UDK 528.063.1

TRANSFORMATION PARAMETERS BETWEEN UCS-2000 AND WGS-84

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Abstract. According to the Order of the Ministry of Agrarian Policy of Ukraine, published in 2016, about the procedure for using the national coordinate system UCS-2000, this was the first time officially presented parameters of the Helmert transformation from the UCS-2000 system to the ITRF-2000 system. However, all software products are used for communication between various coordinate systems as the main coordinate system, WGS-84. The Helmert transformation parameters between the UCS-2000 and WGS-84 systems are found for the new realization of WGS-84 (G1762) based on GPS data and the old realization of the WGS-84, based on the US Satellite Navigation System, known as DOPPLER Transit. It is shown that the use of the transformation parameters of the old realization WGS-84 for the processing of present GPS measurements will result in a systematic error of the order of 0.6 m. Obtained transformation parameters can be used as the first approximation to obtain accurate Helmert transformations based on GPS measurements at points with known co-ordinates in the UCS-2000 system. The described procedure for determining the parameters will be especially useful in the case when a more accurate connection will be established between the systems ITRFyy and WGS-84, than the current one.

Keywords: Helmert transformation parameters, coordinate frame rotation, position vector rotation, UCS-2000, WGS-84.

Introduction

Back in the 90s of the 20th century the Baltic countries – Lithuania, Latvia, Estonia, were successfully integrate their geodetic networks into the EUREF Permanent GNSS Network. As a result, these countries were able to use the high-precision European coordinate system ETRF-89 for the geodetic purposes. This allowed them, in the middle of the 90s, to completely free themselves from the outdated coordinate system SK-42. In particular, Lithuanian geodesists have created the national coordinate system LKS-94, precisely attached to the system ETRF-89 (Aleknavicius & Sinkeviciute, 2008). Terms of its use are legislatively fixed in Resolution N 936 (Nutarimas, 1994). The transformation parameters of this system with the systems SK-42 and WGS-84 are published in (Įsakymas, 1996) and are available to all users.

At the end of 2016, the Ministry of Justice of Ukraine approved the order of the Ministry of Agrarian Policy about the applying the coordinate system UCS-2000, in which the transformation parameters from UCS-2000 to ITRF-2000 were officially presented (Minahropolityky, 2016).

It should be noted that the coordinates of points obtained with GPS measurements are first calculated in the WGS-84 system (Minekoresursiv, 2001). All software for geospatial data processing, such as Digitals, MapInfo, Trimble Geomatics, Topcon Tools, use the standard scheme, shown in Figure 1, for switching from one coordinate system to another.

Thus, when using software, it is necessary to know the transformation parameters from the UCS-2000 to the WGS-84 and vice versa, from WGS-84 to UCS-2000, not the transformation parameters from the ITRF-2000 to the UCS-2000.

Figure 1. Standard software scheme for the transformation from one coordinate system to another

The parameters, presented in Table 1, completely coincide with the unofficial data published in (Savchuk, 2012), according to which the displacement of the center the

Table 1. The Helmert transformation parameters for the conversion from ITRF-2000 to UCS-2000 (Minekoresursiv, 2001)

Parameter	Value
ΔX (m)	–24.322
ΔY (m)	121.372
ΔZ (m)	75.847
ε_X (arc sec)	0
ε_Y (arc sec)	0
ε_Z (arc sec)	0
μ (ppb*)	0

* 1 ppb = 10^{-9}.

UCS-2000 system relative to the center of the ITRF-2000 system has such a parameters:

$$\Delta X = 24.322 \ (m), \ \Delta Y = -121.372 \ (m),$$
$$\Delta Z = -75.847 \ (m).$$

Given the fact that the axes of the UCS-2000 and ITRF-2000 systems are parallel and the scales are equal (Minahropolityky, 2016; Kucher, Stopkhay, Vysotenko, & Renkevych, 2008), the Helmert transformation parameters from the ITRF-2000 to the UCS-2000 have angular parameters $\varepsilon_X, \varepsilon_Y, \varepsilon_Z$ and the scale factor μ equal to zero (Table 1).

A similar problem, namely the problem of transforming positional coordinates between the NAD-83 (2011) and WGS-84 (G1674) systems is discussed in detail in (Soler & Snay, 2004). It is shown that a correct transformation between coordinate systems can be performed only taking into account the transformation epoch.

1. The Helmert method and its features

The transformation of coordinates by the Helmert method is carried out according to this equation (Závoti & Kalmár, 2015; Jekeli, 2012):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + (1+\mu) \cdot \overline{\mathbf{R}} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}, \quad (1)$$

where: X_1, Y_1, Z_1 – coordinates of point in the first coordinate system. In our case this is the ITRF-2000; X_2, Y_2, Z_2 – coordinates of point in the second coordinate (UCS-2000); $\overline{\mathbf{R}} - 3\times 3$ rotation matrix, whose terms depend on the angles between the corresponding axes of the first and the second coordinate systems.

If these angles and the scale factor (see Table 1) are the first-order quantities of smallness, then, to within the second-order quantities of smallness, formula (1) is written as follows (Timár & Molnár, 2013):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 \cong \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + \begin{bmatrix} \mu & +\varepsilon_Z & -\varepsilon_Y \\ -\varepsilon_Z & \mu & +\varepsilon_X \\ +\varepsilon_Y & -\varepsilon_X & \mu \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}. \quad (2)$$

The transformation of coordinates from the first system to the second one, using the approximate Eq. (2), is often called the Bursa-Wolf transformation (Závoti & Kalmár, 2015).

According to (Timár & Molnár, 2013), there are two ways to determine the angles $\varepsilon_X, \varepsilon_Y, \varepsilon_Z$. Eq. (1) uses the angles defined from the axes of the first coordinate system to the axes of the second coordinate system. This option is called "coordinate frame rotation".

If the angles of rotation are determined from the second coordinate system to the first one, then in this case, the system (2) is rewritten as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + \begin{bmatrix} \mu & -R_Z & +R_Y \\ +R_Z & \mu & -R_X \\ -R_Y & +R_X & \mu \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}. \quad (3)$$

The second option, represented by (3), is called "position vector rotation" (Timár & Molnár, 2013).

Obviously, the first option differs from the second one only by the sign of the angles of rotation, that is:

$$\varepsilon_X = -R_X, \varepsilon_Y = -R_Y, \varepsilon_Z = -R_Z. \quad (4)$$

The first option is used in countries such as the US, Canada, Australia and in software developed in these countries, as well as in the Ukrainian software Digitals.

The second option is used in Europe. In particular, all the parameters of the Helmert transformation between the ITRF coordinate systems are presented on the ITRF official website using the second option for determining the angles of rotation of the coordinate axes (ITRF, n.d.). To find the connection between the UCS-2000 and WGS-84 systems, the second version of the Helmert transformation was applied.

Often there is a problem of transformation the coordinates in which there are three instead of two coordinate systems participate, and it is necessary to find the coordinates of the third system using the coordinates of the first system. The parameters of the Helmert transformation for one epoch from the first to the second and from the second to the third coordinate systems are known. If we assume that the angular parameters and the scale factors in the Helmert transformation are the first-order quantities of the smallness, then on the basis of formula (3) we can write:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_3 \cong \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + $$
$$\begin{bmatrix} \mu_1 + \mu_2 & -R_{Z1} - R_{Z2} & +R_{Y1} + R_{Y2} \\ +R_{Z1} + R_{Z2} & \mu_1 + \mu_2 & -R_{X1} - R_{X2} \\ -R_{Y1} - R_{Y2} & +R_{X1} + R_{X2} & \mu_1 + \mu_2 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + $$
$$\begin{bmatrix} \Delta X_1 + \Delta X_2 \\ \Delta Y_1 + \Delta Y_2 \\ \Delta Z_1 + \Delta Z_2 \end{bmatrix}. \quad (5)$$

By analyzing the formula (5) and by extending it to the case of a transformation, in which an arbitrary number of coordinate systems participate, we can formulate the following rule.

If all the angular parameters and the scale factor are the first-order quantities of the smallness, then the parameters of the Helmert transformation for the transition from the first to the n-th coordinate system are equal to the sum of the corresponding parameters between all the previous coordinate systems obtained for one epoch.

This rule was used in (Soler & Snay, 2004) to determine the transformation parameters between the ITRF-2000 and NAD-83 systems.

Similarly, using the formula (3), it can be shown that the parameters of the inverse transformation from the second coordinate system to the first one, up to the second-order quantities of the smallness, are equal to the parameters of the direct transformation, but with the opposite sign, that is:

$$P_{2-1} = -P_{1-2},\qquad(6)$$

where: P_{1-2} – arbitrary direct transformation parameter; P_{2-1} – arbitrary inverse transformation parameter.

2. Transformation parameters between UCS-2000 and WGS-84

As indicated in (ITRF, n.d.), there are two types of WGS-84 realizations:

- new WGS-84 realizations based on GPS data, such as WGS-84 (G730, G873, G1150, G1674 and G1762). For these realizations, there are no official transformation parameters with respect to ITRF systems. It is assumed that the systems ITRF-2008 and WGS-84 (G1674, G1762) are coincide at the level of 10 cm for the epoch of 2005.0;
- old WGS-84 realization, based on the US Satellite Navigation System, commonly known as DOPPLER Transit, which provides station coordinates with an accuracy of about one meter. According to this realization, the transformation parameters between ITRF-90 and WGS-84 for the epoch 1984.0 are published in (ITRF, n.d.; Software, 2018).

2.1. Transformation parameters for new realization WGS-84 (G1762)

Given that the parameters of Helmert transformation for the transition between ITRF-2000 and ITRF-2008 systems are presented in (ITRF, n.d.), it is possible to determine the transition scheme from the UCS-2000 system to the WGS-84 system, which is shown in Figure 2.
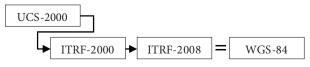

Figure 2. The scheme of coordinate transformation from UCS-2000 to the new realization of WGS-84

According to the passport of the UCS-2000 system (Derzhheokadastr, n.d.), its parameters were determined for the epoch 2005.0. Therefore, the parameters of all the systems involved in determining the connection between the UCS-2000 and WGS-84 systems (see Figure 2) should also be listed for the epoch 2005.0. To do this, the following equation is used (ITRF, n.d.; Soler & Snay, 2004):

$$P(E_2) = P(E_1) + dP \cdot (E_2 - E_1),\qquad(7)$$

where: $P(E_1)$ – one of the seven transformation parameters presented in the upper cells of Table 2, for the tabular epoch; $P(E_2)$ – the same parameter transformed into another epoch; dP – the annual rate of this parameter, represented in the lower cells of Table 2.

Table 2. Helmert parameters for the transformation of coordinates between the ITRFyy and WGS-84 systems, according to (ITRF, n.d.; Software, 2018)

Parameter	from ITRF-2000 to ITRF-2008	from ITRF-2000 to ITRF-90	from ITRF-90 to WGS-84 (old realization)
Epoch	2000.0	1988.0	1984.0
ΔX (m)	0.0019	0.0247	0.060
ΔY (m)	0.0017	0.0235	−0.517
ΔZ (m)	0.0105	−0.0359	−0.223
R_X (arc sec)	0.000	0.00000	0.0183
R_Y (arc sec)	0.000	0.00000	−0.0003
R_Z (arc sec)	0.000	−0.00018	0.0070
μ (ppb)	−1.34	2.45	−11.00
$d(\Delta X)$ (m/year)	−0.0001	0.0000	–
$d(\Delta Y)$ (m/year)	−0.0001	−0.0006	–
$d(\Delta Z)$ (m/year)	0.0018	−0.0014	–
$d(R_X)$ (arc sec /year)	0.000	0.00000	–
$d(R_Y)$ (arc sec /year)	0.000	0.00000	–
$d(R_Z)$ (arc sec /year)	0.000	0.00002	–
$d(\mu)$ (ppb/year)	−0.08	0.01	–

The use of the data from Table 2 and Eq. (5) for $E_1 = 2000$, $E_2 = 2005$ allows to find such parameters of the transformation from ITRF-2000 to ITRF-2008 for the epoch 2005.0:

ΔX (m) = 0.0014, ΔY (m) = 0.0012, ΔZ (m) = 0.0195;

R_X (arc sec) = 0.000, R_Y (arc sec) = 0.000; R_Z (arc sec) = 0,000, μ (ppb) = −1.74.

Since the ITRF-2008 and WGS-84 systems coincide at the level of 10 cm, the transformation parameters between the ITRF-2008 and ITRF-2000 systems, as a result of their smallness, can be ignored. However, it is formally possible to obtain conversion parameters from UCS-2000 to WGS-84, simply by summing the data in Table 1 and the conversion parameters between the ITRF-2008 and ITRF-2000 systems, taking into account the formula (5). The result is presented in Table 3. Parameters defined for the epoch 2005.0.

Table 3. Helmert parameters for the transformation of coordinates from UCS-2000 to WGS-84

Parameter	for WGS-84 (G1762)	for WGS-84 old realization
Epoch	2005.0	1984.0
ΔX (m)	24.3234	24.4067
ΔY (m)	–121.3708	–121.8631
ΔZ (m)	–75.8275	–76.1003
R_X (arc sec)	0.00000	0.01830
R_Y (arc sec)	0.00000	–0.00030
R_Z (arc sec)	0.00000	0.00674
μ (ppb)	–1.74	–8.59

It should be noted that (Soler & Snay, 2004) the above transformation between the ITRF-2000 and ITRF-2008 to find parameters between NAD-83 and WGS-84 are also used.

2.2. Transformation parameters for old realization WGS-84

The process of coordinate transformation in this case can be represented by the following scheme.
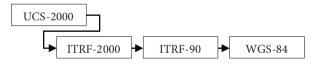

Figure 3. Scheme of coordinate transformation from UCS-2000 to the old realization of WGS 84

The transformation parameters between the UCS-2000 and ITRF-2000 systems and ITRF-90 and WGS-84 systems are presented for different epochs, the first group of parameters for the epoch 2005.0, and the second – for the epoch 1984.0. As in the first and the second cases, there are no rates of change these parameters (Tables 1–2). As indicated in (Kucher et al., 2008), the UCS-2000 is clearly aligned with the ITRF-2000, which means that the transformation parameters between these systems have rates equal to zero. Thus, it is possible to obtain parameters from UCS-2000 to the old realization of WGS-84 for the epoch 1984.0. The transformation parameters from ITRF-2000 to ITRF-90 for the epoch 1984.0, according to the

formula (5) and the data of Table 2, are equal to:

ΔX (m) = 0.0247, ΔY (m) = 0.0259,
ΔZ (m) = –0.0303;
R_X (arc sec) = 0.00000, R_Y (arc sec) = 0.00000;
R_Z (arc sec) = –0.00026, μ (ppb) = 2.41.

The final parameters of the coordinate transformation from the UCS-2000 to the old realization of WGS-84 are shown in Table 3.

According to the data of Table 3, the difference between the linear transformation parameters from the UCS-2000 to the old and new realizations of the WGS-84 system is:

$$DS = \sqrt{DX^2 + DY^2 + DZ^2} = 0.569 \text{ (m)},$$

where:

$$DX = \Delta X_{old} - \Delta X_{new}, \ DY = \Delta Y_{old} - \Delta Y_{new};$$
$$DZ = \Delta Z_{old} - \Delta Z_{new}.$$

This means that using the transformation parameters of the old WGS-84 realization for the processing of current GPS measurements will result in a systematic error of about 0.6 m, which 6 times exceeds the accuracy of communication of the WGS-84 with ITRF-2008 (0.1 m).

Conclusions

It is shown that for communication between the UCS-2000 and all other systems, it is necessary to know the transformation parameters between this system and WGS-84. The analysis of options of the Helmert transformation parameters is performed. It is shown that there are two options of parameters that differ by the sign of the angular elements. The first option is called "coordinate frame rotation". It is used in software from the US, Canada and Australia, as well as in the Ukrainian program Digitals. The second option is "position vector rotation", which is used in European countries. The second version is applied in this work. There are transformation parameters obtained from UCS-2000 to two realizations of the WGS-84: a new realization of WGS-84 (G1762), and an old realization based on the US Satellite Navigation System, commonly known as DOPPLER Transit.

It is concluded that the use of the transformation parameters from UCS-2000 to the old realization of the WGS-84 system for processing of current GPS measurements can cause a systematic error in the coordinates of the points of the order of 0.6 m, which 6 times exceeds the accuracy of communication between the WGS-84 and ITRF-2008.

The resulting transformation parameters from UCS-2000 to WGS-84 are based on data that, as indicated in (Minahropolityky, 2016), are approximate. They can be used as a first approximation to obtain the exact Helmert transformation parameters based on GPS measurements at points with known coordinates in the UCS-2000 system.

The described procedure for parameter determination will be especially useful if a more precise connection will be established between the ITRFyy and WGS-84 systems than the current one (ITRF, n.d.).

References

Aleknavicius, A., & Sinkeviciute, V. (2008). *Kartografija: Mokomoji knyga*. Kaunas: Ardiva. Retrieved from http://vuzf.asu.lt/wp-content/uploads/sites/6/2015/01/kartografija_0.pdf

Derzhheokadastr. (n.d.). *Pasporty Derzhavnoyi heodezychnoyi referentsnoyi systemy koordynat USK-2000* (in Ukrainian). Retrieved from http://dgm.gki.com.ua/ua/pasporti-derjavnoii-geodezichnoii-referencnoii-sistemi-coordinates-usk-2000

Lietuvos Respublikos valstybinės žemėtvarkos ir geodezijos tarnybos prie Žemės ūkio ministerijos Įsakymas dėl valstybinės koordinačių sistemos įvedimo tvarkos. 1996 m. sausio 5 d. Nr. 1. Vilnius (in Lithuanian). Retrieved from https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/TAIS.24435?jfwid=zm7w3rdib

ITRF (n.d.). *Transformation parameters*. Retrieved from http://itrf.ensg.ign.fr/trans_para.php

Jekeli, C. (2012) *Geometric reference systems in geodesy*. Ohio State University. Retrieved from https://kb.osu.edu/dspace/bitstream/handle/1811/51274/Geometric_Reference_Systems_2012.pdf

Kucher, O., Stopkhay, YU., Vysotenko, R., & Renkevych, O. (2008). Vprovadzhennya derzhavnoyi heodezychnoyi referentsnoyi systemy koordynat Ukrayiny – USK-2000. *Novitni dosyahnennya heodeziyi, heoinformatyky ta zemlevporyadkuvannya – Yevropeys'kyy dosvid*, 4, 25-30 (in Ukrainian).

Minahropolityky. (2016). *Poriadok vykorystannia Derzhavnoi heodezychnoi referentsnoi systemy koordynat USK-2000 pry zdiisnenni robit iz zemleustroiu* (Zatverdzheno nakazom Ministerstva ahrarnoi polityky ta prodovolstva Ukrainy vid 02.12.2016 r. No. 509) (in Ukrainian).

Minekoresursiv. (2001). *Svitova heodezychna systema koordynat WGS-84. Osnovni polozhennya. Zv'yazok z inshymy heodezychnymy systemamy* (Zatverdzheno nakazom Ministerstva ekolohiyi ta pryrodnykh resursiv Ukrayiny vid 14.12.2001 r. No. 467) (in Ukrainian). Retrieved from http://gki.com.ua/files/uploads/documents/Norms/WGS-84.pdf

Lietuvos Respublikos Vyriausybės Nutarimas dėl Lietuvos geodezinių koordinačių sistemos įvedimo. 1994 m. rugsėjo 30 d. Nr. 936. Vilnius (in Lithuanian). Retrieved from https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/TAIS.13644?jfwid=zm7w3rdib

Savchuk, S. (2012). Praktychni aspekty zastosuvannya novoyi referentsnoyi systemy USK2000. *17-ta Mizhnarodna naukovo-tekhnichna konferentsiya GEOFORUM"2012*. L'viv-Yavoriv, Ukrayina, p. 22 (in Ukrainian).

Software, C. (2018). *World Geodetic System 1984 (WGS84)*. Confluence.qps.nl. Retrieved from https://confluence.qps.nl/qinsy/en/world-geodetic-system-1984-wgs84-29855173.html

Soler, T., & Snay, R. (2004). Transforming positions and velocities between the International Terrestrial Reference Frame of 2000 and North American datum of 1983. *Journal of Surveying Engineering*, *130*(2), 49-55. https://doi.org/10.1061/(ASCE)0733-9453(2004)130:2(49)

Timár, G., & Molnár, G. (2013). *Map grids and datums*. Eötvös Lóránd University. Retrieved from http://elte.prompt.hu/sites/default/files/tananyagok/MapGridsAndDatums/index.html

Závoti, J., & Kalmár, J. (2015). A comparison of different solutions of the Bursa–Wolf model and of the 3D, 7-parameter datum transformation. *Acta Geodaetica Et Geophysica*, *51*(2), 245-256. https://doi.org/10.1007/s40328-015-0124-6