

## QUALITY ASSESSMENT OF THE HOMOGENEOUS COORDINATE TIME SERIES OF EASTERN EUROPEAN GNSS STATIONS IN THE IGS05 REFERENCE FRAME

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### ABSTRACT

For the first time, a homogeneous coordinate solution in the IGS05 reference frame and the values of the zenith tropospheric refraction for the GPS weeks 935-1399 (from December 12, 1997 to November 4, 2006) were obtained at the GNSS Data Center Analysis of the Main Astronomical Observatory NAS of Ukraine.

The obtained solution is devoid of effects, brought by changes in the methods of processing models, a priori data and software (absolute phase center model combinations of antenna-dome instead of relative models, model of ocean loading FES2004 instead of GOT00.2\_PP, the elevations cut-off angle  $3^\circ$  instead of  $10^\circ$ , etc. were used).

To estimate the quality of the solution, a comparison with the international combined solutions using the Helmert transformation was carried out. The RMS of direct station coordinate differences and correlation coefficients between the solutions estimated by the Main Astronomical Observatory, European GNSS Permanent Network and International GNSS Service are presented.

The obtained results allow making the conclusion that the solution obtained at the GNSS Data Center Analysis of the Main Astronomical Observatory shows a good quality and agrees well with other solutions.

**Keywords:** reprocessing of GPS observations, homogeneous coordinates time series, zenith tropospheric refraction, Global Positioning System.

## 1. INTRODUCTION

At the GNSS Data Center Analysis of the Main Astronomical Observatory NAS of Ukraine, observations of GPS satellites for GPS weeks 935-1399 (December 7, 1997 – November 4, 2006) were reprocessed. The reprocessing was carried out for the 31 GPS stations in the IGS05 reference frame, which are located in Eastern Europe.

*Bernese GPS Software ver. 5.0* [1], developed at the Astronomical Institute of the University of Bern, Switzerland, was used for the reprocessing of GPS observations along with the recommendations of the Central Bureau of European GNSS permanent network, which came into effect from GPS week 1400 [3] for the processing.

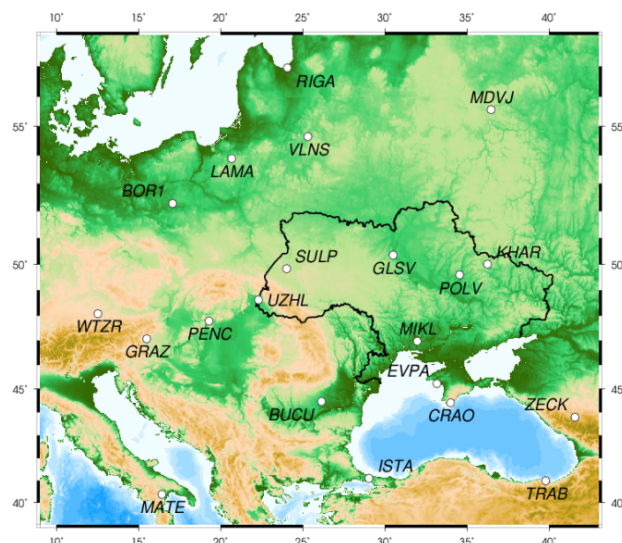
To perform the preprocessing, satellite 30-s observations files in the RINEX format were used. In the reprocessing, improved GPS orbits and Earth rotation parameters are used, which were obtained as a result of reprocessing associated with the improvement of the GPS satellite orbits [10]. The absolute model antenna phase center variations were taken from the ANTEX file. The ocean tidal loading displacements for GPS stations were calculated on the basis of the model FES2004 [4]. The Earth gravity field model JGM3 and ephemeris of the Sun and the Moon DE2000 [8], provided the Jet Propulsion Laboratory, JPL NASA, were used. The a priori coordinates and velocities of stations were taken from the IGS05 catalogue with a reference to the epoch 2000.0. To define the coordinate system, the minimum constraint condition No-Net-Translation on the coordinates of stations GLSV, POLV, MDVJ, BOR1, TRAB, MATE and WTZR was applied. A priori model Saastamoinen [7], defined by option DRY\_NIELL [6], for modeling of zenith tropospheric refraction was used. The tropospheric gradient TILTING [1] for satellites with low elevation angles was used. The Quasi ionosphere free algorithm [1] to fix the phase ambiguities and the global model of the ionosphere on each day, presented by CODE, was used. The nutation and precession model IAU2000 [5] was taken into account, as well.

The process of obtaining solution for the separate GPS week can be divided into several stages: preprocessing of daily sessions of observations; obtaining estimates of coordinates for the every day of observations; estimating of station coordinates for the whole GPS week; obtaining the final tropospheric zenith path delay parameters for each station.

As a result of processing of archival GPS observations at the GNSS Data Center Analysis, the homogeneous coordinate time series and tropospheric zenith path delay parameters for the 464 GPS weeks were obtained [2]. Solution *MAO Repro1* labeled as *MA1* and available at MAO ftp-server (<ftp://ftp.mao.kiev.ua/pub/gnss/products/IGS05/>).

To estimate the quality of the resulting solution *MA1*, comparisons with the combined reprocessing solutions *EPN Repro1* [11-12], performed by European GNSS Permanent Network, and *IGB Repro1* [4] performed by International GNSS Service are presented.

The locations of the GPS stations, which were used to compare three solutions, are shown in the fig. 1. The list of the GPS stations with additional information is presented in the table 1 (see appendix).



**Fig. 1.** Location of the GPS stations in Eastern Europe

## 2. COMPARISON OF THE SOLUTION *MAO REPRO1* WITH A COMBINED SOLUTION *EPN REPRO1*

In 2010, the Working Group of the European GNSS Permanent Network (EPN), i.e., the regional GNSS densification network in Europe, decided to start reprocessing campaign for EPN GPS stations. The processing was carried out in the accordance with the EPN guidelines and geographic location.

EPN began a campaign, called as *EPN Repro1*, in which archival GPS observations were processed. The results of the reprocessing campaign *EPN Repro1* are available at ftp-server EPN (<ftp://igs.bkg.bund.de/EPNrepro1/products/>) [11–12]. Solution was labeled as *EU0*.

Having combined EPN solution made it possible to perform an evaluation of the quality of the reprocessing *MAO Repro1* obtained at the Center for Analysis of GNSS data.

To verify the quality of the solution, the Helmert transformation parameters between the solution *MA1* and the combined solution *EU0* were obtained for stations which are present in both solutions. Minimum and maximum values lie in the following ranges:

### *Translation:*

axis *X*: from –21.2 mm to 18.3 mm,

axis *Y*: from –45.2 mm to 36.9 mm,

axis *Z*: from –23.4 mm to 18.8 mm.

### Mean values:

axis *X*: –0.5 mm,

axis *Y*: 6.2 mm,

axis *Z*: 0.6 mm.

### *Rotation:*

around the axis *X*: from –0.99 ms arc to 0.78 ms arc,

around the axis *Y*: from –0.72 ms arc to 0.87 ms arc,

around the axis *Z*: from –0.80 ms arc to 0.84 ms arc.

Mean values:

around the axis  $X$ :  $-0.12$  mas,

around the axis  $Y$ :  $-0.03$  mas,

around the axis  $Z$ :  $0.10$  mas.

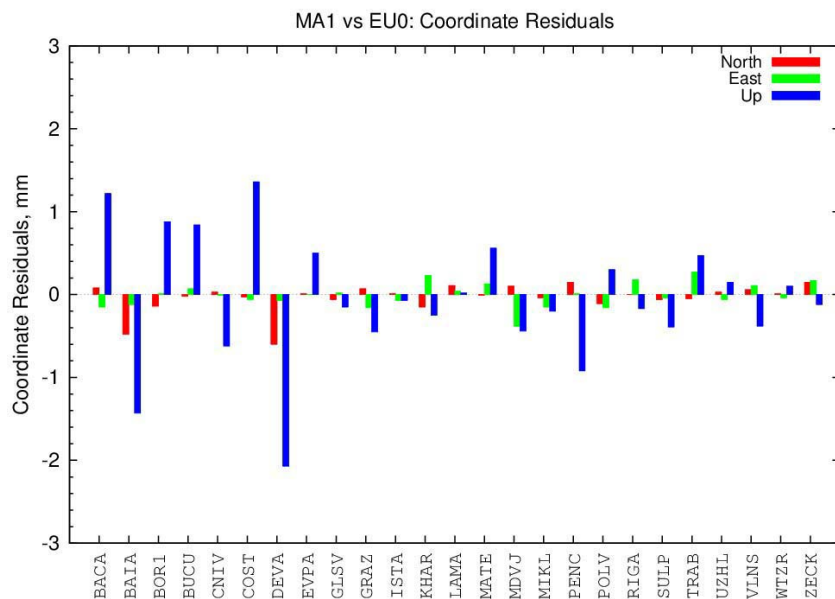
Scale factor:

from  $-1,6 \cdot 10^{-9}$  to  $0,9 \cdot 10^{-9}$ .

Mean value:

$-0.3 \cdot 10^{-9}$

Fig. 2 shows the mean residual values for the coordinates of permanent stations after the Helmert transformation between solutions  $MA1$  and  $EU0$  for stations in two solutions.



**Fig. 2.** The mean residual values for the coordinates after the Helmert transformation between solutions  $MA1$  and  $EU0$

Lowest and highest mean residual module consists of the following values:

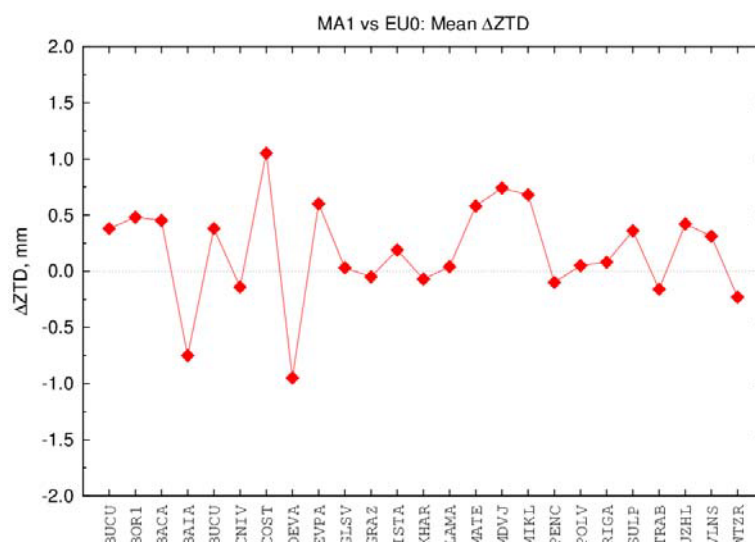
from  $0.00$  mm (station RIGA) to  $0.60$  mm (station DEVA) for the north component,

from  $0.00$  mm (station DEVA) to  $0.38$  mm (station MDVJ) for the east component,

from  $0.01$  mm (station MIKL) to  $2.07$  mm (station DEVA) for the up component.

The resulting non-zero residuals coordinate transformations after Helmert are explained with different way of coordinate system realization (different geometry of networks and a different set of reference stations).

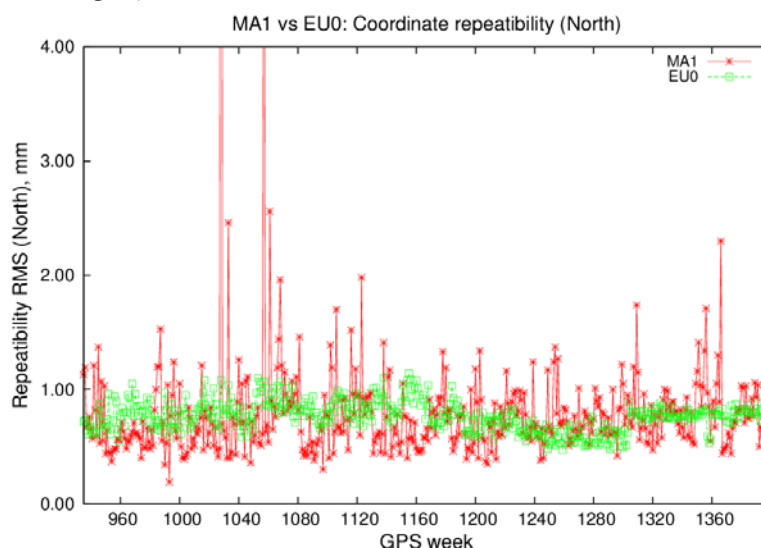
Fig. 3 shows the mean values of the zenith tropospheric refraction differences between solutions  $MA1$  and  $EU0$ .



**Fig. 3.** The mean values of the zenith tropospheric refraction differences between solutions *MA1* and *EU0*

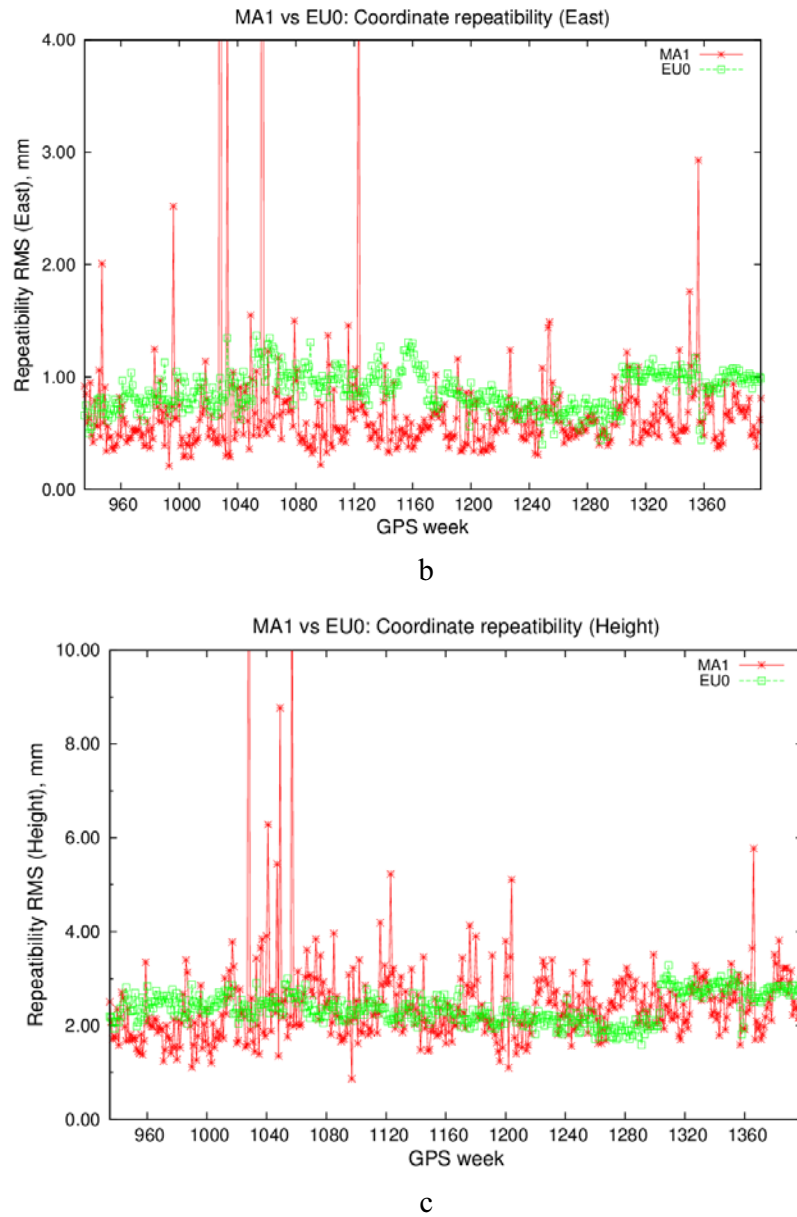
Using tropospheric gradient allows taking into account observations from the GPS satellites observed at low elevations, leading to improved estimates of the zenith tropospheric refraction parameters. Average values of the zenith tropospheric refraction differences lie within the limits (from  $-0.95$  mm DEVA to  $1.05$  mm COST).

One way of quality assessments is a comparison of the coordinate repeatability for the *MA1* and *EU0* solutions. It has been revealed that the repeatability of the coordinates for both solutions are very similar (see the fig. 4).



a

**Fig. 4 (part a).** Coordinate repeatability from the solutions *MA1* and *EU0* (a – north, b – east, c – up components)



**Fig. 4 (parts b and c).** Coordinate repeatability from the solutions *MA1* and *EU0* (a – north, b – east, c – up components)

Mean values of the coordinate repeatability for *MA1* and *EU0* solutions are as follows:

0.8 mm and 0.8 mm for the north component,

0.7 mm and 0.9 mm for the east component,

2.2 mm and 2.4 mm for the up component, respectively.

As one can see from the values above, coordinate repeatability for both solutions is almost at the same level. Based on the foregoing, the quality of the resulting reprocessing solution *MA1* coincides with the combined solution of EPN.

### 3. COMPARISON RESULTS OF THE SOLUTION *MAO REPRO1* WITH THE COMBINED SOLUTION *IGS REPRO1*

International GNSS Service (IGS) initiated a reprocessing campaign called as *IGS Repro1*. Improved GPS orbits and Earth rotation parameters were used in the reprocessing, which were obtained as a result of the reprocessing, associated with the improvement of the GPS satellite orbits [10]. As a result of the reprocessing, the consistent time series of station coordinates were obtained. SINEX files of the solution *IGS Repro1* available at the ftp-server IGS (ftp://igs-rf.ensg.eu/pub/igb/) [9]. Solution is hereinafter labeled as *IGB*.

The existence of combined EPN solution makes it possible to perform an evaluation of the quality of the results with respect to the reprocessing *MAO Repro1* from the Center for Analysis of GNSS data.

To verify a quality of the solution, the Helmert transformation parameters between the solution *MA1* and the combined solution *IGB* were obtained for the stations which are present in both solutions. Minimum and maximum obtained values lie in the following ranges:

*Translation:*

axis *X*: from  $-14.0$  mm to  $24.2$  mm,

axis *Y*: from  $-8.3$  mm to  $26.7$  mm,

axis *Z*: from  $-5.1$  mm to  $29.7$  mm.

Mean values:

axis *X*:  $7.5$  mm,

axis *Y*:  $8.3$  mm,

axis *Z*:  $12.0$  mm.

*Rotation:*

around axis *X*: from  $-0.61$  mas to  $0.49$  mas,

around axis *Y*: from  $-0.61$  mas to  $0.47$  mas,

around axis *Z*: from  $-0.33$  mas to  $0.50$  mas.

Mean values:

around axis *X*:  $-0.31$  mas,

around axis *Y*:  $0.05$  mas,

around axis *Z*:  $0.04$  mas.

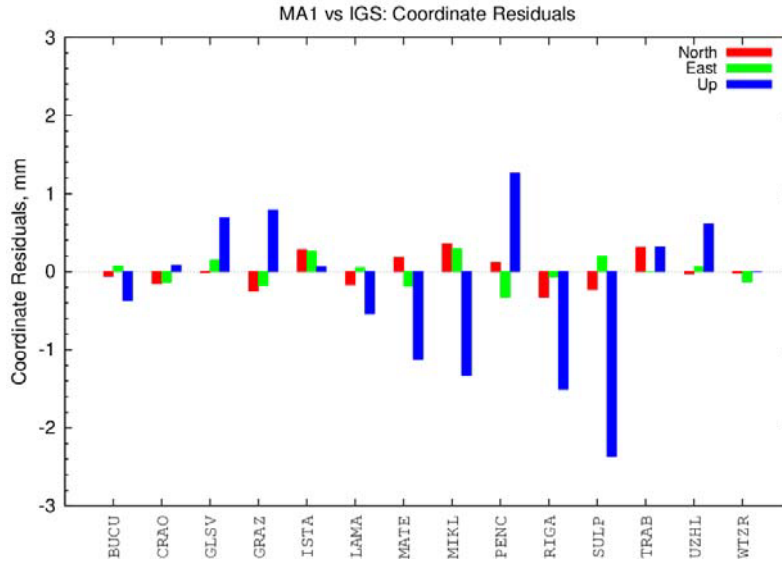
*Scale factor:*

from  $-3,3 \cdot 10^{-9}$  to  $-1,7 \cdot 10^{-9}$ .

Mean value:

$-2,4 \cdot 10^{-9}$

Fig. 5 shows the mean residual values after the Helmert transformation between solutions *MA1* and *IGB* for the coordinates of permanent GPS stations that are present in both solutions.



**Fig. 5.** The mean residual values for the coordinates between solutions *MA1* and *IGB* after the Helmert transformation

The minimum and maximum mean residuals (absolute values) have the following values: from 0.02 mm (station WTZR) to 0.36 mm (station MIKL) for the north component, from 0.00 mm (station TRAB) to 0.33 mm (station PENC) for the east component, from 0.00 mm (station WTZR) to 2.37 mm (station SULP) for the up component.

The main reasons for the insignificant differences between the solutions are the same as those from section 3, namely: a different geometry of networks and different ways of the coordinate system realization.

#### 4. THE ESTIMATION OF THE RMS AND CORRELATION COEFFICIENTS BETWEEN *MAO REPRO1*, *EPN REPRO1* AND *IGS REPRO1*

The existence of three different solutions makes it possible to obtain the estimation of the outer RMS accuracy of the solutions. The Helmert transformation was used for adduction of *MA1* and *EU0* solutions to the *IGB*-like definition, because each solution has its own coordinate realization. It was possible to eliminate systematic errors between the solutions by performing this transformation. Large mutual correlations exist between them as all three solutions are based on the same GPS observations. The method, developed in the MAO NAS of Ukraine, was used to estimate the outer errors and correlation coefficients. The idea of the method is as follows. Suppose we have  $M$  solution of  $N$  common stations. Assuming one of the coordinates ( $X$ ,  $Y$  or  $Z$ ) as  $x$ , for  $i$  station we find the values  $x_i^o$  and the error values  $\sigma_i^o$  :

$$x_i^o = \frac{\sum_{j=1}^M p_i^{(j)} x_i^{(j)}}{\sum_{j=1}^M p_i^{(j)}}, \quad (\sigma_i^o)^2 = \frac{1}{\sum_{j=1}^M p_i^{(j)}},$$

where  $p_i^{(j)} = \sqrt{p_j^{(j)}}$  – weight coordinates for station  $i$  and solution  $j$ , i.e.,  $x_i^j$ . We find a common station coordinate differences  $\Delta x_i^{jo} = x_i^j - x_i^o$  and consider the obtained value



$\{\Delta x_i^{jo}\}_{i=1,\dots,N}$  as random. We use the centered values and determine the expected value squared differences of coordinates in  $l$  and  $k$  solutions:

$$d_{kl} = M\left[(\Delta \hat{x}^{ko} - \Delta \hat{x}^{lo})^2\right] = \sigma_k^2 + \sigma_l^2 - \rho_{kl}\sigma_k\sigma_l$$

where  $M[\cdot]$  – operator of the mathematical expectation;

$\sigma_k$  and  $\sigma_l$  – outer mean square error of determining the coordinates in  $l$  and  $k$  solutions;

$\rho_{kl}$  – correlation coefficient between the corresponding coordinates in  $l$  and  $k$  solutions;

$\Delta \hat{x}^{ko}$  – are centered values of  $\Delta \hat{x}_i^{ko}$ .

A system of equations calculated with mathematical expectations of sums of squares and differences of coordinates  $l$  and  $k$  solutions is considered:

$$\begin{aligned} s_{kl} &= M\left[(\Delta \hat{x}^{ko} + \Delta \hat{x}^{lo})^2\right] = \sigma_k^2 + \sigma_l^2 + \rho_{kl}\sigma_k\sigma_l \\ d_{kl} &= M\left[(\Delta \hat{x}^{ko} - \Delta \hat{x}^{lo})^2\right] = \sigma_k^2 + \sigma_l^2 - \rho_{kl}\sigma_k\sigma_l \end{aligned}$$

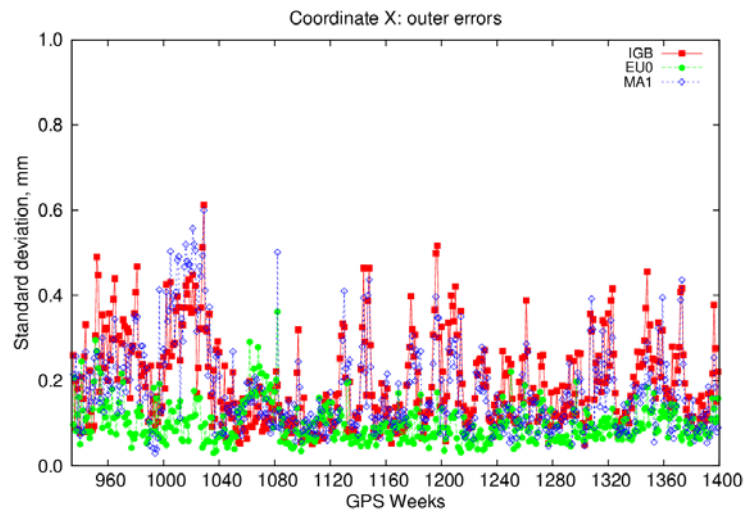
In the case of three solutions, by creating the sum  $d_{kl}$  and  $s_{kl}$  values, we will obtain a linear system of equations  $\sigma_k^2$ ,  $k = 1, 2, 3$ . Whose solution follows as:

$$\begin{aligned} \sigma_1^2 &= \frac{1}{4}(s_{12} + s_{13} - s_{23} + d_{12} + d_{13} - d_{23}), \\ \sigma_2^2 &= \frac{1}{4}(s_{12} + s_{23} - s_{13} + d_{12} + d_{23} - d_{13}), \\ \sigma_3^2 &= \frac{1}{4}(s_{23} + s_{13} - s_{12} + d_{23} + d_{13} - d_{12}). \end{aligned}$$

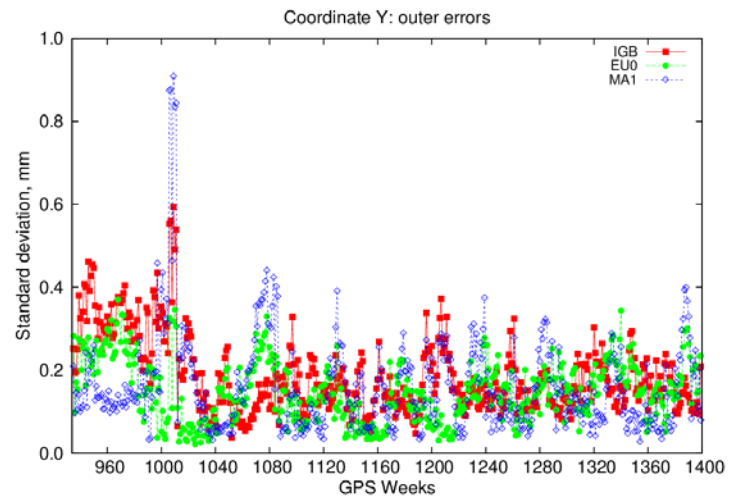
By creating differences of variables  $d_{kl}$  and  $s_{kl}$ , we can obtain expressions for the correlation coefficients:

$$\begin{aligned} \rho_{12} &= \frac{s_{12} - d_{12}}{4\sigma_1\sigma_2} \\ \rho_{13} &= \frac{s_{13} - d_{13}}{4\sigma_1\sigma_3} \\ \rho_{23} &= \frac{s_{23} - d_{23}}{4\sigma_2\sigma_3} \end{aligned}$$

Fig. 6 shows the outer mean square errors for the coordinate components  $X$ ,  $Y$  and  $Z$  for solutions  $MA1$ ,  $EU0$  and  $IGB$  for each GPS week.

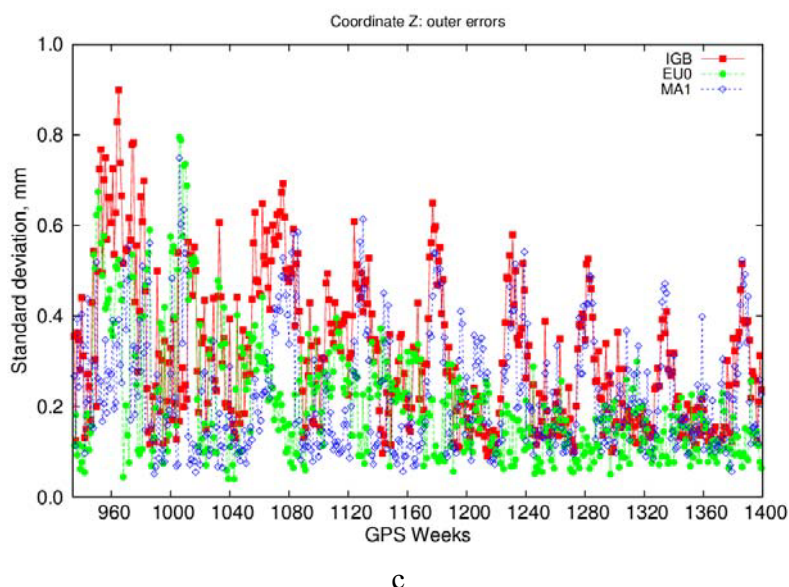


a



b

**Fig. 6 (parts a and b).** The value of outer RMS errors for solutions *MA1*, *EU0* and *IGB* (a – coordinate *X*, b – coordinate *Y*, c – coordinate *Z*)



**Fig. 6 (part c).** The value of outer RMS errors for solutions *MA1*, *EU0* and *IGB* (a – coordinate *X*, b – coordinate *Y*, c – coordinate *Z*)

Mean values of the estimated outer RMS errors and correlation coefficients of solutions *MA1*, *EU0* and *IGB* are given in the table 2.

Table. 2. Outer evaluation of the compatibility of the solutions: the mean error values and correlation coefficients

Coordinates	$\sigma_{MA1}$ , mm	$\sigma_{EU0}$ , mm	$\sigma_{IGB}$ , mm	$\rho_{EU0-MA1}$	$\rho_{IGB-MA1}$	$\rho_{IGB-EU0}$
<i>X</i>	1,7	1,0	1,9	+0,067	-0,774	-0,418
<i>Y</i>	1,6	1,5	1,8	-0,111	-0,610	-0,511
<i>Z</i>	2,3	2,0	3,1	+0,053	-0,659	-0,603

Relatively large values of the correlations between the solutions *IGB-MA1* and *IGB-EU0* may be explained by a different location of GPS stations and a different global coverage of the networks, namely *IGB* is a global network, *EU0* – regional, and *MA1* – local one, accordingly. However, commonly the solution *MA1* shows a similar quality as compared to the *EU0* and *IGB* solutions, because the mean error differences are at a level of just a few millimeters.

## CONCLUSIONS

The reprocessing for GPS weeks 935-1399 was carried out using the software package *Bernese GPS Software ver. 5.0* at the GNSS Data Center Analysis of the Main Astronomical Observatory (MAO) NAS of Ukraine. Homogeneous coordinate time series in the coordinate system IGS05 and tropospheric zenith path delay parameters for 31 GPS stations in Eastern Europe were obtained.

To check the quality of the solution MAO (*MA1*) Helmert transformation parameters between the solution *MA1* and the combined solutions of International GNSS Service (*IGB*) and European Permanent GNSS Network (*EU0*) were obtained. The main differences are caused by distinctions in the network geometry and reference stations different set. The mean values of the zenith

tropospheric refraction differences between solutions *MA1* and *EU0* lie within the limits (from – 0.95 mm for DEVA, Deva, Romania to 1.05 mm for COST, Constanta, Romania).

The mean values of the coordinate repeatability for *MA1* and *EU0* solutions are 0.8 mm, 0.7 mm, and 2.2 mm for the north, east, and up components, respectively. The RMS values of station coordinate repeatability from a direct comparison between the solutions amount to: for *MA1* – 1.7 mm, 1.6 mm and 2.3 mm; for *EU0* – 1.0 mm, 1.5 mm and 2.0 mm; for *IGB* – 1.9 mm, 1.8 mm and 3.1 mm for the X, Y and Z coordinate components, respectively.

The obtained results allow concluding that the solution MAO corresponds to the quality of the reprocessed EPN and IGS solutions.

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Table 1. The list of permanent GPS stations for the observations period GPS weeks 935-1399

Stations	Country	Identification	DOMES	International networks	Receiver	Antenna Dome	Note
Kiev	Ukraine	GLSV	12356M001	EPN, IGS	TRIMBLE 4000SSI	TRM29659,00 NONE	
Simeiz	Ukraine	CRAO	12337M002	IGS, MGN	ROGUE SNR-8000	AOAD/M_T SCIS	
Evpatoria	Ukraine	EVPA	12344M001	EPN	TRIMBLE 4000SSI	TRM29659,00 NONE	
Kharkiv	Ukraine	KHAR	12314M001	EPN, IGS	TRIMBLE 4000SSI	TRM29659,00 NONE	
Mykolaiv	Ukraine	MIKL	12335M001	EPN, IGS	TRIMBLE 4700	TRM41249,00 NONE	
Poltava	Ukraine	POLV	12336M001	EPN, IGS	TRIMBLE 4700	TRM29659,00 NONE	
Lviv	Ukraine	SULP	12366M001	EPN, IGS	TRIMBLE 4700	TRM33429,20+GP NONE RM41249,00 NONE	from 06-10-2001 to 10-13-2001
Uzhgorod	Ukraine	USHL	12301M001	EPN, IGS	TRIMBLE 4000SSI	TRM29659,00 NONE	
Chernihiv	Ukraine	CNIV	15501M001	EPN	TRIMBLE 4000SSI	TRM29659,00 NONE	
Zelenchukskaya	Russian Federation	ZECK	12351M001	EPN, IGS	ROGUE SNR-8000 AOA SNR-8000 ACT ASHTECK Z-XII3	AOAD/M_T NONE AOAD/M_T NONE ASH700936D_M SNOW	to 07-12-2001 from 07-12-2001/ to 10-18-2005 from 07-03-2006
Mendeleevo	Russian Federation	MDVJ	12309M005	EPN, IGS	JPS LEGACY	JPSREGANT_DD_E NONE	
Obninsk	Russian Federation	MOBN	12365M001	IGS	ASHTECK Z-XII3	ASH701945C_M SCIS	
Borowiec	Poland	BOR1	12205M002	EPN, IGS	ROGUE SNR-8000	AOAD/M_T NONE	
Olsztyn	Poland	LAMA	12209M001	EPN, IGS	ROGUE SNR-8000 ASHTECK Z-XII3	AOAD/M_T NONE ASH700936F_C SNOW	to 04-25-1998 from 04-26-1998
Trabzon	Turkey	TRAB	20808M001	EPN, IGS	ASHTECK Z-XII3	ASH700936D_M SNOW	
Istanbul	Turkey	ISTA	20807M001	EPN, IGS	ASHTECK Z-XII3	ASH700936D_M SNOW	
Bucuresti	Romania	BUCU	11401M001	EPN, IGS	ASHTECK Z-XII3	ASH700936D_M SNOW	
Constantia	Romania	COST	11407M001	EPN	ASHTECK Z-X	ASH700936B_M NONE	
Bacau	Romania	BACA	11405M001	EPN	LEICA X1200PRO	LEIAT504 LEIS	
Baia Mare	Romania	BAIA	11406M001	EPN	LEICA X1200PRO	LEIAT504 LEIS	
Deva	Romania	DEVA	11408M001	EPN	LEICA X1200PRO	LEIAT504 LEIS	
Graz	Austria	GRAZ	11001M002	EPN, IGS, ECGN	ROGUE SNR-8000 AOA SNR-8000	AOAD/M_T NONE AOAD/M_T NONE	to 05-10-2000 from 10-05-2000/ to

					ACT ROGUE SNR-8000 ASHTech UZ-12 TRIMBLE NETRS TRIMBLE NETRS	AOAD/M_T NONE ASH701945C_M NONE ASH701945C_M NONE TRM29659.00 NONE	01-07-2000 from 07-01-2000/ to 04-29-2001 from 04-29-2001/ to 03-17-2005 from 03-17-2005/to 03-22-2005 from 03-22-2005
Penc	Hungary	PENC	11206M006	EPN, IGS	TRIMBLE 4000SSI TRIMBLE 5700	TRM14532.00 NONE TRM41249.00 NONE	to 05-20-2003 from 05-22-2003
Vilnius	Lithuania	VLNS	10801M001	EPN, ECGN	ASHTech Z-XII3	ASH700936A_M NONE	
Riga	Latvia	RIGA	12302M002	EPN, IGS, ECGN	ROGUE SNR-8000 AOA BENCHMARK ACT AOA BENCHMARK ACT	ASH700936D_M NONE AOAD/M_T NONE ASH700936D_M NONE	to 0-131-2005 from 01-3-2005/to 05-20-2006 from 05-22-2006/to 17-06-2006
Matera	Italy	MATE	12734M008	EPN, IGS, TOS	ROGUE SNR-800 ROGUE SNR-8100 TRIMBLE 4000SSI	ASH700936D_M NONE AOAD/M_T NONE TRM29659.00 NONE	from 06-18-2006 to 06-08-1999 from 06-18-1999
Bad Koetzting	Germany	WTZR	14201M010	EPN, IGS, TOS, ECGN	ROGUE SNR-8000 AOA SNR-8000 ACT	AOAD/M_T NONE AOAD/M_T NONE	to 06-17-1999 from 06-17-1999

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