International Journal of Remote Sensing and Earth Sciences Vol. 15 No. 2 December 2018: 167-176

GEOMETRIC ASPECTS EVALUATION OF GNSS CONTROL NETWORK FOR DEFORMATION MONITORING IN THE JATIGEDE DAM REGION

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Received: 2 February 2018; Revised: 14 March 2018; Approved: 6 December 2018

Abstract. Many factors led to dam construction failure so that deformation monitoring activities is needed in the area of the dam. Deformation monitoring is performed in order to detect a displacement at the control points of the dam. Jatigede Dam deformation monitoring system has been installed and started to operate, but there has been no evaluation of the geometry quality of control networks treated with IGS points for GNSS networks processing. Therefore, this study aims to evaluate the geometric quality of GNSS control networks on deformation monitoring of Jatigede Dam area. This research data includes the GNSS measurements of five CORS Jatigede Dam stations (R01, GG01, GCP04, GCP06, and GCP08) at doy 233 with network configuration scenarios of 12 IGS points on two quadrants (*jat1*), three quadrants (*jat2*), and *four* quadrants (*jat3* and *jat4*). GNSS networks processing was done by GAMIT to obtain baseline vectors, followed by network processing using parameter method of least squares adjustment. Networks processing with least squares adjustment aims to determine the most optimal by precision and reliability criterion. Results of this study indicate that network configuration with 12 IGS stations in the two quadrants provides the most accurate coordinates of CORS dam stations. Standard deviations value of CORS station given by jat1 configuration are in the range of 2.7 up to 4.1 cm in X-Z components, whereas standard deviations in the Y component are in the range 5.8 up to 6.9 cm. An optimization assessment based on network strength, precision, and reliability factors shows optimum configuration by *jat1*.

Keywords: *Jatigede dam, control network, IGS, GNSS*

1 INTRODUCTION

Jatigede Dam is built on Baribis Thrust which is an intensive and complex tectonic geological structure that causes the level of the dam vulnerability to movement and landslide is increasing (Zakaria, *et al.*, 2011).

Based on the Center for Volcanology and Geological Hazard Mitigation in 2006, Baribis Fault is one of the active faults that potentially produce devastating earthquakes and is in the zone VII of Indonesia's area earthquake prone (Zakaria, *et al.*, 2011).

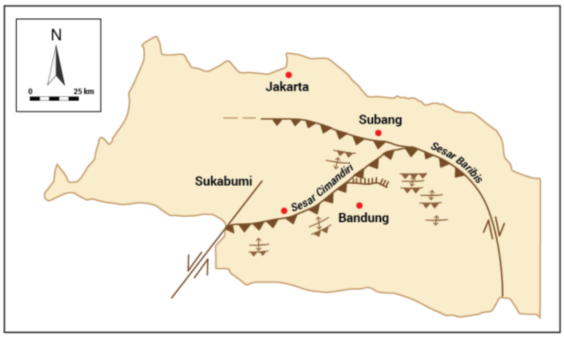


Figure 1-1: Regional Baribis-Cimandiri thrust in West Java (Haryanto, 2001).

One of the efforts to maintain safety of dam construction is to monitor the geometric aspects of the dam

http://dx.doi.org/10.30536/j.ijreses.2018.v15.a2901

deformation. Deformation monitoring is an effective method for analyzing deformation characteristics that occurred in the dam area, and also capable to provide warning systems when there are abnormal symptoms of dams (Cetin, *et al.*, 2000).

Dam deformation monitoring is conducted by using integration of several interrelated disciplines. Geodetic science can contribute in position data recording techniques which used to create an integrated detection system and movement monitoring that occur to dam using permanently installed multi sensors in dam areas. Geodetic sensors implemented are Global Navigation Satellite System (GNSS) and Robotic Total Station (RTS) that work in accordance with their respective functions. Furthermore, the sensor's measurement data are integrated into a system so it could be accessed for practical and scientific purposes (Sunantyo, *et al.*, 2012).

According to Kuang (1991), one of the major aspects of deformation monitoring is geodetic observation network optimization. Optimal means that the control network condition have satisfied the precision quality standards. Control network optimation could be assessed by monitoring observational data of deformation and controlled by IGS point observation data in some IGS distribution scenarios in the quadrant (Nursetiyadi, 2015). Selection of GPS networks with a good strength of figure and satisfied the reliability criteria are required to achieve optimal position accuracy (Lestari and Yulaikhah, 2013). To obtain good GNSS network geometry, constraining to IGS active stations is needed (Panuntun, 2012; Artini, 2014; and Nursetiyadi, 2015). GNSS network processing is necessary to select an equally distributed IGS stations by data quality, data availability, and good network configuration to obtain precise and consistsent station coordinate (Ma'ruf and Rahman, 2008).

Determination of the optimal network monitoring should be done before the installation of monitoring sensors deformation, but the assessment of network optimization remains to be done after the installation of the equipment. Quality assessment of GNSS network is necessary due to the importance of Jatigede Dam. An assessment of geometrical aspect qualities on Jatigede dam monitoring network was done by processing the observation data of GNSS stations and involving the observation data of IGS stations. The quality assessment of GNSS and IGS control network configuration scenarios were conducted by precision and reliability aspects of the network.

2 MATERIALS AND METHODOLOGY

2.1 Data and Tools

Data used in this study were GNSS measurements of five CORS Jatigede Dam stations (R01, GG01, GCP04, GCP06, and GCP08) at *doy* 233 with a network configuration scenario of 12 IGS points on two quadrants (*jat1*), three quadrants (*jat2*), and four quadrants (*jat3* and *jat4*). Other data involved in this study is the observation of 18 IGS points for each configuration on 20 August 2016 (*doy* 233).

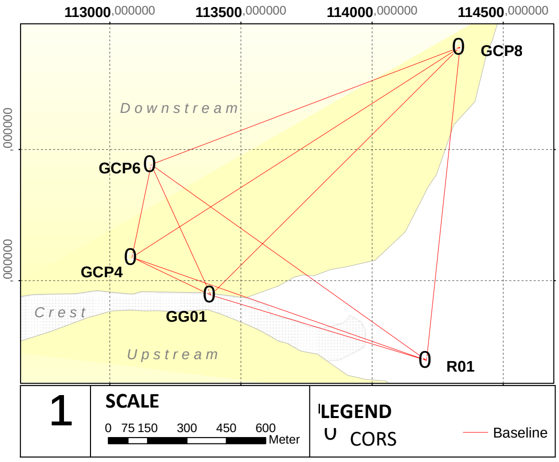


Figure 2-1: Jatigede Dam GNSS control network.

2.2 Methods

Evaluation of control network was carried out on the scenario of GNSS network configurations in the Jatigede Dam Area by involving IGS stations. GNSS networks were processed by the principle of least squares adjustment to obtain the coordinate values of CORS station coordinates, as well as variance-covariance of parameters and observations to compute the precision and reliability of network.

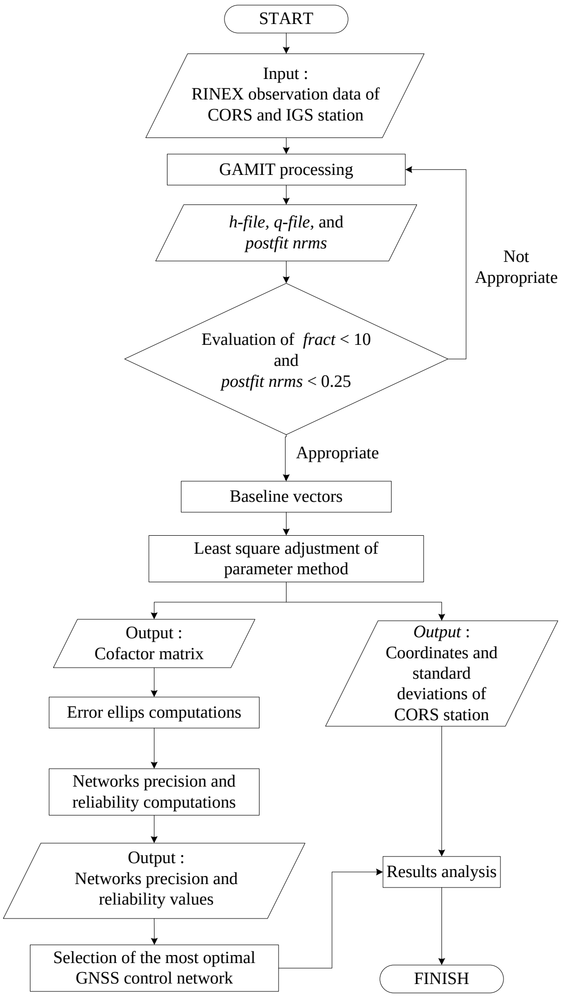
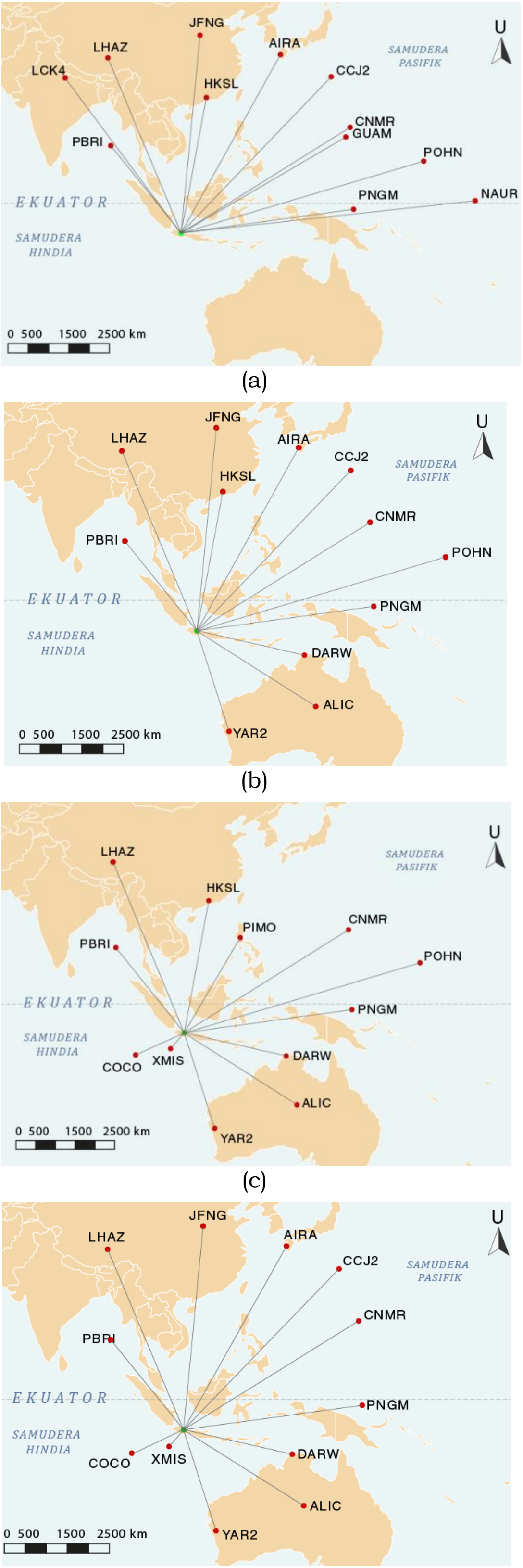


Figure 2-2: Research workflow.

Figure 2-2 shows that GNSS network processing initiated by IGS network establishment to four network configurations consists of 12 IGS points on each network. Network configuration was designed on horizontal projection plane with the division of the quadrant as in Figure 2-3.



(a)

(b)

(c)

(d)

Figure 2-3: Network configuration *jat1* (a), *jat2* (b), *jat3* (c), and *jat4* (d)

Network configurations in Figure 2-3 are *jat1*, *jat2*, *jat3*, and *jat4*. *Jat1* network was established based on IGS position in two quadrants at the north of dam area. *Jat2* network was designed based on IGS position in three quadrants. *Jat3* and *jat4* networks was designed based on IGS position in four quadrants.

GNSS configuration networks was followed by quality checking of CORS station observation data with TEQC. TEQC has main functions to translate, edit, and check observation data quality. Data that has been checked with TEQC is prepared for data processing with GAMIT. GAMIT processed uses least squares adjustment to determined estimate position of GNSS station, orbit and rotation parameters, and phase ambiguity (Lestari, 2006). This process produced network baselines vectors and the quality parameter of *postfit nrms* and *fract.*

Baseline vectors that has been generated from GAMIT processing were used in the least squares adjustment parameter method of the control network to obtain coordinate values and precision of each station in dam area. Least squares adjustment parameter method was used to determining information or measurements of the parameter from geodetic observation data. Processing with least squares adjustment was done by determining amount of measurements (baseline), amount of parameters, and weight of the measurements.

Least squares adjustment computation was initiated by determining amounts of measurement (baseline) and amount of parameters of *jat1*, *jat2*, *jat3*, and *jat4*. The amount of measurements generated from each configuration is 210 baselines (ΔX_1, ΔY_1, ΔZ_1, ΔX_2, ΔY_2, ΔZ_2, ..., ΔX_{70}, ΔY_{70}, ΔZ_{70}). Formation of weight matrix was performed based on the standard deviation value of the baseline measurement between the CORS dam control station and IGS points. The adjustment process yields the desired parameter value ("X" matrix), residual value (matrix "V"), corrected measurement value ("Lb" matrix). Equation of measurement is computed by using mathematical relationship between parameter of measurement (approached coordinate) and observed value (baseline vector) such as (2-1) up to (2-3):

$$\Delta_{Xij} + v_1 = X_j - X_i \tag{2-1}$$

$$\Delta_{Yij} + v_1 = Y_j - Y_i \tag{2-2}$$

$$\Delta_{Zij} + v_1 = Z_j - Z_i \tag{2-3}$$

Δ_{Xij}, Δ_{Yij}, and Δ_{Zij} are baseline vector of point i to j, v_1 are residual value, and X_n, Y_n, and Z_n are coordinate values. The output is the coordinate value and precision of each control station in the dam area.

Quality of GNSS network configuration can be seen on 2D precision represented by absolute error ellipse. Absolute error ellipse computation was computed using standard deviation values of CORS coordinates using equations (2-4) and (2-5).

$$\sigma_{max}^2 = \frac{1}{2}\left[\sigma_x^2 + \sigma_y^2 + \sqrt{\left(\sigma_x^2 - \sigma_y^2\right)^2 + 4\sigma_{xy}^2}\right] \tag{2-4}$$

$$\sigma_{min}^2 = \frac{1}{2}\left[\sigma_x^2 + \sigma_y^2 - \sqrt{\left(\sigma_x^2 - \sigma_y^2\right)^2 + 4\sigma_{xy}^2}\right] \tag{2-5}$$

σ_{max} is semi major axis, σ_{min} is semi minor axis, and σ_{x}^2, σ_{y}^2 are variance of eigen value from variance-covariance of random vector matrix.

Network configurations quality also can be represented in network strength factor by considering the correlation between baseline vector component of GNSS network. Computation network strength factor in equation (2-6) was completed by the variance-covariance of parameters matrix that shows the influence of the configuration strength of network as deformation monitoring objective.

$$\begin{matrix}\text{Network}\\ \text{strength factor}\end{matrix} = \frac{trace(A^T C_L^{-1} A)^{-1}}{u} \tag{2-6}$$

$Trace(A^T C_L^{-1} A)^{-1}$ is summation of diagonal components of $(A^T C_L^{-1} A)^{-1}$ matrix, and u is ammount of parameters.

GNSS network precision and reliability were computed based on variance-covariance matrix of coordinates that had been generated from least squares adjustment. Precision criterion is performed by analysis of scalar function optimization criteria of A-optimality, D-optimality, and E-optimality. Computation of GNSS network optimization criteria of precision and reliability is completed by scalar function of network accuracy that are A-optimality, D-optimality, and E-optimality of eigen values for each configuration (Grafarend, 1974) are shown in equation (2-7) to (2-9).

A-optimality

$$trace\ (\sum xx) = \lambda_1 + \lambda_2 + \ldots + \lambda_n = min \qquad (2\text{-}7)$$

D-*optimality*

$$Det\ (\sum xx\ ) = \lambda_1 \times \lambda_2 \times \ldots \times \lambda_n = min \qquad (2\text{-}8)$$

E-*optimality*

$$\lambda_{maks} = min \qquad (2\text{-}9)$$

$\lambda_1, \lambda_2, \ldots, \lambda_n$ are eigen value of matrix $\sum$xx, and λ_{maks} are maximum eigen value from $\sum$xx matrix.

Network reliability analysis is completed by computations of individual redundancy value, internal reliability and external reliability. In accordance to Yalcinkaya and Teke (2006), the reliability of the control network is computed by equation (2-10) to (2-12).

Individual redundancy

$$Z = r_j = (Q_{VV})_j P_j \qquad (2\text{-}10)$$

Q_{VV} is cofactor matrix of the residuals, P is weight matrix of the observations, and r_j is individual redundancy value.

Internal reliability

$$Z = |\Delta_{0j}| = m_0 \sqrt{\frac{w_0}{p_j r_j}} \qquad (2\text{-}11)$$

m_0 is standard deviation of unit weight, w_0 is lower bound for the non-centrality parameter in dependency of the significance level (a_0) and the required minimum power of the test ($1\text{-}\beta_0$), and Δ_{0j} is internal reliability criterion.

External reliability

$$Z = \delta_{0j}^2 = \frac{1-r_j}{r_j} w_0 \qquad (2\text{-}12)$$

δ_{0j}^2 is external reliability criterion.

3 RESULTS AND DISCUSSION

3.1 GAMIT Processing Result

GAMIT processing resulted based on quality parameters of the process. There are *postfit nrms* and *fract* values. *Fract* values are shown in Figure 3-1 and *postfit nrms* values are shown in Figure 3-2.

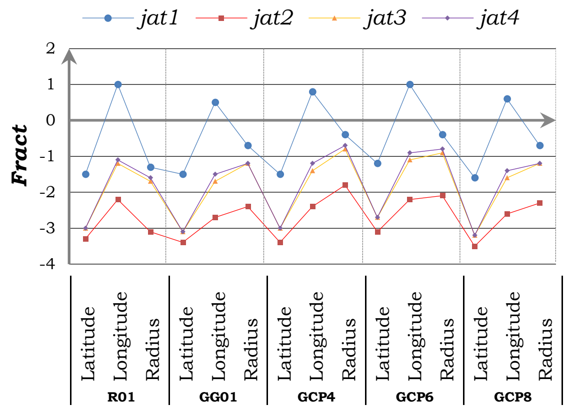


Figure 3-1: Visualization of *fract* values for each CORS stations.

Figure 3-1 shows *fract* values visualization for five stations in four IGS network configurations. *Fract* values were accepted if the value was less than 10. Figure 3-1 also explains variation of *fract* values were similar on each CORS. *Jat3* and *jat4* network configurations show relatively identical graph considering both networks were designed in four quadrants. *Jat3* and *jat4* configurations produce nearest value to zero in longitude and radius components of *fract*.

Table 3-1: Example of baseline vectors and their standard deviations.

No.	***Baseline***			**ΔX (m)**	**ΔY (m)**	**ΔZ (m)**	**$\sigma_{\Delta X}$ (cm)**	**$\sigma_{\Delta Y}$ (cm)**	**$\sigma_{\Delta Z}$ (cm)**
1.	GCP4	to	GCP6	-87.62512	34.02835	349.32539	0.722	1.753	0.467
2.	GCP4	to	GCP8	-1233.52942	-248.05762	790.88403	0.747	1.813	0.483
3.	GCP4	to	GG01	-290.80514	-77.19233	-146.75211	0.787	1.848	0.484
4.	GCP4	to	R01	-1069.1076	-345.08832	-395.18543	0.755	1.800	0.479
5.	GCP6	to	GCP8	-1145.9043	-282.08597	441.55864	0.58	1.413	0.374

Fract values indicated the absence of gross error. *Fract* also indicated that apriori coordinate values were appropriate and given constraints were correct.

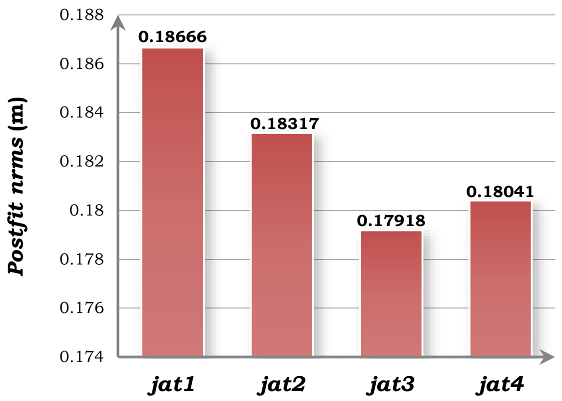


Figure 3-2: *Postfit nrms* values for each network configuration.

Figure 3-2 visualizes *postfit nrms* values for entire configurations of control networks. *Postfit nrms* values are acceptable if the value was less than 0.25 (Herring, *et al.*, 2006). The overall *postfit nrms* value are smaller than 0.25 that indicate the absence of cycle slips effects that have not been omitted. The smallest *postfit nrms* values are in *jat3* network that consist of IGS points deployment on four quadrants, while the highest *postfit nrms* value was in the *jat1* network that consist of IGS points deployment on two quadrants.

GAMIT processing resulted by baseline vector values between GNSS stations and their standard deviations. Generated baselines were used for least squares adjustment, whereas their standard deviations were used as weight of measurements. Some baseline vectors and their standard deviation values of each baseline were shown in Table 3-1.Table 3-1 shows the baseline vectors results of network processing by GAMIT and their standard deviations. Standard deviation value of baseline vectors is in fraction of millimeter up to a centimeter.

3.2 Least Squares Adjustment Result

Least squares adjustment computation generated CORS coordinates estimation and their standard deviations. Standard deviations of CORS coordinates are shown in Figure 3-3.

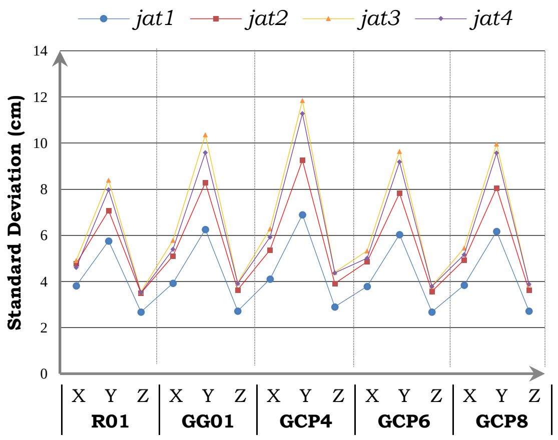


Figure 3-3: Visualization of standard deviations of CORS coordinates.

Based on standard deviations in Figure 3-3, *jat1* is network with highest coordinate precision compared to network configurations with IGS positions in four quadrants (*jat3* and *jat4* configuration). *Jat3* network shows widest range of standard deviations precision of 3.552 cm up to 11.86 cm, while *jat1* network has the smallest standard deviation range of 2.681 cm up to 6.903 cm. The Y component on the graph has a relatively high standard deviation values. Highest standard deviation that shown in Y component shows lowest precision among other components. X and Z components on each CORS had high precision with standard deviation value below 8 cm in each configuration. *Jat1* network shows highest coordinate precision compared to network configurations with IGS positions in four quadrants (*jat3* and *jat4*).

3.3 Absolute Error Ellipse of GNSS Network Result

Error ellipse was computed to represent 2D precision of each network configurations. Error ellipse results are presented in Table 3-2.Table 3-2 shows position precision of point represented by σ_{min} and σ_{max} values on the X and Y axes on networks. Value of σ_{min} and σ_{max} ellipse error have precision in centimeter fraction. Based on Table 3-2, *jat1* configuration was the network with smallest ellipse error among other configurations. Ellipse error values of each configurations are shown in centimeter fraction. Based on network purpose of detecting deformation in very small size, ellipse error values were still quite large. Network with a smaller ellipse error was needed as another strategy to obtain optimal deformation monitoring network.

3.4 Network Strength Factor Computation Result

Network strength factor is determined by the variance-covariance matrix. If the value of the network power factor is small, then the network is said to have good quality and vice-versa. The network strength factor results is shown in Table 3-3.

Tabel 3-3: Network strength factor of GNSS network configuration.

No.	Network Configuration	Network Strength Factor
1.	*jat1*	1.29×10^{-7}
2.	*jat2*	2.68×10^{-7}
3.	*jat3*	1.50×10^{-7}
4.	*jat4*	2.86×10^{-7}

Based on Table 3-3, it can be seen that configuration with IGS points in the four quadrants has a high dependence on the geometry of treated IGS network to CORS coordinates precision. Long distances between Dam GNSS control network and IGS locations are the factors that network geometry of IGS points in a particular quadrant determine the value of network strength factor. This makes *jat1* configuration with IGS points in the two quadrants is the best configuration.

Tabel 3-2: Ellipse error of GNSS network.

GNSS Station	*jat1*		*jat2*		*jat3*		*jat4*	
	σ_{max} (cm)	σ_{min} (cm)	σ_{max} (cm)	σ_{min} (cm)	σ_{max} (cm)	σ_{min} (cm)	σ_{max} (cm)	σ_{min} (cm)
R01	5.768	3.823	7.082	4.770	8.395	4.921	7.985	4.609
GG01	6.254	3.927	8.286	5.113	10.36	5.783	9.593	5.401
GCP4	6.903	4.109	9.264	5.375	11.86	6.286	11.29	5.926
GCP6	6.036	3.793	7.826	4.856	9.643	5.328	9.192	5.007
GCP8	6.182	3.842	8.066	4.936	9.96	5.458	9.57	5.162

Jat1 configuration is the best network in terms of dependence on IGS geometry because of the minimum network strength factor value that is 1.29 x 10^{-7}.

3.5 Precision and Reliability of GNSS Network

Analysis results of scalar function

This research used analysis results of scalar function optimization from criterion of precisions of A-optimality, D-optimality, and E-optimality. The minimum value on each computed precision criteria shows the best GNSS network quality among configurations. Values of network precision computation were shown in Table 3-4.

Tabel 3-4: Network configuration precision value.

Precision Function	*jat1*	*jat2*	*jat3*	*jat4*
A-*optimality*	**3.08 x 10^{-2}**	5.23 x 10^{-2}	7.43 x 10^{-2}	6.73 x 10^{-2}
D-*optimality*	**9.19 x 10^{-44}**	8.39 x 10^{-40}	1.01 x 10^{-37}	2.84 x10^{-38}
E-*optimality*	**6.42 x 10^{-3}**	9.99 x 10^{-3}	1.52 x 10^{-2}	1.38 x 10^{-2}

Table 3-4 represents the optimization criteria of the network from homogeneity and isotropy aspect of the configuration. The minimum A-optimality value was in *jat1* configuration with value of 3.08 x 10^{-2}, and maximum value was in *jat3* configuration with value of 7.43 x 10^{-2}. The A-optimality value indicated the homogeneity of a configuration so that *jat1* network was the best in terms of baseline homogeneity. The *jat1* network has relatively long baselines compared to *jat3* or *jat4* networks that has heterogeneous baseline length although *jat3* or *jat4* were established with IGS points deployment on four quadrants. Minimum value of D-optimality was found in *jat1* configuration with value of 9.19 x 10^{-44}, while the maximum value was in the *jat3* configuration with a value of 1.01 x 10^{-37}. E-optimality criteria of *jat1* configuration shows lowest value of 9.69 x 10^{-3}, whereas the *jat3* configuration has the highest value of 1.52 x 10^{-2}. The minimum D-optimality value represents the isotropic configuration, that showed the network physical character in all directions.

Individual redundancy value indicated an unreliable measure of gross errors in network processing (Kuang, 1991). Individual redundancy value was derived from the diagonal element of residual cofactor matrix that has been generated by least squares adjustment. Individual redundancy for network baselines on average between the CORS on each configuration visualized in Figure 3-4.

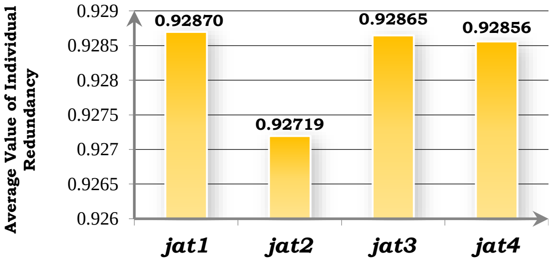


Figure 3-4: Average individual redundancy.

Figure 3-4 shows individual redundancy values of network configuration. Network have satisfied the criterion of critical value that was greater than 0.4. *Jat1* configuration has the highest average individual redundancy compared to *jat2*, *jat3*, and *jat4* networks. Figure 3-4 shows that *jat1* network was the most optimal network considering the individual redundancy aspect. This result implied that *jat1* network has the best ability to detecting small gross errors in network processing.

Internal reliability of control network illustrates the quality that refers to the minimum limit of gross errors that can be detected on numerous observations for the given probability value of error (Kuang, 1991). Internal reliability has critical value of less than $6m_j$ that expressed by Marginally Detectable Error (MDE). Internal reliability computation of GNSS network baselines visualized in Figure 3-5.

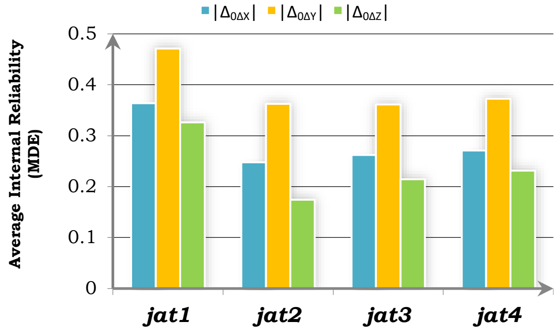


Figure 3-5: Average internal reliability value.

Figure 3-5, shows average values of networks internal reliability of each baseline components. Maximum reliability value is shown in Y $(|\Delta_{0\Delta Y}|)$ component, while the minimum reliability value is shown in component Z $(|\Delta_{0\Delta Z}|)$. Configuration with maximum internal reliability value indicates low sensitivity to gross error. The maximum value of internal reliability shows less reliable observation, while the minimum reliability value indicates high sensitivity to gross errors. Visualization of internal reliability shows that most reliable network configuration is *jat1* network.

External reliability of networks refered to results of individual redundancy computation. In this study, the expected external reliability value was above the critical value of less than **6**. This value was expressed in Bias to Noise Ratio (BNR). Results of external reliability computation on GNSS network baselines are visualized in Figure 3-6.

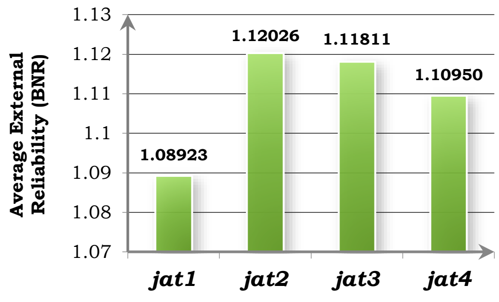


Figure 3-6: Average external reliability value.

Based on Figure 3-6, it can be seen the average value of external reliability of each baseline components on each GNSS networks. Computation of average external reliability on entire components shows that *jat1* network produced the lowest average value compared to the configuration of *jat2*, *jat3*, and *jat4*. The graph shows that the *jat1* network has the smallest effect that has been caused by the presence of an undetectable random error on GNSS observations in network processing.

4 CONCLUSION

GNSS network configurations with IGS positions in two quadrants (*jat1*) is the highest precision network based on estimated coordinates. Utilization of IGS stations in network processing was able to generate precision on X and Z components in the range of 2.7 up to 4.1 cm, while on the Y component the precision is in the range 5.8 up to 6.9 cm.

Optimization assessment of GNSS network configurations shows that Jatigede CORS network is precise and reliable for deformation monitoring by network processing with deployment of IGS station data in *jat1* configuration. Cconfiguration of 12 IGS stations in two quadrants (*jat1*) produced the best network based on network strength, precision, and reliability. *jat1* configuration is able to generate minimum value on network strength factor and external reliability while providing maximum value on individual redundancy values. This result shows that network processing of network that established by IGS stations deployment on two quadrants is more optimal than network processing of network that established by IGS stations deployment IGS stations deployment on of three and four quadrants (*jat3* and *jat4*).

ACKNOWLEDGEMENTS

The authors would like to "Satuan Kerja Non Vertikal Tertentu" of Jatigede Dam dan Leica Geosystems Indonesia for helping this research. The authors thank all the parties who helped provide advices and assistances during the implementation of research.

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