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Analysis of deformation displacement using GNSS technology in the local topocentric coordinate system

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Abstract: With the impact of climate change and the impact of rising sea levels, in some areas of our country, there are deformation displacement phenomena such as subsidence. The paper has studied the method of analyzing vertical displacement deformation (geodynamic displacement based on the use of 3D data obtained from the results of measuring the monitoring network applying GNSS technology in time cycles in the Horizon Coordinate System. The report focuses on analyzing the 3D dynamic displacement model of the central region applying GNSS technology. The research results can serve the basic investigation work in localities with the possibility of subsidence or deformation due to geological faults or environmental impacts.

Keywords: Network adjustment, GNSS, Kalman Filter, vertical displacement, Deformation analysis.

INTRODUCTION

With the application of GNSS technology, the construction of geodetic networks achieves high accuracy in a short time and can be continuously monitored, in a wide range and can determine the displacement vector in the dynamic model. GNSS networks are usually adjusted in geocentric coordinates. For local 3D analysis, it is more convenient to use geocentric coordinates, especially for vertical displacement analysis. Some international and domestic publications have mentioned the application of Kalman filtering to apply in the field of deformation analysis (Welsch, W. M. and HeuneckeYalc, inkaya, M. and Bayrak, T). The adjustment of the spatial grid and displacement analysis in the topocentric

coordinate system allows for a better assessment of horizontal or vertical displacement, thus determining the subsidence of the land area under study.

The paper presents a solution to develop the theory of recurrent adjustment in the analysis of dynamic model deformation displacement of GNSS monitoring network with 4 measurement cycles. The data processing calculation is performed in the topocentric coordinate system.

METHODOLOGY

GNSS free adjustment in the topocentric coordinate system

Free adjustment of GNSS spatial grid in geocentric coordinate system (X,Y,Z) we will have a system of equations of corrections for n baselines has the following form:

$$V_{nx1} = A_{n \times k} \Delta x_{kx1} + L_{nx1} \quad (1)$$

where: A - the coefficient matrix

Δx_{kx1} is the vector of unknowns, V_{nx1} is vector of corrected numbers; $k = 3xt$.

The weight matrix P has the form:

$$P = \begin{pmatrix} P_1 & 0 & 0 & 0 \\ 0 & P_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & P_n \end{pmatrix} \quad (2)$$

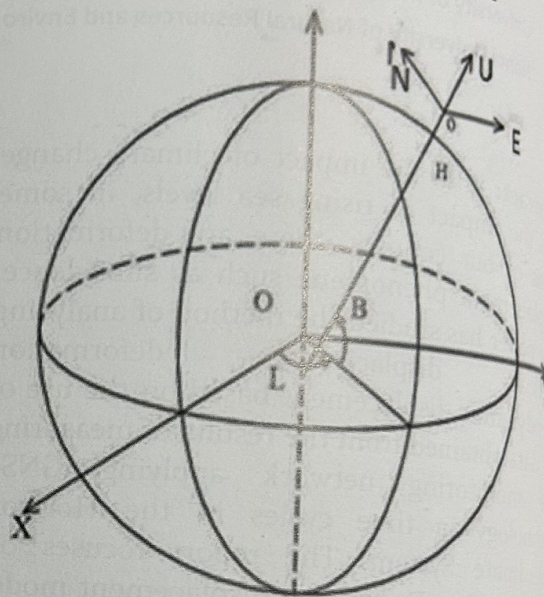
$$P_i = Q_i^{-1} \quad (3)$$

Q_i - the cofactor matrix of the i -th baseline measurements

For each point of the GNSS grid, we have the following formula:

$$\Pi = \begin{pmatrix} \Pi_1 & & \\ & \Pi_2 & \\ & \dots & \\ & & \Pi_n \end{pmatrix} \quad (8)$$
$$S_0 = \frac{VTPV}{\dots}$$

$Q_x = R_z^{\sim}$ - The cofactor matrix



where:

$X_j^{(k)}, Y_j^{(k)}, Z_j^{(k)}$: coordinate of point j at period k ;

v_{xj}, v_{yj}, v_{zj} : velocities of X, Y, Z coordinates of point j ;

a_{xj}, a_{yj}, a_{zj} : accelerations of X, Y, Z coordinates of point j ;

$k = 1, 2, \dots, i$ (i : measurement period number);

$j = 1, 2, \dots, k$ (k : number of points);

From formula (19), the following system of equations can be established:

$$\begin{aligned} x_j^{(k+1)} &= x_j^{(k)} + (t_{k+1} - t_k) v_{xj}^{(k+1)} \\ &\quad + 0,5(t_{k+1} - t_k)^2 a_{xj}^{(k+1)} \\ v_{xj}^{(k+1)} &= v_{xj}^{(k)} + (t_{k+1} - t_k) a_{xj}^{(k)} \\ a_{xj}^{(k+1)} &= a_{xj}^{(k)} \end{aligned} \quad (20)$$

Expression (20) can be rewritten in matrix form as follows:

$$\begin{pmatrix} x_j^{(k+1)} \\ v_{xj}^{(k+1)} \\ a_{xj}^{(k+1)} \end{pmatrix} = \begin{pmatrix} E & (t_{k+1} - t_k)E & 0,5(t_{k+1} - t_k)^2 E \\ 0 & E & E \\ 0 & 0 & E \end{pmatrix} \begin{pmatrix} x_j^{(k)} \\ v_{xj}^{(k)} \\ a_{xj}^{(k)} \end{pmatrix} \quad (21)$$

The Symbol:

$$y_j^{(k+1)} = \begin{pmatrix} x_j^{(k+1)} \\ v_{xj}^{(k+1)} \\ a_{xj}^{(k+1)} \end{pmatrix} \quad (22)$$

$$y_j^{(k)} = \begin{pmatrix} x_j^{(k)} \\ v_{xj}^{(k)} \\ a_{xj}^{(k)} \end{pmatrix} \quad (23)$$

$$y_j^{(k+1)} = G_j^{(k+1)} y_j^{(k)} \quad (24)$$

$$\bar{Y}_{(k+1)} = G_{(k+1)} \hat{Y}_{(k+1)} \quad (25)$$

Here:

$$\bar{Y}_{(k+1)} = \begin{pmatrix} y_1^{(k+1)} \\ y_2^{(k+1)} \\ \dots \\ y_n^{(k+1)} \end{pmatrix} \quad (26)$$

$$\bar{Y}_{(k)} = \begin{pmatrix} y_1^{(k)} \\ y_2^{(k)} \\ \dots \\ y_n^{(k)} \end{pmatrix} \quad (27)$$

$$G_{(k+1)} = \begin{pmatrix} G_1^{(k+1)} & & \\ & \dots & \\ & & G_n^{(k+1)} \end{pmatrix} \quad (28)$$

$$\bar{Y}_{(k+1)} = \begin{pmatrix} y_1^{(k+1)} \\ y_2^{(k+1)} \\ \dots \\ y_n^{(k+1)} \end{pmatrix} \quad (29)$$

$$\bar{Y}_{(k)} = \begin{pmatrix} y_1^{(k)} \\ y_2^{(k)} \\ \dots \\ y_n^{(k)} \end{pmatrix} \quad (30)$$

$$G_{(k+1)} = \begin{pmatrix} G_1^{(k+1)} & & \\ & \dots & \\ & & G_n^{(k+1)} \end{pmatrix} \quad (31)$$

According to Kalman filter theory, if using the calculation results at period t_k , then according to formula (21), predict the current state vector by using the state vector information of the known motion parameters at period t_k and the measurements at period t_{k+1} . collected at period t_{k+1} . The matrix equation system of the motion model used to predict the motion parameters by Kalman filter technique in the grid can be represented as follows:

$$\bar{Y}_{(k+1)} = G_{(k+1)} \hat{Y}_k + S_{k+1,k} \quad (32)$$

$$C_{\bar{Y}(k+1)} = G_{k+1,k} C_Y G_{k+1,k}^T \quad (33)$$

$\hat{Y}^{(k)}$ is the vector of calculated values adjusted at time t_k .

$\hat{Y}_{(k+1)}^T$ - vector of predicted values of coordinates, velocity and acceleration $\hat{Y}_k^T$ - vector of averaged values at time t_k .

At time t_{k+1} , we can use the geodetic grid adjustment results in the previous observation period (t_k) and establish a system of equations of correction numbers according to the least squares method with new measurement values. Thus, at time t_{k+1} , we can consider the geodetic grid points to have been virtually measured with measurement values and weights as the grid adjustment results in this period. Then we have the coefficient matrix of the system of equations of correction numbers in the following form:

$$\hat{A}_{k+1} = (E_{3 \times 3} \quad 0 \quad 0 \dots E_{3 \times 3} \quad 0 \quad 0) \quad (34)$$

$$V = \hat{A}_{k+1} \hat{Y}_{k+1} + L \quad (18)$$

$$\begin{pmatrix} V_{\hat{Y}_{(k+1)}} \\ V_{L_{k+1}} \end{pmatrix} = \begin{pmatrix} E \\ A_{(k+1)} \end{pmatrix} \hat{Y}_{(k+1)} + \begin{pmatrix} 0 \\ L_{k+1} \end{pmatrix} \quad (35)$$

The weight matrix:

$$P = \begin{pmatrix} P_{\hat{Y}_{(k+1)}} & 0 \\ 0 & P_{L_{k+1}} \end{pmatrix} \quad (36)$$

$$P_{\hat{Y}_{(k+1)}} = Q_{\hat{Y}_{(k+1)}}^{-1} \quad (37)$$

$$P_{L_{k+1}} = Q_{L_{k+1}}^{-1} \quad (38)$$

The normal system of equations has the form:

$$\begin{pmatrix} P_{\hat{Y}_{(k+1)}} + A_{(k+1)}^T P_{L_{k+1}} A_{(k+1)} \\ A_{(k+1)}^T P_{L_{k+1}} L_{k+1} \end{pmatrix} \Delta \hat{Y}_{k+1} + \begin{pmatrix} 0 \\ A_{(k+1)}^T P_{L_{k+1}} L_{k+1} \end{pmatrix} = 0 \quad (39)$$

By the recursive formula (Markuze, YU.I, Hoang H):

$$\Delta \hat{Y}_{k+1} = - (P_{\hat{Y}_{(k+1)}} + A_{(k+1)}^T P_{L_{k+1}} A_{(k+1)})^{-1} A_{(k+1)}^T P_{L_{k+1}} L_{k+1} \quad (40)$$

$$\begin{aligned} &= Q_{\hat{Y}_{(k+1)}} Q_{\hat{Y}_{(k+1)}} A_{(k+1)} (Q_{L_{k+1}} \\ &\quad \begin{pmatrix} Q_{L_{k+1}}^{-1} + \\ A_{(k+1)} Q_{\hat{Y}_{(k+1)}} A_{(k+1)}^T \end{pmatrix}^{-1} A_{(k+1)}^T Q_{\hat{Y}_{(k+1)}} \end{aligned} \quad (41)$$

Here:

$$Z_{(k+1)} = Q_{\hat{Y}_{(k+1)}} A_{(k+1)}^T$$

$$N_{(k+1)} = Q_{\hat{Y}_{(k+1)}}^{-1} + Z_{(k+1)}^T A_{(k+1)}^T \quad (42)$$

$$\hat{Y}_{k+1} = \hat{Y}_{(k+1)} + \Delta \hat{Y}_{k+1} \quad (43)$$

Data processing procedures

Step 1: Data preprocessing of GNSS adjustment at each measurement cycle

- Input:
 - Geodetic Datum (the local topocentric coordinate system)
 - Priori coordinates of GNSS points
 - GNSS observations.
- Output
 - Estimated value of coordinates of GNSS points
 - RMS error

Step 2: Calculate the parameters $dU, dN, dE, v_U, v_N, v_E, a_U, a_N, a_E$ over the periods.

Step 3: Displacement analysis based on statistical criteria.

RESULTS

GNSS networks adjustment in the local topocentric coordinate system

To conduct experimental research and analyze the displacement according to the theory presented above, we have performed on GNSS measurement data in the central region of Vietnam (Thach Ban - Cat Tien, Lam Dong province). The monitoring network consists of 6 points (Figure 2). The construction of the network and the measurement was carried out by the Vietnam Institute of Geodesy and Cartography. The landmark is built according to the standard of mandatory centering landmarks placed on the bedrock. Repeat measurement for 4 cycles 2015, 2016, 2017 and 2018, time interval between cycles is one year.

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Table 1

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dU (mm)
dN (mm)
dE (mm)
v _U (mm/year)
v _N (mm/year)
v _E (mm/year)
a _U (mm/year ²)
a _N (mm/year ²)
a _E (mm/year ²)

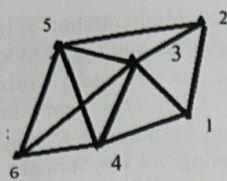


Figure 2. GNSS network Diagram

In the first step, applying the 3D free network adjustment to process the Baselines, the network coordinates were obtained in the 2015, 2016, 2017 and 2018 cycles. Conduct assessment of the change of milestones between 2 cycles $i-j$ (j - number of cycle): $T_U = dU/m_{dU}$, $T_N = dN/m_{dN}$, $T_E = dE/m_{dE}$. Check the Criteria (t -distribution) (Ghilani, C., Wolf, P.; (2017)): $|T_U| < q_U$, $|T_N| < q_N$, $|T_E| < q_E$. If the test value is greater then the critical value, then there are significant deformations in the points.

Calculation results and checking statistical criteria can be seen that all 6 points have shifted.

Calculation of displacement parameters

In each observation period, calculations and adjustments are made according to formulas (1)-(18). These results are used to calculate the displacement parameters 1-2, 1-2-3, 1-2-3-4 according to formulas (25) to (44). The calculation results are presented in the following tables (Round to mm).

Table 1: Displacement parameters dU, dN, dE (mm), $V_U, V_N, V_E, a_U, a_N, a_E$ between 2015 and 2016

	1	2	3	4	5	6
dU (mm)	51	11	-15	28	-39	-4
dN (mm)	0	0	0	0	0	0
dE (mm)	0	0	0	0	0	0
V_U (mm/year)	61	13	-18	33	-47	-4
V_N (mm/year)	0	0	0	0	0	0
V_E (mm/year)	0	0	0	0	0	0
a_U (mm/year ²)	20	5	-6	11	-16	-2
a_N (mm/year ²)	0	0	0	0	0	0
a_E (mm/year ²)	0	0	0	0	0	0

Table 2. Displacement parameters dU, dN, dE (mm), $V_U, V_N, V_E, a_U, a_N, a_E$ between 2015, 2016, 2017

	1	2	3	4	5	6
dU (mm)	11	-76	-47	-31	-46	-13
dN (mm)	0	0	0	0	0	0
dE (mm)	0	0	0	0	0	0
V_U (mm/year)	-86	-91	-40	-20	8	-12
V_N (mm/year)	0	0	0	0	0	0
V_E (mm/year)	0	0	0	0	0	0
a_U (mm/year ²)	-91	-53	-16	-86	32	-5
a_N (mm/year ²)	0	0	0	0	0	0
a_E (mm/year ²)	0	0	0	0	0	0

Table 3 Displacement parameters dU, dN, dE (mm), $V_U, V_N, V_E, a_U, a_N, a_E$ between 2015, 2016, 2017 and 2018

	1	2	3	4	5	6
dU (mm)	12	-193	-10	0	-33	-12
dN (mm)	0	0	0	0	0	0
dE (mm)	0	0	0	0	0	0
V_U (mm/year)	22	-144	70	0	23	71
V_N (mm/year)	0	0	0	0	0	0
V_E (mm/year)	0	0	0	0	0	0
a_U (mm/year ²)	41	-53	68	0	20	11
a_N (mm/year ²)	0	0	0	0	0	0
a_E (mm/year ²)	0	0	0	0	0	0

DISCUSSION

From the results of calculating the displacement parameters (from table 1 to table 3), we can clearly see that there is only a displacement of the U coordinate, that is, only a rise and fall. The horizontal displacement is stable. Point 1 through 4 cycles tends to rise, points 2, 3, 5, 6 sink. Only point 4 to cycle 4 is stable. This result shows the superiority of the

adjustment in the topocentric coordinate system. If the correction was in the geocentric coordinate system, the picture would not be so clear.

CONCLUSION

In this paper, the recurrent adjustment theory combined with Kalman filter has been developed to solve the problem of assessing the displacement and deformation of the land due to the impact of natural disasters or climate change. To implement this solution, it is necessary to apply GNSS satellite technology. The monitoring network is adjusted separately in each measurement cycle. Synthesis and analysis of displacement are performed in the horizon coordinate system. The advantage of this method is that it allows us to clearly see the displacement in the horizontal or vertical direction. The experimental results show the effectiveness of the method through the detection of vertical displacement of the monitoring network points.

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