Detection of erroneous values in the measurement of local geodetic networks

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For processing the results of local geodetic network (LGN) measurement with possible erroneous values and coordinates: d (slope distances between the points), ω (horizontal angles), z (zenith distances). $C_{DB} = [X, Y]_{DB}$ (coordinates of the datum points), $C^0_{UB} = [X^0, Y^0]_{UB}$ (coordinates of approximately determined points) and detecting the errors it is appropriate to use a technique that will be further demonstrated in a real situation of the trilateration LGN (fig. 1) with a massive contamination of the simulated errors in the measured elements and numerically determined values.

Key words: *Local Geodetic Network, Method of least squares, robust adjustment, weight iteration adjustment*

Introduction

LGN are most often established in a specific space according to the necessity and utility in relationship to the existing geodetic surface, as well as independent networks forming highly accurate local geodetic control in the respective area. On the territory of the Slovak Republic (SR), LGN are generally formed either in S-JTSK system (national reference coordinates system), local purpose-built systems or in ETRS-89 system according to the measurement technology and methods used.

LGN established in S-JTSK are most often formed using the existing national surface to which further points are added based on the requirements and purpose of the LGN in such a way that the properties of LGN that consist of the national network points and currently established new points are compatible (Sütti et al., 2000; Weiss et al., 2004; Weiss et al., 2005).

LGN formed in this way most often constitute part of S-JTSK system, though often it is also built as an independent network with a suitable 2D coordinate system.

As a rule, while establishing LGN the points taken over from the national networks into LGN have to be unconditionally verified in terms of appropriate compatibility, newly established points have to be measured and expressed in coordinates (with approximate coordinates $C^0 = [X^0, Y^0]$) in the local coordinate system used as well as connecting elements (lengths, horizontal and vertical angles,..) of the established new points have to be determined with the required accuracy.

It is obvious that while measuring minor control points of the LGN it might happen, as it frequently does, that some of the geometric points in the LGN structure are erroneously measured and as a result of that some of the values measured and approximate coordinates C^0 of the newly established points are erroneously determined: determined points (UB) which then have unrealistic coordinate positions.

Adjustment of LGN

Adjustment is carried out according to the following procedure: adjustment by Least Square Method (LSM) GMM (Gauss-Markov model) of the proxy measurement with full rank of matrix N and couplings (fixed adjustment). Input and the most important output matrices and values obtained from the estimation process are given.

S-JTSK coordinates (reduced) C_{DB}, of compatible DB as shown in tab. 1.

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Tab. 1. Coordinates C_{DB} v S-JTSK.

DB	X [m]	Y [m]
1	9 001,123	4 506,299
2	9 502,490	2 798,622
3	9 894,233	3 803,973
8	9 413,376	4 904,569

Approximate coordinate values C_{UB}^0, of the determined (new) points UB in the LGN (C_{UB}^0 determined from measured values and coordinates C_{DB}, C_{UB}^0) are given in tab. 2.

Tab. 2. Approximate coordinate values C_{UB}^0 v S-JTSK.

UB	X^0 [m]	Y^0 [m]
4	9 100,838	3 299,980
5	9 400,545	3 697,824
6	9 775,900	3 080,370
7	9 842,503	4 393,265
9	9 546,226	4 251,061

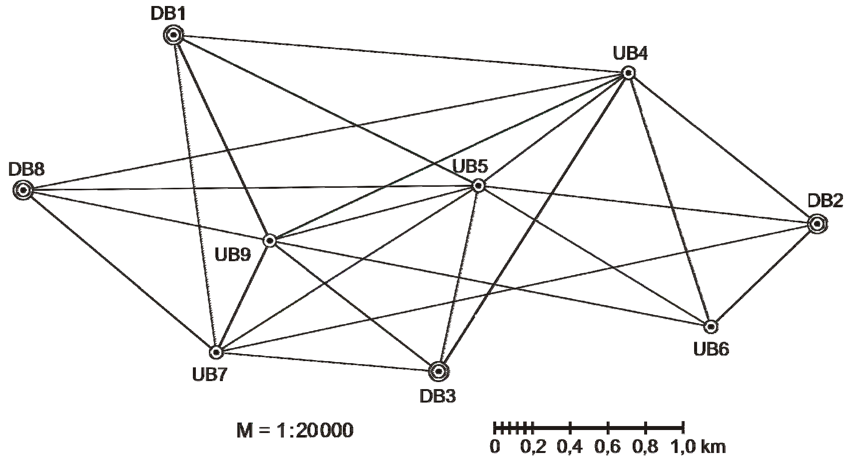

Fig. 1. Positioning trilateration network (LGN).

Cofactors q_i of the above-mentioned values L_i z distance vectors $\underset{(n,1)}{L}$ in LGN. Cofactors are determined according to:

$$q_{Li} = \frac{s_{Li}^2}{\sigma_{Li}^2},$$

where: s_{Li} is the a posteriori standard deviation of the measured distance L_i determined by multiple measurements of the distance L_i,

σ_{Li} for the distance L_i the a priori standard deviation is defined by the equation $\sigma_{Li} = 3mm + d[km] \cdot 10^{-6}\,mm$ presented by the producer of the distance meter.

Cofactors q_{Li} form a cofactor matrix Q_L with the values q_{Li} on its diagonal:

$$\underset{(1,24)}{Q_L} = [1{,}7\ \ 0{,}6\ \ 1{,}3\ \ 1{,}2\ \ 0{,}8\ \ 1{,}1\ \ 0{,}8\ \ 0{,}8\ \ 1{,}0\ \ 1{,}3\ \ 1{,}6\ \ 1{,}4\ \ 1{,}1\ \ 0{,}8\ \ 1{,}2\ \ 1{,}3\ \ 0{,}6\ \ 1{,}6\ \ 1{,}3\ \ 0{,}7\ \ 0{,}7\ \ 1{,}7\ \ 1{,}6\ \ 0{,}9].$$

From the application of a LSM adjustment algorithm the adjusted estimates of the coordinates $\hat{C}_{UB}$ in the LGN are determined according to:

$$\hat{C}_{UB} = C_{UB}^0 + d\hat{C}_{UB},$$

where C^0_{UB} are approximate values of point coordinates of the UB and for $d\hat{C}$ the following applies (Bill, 1984; Grafarend et al., 1993; Pelzer, 1980, 1985; Wolf, 1997; Jäger et al., 2005):

$$d\hat{C} = G \cdot dL .$$

Vector $d\hat{C}$ is formed by the matrices:

$$G = (A^T Q_L^{-1} A)^{-1} A^T Q_L^{-1},$$

where A is configuration matrix of the LGN characterizing the LGN structure, distribution of its points and Q_L is a cofactor matrix of the measured values L in the LGN,

$$dL = L - L^0,$$

where L is a vector of measured values (i.e. measured values of distances in LGN) and L^0 is a vector of approximate values of these values (i.e. distances calculated from the coordinates).

In the LGN in question, the following values are determined for the measured distances L_i and for their approximate values $L_i^0 = f(C_{DB}, C^0_{UB})$, as well as for their differences $dL_i = L_i - L_i^0$:

Tab. 3. Measured distances L, approximate distance values $L_i^0 = f(C_{DB}, C^0_{UB})$ and their differences dL .

	d	**L [m]**	**L⁰ [m]**	**dL [m]**
1	4–6	709,927	709,8854	0,0416
2	2–6	392,550	,6003	-0,0503
3	2–4	642,409	,4050	0,0040
4	3–4	939,941	,9386	0,0024
5	3–9	566,555	,5656	-0,0106*
6	4–9	1050,204	,2026	0,0014
7	1–4	1210,478	,4332	0,0448
8	1–5	901,755	,7593	-0,0043
9	5–8	1206,806	,8132	-0,0072
10	4–8	1634,747	,7434	0,0036
11	4–5	498,107	,1005	0,0065
12	2–5	904,962	,9624	-0,0004
13	2–7	1630,454	,4892	-0,0352
14	1–7	849,005	,9387	0,0663
15	1–9	601,906	,9001	0,0059
16	8–9	666,874	,8747	-0,0007
17	7–8	667,595	,5191	0,0759
18	5–7	823,990	,9934	0,0069
19	5–6	722,631	,5931	0,0379
20	6–9	1193,036	,0078	0,0282
21	5–9	572,094	,0963	-0,0023
22	3–5	504,968	,9707	-0,0027
23	3–7	591,506	,5582	-0,0522
24	7–9	328,667	328,6366	0,0304

* dL up to ± 10 mm are normally not included in the analysis.

Estimates of coordinate compliments $d\hat{C}_{UB} = [d\hat{X} \;\; d\hat{Y}]_{\mathrm{UB}}$ from the adjustment (to the approximate coordinate values) C^0_{UB4}, C^0_{UB5}, C^0_{UB6}, C^0_{UB7}, C^0_{UB9} :

Tab. 4. Estimates of coordinate compliments $d\hat{C}_{UB} = [d\hat{X} \;\; d\hat{Y}]_{\mathrm{UB}}$.

Point	**$d\hat{X}$ [m]**	**$d\hat{Y}$ [m]**
4	-0,0088	0,0156
5	-0,0054	0,0015
6	-0,0050	0,0517
7	0,0589	0,0489
9	0,0038	0,0114

Estimates of coordinates $\hat{C}_{UB} = C^0_{UB} + d\hat{C}_{UB}$ and their standard deviations $s_{\hat{X}}, s_{\hat{Y}}$:

Tab. 5. Estimates of coordinates and their standard deviations.

Point	$\hat{X}$ [m] ± $s_{\hat{X}}$ [mm]	$\hat{Y}$ [m] ± $s_{\hat{Y}}$ [mm]
4	9100,829 ± 11,1	3299,996 ± 7,5
5	9400,540 ± 12,1	3697,826 ± 6,7
6	9775,895 ± 12,1	3080,422 ± 9,4
7	9842,562 ± 8,9	4393,314 ± 8,3
9	9546,230 ± 10,2	4251,072 ± 7,3

Quadratic form of residuals: $kf(V) = 2659{,}8$.

The a priori standard deviation of measurements: $s_0 = 13{,}8mm$.

Residuals $V[mm] = Ad\hat{C}_{UB} - dL$:

Tab. 6. Residuals of individual measured distances.

d	4–6	2–6	2–4	3–4	3–9	4–9	1–4	1–5	5–8	4–8	4–5	2–5
V	-26,9	9,7	-10,7	13,4	-0,7	7,7	-30,0	3,3	8,8	13,4	6,8	-0,5
d	2–7	1–7	1–9	8–9	7–8	5–7	5–6	6–9	5–9	3–5	3–7	7–9
V	-0,3	-1,4	2,3	12,6	-0,6	-2,1	5,1	9,7	-4,9	8,3	2,7	9,7

Estimates (adjusted values) $\hat{L} = L + V$ $[m]$ of the measured distances, their standard deviations:

Tab. 7. Estimates of the measured distances and their standard deviations.

d	$\hat{L}$ [m]	$s_{\hat{L}}$ [mm]	*d*	$\hat{L}$ [m]	$s_{\hat{L}}$ [mm]
4–6	709,900	13,3	**2–7**	1630,454	8,6
2–6	392,560	10,0	**1–7**	849,004	8,7
2–4	642,398	9,8	**1–9**	601,908	9,1
3–4	939,954	9,6	**8–9**	666,887	7,0
3–9	566,554	7,6	**7–8**	667,594	7,8
4–9	1050,212	9,4	**5–7**	823,988	10,3
1–4	1210,448	7,7	**5–6**	722,636	11,2
1–5	901,758	7,9	**6–9**	1193,046	9,5
5–8	1206,815	6,7	**5–9**	572,089	8,0
4–8	1634,760	7,3	**3–5**	504,976	12,0
4–5	498,114	10,2	**3–7**	591,504	8,1
2–5	904,961	6,7	**7–9**	328,670	10,2

From the outputs of the partial results of adjustment it clearly follows that different values – results of adjustments are unacceptable because of distorting unrealistic high values of practically all the parameters of the given LGN due to the presence of various errors in the network elements.

We assume, based on this situation, that though methodology of processing the LGN is correct (dependable programs), some values obtained when determining C^0_{UB} and measurements of geometric elements connecting the network points are erroneous.

Causal analysis of erroneous results from the adjustment

From the results of adjustment with unacceptable values it is possible and necessary to identify a variety of errors in the network measurement and their presence in the estimates of individual output values. Their presence – the errors can be identified using the analysis of outputs from the adjustment and eliminate by replacing the respective erroneous values by accurate values, i.e. obtain realistic values for all the output values from the adjusted LGN.

As it follows from partial calculations of values (dL, $d\hat{C}$, $\hat{C}$, $s_{\hat{C}}$, V, $kf(V)$, s_0, $\hat{L}$, $s_{\hat{L}}$, ...), as well as from further parameters of LGN such as indicators of internal and external reliability of the LGN, distribution of positional accuracy of points on the territory of LGN, etc., the network examined has the following realistic erroneous positions and properties:

- vector $dL = L - L^0$ showed 10 significantly erroneous values dL in the distances : 4–1, 6–2, 6–4, 6–5, 6–9, 7–1, 7–2, 7–3, 7–8, 7–9, which were generated either due to errors in the respective measurements or as a result of erroneous approximate coordinates C^0_4, C^0_6, C^0_7 of the points UB4, UB6 and UB7.

Vector dL is therefore a carrier of influence (apart from the correct values dL) as well as 10 erroneous elements (distances) dL in the structure of LGN which are locally connected do 3 points of the network: 4, 6, 7. Distribution of 10 erroneous distances in the LGN which form erroneous coordinate positions of 3 UB points (UB4, UB6, UB7), is shown in fig. 2,

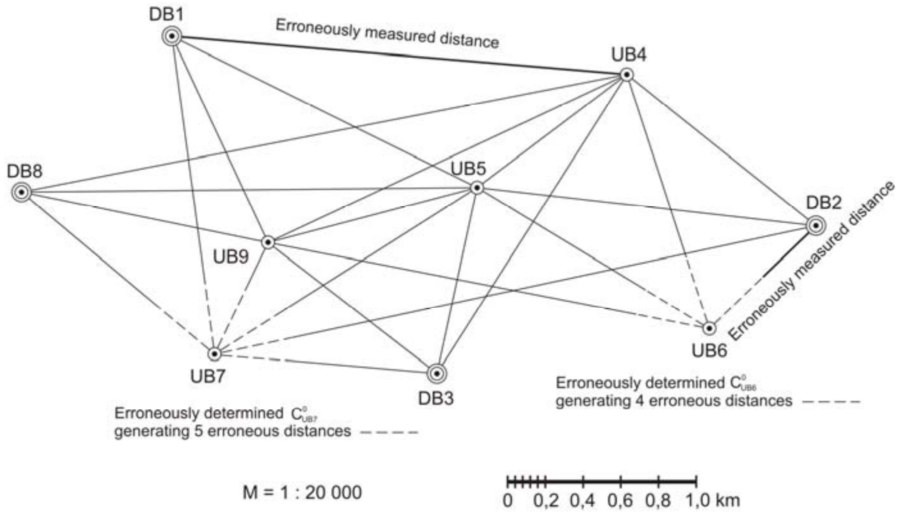

Fig. 2. Contamination of LGN with errors in coordinates and distances.

- numerical values of coordinate cofactors $d\hat{C}_{UB}$ indicate that the most distorting effect on C_{UB} is created by UB6, UB7 as well as partially by UB4, UB9 , the positions of which are according to the analysis of values dL are strongly influenced by the erroneous distances and coordinates of the points UB4, UB6, UB7.

  If in the LGN there were no erroneously determined elements d, C^0_{UB}, all the $d\hat{C}_{UB}$ would create non-zero numeric values only in mm area or lower.

- significantly high values $s_{\hat{X}}, s_{\hat{Y}}$ (higher than 6–7 mm) also give evidence of an acceptable value structure of the adjusted LGN with its coordinate properties,
- the set of high values V_i in the vector of residuals $V = Ad\hat{C} - dL$ indicates strong contamination of the vector of residuals V, generated by the values $d\hat{C}$ and dL,
- heavy contamination of V vector by high values of the elements V_i , result in high numerical values also for the quadratic form of residuals $kf(V)$ and the a posteriori standard deviation s_0 characterizing the accuracy of measurements,
- estimates $\hat{L} = L + V$ are also erroneous and unacceptable due to deviation of values V_i of the V vector.

Identification and elimination of errors in the LGN

In every even deemed trilateration LGN network two sources (types) of errors can be present:

- errors in the measurement of distances between LGN points,
- errors in determining C^0 for some measured UB points as a result of erroneous respective distance and angle measurements.

That is why in the analysis of the errors measured and calculations of the determined values it is necessary to identify:

- which distances are wrongly measured, i.e. with high differences dL (tab. 3),
- which UB are determined with erroneous coordinates (C^0), i.e. with deviated $d\hat{C}_{UB}$ a $\hat{C}_{UB}$ values (tab. 4, tab. 5),

as in the given situation of the trilateration network only these 2 sources and types of errors influenced and contaminated all the outputs from the LGN adjustment.

Thus, in the given case different significant values of the respective "reduced distances" dL (tab. 3) appertain to all the measured distances knotted in the point UB6. That way the state is expressed and described where coordinates of the point UB6 were erroneously measured, therefore a significant positional error was made in determining C^0_{UB6} which generated output of erroneous approximate coordinates $[X^0\ Y^0]_{UB6}$.

Equally it also applies for the measurement of distances which are relative to the point UB7. This situation also indicates that the coordinates of the point UB7 were not correctly determined and therefore the point UB7 was assigned erroneous approximate coordinates $[X^0\ Y^0]_{UB7}$ in the context of the LGN measurement. The situation is not affected by the fact that the distance between UB7-UB5 (tab. 3) has no significant error.

From the analysis it appeared that unacceptable results of the LGN adjustment were due to the following reasons:

- measured distances d_{14}, d_{26} with mistakes which show significant dL values (tab. 3),
- erroneously determined approximate coordinates C^0 of the points UB6 and UB7 which generated 4 mistakes in the respective distances relative to the point UB6 as well as 5 errors in the distances relative to the point UB7 (fig. 2) which all have deviated dL values (tab. 3).

Correction of erroneous measurements and calculations in LGN

When unacceptable results from the adjustment for the $d\hat{C}$, $\hat{C}$, $s_{\hat{C}}$, V and other values are obtained, it is necessary to perform new correct measurements of the values for the calculations of the correct approximate coordinates C^0_{UB6}, C^0_{UB7} and d_{14}, d_{26} values to determine correct values of these distances.

In this specific case on the basis of the analysis of input and output values of the respective calculations as well as identification of erroneous geometric elements in the LGN structure, "the correct values" of the d_{41}, d_{26} distances (tab. 8) and "correct values" of the C^0_{UB6}, C^0_{UB7} coordinates of the UB6 and UB7 points (tab. 9) were determined.

Tab. 8. Erroneous and correct values of distances.

d	**DB1–UB4** [m]	***d***	**DB2–UB6** [m]
d_{14}	1210,478	d_{26}	392,550
cor d_{14}	1210,425	*cor* d_{26}	392,594
dif	-0,053	***dif***	0,044

Tab. 9. Erroneous and correct values of approximate coordinates.

Point	X^0 **[m]**	Y^0 **[m]**	
UB6	9775,900	3080,370	erroneous
***cor* UB6**	9775,926	3080,333	newly determined correct
dif	0,026	-0,037	difference
UB7	9842,561	4393,216	erroneous
***cor* UB7**	9842,503	4393,265	newly determined correct
dif	-0,058	0,049	difference

On the basis of the exchange (replacement) of the erroneous coordinates C^0_{UB6}, C^0_{UB7} as well as erroneous distances d_{41}, d_{26} from the initial measurements for the corresponding correct realistic values $cor\ C^0_{UB6}$, $cor\ C^0_{UB7}$, $cor\ d_{14}$, $cor\ d_{26}$, determined by the analysis, a new adjustment of the LGN was carried out and the following LGN values of the elements were obtained:

Matrix dL [m] :

dL = [0,0054 0,0022 0,0040 0,0024 -0,0106 0,0014 -0,0082 -0,0043 -0,0072 0,0036 0,0065 -0,0004
(24,1) 0,0006 0,0022 0,0059 -0,0007 0,0011 0,0069 -0,0072 -0,0131 -0,0023 -0,0027 0,0017 -0,0007].

Estimates of coordinate compliments $d\hat{C}_{UB} = [d\hat{X} \;\; d\hat{Y}]_{UB}$ from the new adjustment:

Tab. 10. Estimates of coordinate compliments from the new adjustment:

Point	$d\hat{X}$ [m]	$d\hat{Y}$ [m]
UB4	-0,0078	-0,0034
UB5	-0,0001	-0,0032
UB6	-0,0038	-0,0081
UB7	0,0044	-0,0026
UB9	0,0083	0,0022

Estimates of coordinates $\hat{C}_{UB} = C^0_{UB} + d\hat{C}_{UB}$, standard deviations $s_{\hat{X}}, s_{\hat{Y}}$ of coordinate estimates:

Tab. 11. Estimates of coordinates and their standard deviations.

Point	$\hat{X}$ [m] ± $s_{\hat{X}}$ [mm]	$\hat{Y}$ [m] ± $s_{\hat{Y}}$ [mm]
UB4	9100,830 ± 2,8	3299,979 ± 1,9
UB5	9400,545 ± 3,1	3697,821 ± 1,7
UB6	9775,922 ± 3,1	3080,325 ± 2,4
UB7	9842,565 ± 2,3	4393,213 ± 2,1
UB9	9546,234 ± 2,6	4251,063 ± 1,9

Residuals $V[mm] = Ad\hat{C}_{UB} - dL$:

Tab. 12. Residuals of individual measured distances.

d	4–6	2–6	2–4	3–4	3–9	4–9	1–4	1–5	5–8	4–8	4–5	2–5
V	-3,0	1,0	3,5	2,4	3,8	0,4	4,2	1,4	4,0	-5,4	-2,0	3,6
d	2–7	1–7	1–9	8–9	7–8	5–7	5–6	6–9	5–9	3–5	3–7	7–9
V	2,9	1,8	2,5	4,5	-0,3	-5,0	1,1	0,7	-0,8	2,2	0,6	-0,7

A priori standard deviation from measurement is: $s_0 = 3{,}5\ mm$ as well as further output values from the adjustment with acceptable values.

On the basis of numerical values of individual output values and matrices as well as their elements it appears that initial measurement of the LGN with the correction of the erroneous measurements performed $(d_{41},\ d_{26},\ C^0_{UB6},\ C^0_{UB7})$ is satisfactory, good quality and suitable for various geodetic tasks and solutions.

Verification of the acceptability of adjustment results after correction

The results of adjustment expressed by the respective values $dL,\ d\hat{C},\ \hat{C},\ V, \ldots$ can be assessed either visually, based on experience and logical evaluation, e.g. the values $dL,\ V, \ldots$ (must be minimum) or the resulting values can be assessed and evaluated on the basis of statistical verification of their significance using appropriate statistical tests, e.g. for the values $V,\ s_0,\ (n-u)\,s_0^2/\sigma_0^2,\ dL, \ldots$ and others.

For the groups of the adjustment output values, even with acceptable visual evaluation of the results, the a posteriori variance factor test $s_0^2 = kf(V)/(n-u);\ H_0 : \sigma_0^2 = E(s_0^2)$ is used for a comprehensive mathematical assessment (Böhm, 1990; Caspary, 1988; Mikhail, 1979; Bill, 1984; Koch, 1988).

The test verifies the correctness of the mathematical model of the estimates and compatibility of observations, i.e. identifies the presence of observations with unacceptable errors in the model:

$$\hat{C} = C^0 + (A^T Q_L^{-1} A)^{-1} A^T Q_L^{-1} (L - L^0),$$

inappropriate volumes of the sets of measurements, the presence of deviated measurements and other inference states and conditions or situations between components of the model.

The appropriateness of the model for determination of the resulting output parameters by LSM is generally assessed using the test of null hypothesis $H_0 : \sigma_0^2 = E(s_0^2)$ (against the alternative hypothesis $H_A : \sigma_0^2 \neq E(s_0^2)$) at the appropriate significance level α. Test statistics T (with $\chi^2 -$ distribution) is as follows:

$$T = \frac{(n-u)s_0^2}{\sigma_0^2} \sim \chi^2(n-u),$$

where s_0^2 is a posteriori variance factor, σ_0^2 is a priori variance factor, n is number of the values measured, u is number of the determined parameters.

If $T < T_\alpha$, H_0 is not rejected, the test doesn't indicate differences between observations L and the mathematical model, i.e. the values of V_i residuals are not deviated. If $T > T_\alpha$, H_0 with α risk is rejected.

Testing of V_i residuals from the vector $V = Ad\hat{C} - dL$, is generally carried out along with the test of the model which can be performed in a number of ways (Heck, 1981; Baarda, 1968, 1976; Pope, 1978; Krüger, 1980; Vaníček, Krakiwsky, 1986; Ethrog, 1991 and others).

Deviating values V_i in the vector V indicate that they are contaminated with various types and magnitude of errors which have to be corrected (as a rule measures the values in question again).

In assessing the acceptability as well as other results of the adjustment of the LGN after correction it is useful to verify both interior and exterior reliability of the adjusted network.

The vector ∇_L of the limit value errors ∇_{Li}, containing the elements:

$$\nabla_{Li} = \frac{s_{Li}}{\sqrt{r_i}}\delta_0, \ i = 1,2,...,n,$$

is appropriate to be used for assessment of the interior reliability of the network, (where r_i are observation redundancies characterizing the quality of the network geometry and δ_0 is the significance parameter), from which major errors ("gross") can be identified, minor errors are not detectable. The lower are ∇_{Li} in the network, the higher the interior reliability of the network is.

Exterior reliability of the network is characterized by the matrix:

$$\nabla_{\hat{C}_{UB}} = N^{-1}A^T Q_L^{-1} diag(\nabla_L),$$

expressing the influence of ∇_L vector on coordinate estimates $\hat{C}$ of the determining points UB in the network. $\nabla_{\hat{C}_{UB}}$ is graphically represented by vectors giving the size and direction of undetectable errors in the values L_i in each point UB.

Conclusion

Building LGN by terrestrial means, it can be expected that while measuring the network there occur various errors, most often in the determination (measurement) of some distances, horizontal angles and in the erroneous measurement of the determined new points UB in the LGN, therefore in their determination with erroneous approximate coordinates.

Possible errors appear and affect calculations of partial results of the adjustment, so the estimating process doesn't show acceptable results. The technique of detecting errors that affect the resulting values and the ways of obtaining correct acceptable results is described in this paper.

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