c}, \tag{6}$$

where $\hat{a}$, $\hat{b}$, $\hat{c}$ are the estimated coefficients and x, y are the plane coordinates, or a spherical surface of the form

$$\mathbf{a}^{\mathbf{T}}\hat{\mathbf{x}} = \begin{bmatrix} 1 & \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\varphi \end{bmatrix} \cdot \begin{bmatrix} \hat{d}_0 \\ \hat{d}_1 \\ \hat{d}_2 \\ \hat{d}_3 \end{bmatrix} = \hat{d}_0 + \hat{d}_1\cos\varphi\cos\lambda + \hat{d}_2\cos\varphi\sin\lambda + \hat{d}_3\sin\varphi \quad (7)$$

where $\hat{d}_i$ are the coefficients of the model and φ, λ the geodetic coordinates of a point.

CASE STUDY IN ATTICA – GREECE

The study of the effect of the transformation between global and national reference system in the final coordinates of GCPs and CPs is performed in an area 10 km × 10 km approximately. The area under study is located in the northern part of Attica region in Central Greece. In Figure 2 the locations of the GCPs, the CPs and the benchmarks of the national trigonometric network used in our computations are depicted.
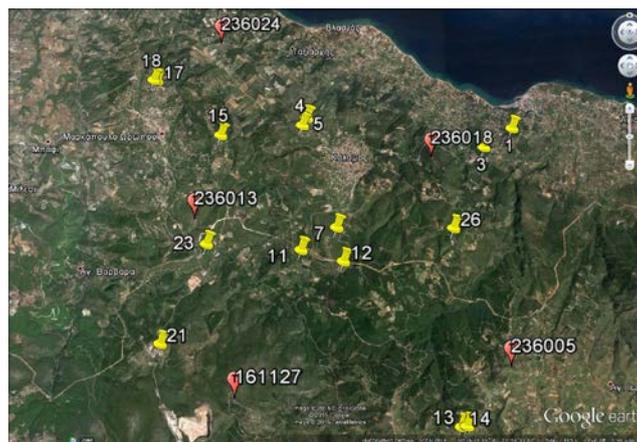
Figure 2: The area under study in Northern Attica – Greece and the locations of the GGRS87 benchmarks (red pins) and the GCPs and CPs (yellow pins).

Two pairs of dual frequency GPS receivers (Topcon Hiper Pro and JAVAD Triumph-1) were used in the measurement procedure. The duration of GPS observations of each point was 1 hour. This duration is adequate for precise positioning both horizontally as well as vertically. A cut-off angle of 10° and a logging interval of 15 sec were chosen. The processing of the GPS observations was performed using Trimble Business Center ver. 1.12 software.

Four different cases of processing were studied.

Case 1. The transformation between WGS84 and GGRS87 datums was done using three translation parameters DX = 199.723 m, DY = -74.03 m and DZ = -246.018 m (Fotiou, 2007). These parameters are used in most commercial software packages for the transformation between WGS84 and GGRS87. In order to estimate orthometric height of GCPs and CPs, the EGM2008 geoid model was used. The computation of WGS84 coordinates of GCPs, CPs and benchmarks was done using WGS84 coordinates for the reference HEPOS station. The EPN (EUREF Permanent Network) station NOA1 (http://www.gein.noa.gr/services/GPS/noa_gps.html) was used for the efficient estimation of ITRF/WGS84 coordinates for the HEPOS reference station.

Case 2. HTRS07 coordinates were computed using the HTRS07 coordinates of the HEPOS station. The transformation of HTRS07 coordinates to GGRS87 was done using HEPOS Transformation Tool, a software which implements the official transformation procedure issued by HEPOS, i.e. a 7-parameter model (DX = 203.437 m, DY = -73.461 m, DZ = -243.594 m, ε_X = -0.170 arcsec, ε_Y = -0.060 arcsec, ε_Z = -0.151 arcsec, m = -0.294 ppm) and two correction grids for Easting and Northing (Katsampalos et al., 2010). Orthometric heights were computed using HEPOS geoid model, a "geometric" geoid estimated by means of GPS measurements at benchmarks with known orthometric heights (Gianniou, 2011). A GPS receiver visited all GCPs, CPs and benchmarks and the solution was computed directly using data from permanent reference station of HEPOS.

Case 3. HTRS07 coordinates were computed using the HTRS07 coordinates of the HEPOS station. The transformation of HTRS07 coordinates to GGRS87 was done using a local 7-parameter model (Eq. 1) computed by Least Squares Adjustment of the GPS measurements made at the five trigonometric benchmarks shown in Fig 2. Geoid information was computed by interpolation on GGRS87 official geoid map (Foriou, 2007). The estimated local parameters were applied to the HTRS07 coordinates of all GCPs and CPs in order to estimate their GGRS87 coordinates.

Case 4. The transformation procedure was done separately for the horizontal and vertical components. Transformation parameters were computed by Least Squares Adjustment of the GPS measurements made at the five trigonometric benchmarks shown in Fig 2. A local 4-parameter similarity transformation model on the projection plane was used for the horizontal positioning (Eq. 3) and geoid corrector plane (Eq. 5 and 6) and spherical surfaces (Eq. 5 and 7) in combination with various geoid models (EGM2008 and EIGEN-6C4) were used for the vertical positioning. The approximated GGRS87 benchmark coordinates of Case 1 were transformed to the projection plane (Transverse Mercator projection with a central meridian at 24 degrees) and the 4 parameters of the similarity model of Eq. 3 were estimated using Least Squares Adjustment.

RESULTS

The different solution strategies resulted in different estimations of the projection coordinates and orthometric heights of the GCPs and the CPs. The utilization of the 3-parameter transformation (DX, DY, DZ) for final coordinate computation (Case 1) cannot offer cm or even dm accuracy. The statistics of the differences between the 3-parameter solution and the other cases studied are presented in Table 1. Case 2 – 4 solution differ systematically to the Case 1 solution at 1 meter level in Easting, 34 cm in Northing and from 9 to 15 cm in the orthometric height. This bias indicates that the 3-parameter transformation provided in the commercial software is not suitable due to datum inconsistencies between conventionally established national system GGRS87 and satellite based measured GCPs and CPs.

Table 1: Statistics of the differences Easting (ΔE), Northing (ΔN) and Height (ΔH) between 3-parameter solution (Case 1) and the other cases in GCPs and CPs locations. Units are m.

|	**Mean** (m)			**Standard deviation (SD)** (m)		
	ΔE	**ΔN**	**ΔH**	**ΔE**	**ΔN**	**ΔH**
Case 2 – Case 1	-0.956	0.347	-0.086	0.011	0.008	0.031
Case 3 – Case 1	-0.967	0.342	-0.151	0.007	0.008	0.091
Case 4 (EGM2008, p.c.s.) – Case 1	-0.968	0.337	-0.159	0.005	0.006	0.078
Case 4 (EIGEN6C4, p.c.s.) – Case 1	-0.968	0.337	-0.159	0.005	0.006	0.078
Case 4 (EGM2008, s.c.s.) – Case 1	-0.968	0.337	-0.144	0.005	0.006	0.083
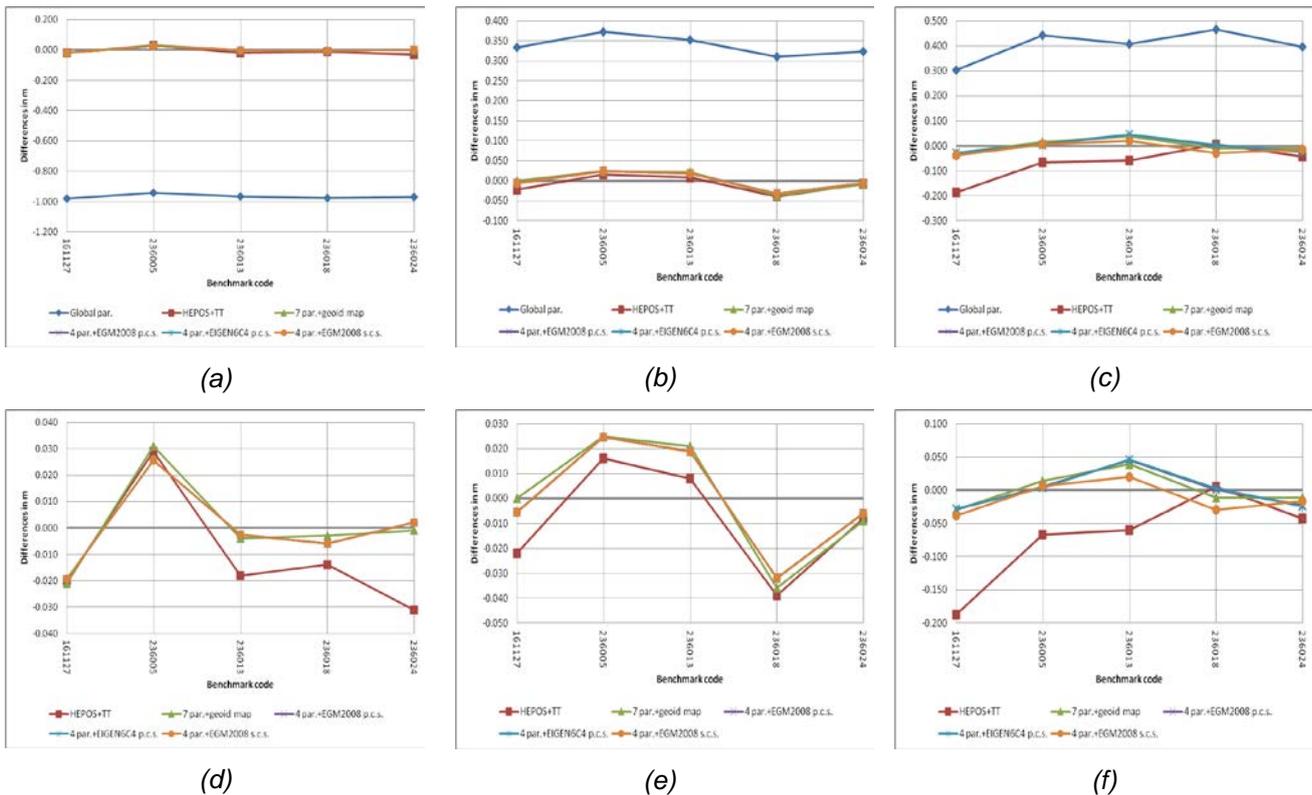
Figure 3: Differences in GGRS87 benchmarks in (a) Easting, (b) Northing and (c) Height and focus to Cases 2 – 4 in (d) Easting, (e) Northing and (f) Height. Notations: Global par.= Case 1, HEPOS+TT = Case 2, 7par.+geoid map = Case 3, 4par.+EGM2008 p.c.s. = Case 4 using EGM2008 geoid and planar corrector surface, 4par.+EIGEN6C4 p.c.s. = Case 4 using EIGEN6C4 geoid and planar corrector surface, 4par.+EGM2008 s.c.s. = Case 4 using EGM2008 geoid and spherical corrector surface.

In order to choose the best solution the internal accuracy of each case is examined. This test is based on the known projection coordinates of the national network benchmarks. Five trigonometric points with known GGRS87 coordinates (taken from the national trigonometric network) are used in the comparisons. The internal accuracy of the transformation can be evaluated by the estimated residuals at the benchmarks used for the parameters approximation.

Figures 3(a), 3(b) and 3(c) show the differences between known GGRS87 coordinates (Easting, Northing and Height, respectively) and GGRS87 coordinates computed using cases 1, 2, 3 and 4. The bias between case 1 (the official parameters solution) and the rest of the cases studied is clearly revealed. Figures 3(d), 3(e) and 3(f) show magnified views of 3(a), 3(b) and 3(c) for cases 2, 3 and 4 (the local transformation cases). As it was expected, local transformation parameters estimated using GGRS87 benchmarks in combination with a spherical corrector surface from a global geoid model outperformed any other case study. A first glance on the internal accuracy of the solution is given by the standard deviation of the differences at known benchmarks, which was estimated 1.3 cm, 2.3 cm and 2.4 cm in Easting, Northing and Height, respectively. Nevertheless, for a thorough analysis on the internal accuracy of each procedure a wider area must be selected and an increased number of known benchmarks must be chosen.

CONCLUSIONS

The representation of the distortion of a national network established by classical geodetic techniques is feasible using satellite positioning techniques. In addition, the final product of satellite

imagery has to be referenced to the official national network. The effect of the transformation parameters used for the transformation from a global 3D system to a local 2D horizontal and 1D vertical system was examined. A bias was identified for both horizontal as well as vertical component at GCP and CP locations. Various transformation schemes were proposed for the efficient elimination of the bias and the consistent incorporation of the physical meaning of the height was achieved through the concept of the geoid. Two global geoid models were used and the discrepancies in local height component was taken into account through the introduction of planar and spherical geoid corrector surfaces. The internal accuracy of each procedure was validated at benchmarks of the Greek national trigonometric network. The use of local transformation parameters in addition to a spherical corrector surface for a global geoid model was proven to be the best choice, taken into account the differences at benchmarks location. The use of a geoid estimated by local gravity data is expected to improve the height component accuracy.

ACKNOWLEDGMENTS

REFERENCES

Andritsanos, V.D., (2000): Optimum combination of terrestrial and satellite data using spectral methods for applications in Geodesy and Oceanography. PhD Thesis, in Greek. Department of Geodesy and Surveying. Aristotle University of Thessaloniki.

Andritsanos, V.D., G. Fotopoulos, A. Fotiou, C. Pikridas, D. Rossikopoulos and I.N. Tziavos (2004): New local geoid model for northern Greece. Proceedings of the 3rd International Central and Eastern Conference on Engineering Surveying, FIG Regional Central and Eastern European Conference, Bratislava, Slovakia, 11-13 November 2004.

Bomford, G. (1980): Geodesy. Oxford University Press.

Cramer, M., D. Stallmann and N. Haala (2000): Direct Georeferencing using GPS/Inertial exterior orientations for Photogrammetric Applications. IAPRS proceedings, Vol. XXXIII, Amsterdam.

Fotiou, A. (2007): Geometrical Geodesy (in Greek). Theory and Practice. Ziti eds. Thessaloniki.

Fotopoulos, G. (2003): An analysis on the optimal combination of geoid, orthometric and ellipsoidal height data. PhD Thesis. Department of Geomatics Engineering. The University of Calgary. Alberta. Canada.

Gianniou, M., (2009): National Report of Greece to EUREF 2009. EUREF 2009 Symposium, May 27-30 2009, Florence, Italy.

Gianniou, M., (2011): National Report of Greece to EUREF 2011. EUREF 2011 Symposium, May 25-28 2011, Chisinau, Moldova.

Hofmann – Wellnhof, B. and H. Moritz (2005): Physical Geodesy. Springer.

Jäger, R., S. Schneid, S. Kälber and S. Seiler (2006): Precise Transformation of Classical Networks to ITRF by CoPaG and Precise Vertical Reference Surface Representation by DFHRS – General Concepts and Realisation of Databases for GIS, GNSS and Navigation Applications. Presented at GEOS 2006 Symposium, 16 – 18 March, 2006, Prague, Czech Republic.

Kasser M. and J. Breton (2003): Necessity to Work in a Reference Frame in France. FIG Working Week 2003. Paris, France, April 13 – 17.

Katsampalos, K., C. Kotsakis and M. Gianniou, (2010): Hellenic Terrestrial Reference System 2007 (HTRS07): a regional densification of ETRS89 over Greece in support of HEPOS. Bollettino di Geodesia e Scienze Affini, Vol. LXIX , N. 2-3, 2010, pp. 329-347.

Kotsakis C. and M. G. Sideris (1999): On the adjustment of combined GPS/levelling/geoid networks. Journal of Geodesy, vol. 73, no. 8, pp.412 – 421.

Liebold F. and H. - G. Maas (2014): Integrated Georeferencing of LIDAR and Camera Data acquired from a moving platform. IAPRS Proceedings, vol. XL-3, pp. 191 – 196.

Ruotsalainen, R. (2003): The change of National Datum in Finland. NLS Technical Meeting. Internet resources: http://www.samenland.nl/pdf/the_change_of_coordinate_system_in_finland.pdf

Skaloud, J. (1999): Optimizing Georeferencing of Airborne Survey Systems by INS/DGPS. PhD Thesis. Department of Geomatics Engineering. The University of Calgary. Alberta. Canada.

Torge, W. (2001): Geodesy. 3rd edition, de Gruyter eds.

Yildiz, F. and S. Y. Oturanc (2014): An Investigation of Direct and Indirect Geo-Referencing Techniques on the Accuracy of Points in Photogrammetry. Intern. J. of Environmental, Geological and Geophysical Engineering, Vol. 8, No 9, pp. 618 – 621.