IMPACTS OF MEASURING AND NUMERICAL ERRORS IN LSM ADJUSTMENT OF LOCAL GEODETIC NETWORK

VPLYVY MERAČSKÝCH A VÝPOČTOVÝCH CHÝB V MNŠ VYROVNANÍ LOKÁLNEJ GEODETICKEJ SIETE

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Abstract

The Local Geodetic Network (LGN) adjustment is affected by various errors, whether arisen from measuring or calculating works. The measuring errors occurred in the consistent LGS measuring can be detected by control calculations in dL using redundant measurements. The numerical errors may be detected, or the accuracy of the formulas used can be verified by control calculations in a configuration matrix A and control relations, which should show zero values.

Abstract

Na vyrovnanie lokálnej geodetickej siete (LGS) vplývajú rôzne chyby, ktoré vznikli či už pri meracích alebo počtárskych prácach. Meračské chyby vzniknuté pri dôslednom zameraní LGS sa dajú odhaliť kontrolnými výpočtami v dL pomocou nadbytočných meraní. Výpočtové chyby sa môžu odhaliť, resp. overiť správnosť použitých vzorcov pomocou kontrolných výpočtov v konfiguračnej matici A a kontrolných vzťahov, ktoré by mali vykazovať nulové hodnoty.

Key words: LGN, LSM, measuring and numerical errors.

1 INTRODUCTION

While measuring geometrical quantities needed for various calculations to determine the parameters and characteristics of a LGN, it is impossible to achieve, or ensure always error-free quality and reliability of performances and results. Is it realistic to expect, even when safeguarding carefully the measuring and processing activities, that some of the elements being measured can be for various reasons measured erroneously and then by miscalculations also the results, i.e. the correctness of the entire adjustment, affected.

Coordinate estimates of new established datum points (DB) in a LGN are a function of the joint impact of several different (by content and structure) matrices, containing both the given quantities (DB coordinates) and also the values of measured quantities with their quality assessment (cofactors) as well as the effects of the geometric structure of the generated LGN to its different resulting parameters.

It is therefore necessary to highlight the effect of individual argument matrices in the structure and values of the developed matrix $\hat{C}_{UB}$ even in a general view and the dependence of its properties on the impact of the matrices C^0_{UB} as well as $L,\ L^0,$ or $dL = L - L^0$ and Q_L.

2 THE EFFECT OF ERRORS ON THE LGN DEVELOPMENT

Let us consider a LGN, whose point field is created by:

- verified (compatible) points of the state point field used for the LGN as datum points (DB) with fixed coordinates in the state system,
- points "new", formed under the LGN purpose, i.e. determined points (UB), complementing the DB to the overall needful point field for the LGN.

In thus created LGN its necessary characteristics and properties are determined by the LGN adjustment (a bound LSM adjustment is assumed), from where we get the coordinate estimates $\hat{C}_{UB}$ by:

$$\hat{C}_{UB} = \begin{bmatrix} \hat{X}_{UB1} \\ \hat{Y}_{UB1} \\ \\ \hat{X}_{UBp} \\ \hat{Y}_{UBp} \end{bmatrix} = C^0_{UB} + (A^T Q_L^{-1} A)^{-1} A^T Q_L^{-1} \cdot dL = \qquad (1)$$

$$= C^0_{UB} + N^{-1} A^T Q_L^{-1} (L - L^0) =$$

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

As resulting from (1), the coordinates $\hat{C}_{UB}$ are formed by the prescribed interactive effect of matrices:

$\underset{(n,2u)}{A}$ configuration matrix of a complete LGN, where p is a number of UB,

$\underset{(n,1)}{L}$ vector of measurands in the LGN (lengths, horizontal and vertical angles and other quantities),

$\underset{(n,1)}{L^0}$ approximate values of quantities in the LGN from calculations, (2)

$\underset{(n,n)}{Q_L}$ cofactor vector matrix L,

$\underset{(p,2)}{C^0_{UB}}$ approximate UB coordinates determined by measurements of appropriate quantities and by necessary calculations, and therefore the coordinates $\hat{C}_{UB}$ are a function of all geometric elements (2) in terms of:

$$\hat{C}_{UB} = f(A,\ L,\ L^0,\ Q_L,\ C^0_{UB}), \qquad (3)$$

whose elements require for obtaining correct results an errorless structural content of all the matrices involved in the LGN adjustment.

Elements in the matrices (3), involved in the adjusting process, (functions of measured, or computed values $d,\ z,\ \omega,\ C^0,\ ...)$ either affect by their correctness the generation of correct results or when the matrices (3) are encumbered with errors, also the matrices produce erroneous results of the adjustment.

3 STRUCTURE OF ARGUMENT MATRICES IN THE LGN ADJUSTMENT

- Matrix $\underset{(n,2u)}{A}$:

contains in rows for each geometric quantity of the net (L_i) coefficients "a". E.g. in the row for d_{ij}^0 these are the coefficients: "a_{iX}" "a_{iY}" and "$-a_{iX}$" "$-a_{iY}$", some of which may be incorrect due to erroneous, or insufficiently "approximate" coordinates C_{UBi}^0, C_{UBj}^0 of terminal points of the measured length d_{ij}^0 (Fig. 1, Fig. 2).

	…	UB_i X_i^0	Y_i^0	…	UB_j X_j^0	Y_j^0	…	UB_k X_k^0	Y_k^0	DB_1	…
$\underset{(n,2u)}{A} =$											
⋮											
d_{ij}^0		a_{iX}	a_{iY}		$-a_{jX}$	$-a_{jY}$					
⋮											
⋮											
ω_{jik}^0		a_{iX}	$-a_{iY}$		$-a_{jX}$	$-a_{jY}$		$-a_{kX}$	a_{kY}		
⋮											

Fig. 1 *Coefficients "a" in the matrix A*

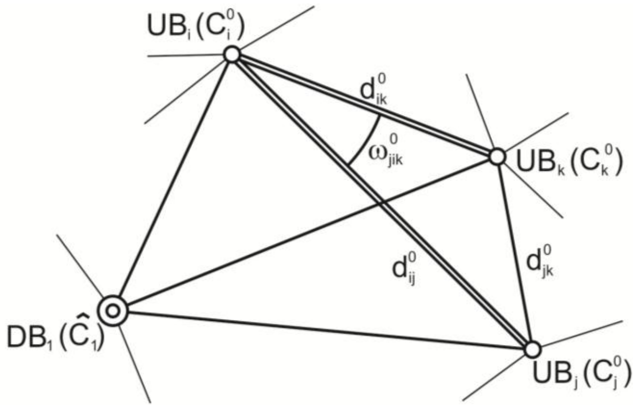

Fig. 2 *The geometry of lengths and angles in a LGN*

E.g. for the length d_{ij}^0 between the points UB$_i$, UB$_j$, for one terminal point UB$_i$ the appropriate coefficients a_{iX}, a_{iY} in the matrix A are, as follows:

$$a_{iX} = \frac{\partial d_{ij}^0}{\partial X_i^0} = \frac{X_j^0 - X_i^0}{\sqrt{(X_j^0 - X_i^0)^2 + (Y_j^0 - Y_i^0)^2}} = \frac{X_j^0 - X_i^0}{d_{ij}^0} = \frac{f_{dX}(C_i^0, C_j^0)}{f_d(C_i^0, C_j^0)}, \tag{4}$$

$$a_{iY} = \frac{\partial d_{ij}^0}{\partial Y_i^0} = \frac{Y_j^0 - Y_i^0}{\sqrt{(X_j^0 - X_i^0)^2 + (Y_j^0 - Y_i^0)^2}} = \frac{Y_j^0 - Y_i^0}{d_{ij}^0} = \frac{f_{dY}(C_i^0, C_j^0)}{f_d(C_i^0, C_j^0)}$$

and analogously for the other terminal point UB $_j$ of this length d_{ij}^0 :

$$a_{jX} = \frac{\partial d_{ij}^0}{\partial X_j^0} = -\frac{X_j^0 - X_i^0}{\sqrt{(X_j^0 - X_i^0)^2 + (Y_j^0 - Y_i^0)^2}} = -\frac{X_j^0 - X_i^0}{d_{ij}^0} = -\frac{f_{dX}(C_i^0, C_j^0)}{f_d(C_i^0, C_j^0)},$$
$$a_{jY} = \frac{\partial d_{ij}^0}{\partial Y_j^0} = -\frac{Y_j^0 - Y_i^0}{\sqrt{(X_j^0 - X_i^0)^2 + (Y_j^0 - Y_i^0)^2}} = -\frac{Y_j^0 - Y_i^0}{d_{ij}^0} = -\frac{f_{dY}(C_i^0, C_j^0)}{f_d(C_i^0, C_j^0)}. \qquad (5)$$

Similar structures of coefficients a_{iX}, a_{iY}, a_{jX}, a_{jY} apply to all points UB and DB generating the measured lengths between them. Any errors in the values X_i^0, Y_i^0 and X_j^0, Y_j^0 thus generate incorrect, unrealistic values of the corresponding coefficients a_{iX}, ..., a_{jY} and thus also a defective structure of the matrix A.

The same is true for coefficients " a " of horizontal angles ω_{jik}^0 in the matrix A where the coefficients a_{jX}, a_{jY}, a_{iX}, a_{iY}, a_{kX}, a_{kY}, e.g. for the angle ω_{jik}^0 (Fig. 2) are, as follows:

$$a_{jX} = \left(\frac{\partial \omega_{jik}^0}{\partial X_j^0}\right)^0 = \frac{Y_j^0 - Y_i^0}{(d_{ij}^0)^2} = \frac{f_{dY}(C_i^0, C_j^0)}{f_d(C_i^0, C_j^0)},$$
$$a_{jY} = \left(\frac{\partial \omega_{jik}^0}{\partial Y_j^0}\right)^0 = -\frac{X_j^0 - X_i^0}{(d_{ij}^0)^2} = -\frac{f_{dX}(C_i^0, C_j^0)}{f_d(C_i^0, C_j^0)},$$
$$a_{iX} = \left(\frac{\partial \omega_{jik}^0}{\partial X_i^0}\right)^0 = \left(\frac{Y_k^0 - Y_i^0}{(d_{ik}^0)^2} - \frac{Y_j^0 - Y_i^0}{(d_{ij}^0)^2}\right) = \frac{f_{dY}, f_{dY}(C_i^0, C_j^0, C_k^0)}{f_{dij}, f_{dik}(C_i^0, C_j^0, C_k^0)},$$
$$a_{iY} = \left(\frac{\partial \omega_{jik}^0}{\partial Y_i^0}\right)^0 = \left(-\frac{X_k^0 - X_i^0}{(d_{ik}^0)^2} + \frac{X_j^0 - X_i^0}{(d_{ij}^0)^2}\right) = \frac{f_{dX}, f_{dX}(C_i^0, C_j^0, C_k^0)}{f_{dij}, f_{dik}(C_i^0, C_j^0, C_k^0)}, \qquad (6)$$
$$a_{kX} = \left(\frac{\partial \omega_{jik}^0}{\partial X_k^0}\right)^0 = -\frac{Y_k^0 - Y_k^0}{(d_{ik}^0)^2} = \frac{f_{dY}(C_i^0, C_k^0)}{f_d(C_i^0, C_k^0)},$$
$$a_{kY} = \left(\frac{\partial \omega_{jik}^0}{\partial Y_k^0}\right)^0 = \frac{X_k^0 - X_i^0}{(d_{ik}^0)^2} = \frac{f_{dX}(C_i^0, C_k^0)}{f_d(C_i^0, C_k^0)}$$

and show by their structure, that due to the erroneous determination of the relevant coordinates $C^0 = [X^0 \; Y^0]$ of UB points, or erroneous determination of approximate values of horizontal lengths and angles, also the matrix A may enter into the adjusting process with a wrong structure.

- Matrix $\underset{(n,1)}{L}$:

contains the quantities needed in the LGN processing, obtained from the measurements: lengths d between pairs of LGN points reduced to the plane of projection, horizontal angles ω also reduced to the plane of map projection, zenith angles z and other necessary quantities, which in addition to the weighted with random errors may be contaminated also by the influence of latent systematic errors. Their effect is appropriately reflected in all measured quantities between the DB, UB points and between the points DB and UB.

However, it is to be expected also that e.g. in using inadequate measuring instruments, incorrect measurement procedures, due to various mistakes, some latently defective functions of devices and the like, also the measured values $d,\ \omega,\ z,\ \ldots$ may be significantly incorrect. The elements L_i encumbered with errors of the matrix L within the meaning of the dependence (3) then affect the results of the LGN adjustment (coordinate estimates $\hat{C}_{UB}$ and other parameters) to a different, distorted and devalued extent.

- Cofactor matrix $\underset{(n,n)}{Q_L}$:

The matrix Q_L of the vector of measured values $\underset{(n,1)}{L}$ can be created by different procedures such as using a priori variances σ_0^2 (of the manufacturer of the device) and aposteriori variances s_0^2 (obtained on the basis of performed measurements) by $q_i = (s_0^2)_i / \sigma_0^2$, the Minque , Bique methods and other procedures (Wolf 1968, Mikhail 1976, Höpcke 1980, Pelzer 1980, 1985, Ressmann 1980, Weiss et al., 2008). According to different methodological principles and experiences formed cofactors q_i however need not always significantly affect by their matrix $Q_L = diag(q_1,\ldots,q_i,\ldots,q_n)$ formed estimates $d\hat{C}_{UB}$ and therefore either the final results of the UB coordinates $\hat{C}_{UB}$. In justified cases (well measurement conditions and the homogeneity of observations, etc.), also unit cofactors $q_i = 1,\ i = 1,\ 2,\ \ldots,\ n.$ are used for all L_i. For various measurands, i.e. measured lengths and angles, the cofactors are obtained, as follows: $q_{d(\omega)i} = \sigma_{d(\omega)i}^{\ 2} / \sigma_0^2$, where $\sigma_0^2 = (\Sigma\sigma_{d_{ij}}^{\ 2} + \Sigma\sigma_{\omega_{jik}}^{\ 2}) / n$. The creation of reliable cofactors, adequate to equipment features and current measurement conditions, represents in the LGN adjustment an important influencing factor to obtain real values of various LGN parameters.

- Matrix $\underset{(n,1)}{L^0}$:

contains numerically determined (not by measuring) approximate values $d^0,\ \omega^0,\ z^0,\ C^0,\ldots,$ of relevant variables, i.e. lengths, horizontal angles, zenith angles, approximate values of UB coordinates and other possible, or necessary quantities based on known procedures for their calculation.

Approximate values of $L_i^0,\ i = 1,\ 2,\ \ldots,\ n$ together with their measured values L_i create a matrix $\underset{(n,1)}{dL}$ with elements $dL_i = L_i = L_i^0$, i.e. with "complements" to approximate values L^0 of variables in the net. The elements dL_i on the basis of their significant or negligible value (typically: $dL < (1-3)\ mm,\ dL < (1-5)^{\ cc}$) indicate either the numerical acceptance of the value dL_i or significant, unacceptable value dL_i, indicating a significant discrepancy between L and L^0.

- Matrices C_{UB}^0 and $\hat{C}_{UB}$:

coordinates $(C_{UB}^0 = [X^0\ Y^0]_{UB})$ of UB points are for the LSM processing of the LGN determined (based on their orientation with simple structural links, as a system of rayons, intersections, etc. in relation to the DB) as coordinates without any adjustment and are declared as the approximate coordinates C^0 of UB points. These then within the LGN adjustment finally get their values $\hat{C}_{UB}$, by adding coordinate complements $d\hat{C}_{UB}$ to the respective values C_{UB}^0;

coordinates of datum points $(C_{DB} = [X\ Y]_{DB})$ in the LGN will be considered as non-encumbered with nonrandom errors. These points based on the results of their compatibility verification (Bill 1984, Weiss et al., 2004, Pukanská et al. 2007, Labant et al. ,2009, Weiss et al., 2010), with acceptable congruences of coordinate point and its physically measuring mark, may be regarded as datum points (DB), whose coordinates will not in the net adjustment adversely affect the resulting LGN parameters.

4 CONTROL RELATIONS IN THE ADJUSTMENT

To assess the structural and content correctness of the used matrices and quantities as well as the final results of the adjusting process their numerical accuracy is verified.

Typically, different valid relations are used, created from products of individual matrices, which provide in case of their correctness a zero output: $\underset{(1,1)}{0}$, i.e. zero value as a result for a given matrix product, or give acceptable values close to 0.

Checks of matrix solution accuracy are realized both in the structure of individual matrices (e.g. in A), namely in terms of accuracy of numerical values in rows, or in columns. E.g. row controls in A in which zero sums of coefficients are to be created, i.e. in each row j $(j = 1,\ 2,\ ...,\ n)$ the sum $a_{i,1} + a_{i,2} + \ ... \ + a_{i,2n} = \underset{(1,1)}{0}$.

Other forms of adjustment controls are different product blocks of suitable matrices $A,\ Q_L,\ dL,\ V,\ d\hat{C},\ C^0$, created on the basis of their property of binding suitability. If the product blocks are correct, they are equal to 0 (in theory), or equal to small numerical values, which are negligible (in practice).

To the controls of the above method e.g. the following relations can be applied:

$$\underset{(1,n)}{dL} \cdot \underset{(n,n)}{Q_L^{-1}} \cdot \underset{(n,2u)}{A} \cdot \underset{(2u,1)}{d\hat{C}} = \underset{(1,1)}{0},$$

$$\underset{(1,n)}{dL} \cdot \underset{(n,n)}{Q_L^{-1}} \cdot \underset{(n,1)}{dL} = \underset{(1,1)}{0},$$

$$\underset{(1,n)}{V} \cdot \underset{(n,n)}{Q_L^{-1}} \cdot \underset{(n,1)}{dL} = \underset{(1,1)}{0}, \qquad (7)$$

$$\underset{(1,n)}{dL} \cdot \underset{(n,n)}{Q_L^{-1}} \cdot \underset{(n,1)}{V} = \underset{(1,1)}{0},$$

$$\underset{(2u,n)}{A} \cdot \underset{(n,n)}{Q_L^{-1}} \cdot \underset{(n,1)}{V} = \underset{(2u,1)}{0},$$

and other appropriate similar structures of numerical values (Wolf 1968, Reissmann 1980, Höpcke 1980, Böhm et al. ,1990, Weiss et al., 2009).

If the control relations show instead of the theoretical values "0" non-zero values, which is always actual, and these will be smaller than 0.001 (or other limits), the results of the adjustment may be accepted, otherwise they are rejected and it is necessary to explore their genesis in the adjusting process.

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RESUMÉ

Predkladaný článok sa zaoberá vplyvom rôznych chyb, ktoré vznikli či už pri meracích alebo počtárskych prácach, na vyrovnanie lokálnej geodetickej siete (LGS). Je reálne očakávať aj pri starostlivom zabezpečení meračskej a spracovateľskej činnosti, že niektoré z meraných prvkov môžu byť z rôznych dôvodov chybne zamerané a potom chybnými výpočtami ovplyvnené aj výsledky t.j. korektnosť celého vyrovnania.

Uvažujeme LGS, ktorej bodové pole tvoria: 1. overené (kompatibilné) body bodového poľa použité pre LGS ako dátumové body DB s fixnými súradnicami, 2. body „nové“, založené podľa účelu LGS, t.j. tzn. určované body UB, doplňujúce DB na celkové potrebné bodové pole pre LGS. Na základe vyrovnania LGS, z ktorého odhady súradníc $\hat{C}_{UB}$ sa vytvárajú predpísaným interakčným pôsobením matíc: $\hat{C}_{UB} = f(A,\ L,\ L^0,\ Q_L,\ C^0_{UB})$, ktorých prvky vyžadujú pre korektné výsledky bezchybnú štruktúru matíc pôsobiacich vo vyrovnaní LGS.

Matica dizajnu A obsahuje v riadkoch pre jednotlivé geometrické veličiny siete (L_i) koeficienty „a“, ktoré sú parciálnymi deriváciami príslušných približných dĺžok d^0_{ij} a uhlov ω^0_{jik} podľa príslušných súradníc $X_i^0\ Y_i^0$. V dôsledku chybných určení súradníc $C^0 = [X^0\ Y^0]$ bodov UB, resp. chybných určení približných hodnôt vodorovných dĺžok a uhlov, aj matica A môže vstupovať do vyrovnávacieho procesu s chybnou štruktúrou.

Matica nameraných veličín L obsahuje veličiny potrebne v spracovaní LGS, získané z meraní: dĺžky d a vodorovné uhly ω redukované do roviny kartografického zobrazenia, zenitové uhly z i ďalšie. Ich pôsobenie sa primerane prejaví vo všetkých meraných veličinách medzi bodmi DB, bodmi UB a medzi bodmi DB a UB. Pri použití neadekvátnych meracích prístrojov, nesprávnych meracích postupov, v dôsledku rôznych omylov, je tiež očakávateľný negatívny vplyv na výsledky vyrovnania LGS.

Kovariančná matica Q_L vektora meraných hodnôt L sa môže vytvoriť rôznymi postupmi ako napr. s použitím apriórnych variancií σ_0^2 (od výrobcu prístroja) a aposteriórnych variancií s_0^2 (získaných na základe vykonaných meraní) podľa $q_i = s^2_{0i} / \sigma^2_0$, a inými postupmi. Tvorba spoľahlivých kofaktorov, ktoré sú adekvátne vlastnostiam prístrojov a aktuálnym podmienkam merania, je vo vyrovnaní LGS dôležitým ovplyvňujúcim faktorom získania reálnych hodnôt rôznych parametrov LGS.

Matica L^0 obsahuje numericky určené približné hodnoty $d^0,\ \omega^0,\ z^0,\ C^0, \ldots$ príslušných veličín. Približné hodnoty veličín $L_i^0,\ i = 1,\ 2,\ \ldots,\ n$ spolu s ich nameranými hodnotami L_i vytvárajú maticu doplnkov $dL_i = L_i = L_i^0$. Prvky dL_i na základe ich významnej alebo zanedbateľnej hodnoty signalizujú numerickú prijateľnú hodnotu alebo významnú, neprijateľnú hodnotu dL_i, ktorá oznamuje rozpor medzi L a L^0.

Matica C^0_{UB} sú súradnice bez vyrovnania a deklarujú sa za približné súradnice C^0 bodov UB. Tieto v rámci vyrovnania LGS získajú potom definitívne svoje hodnoty $\hat{C}_{UB}$, pridaním súradnicových doplnkov $d\hat{C}_{UB}$ k príslušným hodnotám C^0_{UB}. Body na základe výsledkov z ich overenia na kompatibilitu s prijateľnou

kongruenciou súradnicového bodu a jeho fyzicky meračskej značky, možno považovať za dátumové body (DB), ktorých súradnice nebudú vo vyrovnaní siete negatívne ovplyvňovať výsledné parametre LGS.

V štruktúre jednotlivých matíc (napr. v A) sa realizujú kontroly správnosti maticového riešenia a to z hľadiska správnosti numerických hodnôt v riadkoch, resp. v stĺpcoch. Napr. riadkové kontroly v A, v ktorých sa majú vytvárať nulové súčty koeficientov, t.j. v každom riadku j $(j = 1,\ 2,\ ...,\ n)$ súčet $a_{i,1} + a_{i,2} + \ ... \ + a_{i,2n} = 0.$ Iné formy kontrol vyrovnania predstavujú rôzne súčinové bloky z vhodných matíc $A,\ Q_L,\ dL,\ V,\ d\hat{C},\ C^0,$ vytvorené na základe ich vlastností a väzbovej vhodnosti. Ak sú súčinové bloky korektné, sú rovné 0. V prípade nenulových hodnôt sa zamietajú a je potrebné pátrať vo vyrovnávacom procese po ich vzniku.

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