Evaluating GPS CORS Data for Crustal Deformation Analysis in East Java

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Abstract—**Pollution The tectonic setting of Indonesia is very complex due to its location on the boundaries of several major tectonic plates. The complexity of the tectonics also makes Indonesia prone to natural disasters such as earthquakes, tsunamis, volcanic eruptions etc. Crustal deformation caused by the tectonics activities can be monitored using geodetic techniques such as Global Positioning System (GPS) survey, Interferometry Synthetic Aperture Radar (InSAR) processing, etc. In this research, we analyze the crustal deformation in the northern part of East Java using ten GPS Continuously Operating Reference Stations (CORS) data provided by the Indonesian Geospatial Information Agency from 2015 to 2018. The results showed the horizontal movement toward southeast for all the stations. The horizontal velocity rates are range between 2.63 cm/yr and 2.96 cm/yr. For the vertical displacements, nine stations are subject to subsidence with the rates range from -0.021cm/yr to -0.4 cm/yr that we suspect related to the geological settings of the study area.**

Keywords— **GPS CORS, Crustal Deformation, Velocity Rate, Strain Analyzes, GPS CORS Stations**

I. INTRODUCTION

INDONESIA is located at the confluence of three large tectonic plates namely the Eurasia plate in the north, Indo-Australian plate in the south and the pacific plate in the eastern part of the archipelago, the relative movement of the three mega plates define distinct subduction collision system in Indonesi [1]. According to [2],the subduction zone is the most seismically active zone of the world. On the other hand, the interaction between plates form Sunda Arc also known as volcanic arc made Sumatra island, Java island, Sunda strait and Lesser Sunda Island [3]. The complexity of the tectonics also makes Indonesia prone to natural disasters such as earthquakes, tsunamis, volcanic eruptions etc. Among these natural disasters, Earthquake is a big menace to Indonesia.

The subduction active zone in south part of Java is a meeting zone between the Indo-Australian plate and the Eurasian plate [4]. These plates meet at the bottom of the Indian ocean and move towards north [5]. East Java is an area that has a lot of seismic activities in the south. The earthquake that occurred in East Java was generally caused by subduction zone in the south of Java. According to USGS, more than 180 earthquakes of magnitude between 2.5 and 7 have been recorded in East java from the year 2015 to 2018 and most of the quakes occurred in south part of East Java.

The impact of seismic activities on the three mega plates, among others, is the earthquake magnitude whose frequency tends to increase from year to year. In this zone the deformation of the earth's crust is caused by the interaction of tectonic plate movements and seismic activities as the result, the position of a point can change dynamically [5]. In their research, [6] identified the large compressional strain in the east-west of Madura strait and suggested that, that strain is related to the kendeng fault which is an active fault from the central part of central java eastward to Madura strait. Again, the strain rate estimated by the above research suggested that the Indonesian big cities such as Jakarta is near Jakarta fault, while Surabaya and Semarang cities are near the kendang fault. Recent study has revealed the existence of earthquake source in East Java region that comes from Kendeng fault. The fault proved still active with movement of about 5 mm/yr.

Several techniques such as seismic soundings, strain-meter readings modern and classic geodetic methods have been used to analyze the crustal motion and deformation. Among modern geodetic methods, space geodesy plays an important role in crustal deformation studies. These techniques are satellite-based technologies Global Navigation satellite system represented by GPS and GLONASS. Currently, the Continuous GPS measurements and the Interferometric Synthetic Aperture Radar are used in determining the components of crustal deformation. However, GPS is the most significant method because it provides high observation precision, can provide observation with few mm precision, 1mm horizontal and 3mm vertical components deformation [7]. The positioning satellite-based technology in this research is the Global Navigation Satellite System Continuous Operating Reference System GNSS CORS or GPS CORS. CORS is a GNSS system which operates continuously for 24 hours as reference to positioning with a high level of accuracy.

In Indonesia CORS stations are also called Indonesia permanent GPS stations and those stations are used for deformation and geodynamics Survey. CORS record data 24 hours a day. An addition to that, it is placed and installed in an open space or in a free obstacles area to minimize the multipath effects on the observation. Generally, CORS is used as a reference in controlling the geodetic networks spread throughout the Indonesian islands [8]. CORS has a high level of rigidity that is often used as a base for binding and processing baselines. The position of the point that has been tied to CORS, can be seen whether there has been a change or not, and the magnitude of the change in position that occurred. The movement of the Indian and the Eurasian plates could affect the position of CORS in East Java. By means of the Ina-CORS observation stations namely CLMG, CMJT, CNGA, CPAI, CPAS, CSBY, CSIT, CSMN, CSMP, CTBN, this research provide the current information on deformation in the study area and interpreted as the change in position of the stations and the velocity of the shift arising from tectonics and the kendang fault activities in the North east of java. GPS data from the Ina-CORS observation station processed using scientific software, GAMIT / GLOBK 10.7 and GMT (Generic Mapping Tools) for plotting the calculation results in the form of a shift direction map[9]

II. METHOD

A. Study Area

This study was conducted in East Java in its northern part which includes the cities where GPS CORS are installed. The inaCORS are installed in Lamongan (CLMG), Mojokerto (CMJT), Nganjuk (CNGA), Paiton (CPAI), Pasuruan (CPAS), Surabaya(CSBY), Situbondo(CSIT), Sampang(CSMP), Sumenep(CSMN) and in Tuban(CTBN)

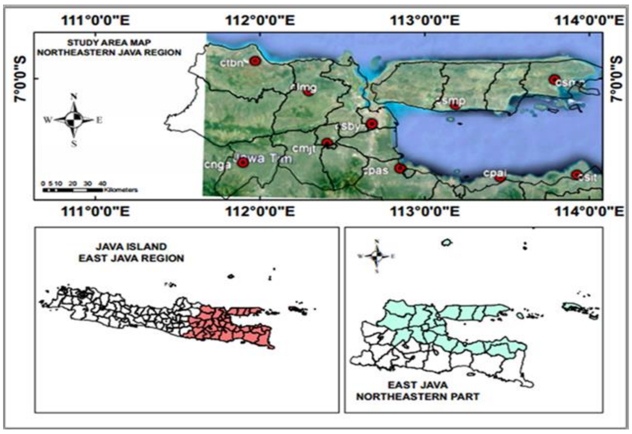

Figure 1. Study Area Map

Based on its seismicity history, Java Island is dominated by earthquakes related to subduction zone and to the faults [10]. In past two decades, four earthquakes have occurred in this area and have caused significant damage. These earthquakes are the East Java tsunami earthquakes with Mw 7.6 occurred in 1994, earthquake with magnitude 7.7 occurred in 2006 and the west java earthquake Mw7.0 in 2009, an addition to those earthquakes is the significant tsunami earthquake with Mw 7.5 occurred in 1921. Within a period 2009 to 2015, the seismic activities that still occur in java island are found around the earthquake location of 1994 to 2006. The tsunami earthquake of 1994 is unique with thrust earthquake mechanism and followed by an aftershock whose most of the mechanisms are normal faults.

In east Java, more than 180 earthquakes of magnitude between 2.5 and 7 were recorded by the USGS .in east and most of these earthquakes are related to the subduction zone in the southern part of the Java because many earthquakes occurred in southeastern part of east Java. In their research, [6] identified the large compressional strain in the east-west of Madura strait and suggested that, that strain is related to the kendeng fault which is an active fault from the central part of central Java eastward to Madura strait. Again, the strain rate estimated by the above research suggested that the Indonesian big cities such as Jakarta is near Jakarta fault, while Surabaya and Semarang cities are near the kendang fault which passes through southern outskirts of Surabaya and traverses a 300km length westward of east Java. This study aimed to determine the movement of CORS BIG stations relative to the fault mentioned above.

B. Data Acquisition and Processing

Based on the research title, this study is aimed to analyze the deformation in the northeastern part of Java using GPS CORS data from 10 stations namely CLMG, CMJT, CNGA, CPAI, CPAS, CSBY, CSIT, CSMN, CSMP and CTBN located in study area. We also used GPS observation data from 17 IGS stations namely AIRA, ALIC, BAKO, COCO, DARW, IISC, JOG2, KARR, KAT1, MRO1, NAUR, PIMO, SOLO, TOW2, XMIS and YAR2. The observations data of four year, 2015 2016 2017 and 2018 were used together with brdc file that contains precise ephemeris data, precise igs orbits file in igs sp3 format, meteorological file for meteorological modeling, Ionospheric file for ionospheric modeling. The data mentioned above is acquired by different ways, here the rinex observations data for GPS CORS were provided by the Indonesian geospatial information agency also known as BIG while rinex observation data for IGS stations, navigation data, precise ephemeris data, meteorological and ionospheric data is downloaded from Scripps Orbit and Permanent Array Center (SOPAC) data archives using GAMIT command sh_get_nav, sh_get_orbits, sh_get_met, sh_get_ion [11]. Besides that, three other important data used in the processing are used in this paper are the ocean tide model FES2004 has been used for the removal of contributions from ocean tidal loads at the site locations, the atmospheric modelling data (atmdisp_cm.YYYY) and weather modelling data (vmf1grid.YYYY) downloaded at ftp://everest.mit.edu/pub/GRIDS.

In this paper we used GPS continuous reference stations and GAMIT, version 10.7 to derive the loosely constrained site coordinates. GAMIT is used to produce estimates and an associated covariance matrix of station positions and (optionally) orbital and Earth-rotation parameters which are then input to GLOBK to estimate positions and velocities. The site position estimates and their rates were estimated in ITRF2008 by stabilizing more stable continuous sites and core IGS reference sites using GAMIT/GLOBK, GLORG. GPS data processing or network alignment using GAMIT use double difference technique, here computations are done by means of the principle of the least squares calculated weighted parameters.

For example, measurements using two points measurement data observations (A) and (B) and two satellites (i) and (j). Distance formed from two the observation points are shown in equations 1 and 2

The following equation is an example of measurement using data from two observation points A and B, and two GPS satellites (i) and (j), the observation equation is:

$$\rho_A^i\sqrt{[X^i(t)-X^A]^2+[Y^i(t)-Y^A]^2+[Z^i(t)-YZ^A]^2} \quad (1)$$

$$\rho_B^j\sqrt{[X^j(t)-X^B]^2+[Y^j(t)-Y^B]^2+[Z^j(t)-Z^B]^2} \quad (2)$$

With the coordinates of the observation point (A) approach is (X_A^O, Y_A^O, Z_A^O) then the coordinates of the observation station (A) are determined by equation 3

$$X_A = X_A^O + dX_A$$
$$Y_A = Y_A^O + dY_A \quad (3)$$

$$Z_A = Z_A^O + dZ_A$$

After the linearization process is carried out, the equations 1 and 2 become equation 4

$$\rho_A^i = \rho_A^{i0} + cx^i(t)dX_A + cy^i(t)dY_A + cz^i(t)dZ_A \quad (4)$$

$$\rho_B^j = \rho_B^{j0} + cx^j(t)dX_B + cy^j(t)dY_B + cz^j(t)dZ_B \quad (5)$$

Where

cx : The derivative equation of dX

cy : The derivative equation of dY

cz : The derivative equation of dz

By substituting the 4 equation in the double difference equation between observers and satellites, the double difference equation become the following [11]

$$\Delta\nabla L_{AB}^{ij}(t) = \Delta\nabla\rho_{AB}^{ij0}(t) + \nabla cx^{ij}(t)dX_A + \nabla cy^{ij}(t)dY_A + \nabla cz^{ij}(t)dZ_A + \lambda\Delta\nabla N_{AB}^{ij} + \Delta\nabla v C_{AB}^{ij}(t) \quad (6)$$

This double difference equation uses different phase data. Furthermore, do the least squares of weighted parameters to get the coordinates of the observer (A).

The results of observation data processing using GAMIT in the form of a biased solution fixed and bias free solution. This solution is obtained from a double difference calculation the phase difference data is done twice, which is fixed ambiguity and ambiguity float. Phase ambiguity is caused by the ambiguity of the number of full waves and not full recorded by a GPS receiver.

In this paper we analyzed the result of GAMIT processing by the post fit nrms value , this value must be less than 0.25 as the indication of good results means that effects of the cycle slips on the data were eliminated, further more we evaluated the results of the phase ambiguity wide lane and narrow lane to be greater than 80% and 70% respectively and the fract value must be less than 10 [11]. Fract value is a comparison between adjust values and formal values. Fract value is used to analyze whether there are odd and adjusted values the need for iterations to get an adjust value that is free of nonlinear effects. Adjust value indicates the amount of leveling given in the parameter count. While formal values indicate uncertainty in giving weight for the calculation of the least squares. Control of the quality of the fract value is that this rate should be less than 10. This is due to the fact that observations obtained with a GPS receiver is associated with some biases and errors and their impact affect the accuracy of the final results.

The calculation process on GLOBK is a Kalman Filter process to combine results solutions processing observation data. There are three main programs in GLOBK, namely GLOBK, GLRED, and GLORG. GLOBK is a Kalman Filter process for combine GAMIT's daily processing data and to estimate the average positions of the observation points. GLORG binds observation points of the given reference points. Whereas GLRED calculate the position of each day, so that accuracy of position obtained can be compared per time. In this study we tested the coordinates repeatability and evaluate the wrms by sh_glred -s <yyyy> <d1> <yyyy> <d2> -expt <expt> -opt H G E command that results in time series of CORS stations per year of observation. Example of sh_lred command used in this study sh_glred -s 2015 001 2015 365 -expt 2015 -opt H G E the results of this command are the cartesian and topocentric coordinates of the stations and their standard deviation as well as the time series plots in year 2015, the detail about this is discussed in the following section.

To evaluate results GLOBK processing can be seen in the log file and time series plot. Log file shows the consistency of daily data internally and used time series plots to see data outliers. Log files contain statistical values including standard deviation which is used for analysis of the processed coordinate values. While the plot time series displays values of weighted root mean square (wrms) and normal root mean square (nrms). A good wrms value and does not indicate data outliers are below 10 mm [11].

III. RESULT AND DISCUSSION

GPS observation data are subject to biases, in deformation

Table 1.
Cartesian Coordinates of CORS Stations

No.	Station	Cartesian coordinates			Standard deviation		StdZ(mm)
		X(m)	Y(m)	Z(m)	StdX(mm)	StdY(mm)	
1	CLMG	-2404552	5855181	-782302	0.00503	0.00969	0.00319
2	CMJT	-2414319	5845522	-823221	0.00502	0.00961	0.00312
3	CNGA	-2358757	5866022	-838479	0.00446	0.008	0.00299
4	CPAI	-2523479	5795189	-850974	0.00543	0.00965	0.00335
5	CPAS	-2460056	5823475	-843592	0.00552	0.01041	0.00354
6	CSBY	-2443858	5835258	-808826	0.00542	0.00933	0.00317
7	CSIT	-2572292	5773969	-849286	0.00718	0.01439	0.00405
8	CSMN	-2562324	5788981	-774150	0.00621	0.01132	0.00381
9	CSMP	-2498249	5814288	-793589	0.00488	0.0088	0.00318
10	CTBN	-2370863	5872094	-758114	0.0057	0.01117	0.00372

analysis it is very important to check the accuracy of the data to see if data are free of any error. In this study we access the quality of GPS data by results of GAMIT in postfit nrms and phase ambiguities results. The postfit nrms error results and phase ambiguity for sample days i.e.15 days are shown in Table 1. We access this using sample days because we processed all the days of the year, i.e. 365 days in 2015, 366 in 2016 and 365 in 2017 and 2018.

The postfit nrms value is less than 0.5 in all the four years this indicate that our results are ready to be used in GLOBK processing process. As for the phase ambiguity the wide lane (WL) value is greater than 80% and narrow lane value is greater than 70%, this is also good for the next process because it indicates that all the effects of the phase ambiguities and cycle slip were removed. This implies that our results meet the processing criteria.

The following step is to evaluate the coordinates repeatability, using GLOBK. we obtained the time series plot of every station for four year and the cartesian and topocentric coordinates of observation stations as well as their standard deviation per year of observation. In this paper we present the time series plot of on station, CLMG (lamongan CORS station). Figure 2 shows plots of coordinate repeatabilities for CLMG station in the year 2015.

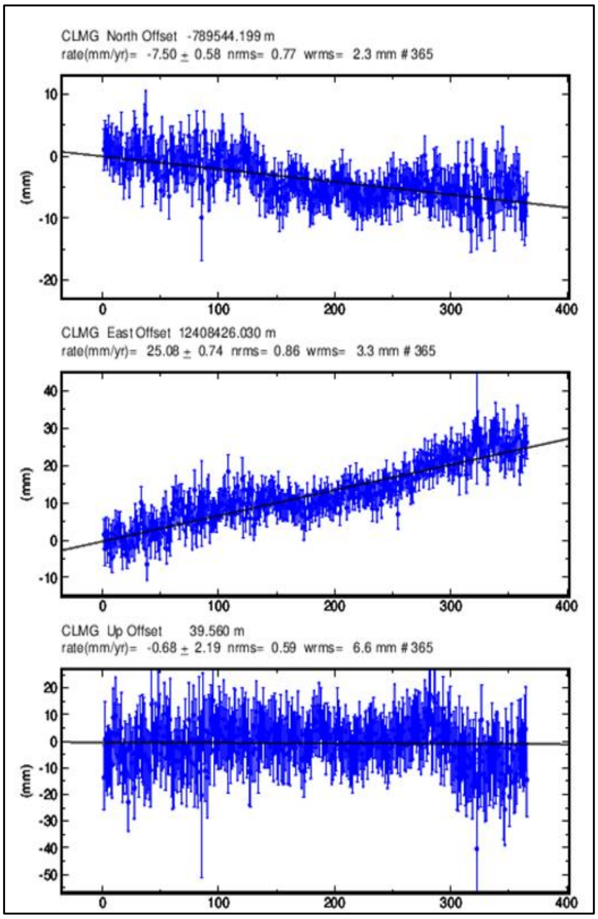

Figure 2. Time Series Plot For CLMG Station

In the Figure 2, the North offset WRMS is 3.3mm, 3.3mm for East offset and 6.6mm for the Up offset. The WRS are less than 10 which indicate that the data in 2015 do not contains the outliers. For the year 2016, we obtained plots of coordinate repeatabilities for CLMG station as shown in Figures 3.

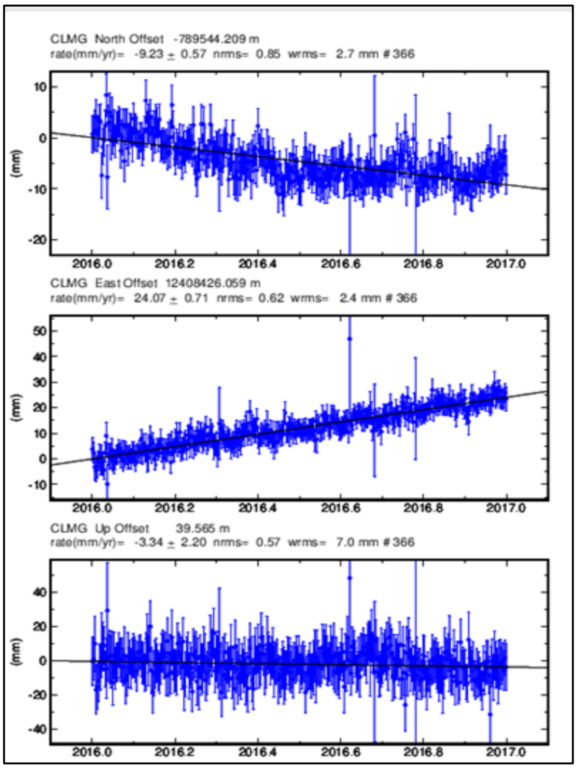

Figure 3. Time Series of CLMG in 2016

As shown in the above figure the WRMS for North offset is equal to 2.7mm, for East offset WRMS is 2.4mm and the WRMS for up offset in 2016 is 7.0mm. the WRMS value in 2016 is less than 10, this implies that there are no outliers in 2016 data. For the year 2017, we obtained plots of coordinate repeatabilities for CLMG station as shown in Figure 4

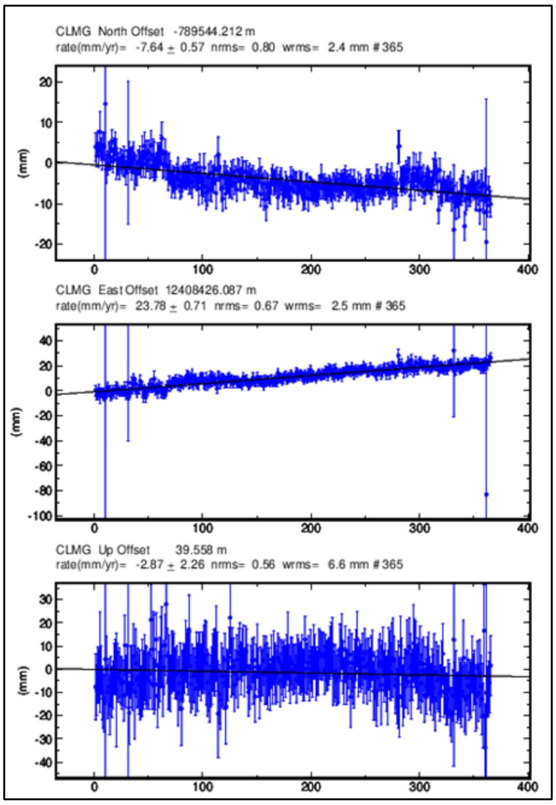

Figure 4. Coordinates Repeatability Plot of The Station in 2017

As shown in the Figure 4 the WRMS for North offset is equal to 2.4mm, for East offset WRMS is 2.5mm and the WRMS for up offset in 2017 is 6.6mm. the WRMS value in

2016 is less than 10, this implies that there are no outliers in 2017 data. For the year 2018, we obtained plots of coordinate repeatabilities for CLMG station as shown in Figure 5.

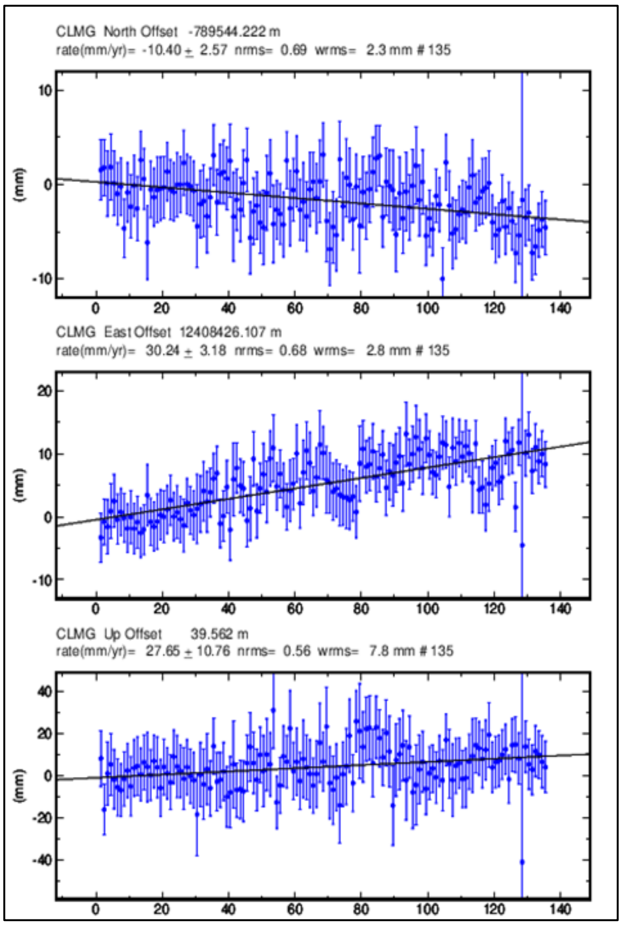

Figure 5. Time Series Plot of CLMG Station for Year 2018

As shown in the above figure the WRMS for North offset is equal to 2.4mm, for East offset WRMS is 2.5mm and the WRMS for up offset in 2018 is 6.6mm. the WRMS value in 2016 is less than 10, this implies that there are no outliers in 2018 data.

Deformation studies in the area using GPS involve analyzing the shift or displacement of the observation stations in the study area.

The aim of this study is to derive GPS velocity from ten observation stations in Northeastern art of Java, after processing single year we combine all the years to determine the final coordinates in ITRF2014, these final coordinates are used to determine velocity of movement of CORS stations. The results of sh_combine are coordinates and their time series, the coordinates derived in this process are used and we provided velocity from the final coordinates.

In this paper we present the final coordinates of the 10 observation stations as the combination of four year coordinates the purpose of this is to determine the final coordinates to be use in deriving the velocity of the CORS station in the study area. The results of combining the four year of observation are shown in the Table 2 and Table 3.

Plotting the final position of station, the Figure 6 is the position plotting of CLMG station used as the example in this paper, this plot is viewed using GGMatlab time series view to remove the outliers, velocity is provided after removing the outliers in the solution.

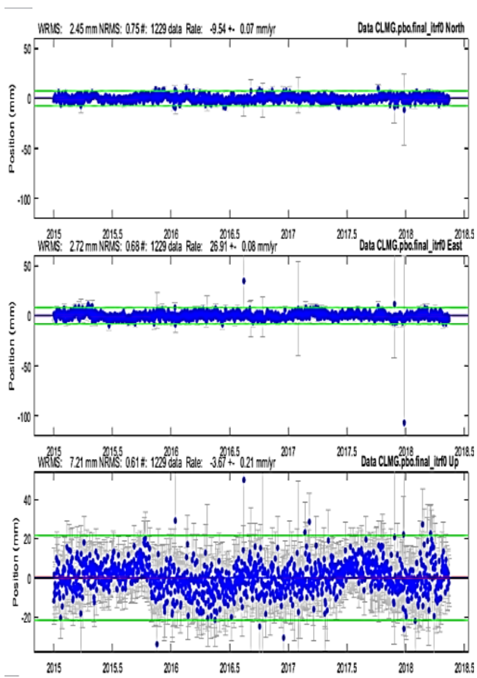
Figure 6. Time Series of CLMG in Four Years

The image above is the position plot of CLMG, we plotted all the stations the above image is the example of the final coordinates plot results of combining the four years of observation. After plotting the final position for each station, we used GGMatlab tsview to view the outliers data in time series. Table 3 shows the position of stations and its velocity after removing few of data which are considered as outliers.

The results in Table 3 indicate that all the stations in the research study are subject to deformation, the negative sign on the north rate (vn) indicate the stations are moving in the south direction, the east velocity rate with a positive sign means that the stations move eastward and the negative vertical velocity(vu) indicate subsidence in the area. In general, the stations move SE with subsidence.

The Figure 7 indicate the map of CORS stations in study area with their velocities indicated by a red arrow. The map also shows the active faults in the area indicated by red lines. The velocity map indicates that all the stations in the research study are subject to movement and the stations move South-East direction this is due to the presence of active faults in the study area. The Vertical velocity map (Observed vertical velocity vectors for geodetic stations in Northeastern Java obtained from GPS) is shown in the figure 8, the Error ellipses and major faults are also illustrated, the red lines on the map are the active faults.

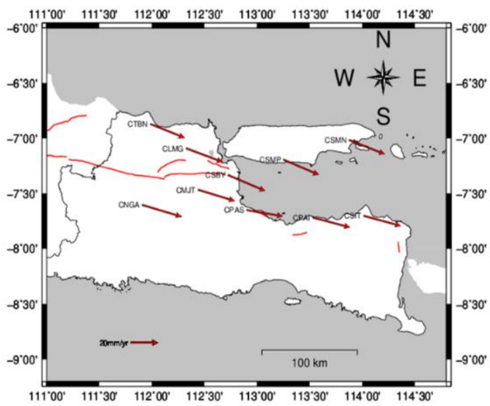

Figure 7. Stations Horizontal Velocity Map

Table 2.
Topocentric Coordinates of CORS Stations

No	Topocentric coordinates			Standard deviation		StdU(mm)
	North(m)	East(m)	Up(m)	stdN(mm)	stdE(mm)	
1	-789544	12408426	39.56696	0.00297	0.00374	0.01033
2	-831064	12410831	53.72023	0.00293	0.00369	0.01025
3	-846552	12347715	86.60718	0.00275	0.00334	0.00862
4	-859248	12523662	44.16467	0.00305	0.00369	0.01053
5	-851751	12456166	43.34169	0.00312	0.00389	0.01125
6	-816454	12445757	51.24964	0.003	0.00375	0.01017
7	-857529	12577308	72.27805	0.00381	0.00453	0.01549
8	-781276	12581527	40.74312	0.00338	0.00417	0.01235
9	-800994	12507833	46.09627	0.00291	0.00346	0.00953
10	-765016	12376693	36.16193	0.00331	0.00407	0.01198

Table 3.
GPS derived velocities (horizontal E and N and vertical Up rate) of CORS stations in ITRF 2014

Station	Longitude (deg)	Latitude(deg)	East rate(mm/yr)	North rate(mm/yr)	up rate(mm/yr)
CLMG	112.3250	-7.0920	26.70	-9.48	-3.50
CMJT	112.4401	-7.4653	27.42	-6.90	-1.15
CNGA	111.9051	-7.6046	27.74	-7.64	-4.00
CPAI	113.5309	-7.7192	26.91	-6.98	-2.40
CPAS	112.9007	-7.6515	26.58	-4.28	-2.17
CSBY	112.7248	-7.3347	27.37	-11.22	-2.23
CSIT	114.0118	-7.7032	25.40	-7.11	-1.17
CSMN	113.8754	-7.0184	26.38	-9.93	-2.16
CSMP	113.2515	-7.1951	25.86	-10.58	-0.21
CTBN	111.9867	-6.8724	24.03	-10.79	-0.70

The above Figure 7 is a map showing the direction of movement of stations in research location, all the stations are moving south-east direction as shown in the map. Determination of direction of movement is one of parameter of deformation in an area.

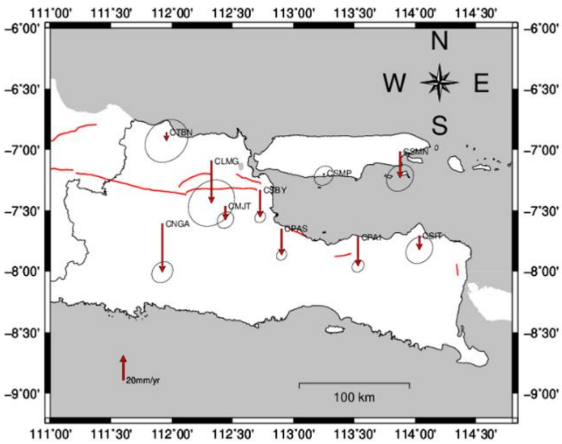

Figure 8. The Vertical Velocity Map of The Study Area

IV. CONCLUSION

This study has come up with two following conclusions :

1. The results of this research indicates that during GAMIT processing, the postfit nrms error less than 0.5, and the phase ambiguities WL and NL are greater than 80% and 70% all these indicate that effects of the cycle slips in the solution were removed. Therefore, the results of GAMIT in this study are the input data for the next processing by the global Kalman filter.
2. The time series plot indicates that there are outliers in the up components for CLMG, CPAI, CTBN in 2018 and CMJT in 2015 and we suggest that this is due to the local conditions of stations, for CMJT site the antenna type was changed and this caused the uncertainties in up components.
3. The Velocity rate range between 2.63cm/yr and 2.96cm/yr for horizontal and vertical range between -0.021cm/yr to -0.4 cm/yr. Is important to investigate the cause of the subsidence in this area.

4. It can be seen on the velocity map provided by this paper that the deformation in the study area may due to the active faults in the research location (see the red lines on the map)

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