Monitoring the displacement of the Ba River fault zone of Vietnam using GNSS technology

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SUMMARY

The monitoring of deformation due to the impact of faults and landslides due to the influence of climate change is a problem arising from reality. In this paper, on the basis of application of Kalman filter theory with GNSS data of Ba river area (Central Vietnam) to analyze displacement. The data of the first 3 cycles are used to analyze the transition from year to year and are the basis for forecasting the shift in cycle 4 and comparing it with the actual measurement results of cycle 4. Calculation Experiment with specific data on the territory of Vietnam. This is a technology that can enable effective use of GNSS technology for environmental analysis in mining and geological research.

.**SUMMARY**

Việc quan trắc biến dạng do tác động của đứt gãy và sạt lở đất do ảnh hưởng của biến đổi khí hậu là vấn đề nảy sinh từ thực tế. Trong bài báo này, trên cơ sở ứng dụng lý thuyết lọc Kalman với dữ liệu GNSS khu vực sông Ba (miền Trung Việt Nam) để phân tích chuyển dịch biến dạng. Số liệu của 3 chu kỳ đầu được sử dụng để phân tích chuyển dịch qua từng năm và là cơ sở để dự báo chuyển dịch ở chu kỳ 4 và so sánh với kết quả đo đạc thực tế của chu kỳ 4. Tiến hành tính toán thực nghiệm với số liệu cụ thể trên lãnh thổ Việt Nam. Đây là công nghệ có thể cho phép sử dụng hiệu quả công nghệ GNSS để phân tích môi trường trong khai thác khoáng sản và nghiên cứu địa chất.

Keywords: GNSS application, GNSS monitoring, Kalman filter, Adjustment computation

1 INTRODUCTION

The application of Global Navigation Satellite System (GNSS) technology has created a very effective breakthrough in geodynamics and deformation monitoring. GNSS networks are three-dimensional spatial networks, so iterative measurement allows simultaneous determination of both horizontal and vertical displacement vectors of the earth's crust. With the basic advantages of satellite positioning technology such as not requiring navigation between points, measurements can be carried out in all weather conditions, it is possible to quickly develop a geodynamic network on a large scale territory.

A number of studies have mentioned the problem of applying GNSS technology to study geodynamics:Acar, Özlüdemir, M., Çelik, R., Erol, S.Ayan, T.2(004);Erol, S., Erol, B., and Ayan, T.(2005); Shults, R., Anenkov, A. (2018). On the application of Kalman filter, have focused on building models applying Kalman filter to analyze geodetic monitoring observations :Welsch, W., Heunecke, O.(2001);, applied Kalman filter with color noise to study deformation analysis (Kuhlmann, H., Kalman,(2003)). However, in these works, the problem of reliable displacement forecasting has not been mentioned. This is a problem of concern in disaster risk prediction in Vietnam.

In this paper, we present the results of applying the GNSS network adjustment with the Kalman filter technique to analyze and predict the displacement on the experimental area of the Ba River of Vietnam.

2 METHODOLOGY

2.1. Theoretical background

2.1.1. GNSS free adjustment

Suppose in the GNSS network there are t points to be determined. The unknowns will be the geocentric coordinates which will be (X_i, Y_i, Zi), (i=1, 2...t). The system of equations of corrections for n baselines has the following form:

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

Here A - the coefficient matrix

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

The weight matrix P has the form:

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

$$P_i = Q_i^{-1} \tag{3}$$

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

The normal system of equations has the form:

$$R\Delta x_{kx1} + b_{kx1} = 0 \quad . \tag{4}$$

Where:

$$R = A^T P A, \tag{5}$$

$$b = A^T P L. \tag{6}$$

The condition has the following form:

$$C\Delta x = 0 \quad . \tag{7}$$

The unknown vector is :

$$\Delta\mathbf{x} = -R^{\sim} b \tag{8}$$

In which, $R^{\sim}$ is the general inverse matrix:

$$R^{\sim} = (R + CC^T)^{-1} - TT^T = \mathbf{Q_x} \tag{9}$$

$$T = B(C^T B)^{-1} \tag{10}$$

$$B^T = (B_1 \quad B_2 \quad \dots \quad B_n)$$
(11)

Where:

n is the number of measurements;

$$B_i = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}; \text{ i=1, 2,...n.} \tag{12}$$

$$C^T = (B_1 \quad \cdots \quad B_k \quad 0 \quad \dots \quad 0) \tag{13}$$

B_i- Block matrices for stable points; (i= 1,2,...k), 0-blocks for unstable points

In the case of C = B, the general inverse matrix is calculated by the formula:

$$R^{+} = (R + BB^T)^{-1} - TT^T \tag{14}$$

Here the matrix T is defined by the formula (8)

For an accurate assessment, the following quantities need to be calculated:

$$s_0 = \sqrt{\frac{\mathrm{V^T PV}}{\mathrm{n-k+d}}} \tag{15}$$

d is the number of defects of the network (d = 3).

The covariance matrix is :

$$\mathrm{K}_x = s_0^2\, \mathrm{Q_x} \tag{16}$$

2.1.2. Kalman filter in 3D displacement analysis

The kinematic model over time with coordinates, velocity and acceleration is represented by the following formula (Acar, Özlüdemir, M., Çelik, R., Erol, S.Ayan, T.(2004)),:

$$X_j^{(k+1)} = X_j^{(k)} + (t_{k+1} - t_k)v_{Xj} + 1/2(t_{k+1} - t_k)^2 a_{Xj}$$

$$Y_j^{(k+1)} = Y_j^{(k)} + (t_{k+1} - t_k)v_{Yj} + 1/2(t_{k+1} - t_k)^2 a_{Yj}$$

$$Z_j^{(k+1)} = Z_j^{(k)} + (t_{k+1} - t_k)v_{Zj} + 1/2(t_{k+1} - t_k)^2 a_{Zj}$$

(17)

where $X_j^{(k+1)}$, $Y_j^{(k+1)}$, $Z_j^{(k+1)}$: coordinate of point *j* at period (k+1).

$X_j^{(k)}$, $Y_j^{(k)}$, $Z_j^{(k)}$: 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, . . . , *i* (*i*: measurement period number)

j=1, 2, . . . , k (k: number of points)

The system of equations of the motion model used to predict motion parameters by Kalman filtering technique in 3D meshes can be represented as a matrix as follows:

$$\bar{\mathrm{Y}}_{(\mathbf{k+1})} = \mathbf{T}_{(\mathbf{k+1})} \hat{\mathrm{Y}}_{(\boldsymbol{k+1})} \tag{18}$$

Where:

$$\hat{\mathrm{Y}}^{\mathbf{T}}_{(k+1)} = (\mathrm{X} \quad \mathrm{Y} \quad \mathrm{Z} \quad \mathrm{v_X} \quad \mathrm{v_Y} \quad \mathrm{v_Z} \quad \mathrm{a_x} \quad \mathrm{a_Y} \quad \mathrm{a_Z})_{(k+1)}$$

$$\bar{Y}^{\mathbf{T}}{}_{(k)} = (X \quad Y \quad Z \quad v_X \quad v_Y \quad v_Z \quad a_x \quad a_Y \quad a_Z)_{(k)} \tag{19}$$

$$T_{k+1,k} = \begin{pmatrix} E & E(t_{k+1} - t_k) & E(0,5(t_{k+1} - t_k)^2 \\ 0 & E & E(t_{k+1} - t_k) \\ 0 & 0 & E \end{pmatrix} \tag{20}$$

where $\bar{Y}^{T}{}_{(k+1}$: prediction status (position, velocity, acceleration) vector at period (k+1)

$\hat{Y}^{\mathbf{T}}{}_{k}$: state vector at period k

The equation with the noise factor will be as follows:

$$\bar{Y}_{(\mathbf{k+1})} = T_{(\mathbf{k+1})}\hat{Y}_{\boldsymbol{k}} + S_{k+1,k} \tag{21}$$

$$K_{\bar{Y}(\mathbf{k+1})} = T_{\mathbf{k+1,k}} K_Y \, T^{T}_{k+1,k} + S_{k+1,k} K_S \, S^{T}_{k+1,k}$$

$K_{\hat{Y}\mathbf{k}}$: the covariance matrix of state vector at period k.

K_S: the covariance matrix of system noises at period k.

At time t_{k+1}, we measure the GNSS network and can establish

a system of measurement equations (filter equations) as follows:

$$v_{l,k+1} = A_{k+1}\hat{Y}_k - l_{k+1} \tag{22}$$

$$l_{k+1} + v_{l,k+1} = A_{k+1}\hat{Y}_k \tag{23}$$

Combining expressions (18) and (23) we have the following formula:

$$V = \hat{A}_{\boldsymbol{k+1}}\hat{Y}_{\boldsymbol{k+1}} + L \tag{24}$$

Here we denote:

$$V = \begin{pmatrix} v_{k+1} \\ V_{l,k+1} \end{pmatrix}$$

$$\hat{A}_{\mathbf{k+1}} = \begin{pmatrix} \mathbf{E} \\ \boldsymbol{A_{k+1}} \end{pmatrix} \tag{25}$$

$$\hat{A}_{\mathbf{k+1}} = \begin{pmatrix} \mathbf{E} \\ \boldsymbol{A_{k+1}} \end{pmatrix} \tag{26}$$

$$L = -\begin{pmatrix} \bar{Y}_{k+1} \\ \mathbf{l}_{k+1} \end{pmatrix} \tag{27}$$

Covariance Matrix:

$$K_{k+1} = \begin{pmatrix} K_{\bar{Y}(\mathbf{k+1}} & 0 \\ 0 & K_{l,k+1} \end{pmatrix} \quad (28)$$

The A_{k+1} matrix in expression (26) in the case of taking the measured value l equal to the value corrected after the network adjustment at period (k+1) will be:

$A_{k+1}^{T} = (\ E\ \ 0\ \ 0\ )$..

Here: $E_{(kxk)}$ - Unit matrix , k- number of unknowns.

2.1.3. The covariance matrix of state vectors

From formula (24) we have:

$$R_{k+1}\hat{Y}_{\boldsymbol{k+1}} + b = 0 \quad (29)$$

$$R_{k+1} = \hat{A}_{k+1}^{T} K_{k+1}^{-1} \hat{A}_{\boldsymbol{k+1}} \quad (30)$$

$$b = \hat{A}_{\boldsymbol{k+1}}^{\mathbf{T}} K_{k+1}^{-1} L_{\mathbf{k+1}} \quad (31)$$

The Gain matrix will be:

$$G_{\mathbf{k+1}} = K_{\bar{Y}(\mathbf{k+1}} A_{k+1}^{T} \ (K_{l,k+1}^{-1} + A_{k+1} K_{\bar{Y}(\mathbf{k+1}} A_{k+1}^{T})^{-1} \quad (32)$$

The state vector at time t_{k+1} will be:

$$\hat{Y}_{k+1} = \bar{Y}_{k+1} + G_{k+1}\ (l_{k+1} - A_{k+1}\ \bar{Y}_{k+1}\ ) \quad (33)$$

From expressions (26),(28) and (30) we have:

$$R_{k+1} = K_{\mathbf{l},k+1}^{-1} + A_{k+1}^{T} K_{l,k+1}^{-1}\ A_{k+1} \quad (34)$$

The covariance matrix of the state vector $\hat{Y}_{k+1}$ will be:

$$R_{k+1} = K_{l,k+1}^{-1} + A_{k+1}^{T} K_{\mathbf{l,k+1}}^{-1}\ A_{k+1} \quad (35)$$

Following the recurrence formula (Markuze, YI, Hoang H.,1991), we have the expression:

$$(K_{\bar{Y}(\mathbf{k+1})}^{-1} + A_{k+1}^{T} K_{\mathbf{l,k+1}}^{-1}\ A_{k+1})^{-1} = K_{\bar{Y}(\mathbf{k+1}} - K_{\bar{Y}(\mathbf{k+1}} A_{k+1}^{T} N^{-1}\ A_{k+1}\ K_{\bar{Y}(\mathbf{k+1})} \quad (36)$$

1

The matrix: $\mathrm{N} = (\mathrm{K}_{l,k+1}^{-1} + \mathrm{A}_{\mathrm{k+1}}\mathrm{K}_{\bar{\mathrm{Y}}(\mathbf{k+1}}\mathbf{A}_{\boldsymbol{k+1}}^{\mathbf{T}})$.

Combining the expressions (32),(35),(36) we have the covariance matrix of the state vector at time t_{k+1} which will be::

$$\mathrm{K}_{\mathrm{k+1}} = \mathrm{K}_{\bar{\mathrm{Y}}(\mathbf{k+1}} - \mathrm{G}_{\mathrm{k+1}}\,\mathrm{A}_{\mathrm{k+1}}\,\mathrm{K}_{\bar{\mathrm{Y}}(\mathbf{k+1})} \qquad (37)$$

2.2. Analysis of displacement

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

- Input:
  - Geodetic Datum
  - Priori coordinates of GNSS points
  - GNSS observations.
- Output
  - Estimated value of coordinates of GNSS points
  - RMS error

Step 2: Calculate the parameters dX, dY, dZ, v_X, v_Y, v_Z, a_x, a_Y, a_Z over the periods according to the formulas (19)-(37)

Step 3: Displacement analysis based on statistical criteria

Step 4: Calculate the forecast vector and compare it with the calculated value from the measurement

3 EXPERIMENT AND RESULT

3.1. GNSS networks adjustment in the geocentric coordinate system WGS-84.

To study the shifting activities of the southern region of Vietnam, a monitoring network has been established including 8 points, measured by GNSS technology. 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.The experimental area was carried out in Ba River area, in the Central region - Central Highlands of Vietnam. Repeat measurement for 4 cycles 2015, 2016, 2017 and 2018, time interval between cycles is one year. Figure 1, the location of the monitoring landmarks of the study area is shifting.

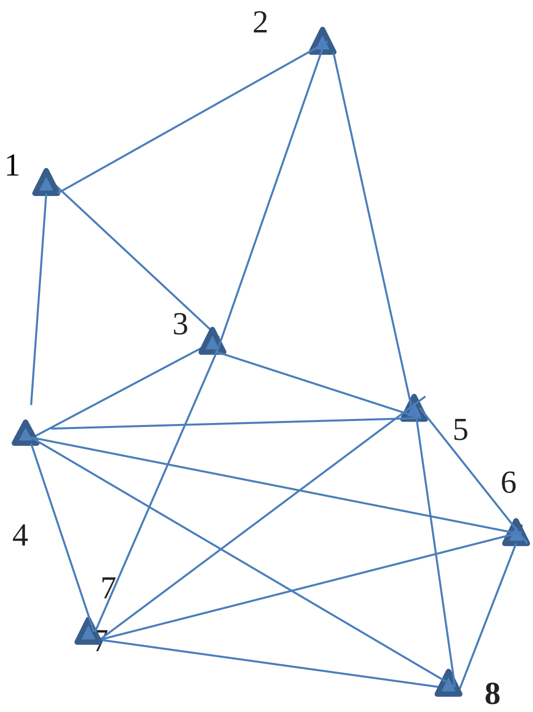

Figure 1. GNSS network Diagram

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 1-j (j- number of cycle):$T_X=dX/m_{d\backslash x}$, $T_Y=dX/m_{d\backslash Z}$, $T_Z=dZ/m_{d\backslash Z}$ .Check the Criteria (t-dítribution) (Ghilani, C., Wolf, P:,(2017)): $|T_X| < q_X$, $|T_Y|<q_Y$,$|T_Z| < q_Z$,. 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 8 points have shifted.

3.2. Calculation of displacement parameters

In the second cycle, we only calculate the displacement of the coordinates of the points and the displacement velocity. The calculation results are presented in Table 1 .

Table 1 . Displacement parameters dX, dY, dZ , $v_{X,}$, v_Y, v_Z a_X, a_Y,a_Z between 2015 and 2016.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8
dX(m)	-0,020	-0,035	-0,025	-0,024	-0,024	-0,009	-0,018	-0,018
dY(m)	-0,027	-0,012	-0,037	-0,034	-0,026	-0,036	-0,064	-0,031
dZ(m)	-0,024	-0,020	-0,028	-0,031	-0,026	-0,024	-0,035	-0,018
$v_{X(m/yeear)}$	-0,024	-0,042	-0,030	-0,0292	-0,029	-0,011	-0,022	-0,022
$v_{Y(m/yeả)}$	-0,032	-0,014	-0,044	-0,041	-0,032	-0,043	-0,077	-0,038
$v_{Z(m/yeear)}$	-0,029	-0,024	-0,034	-0,037	-0,031	-0,028	-0,041	-0,021

Continue to calculate for cycles 2-3 and 3-4 according to the formulas (19)- (37). Results: $dX_{1j}=X_j-X_1$, $dY_{1j}=Y_j-Y_1$, $dZ_1j= Z_j-Z_1$ (j- number of measurement cycles) for 8 points, and calculate velocitis and accelerations. The index 1 is the value at the first cycle. Calculation results are shown in Tables 2 and 3.

Table 2 . Displacement parameters dX, dY, dZ and $v_{X,}$, v_Y, v_Z between 2015 and 2017.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8

dX(m)	-0,050	-0,06	-0,043	-0,055	-0,048	-0,040	-0,031	-0,041
dY(m)	-0,013	0,008	-0,043	-0,036	-0,024	-0,032	-0,067	-0,033
dZ(m)	-0,034	-0,026	-0,037	-0,044	-0,037	-0,048	-0,050	-0,027
$v_{X(m/yeear)}$	-0,035	-0,021	-0,015	-0,034	-0,024	-0,042	-0,010	-0,026
$v_{Y(m/yeå)}$	0,0339	0,035	0,010	0,014	0,017	0,024	0,027	0,013
$v_{Z(m/yeear)}$	-0,002	0,001	0,001	-0,006	-0,005	-0,024	-0,006	-0,005
$a_{X(m/yeear^2)}$	-0,010	0,009	0,006	-0,006	-0,000	-0,022	0,005	-0,005
$a_{Y(m/yeear^2)}$	0,040	0,031	0,031	0,032	0,029	0,040	0,061	0,029
$a_{Z(m/yeear^2)}$	0,015	0,014	0,019	0,016	0,014	-0,000	0,019	0,010

Table 3 . Displacement parameters dX, dY, dZ , $v_{X,}$, v_Y, v_Z a_X, a_Y,a_Z between 2015 and 2018.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8
dX(m)	-0,077	-0,089	-0,070	-0,082	-0,074	-0,076	-0,063	-0,082
dY(m)	-0,041	-0,022	-0,065	-0,070	-0,041	-0,043	-0,078	-0,032
dZ(m)	-0,050	-0,037	-0,048	-0,057	-0,045	-0,063	-0,061	-0,031
$v_{X(m/yeear)}$	-0,031	-0,025	-0,025	-0,029	-0,026	-0,045	-0,032	-0,044
$v_{Y(m/yeå)}$	0,074	-0,027	-0,014	-0,027	-0,010	0,000	0,010	0,012
$v_{Z(m/yeear)}$	-0,011	-0,006	-0,0100	-0,006	-0,002	-0,015	-0,002	0,000
$a_{X(m/yeear^2)}$	-0,003	0,003	-0,001	-0,001	-0,001	-0,013	-0,008	-0,012
$a_{Y(m/yeear^2)}$	0,040	-0,014	0,005	-0,003	0,002	0,009	0,023	0,015
$a_{Z(m/yeear^2)}$	0,004	0,004	0,008	0,008	0,009	0,004	0,012	0,007

The calculation results of displacement parameters of 8 points in the GNSS network in unstable areas can help geologists analyze the hazard level of the study area. n the study also consider the problem of displacement prediction. From the calculation results, the displacement parameters of the 3rd period will determine the forecast vector of the fourth period and compare with the adjusted vector in the table 3. The comparison results show that for the X-axis, the difference is between 10mm and 25 mm, and the Z-axis is from 4 to 21 mm. Particularly for the Y-axis, the biggest difference is up to 80mm. However, the forecast vector accurately reflects the actual displacement trend, so this result can be preliminary ninformation for consideration of risk prevention for dangerous fault zones.

4. SUMMARY AND CONCLUSION

In the paper, we continue to study the problem of applying free variance theory and dynamic model, based on Kalman filter theory to study displacement in Ba River area in the central-highlands of Vietnam. In the spatial model, using the GNSS measurement results in 4 cycles allows to determine the 3D displacement vector as well as the displacement speed and velocity parameters. Such an approach allows a full assessment of the displacement picture of an unstable region in central Vietnam.

The content of the proposed methodology includes: Free network adjsttment in each cycle, statistical analysis, calculation of displacement parameters, and a predictive vector for the next cycle.The experimental calculation results allow to determine the displacement parameters in the Ba River region in the central region - Central Highlands of Vietnam.

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