Preliminary results in the achievement of the new gravity system of Republic of Moldova

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ABSTRACT

The achievement of the national gravity reference network of Republic of Moldova (**NGRNM**) represents the first step in merging gravity networks of Romania and Republic of Moldova. The project started as a joint venture of the Institute for Geophysics and Geology of the Academy of Sciences of Republic of Moldova and the Geological Institute of Romania. It is part of a larger program, GRANAT (**G**ravity **N**etworks **A**dvanced **T**ies), aimed to join gravity images over the state borders of Romania, Ukraine and Republic of Moldova, in an area where several major geotectonic units met each other along the SW margin of the East European Plate.

The paper mainly deals with problems connected to gravity determinations along the **NGRNM** ties and their adjustment. The **NGRNM** consists of seven first order gravity stations regularly spaced over the Moldavian territory. They have been tied within a triangle network with central base station (Chisinau) by using a LaCoste & Romberg model D gravity meter. Gravity vertical gradient determinations in every base station have been also performed by repeated measurements at every site at two different levels: 0.30 meters, and 0.80 meters above the ground.

The **NGRNM** has been adjusted by least square method as a free network, using four stochastic models based on various weighting systems.

Provisional absolute gravity values within the **NGRNM** have been obtained by connecting the new network to the national reference networks of Romania.

Key words: gravity, reference network, Republic of Moldova, GRANAT project

GENERAL CONSIDERATIONS

Located in the eastern part of the Central Europe (Fig. 1), Republic of Moldova was one of the components of the former Soviet Union. After getting the independence, the new state faced a lot of problems connected to its new status, and, among them, the necessity for a national gravity system, as close as possible to the EU gravity standard.

Taking the advantage of the fact that one of the neighboring countries, Romania, had been actively taking part to the UNIGRACE project (Rosca, 1999; Rosca and Besutiu, 2000), aimed to the integration of the gravity systems of the former European socialist countries into the EU system, a joint venture of the Institute of Geophysics and Geology of the Moldovan Academy of Sciences, and the Geological Institute of Romania started in the year 2000 in order to accomplish this task. Actually, this work represents, in a way, an extent of the above mentioned EU funded project, and is part of a larger project, GRANAT (**G**ravity **N**etworks

Advanced **T**ies), which was aimed to join gravity images over the state borders of Romania, Ukraine and Republic of Moldova, in an area where several major geotectonic units met each other: East European Plate, Alpine Carpathian Orogene, North Dobrogea folded belt, Moesian Plate and Scythian Plate.

NETWORK DESIGN

The design and field activities for the achievement of the national gravity reference network of Moldova (**NGRNM**) were thoroughly presented in a previous paper (Besutiu et al, 2001b). However, for a better understanding of the stochastic models used in the adjustment, in the followings the main aspects of its achievement will be summarized.

The gravity reference network was designed as a triangle network with central station, in a similar manner to the former 1st order gravity reference network of Romania (Botezatu, 1961). Location of the gravity stations were mainly planned on the concrete pillars of the seismological stations of the National Seismic Monitoring Network of Republic of Moldova (Chisinau, Soroca, Cahul, Leova).

As this configuration proved to be too scarce for gravity purposes, several base stations were added to appropriately cover the territory: Balti (located at the orthodox cathedral "St. Nicolae", in the central part of the city), Ungheni (at the orthodox church "St. Alexander Nevski"), and Causeni (at the memorial dedicated to Alexei Mateevici, located in the central square of the town). Table no. 1 shows the geographical coordinates of the NGRNM base stations.

Table no. 1 - Location of the NGRNM base stations

Station code	latitude	longitude
CHISINAU*	46º59' 52.0"	28º 40' 05.0"
SOROCA*	48º 07' 53.5"	28º 20' 31.0"
BALTI	47º 45' 40.0"	27º 56' 00.0"
UNGHENI	47º 12' 00.0"	27º 48' 00.0"
LEOVA*	46º 28' 24.6"	28º 14' 53.3"
CAHUL*	45º 54' 18.8"	28º 12' 02.4"
CAUSENI	46º 38' 15.0"	29º 24' 30.0"

Asterisks mark common location with seismic monitoring network stations.

Special forms including map sketches and photos have been also provided for a complete description of every base station.

DATA ACQUISITION

Instruments

Gravity determinations along the **NGRNM** ties were performed by using the LaCoste & Romberg D-214 meter owned by the Geological Institute of Romania.

During the works, factory scale factor has been used to turn direct readings into gravity units. However, the meter has been checked up before, and after the end of the field campaign, by measuring along the UNIGRACE calibration line Cluj-Napoca – Belis (Besutiu et al, 2001a). Figures provided by factory were fully confirmed by gravity range determined along this calibration line (172.118 mgals).

Although the meter is fully thermostatic, due to the extremely low external temperatures experienced during the works, small variations of the temperature inside the instrument occurred during the measurements.

Consequently, the measuring temperature was carefully read every time, and took into consideration as a weighting constraint when adjusting the results.

Methodology

As previously mentioned, the **NGRNM** was designed as a triangle network with central station. Each gravity tie was measured at least twice, within independent measuring loops performed in different days. At least three dial readings were taken each time at every location.
Drift and tidal corrections have been applied to every measurement. Average values of the distinct determinations were taken into consideration as representative values for each gravity tie. The quality of the obtained results was carefully examined and evaluated (Besutiu et al, 2001b). Table no. 2 summarizes the results.

Table 2 - Mean gravity and associated measuring parameters along the NGRNM ties

Network tie	**Tie code**	**Δg (mgal)**	**rms (mgal)**	**e (mgal)**	**Δt (^{0}C)**	**ΔT (minutes)**
Chisinau-Soroca	1	120.217	0.018	0.008	0.10	375
Chisinau-Balti	2	79.518	0.018	0.007	0.06	366
Balti-Soroca	3	40.701	0.002	0.002	0.01	223
Ungheni-Balti	4	45.272	0.002	0.002	0.02	156
Chisinau-Ungheni	5	34.236	0.010	0.006	0.08	320
Chisinau-Albita	6	13.969	0.006	0.005	0.08	290
Leova-Albita	7	30.037	0.005	0.005	0.01	200
Leova-Chisinau	8	16.068	0.014	0.004	0.09	314
Cahul-Chisinau	9	96.858	0.012	0.004	0.15	598
Cahul-Leova	10	80.795	0.002	0.002	0.05	268
Causeni - Cahul	11	91.430	0.020	0.020	0.02	600
Causeni-Chisinau	12	5.442	0.010	0.004	0.13	278

where Δg = mean gravity value along the network tie
rms = mean standard deviation of a measurement
e = standard deviation of the mean gravity
Δt = maximum temperature deviation during the measuring loop
ΔT = mean duration of the measuring loop

Fig. 2 presents the network design and triangle closures.

NETWORK ADJUSTMENT

Network adjustment has been performed under the hypothesis that measurements along the ties have been affected by random errors only. Systematic effects (such as the influence of the scale factor for instance) have been not taken into account at this research stage.
Mean gravity value observed along the network ties was the entity to be adjusted according to the adopted model

$$\Delta G_i = \Delta g_i + v_i \qquad (i = 1,2, \dots ,12) \qquad (1)$$

where ΔG_i represents an estimate of the gravity after the adjustment

Δg_i represents the observed gravity (before the adjustment)

v_i represents the correction to remove the observation error

Least square method in the variant of conditioned direct observations within a free network has been considered. As random errors affecting the observations have been considered to represent a normal repartition, the adjustment was made under the well–known constraint of minimization (2)

$$[pvv] = \sum_{i=1}^{12} p_i v_i^2 = V * PV \qquad (2)$$

where p_i represents the weight of the observation *i* (i = 1,2, … , 12)

P is the weight diagonal matrix ($P = [p_{ii}]$)

V is the corrections (v_i) vector ($V = [v_i]$)

V* represents its transposed matrix.

According to Wolf (1975) and Detrekoi (1991) the weights can be inferred from a simple equation

$$p_i = \frac{c^2}{m_{l_i}^2} \quad (i=1, 2, \ldots, 12) \qquad (3)$$

where c is the unit weight error, and m_{l_i} is the RMS error of the mean value of the observations along the tie **i**.

It has been previously demonstrated (Detrekoi, 1991) that **c** value can be estimated from

$$\bar{c}^2 = V^* PV/f \qquad (4)$$

where f is the number of conditional equations, and P is the weights diagonal matrix.

Four functional-stochastic models have been used during the network adjustment, based on different weighting systems:

a) equal accuracy observations, meaning

$$p_i = 1 \qquad (5)$$

b) weights related to the temperature variations during the measuring cycle,

$$Y_i = 0.06/\Delta t_i \qquad (6)$$

c) weights related to the eventual drift nonlinearities, depending on the length of the measuring loop

$$Z_i = 314/d_i \qquad (7)$$

and, finally,

d) weight as a function of the RMS error of the observations on each tie, meaning

$$X_i = (0.004)^2/m_{l_i}^2 \qquad (8)$$

The weight systems used for the network adjustment are shown in Table no.3.

Table 3 - Weighting systems used in the adjusting

weighting factor	RMS error of the gravity mean value (mgal)		temperature variations		duration of the measuring cycle	
gravity tie i	m_{l_i}	weight X_i	Δt_i (^0C)	weight Y_i	d_i (minutes)	weight Z_i
1	0.008	1/4	0.10	3/5	375	314/375
2	0.007	16/49	0.06	1	366	157/183
3	0.002	4	0.01	6	223	314/223
4	0.002	4	0.02	3	156	157/78
5	0.006	4/9	0.08	3/4	320	157/160
6	0.005	16/25	0.08	3/4	290	157/145
7	0.005	16/25	0.01	6	200	157/100
8	0.004	1	0.09	2/3	314	1
9	0.004	1	0.15	2/5	598	157/299
10	0.002	4	0.05	6/5	268	157/134
11	0.020	1/25	0.02	3	600	157/300
12	0.004	1	0.13	6/13	278	157/139
unit weight before the adjustment	0.004	1	0.06	1	314	1

Table no. 4 illustrates the conditional equations as inferred from the triangle closures.

Table no. 4 Conditional equations within the network adjustment

Network triangle	network tie	tie code i	observed gravity l_i (mgal)	RMS error $\pm m_{l_i}$ (mgal)	**Conditional equation**	**Tolerance threshold** (mgal)
I	Chisinau → Soroca	1	120.217	0.008	$-v_1+v_2+v_3+$ **0.002**=0	**0.0108**
	Chisinau → Balti	2	79.518	0.007		
	Balti → Soroca	3	40.701	0.002		
II	Chisinau → Balti	2	79.518	0.007	$-v_2+v_4+v_5-$ **0.0100**=0	**0.0094**
	Chisinau → Ungheni	5	34.236	0.006		
	Ungheni → Balti	4	45.272	0.002		
III	Chisinau → Leova	8	-16.068	0.004	$v_6+v_7-v_8+$ **0.0000** =0	**0.0081**
	Chisinau → Albita	6	13.969	0.005		
	Albita → Leova	7	-30.037	0.005		
IV	Chisinau → Cahul	9	-96.858	0.004	$-v_8+v_9+v_{10}+$ **0.0050**=0	**0.0060**
	Cahul → Leova	10	80.795	0.002		
	Chisinau → Leova	8	-16.068	0.004		
V	Chisinau → Cahul	9	-96.858	0.004	$-v_9+v_{11}+v_{12}-$ **0.0140**=0	**0.0208**
	Cahul → Causeni	11	-91.430	0.020		
	Chisinau → Causeni	12	-5.442	0.004		

The last column in Table 4 shows the tolerance threshold (Detrekoi, 1991). The appropriate quality of the gravity observations is emphasized by the fact that no closure is above the computed tolerance. The slight disagreement noticed in the case of triangle II is insignificant, and much below the instrument accuracy.
The matrix of the coefficients of the normal equations (N) will be

$$N = A^{*}P^{-1}A \tag{9}$$

where P^{-1} represents the inverse of the weight matrix.
The corrections vector has been obtained through the inverse matrix of the coefficients of the normal equations system (N^{-1})

$$V = - P^{-1}AN^{-1}T \tag{10}$$

where T is the closures vector.
The covariance matrix is defined by

$$Q = [q_{ij}] = P^{-1} - (P^{-1}A)\, N^{-1}(A^{*}P^{-1}) \qquad i, j = 1, 2 \ldots 12 \tag{11}$$

and unit weight after the adjustment

$$\bar{c} = (V^{*}PV / f)^{1/2} \tag{12}$$

where f is the number of equations used.

RMS error of the adjusted gravity on each tie was computed from the coefficients of the covariance matrix and the related unit weight

$$m_i = \bar{c}\ (q_{ii})^{1/2} \tag{13}$$

The coefficients of the equations and the results of the network adjustment for various stochastic models using different weighting systems are shown in Table 5.

Table 5 Conditional equations and adjustment variants for various weighting systems

Gravity tie	Conditional equations coefficients (equal weight)					adjustment values for various weighting systems			
i	I	II	III	IV	V	a	b	c	**d**
1	-1					-0.0005	-0.0011	-0.0012	**-0.0025**
2	1	-1				-0.0030	-0.0037	-0.0033	**-0.0046**
3	1					0.0005	0.0007	0.0001	**0.0002**
4		1				0.0035	0.0021	0.0013	**0.0005**
5		1				0.0035	0.0042	0.0054	**0.0048**
6			1			0.0000	-0.0001	-0.0005	**0.0009**
7			1			0.0000	-0.0001	-0.0001	**0.0009**
8			-1	-1		0.0001	-0.0002	-0.0005	**0.0017**
9				1	-1	-0.0048	-0.0054	-0.0061	**-0.0027**
10				1		-0.0001	0.0002	0.0006	**-0.0006**
11					1	0.0046	0.0059	0.0011	**0.0109**
12					1	0.0046	0.0027	0.0068	**0.0004**
t^*	0.002	-0.010	0	0.005	-0.014				
[pvv]						$9.9381.10^{-5}$	$8.1311.10^{-5}$	$7.9358.10^{-5}$	**$0.7613.10^{-5}$**
unit weight error			before adjustment			1.0000	314.0000	0.0600	**0.0040**
			after adjustment			0.0045	0.0040	0.0040	**0.0027**
| deviation |						0.9955	313.9960	0.0560	**0.0013**

where

a, equal weights

b, weighting according to the length of the measuring cycle

c, weighting according to the temperature deviation inside the meter

d, weighting according to the RMS error of the observations mean value

Among the four solutions of the network adjustment the best fit to the constraint

$$[pvv] = \min \qquad (14)$$

is reached for the variant "**d**" (weighting related to the RMS error of the mean gravity along the tie), which was somehow expected, as in this case the used weight cumulates the action of all error factors.

On the other hand, the worse fit was obtained in the case of the weight based on the length of the measuring cycle (variant "**b**"). This shows that LaCoste & Romberg gravity meter accuracy was practically not dependent on the drift factor.

Gravity ties considered after the network adjustment are presented in Table no. 6.

Table 6 Observed and adjusted gravity along the network ties

i	gravity tie	Δg_i (mgal)	v_i (mgal)	ΔG_i (mgal)	m_i (mgal)
1	Chisinau → Soroca	120.217	-0.0025	120.2145	± 0.0029
2	Chisinau → Balti	79.518	-0.0046	79.5134	± 0.0028
3	Balti → Soroca	40.701	0.0002	40.7012	± 0.0013
4	Ungheni → Balti	45.272	0.0005	45.2725	± 0.0013
5	Chisinau → Ungheni	34.236	0.0048	34.2408	± 0.0028
6	Chisinau → Albita	13.969	0.0009	13.9699	± 0.0026
7	Albita → Leova	-30.037	0.0009	-30.0361	± 0.0026
8	Chisinau → Leova	-16.068	0.0017	-16.0663	± 0.0018
9	Chisinau → Cahul	-96.858	-0.0027	-96.8607	± 0.0019
10	Cahul → Leova	80.795	-0.0006	80.7944	± 0.0013
11	Cahul → Causeni	-91.430	0.0109	-91.4191	± 0.0032
12	Chisinau → Causeni	-5.442	0.0004	-5.4416	± 0.0026

where
Δg_i represents the observed gravity along the tie *i*
v_i is the correction along the tie *i*
ΔG_i represents the adjusted gravity along the tie *i*
m_i is the RMS error after the adjustment

NETWORK DATUM

As previously mentioned, NGRNM datum was provided by connecting the Moldovan network to the national gravity reference networks of Romania (Besutiu et al, 1994). To avoid long measuring cycles when crossing the state border checking points, the transfer operation was planned and executed in two steps.
During **the first step**, the transfer station Albita, located in the cross-border area, was tied to the national gravity reference network of Romania. To monitor the quality of the determinations a triangle system was used (Fig. 3). Two base stations (conventionally called station N and station S) were used to transfer the absolute gravity value into the cross-border area. Table no. 7 summarizes the results of these determinations.

Table no. 7 Gravity ties between Albita and the Romanian gravity reference networks

Base station code	Absolute gravity (mgals)	Gravity tie to Albita (mgals)	Gravity transferred (mgals)
Station N	980735.45 ± 0.046	46.050 ± 0.030	980781.500 ± 0.060
Station S	980749.83 ± 0.050	31.669 ± 0.030	980781.499 ± 0.060

Triangle closure (0.001 mgals) was far below the instrumental accuracy, advocating for the high quality of the gravity transfer.
Thereafter, the average absolute gravity value transferred to the Albita station was considered 980780.500 ± 0.060 mgals.

The second step in the datum transfer consisted in gravity ties between the base station Albita and the central base station of the NGRNM, Chisinau. A similar triangle system was used on purpose, by linking the Romanian Albita transfer station to both Chisinau and Leova NGRNM base stations (see Fig. 2). This

absolute gravity transfer triangle was then integrated into the stochastic model for NGRNM adjustment, and observed values accordingly corrected. Finally, the absolute gravity assigned to the central station of the NGRNM, Chisinau, was equal to 980767.530 mgals.
Following this operation, absolute gravity values were transferred to each base station of the NGRNM through the adjusted gravity ties connecting them to the central station. The results are summarized in table no. 8.

Table no. 8 Absolute gravity values and the vertical gradient of the gravity within the base stations of NGRNM

Station code	Geographical co-ordinates		Absolute gravity (mgals)		Vertical gradient (mgals/m)	
	latitude	longitude	Mean value	rms	Mean value	rms
CHISINAU*	46º 59’ 52.0”	28º 40’ 05.0”	980767.530	±0.067	-0.279	±0.007
BALTI	47º 45’ 40.0”	27º 56’ 00.0”	980847.043	±0.067	-0.282	±0.003
CAHUL*	45º 54’ 18.8”	28º 12’ 02.4”	980670.669	±0.067	-0.295	±0.006
CAUSENI	46º 38’ 15.0”	29º 24’ 30.0”	980762.088	±0.067	-0.294	±0.007
LEOVA*	46º 28’ 24.6”	28º 14’ 53.3”	980751.467	±0.067	-0.323	±0.006
SOROCA*	48º 07’ 53.5”	28º 20’ 31.0”	980887.745	±0.067	-0.284	±0.008
UNGHENI	47º 12’ 00.0”	27º 48’ 00.0”	980801.771	±0.067	-0.309	±0.005

***** located on the pillars of the National Seismic Monitoring Network

It should be mentioned that absolute gravity values in the table refer to the relative height of 0.30 meters above the ground. Vertical gradient values, valid between 0.30 m and 0.80 m (Besutiu et al, 2001b), are also added to allow eventual gravity transfers from NGRNM to other locations according to the height of the tripod of the meter used.

FINAL REMARKS

The new national gravity reference network of Republic of Moldova was achieved as a triangle network with central base station located in the capital of the country. Gravity measurements along its ties were performed by using the high accuracy LaCoste and Romberg D-214 meter owned by the Geological Institute of Romania. The obtained accuracy was fully within the instrumental range. Starting from the triangle closures, the network was adjusted by using least square method for several weighting systems. Among them, the best result was obtained when referring to the standard deviation of the mean gravity values along the ties.
NGRNM datum was provided by transferring absolute gravity from the Romanian gravity reference network to its central base station.
It is expected that provisional absolute gravity values, as provided in the table no. 8, would be slightly altered after re-adjusting the Romanian national gravity reference networks by constraining them on the UNIGRACE absolute base stations. However, mention should be made to the fact that comparisons between the actual Romanian gravity system, and the gravity standard of the Central and Western Europe, showed an excellent scale factor and small differences only in the network datum (Besutiu et al, 2001a). Therefore, it is likely that the gravity system of Republic of Moldova would be easily integrated into the EU gravity standard.

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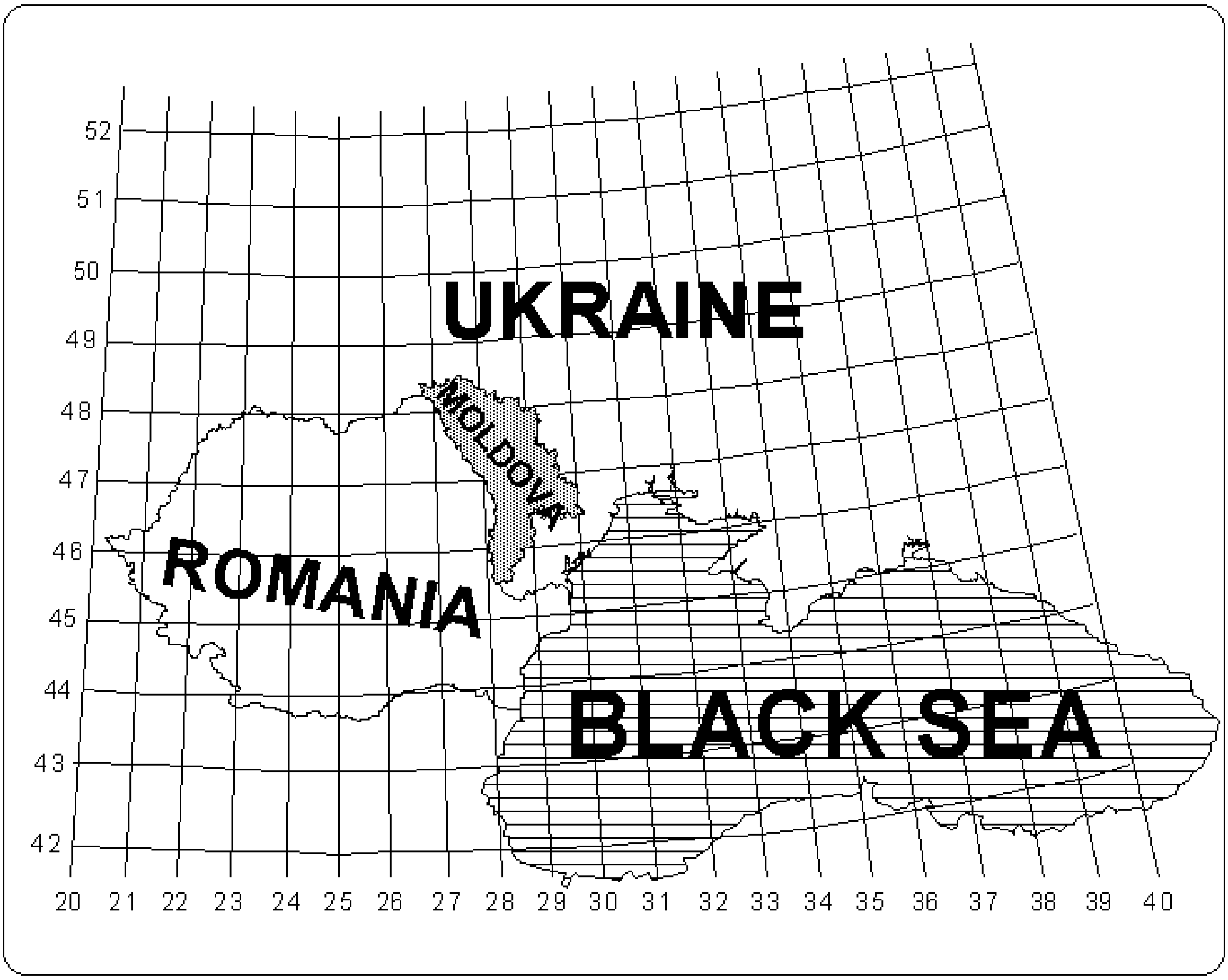

Fig. 1 Location of the study area

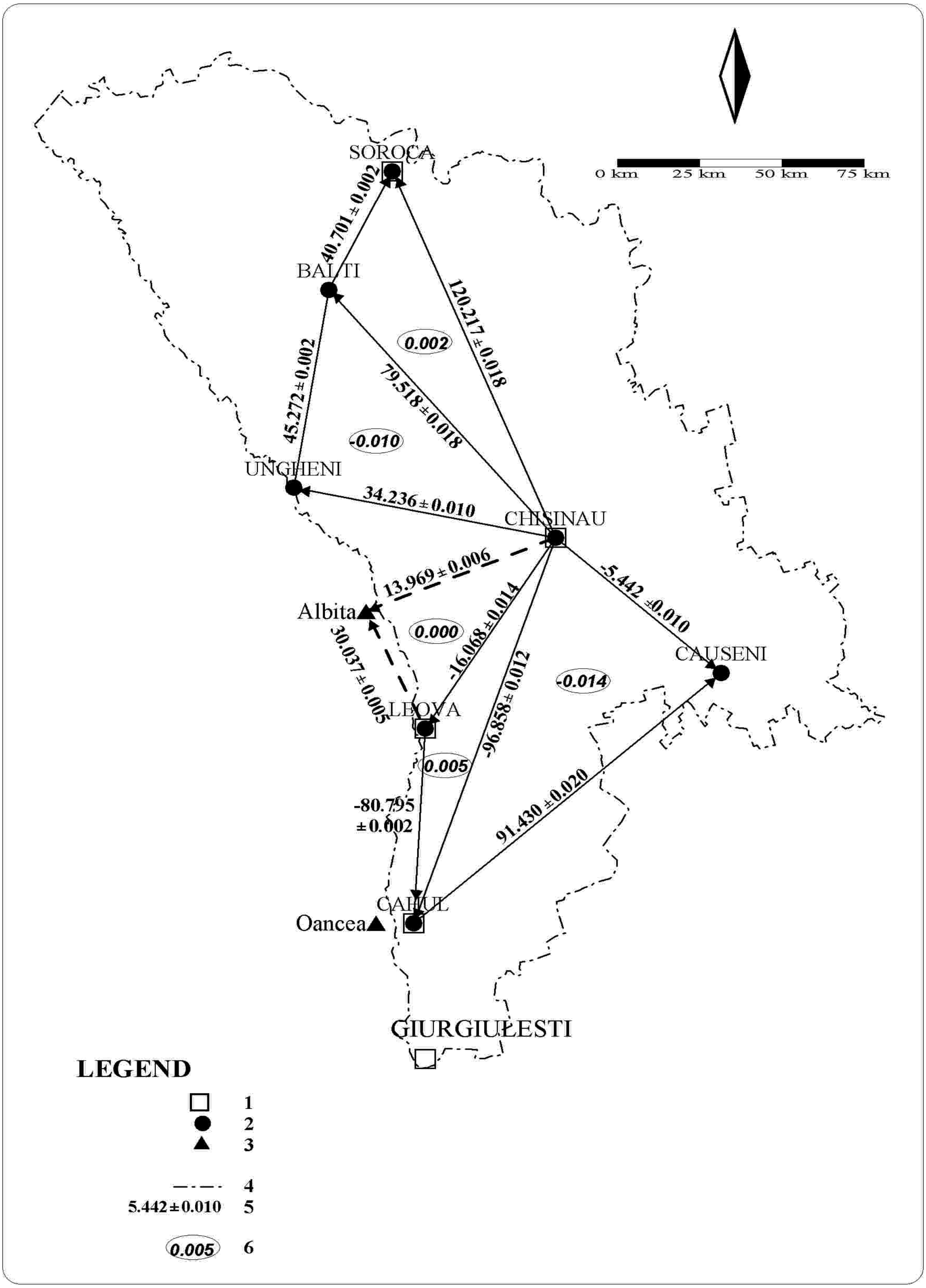

Fig. 2 Gravity variations along the ties of the Moldovan gravity reference network and triangle closures

1, seismic monitoring base stations; 2, gravity reference network base stations; 3, Romanian base station for the gravity datum transfer; 4, state border; 5, gravity range (in mgals); 6, triangle closure (in mgals)

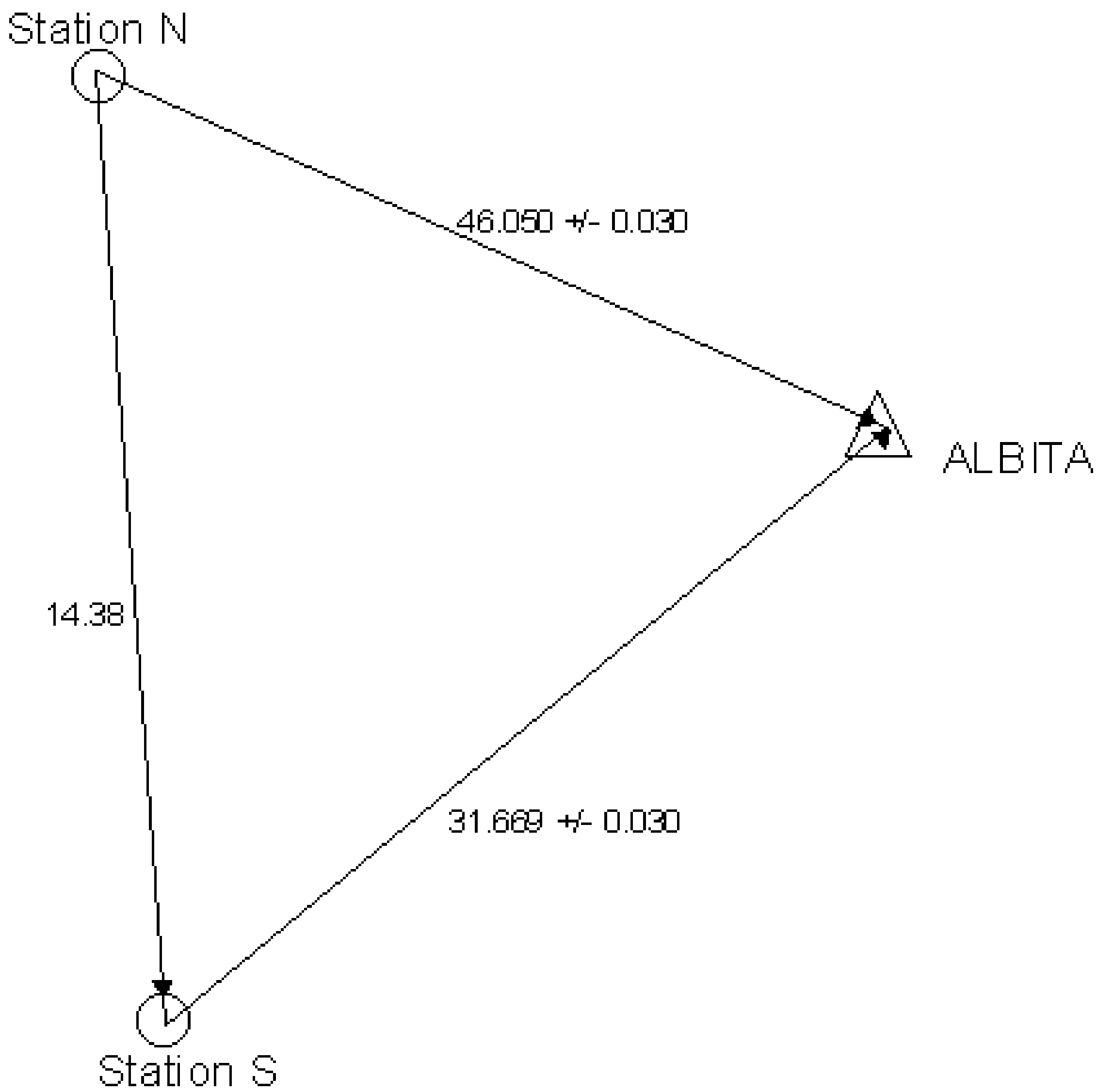

Fig. 3 The design of the network for the gravity datum transfer from the Romanian gravity reference networks to border area