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Abstract. Sulawesi microplate Island is located at famous triple junction area of the Eurasian, India–Australian, and Philippine Sea plates. Under the influence of the northward moving Australian plate and the westward motion of the Philippine plate, the island at Eastern part of Indonesia is collide and with the Eurasian plate and Sunda Block. Those recent microplate tectonic motions can be quantitatively determine by GNSS-GPS measurement. We use combine GNSS-GPS observation types (campaign type and continuous type) from 1997 to 2015 to derive newly velocity field of the area. Several strategies are applied and tested to get the optimum result, and finally we choose regional strategy to reduce error propagation contribution from global multi baseline processing using GAMIT/GLOBK 10.5. Velocity field are analyzed in global reference frame ITRF 2008 and local reference frame by fixing with respect alternatively to Eurasian plate - Sunda block, India–Australian plate and Philippine Sea plates. Newly results show dense distribution of velocity field. This information is useful for tectonic deformation studying in geospatial era.

BACKGROUND

The convergence of three major tectonic plates (Eurasian, Australian and Philippine plates) produce a very complex deformation at eastern Indonesia archipelago. The collision zone between southeast Sunda Platform and Sula domain [1 - 2] create Sulawesi Island (figure 1). This collision is accommodated by the Palu-Koro fault at southwestern limit, the Matano fault at southern limit and by subduction under the north arm of Sulawesi [3]. The geodynamic of this Island, the model and motion observation, is studied by geodetic approach using GNSS-GPS technique.

The specific objectives of Sulawesi GPS campaigns are to identify area with high seismicity activities, to asses strain accumulation, to get the integrated kinematic-dynamic modeling of the area and to get better understanding the relationship between seismicity, geological data and geodetic results.

DATA AND METHOD

The Sulawesi observation were carried out under cooperation between Geospatial Information Agency (BIG, former BAKOSURTANAL, Indonesia), Delft Institute for Earth-Oriented Space Research (DEOS, TU-Delft,

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Netherlands) and Institut Teknologi Bandung (ITB, Indonesia). The observation consists of two types of data: continuous type from BIG-CORS station and campaign type. Those campaigns received additional support (equipment and/or personnel) from DSMM (Kuala Lumpur-Malaysia), the Ecole Normale Superieure (ENS, Paris-France), Scripps Institute for Oceanography (USA) and the University of Canberra (Australia). The observations took place from 1997-2015. Site occupation during observation are represent the grouping of Sulawesi network points that base on the interest problems in Sulawesi, i.e.: the main Sulawesi Network for regional observations of Sulawesi Island, Palu-Koro Transect for local monitoring of Palu-Koro Fault Systems at Central Sulawesi and Gorontalo Transect for local monitoring of Gorontalo Fault at the North Arm of Sulawesi. Figure 2 show the distribution of Sulawesi station and continuous station type. To accomplish the positioning of the Sulawesi network in a global reference frame, there were added data of stations nearby Sulawesi which are supplemented by the International GPS Service for Geodynamics (IGS) tracking network.

The GNSS-GPS data of all observation campaigns were analyzed with GAMIT/GLOBK 10.5 [4]. For each of the measurement, daily solutions were calculated in 24-hours session with 30 second sampling rate using GAMIT and in each session the theoretical values for phase and pseudorange observable are modeled. Station coordinates, phase biases and zenith delay parameter are adjusted by a least square method. The observable were examined in the ionosphere-free combination (LQ forming double differences to eliminate clock errors and tropospheric parameter were estimated using Saastamoinen model every one hour for each station. The antenna phase center variations we're model using the IGS table and IGS orbits were kept fixed for each individual session. The phase ambiguities are estimated as real values in the first step and it was attempted to resolve the phase ambiguity using a routine developed by [5].

The quality assessment of the individual solution is base on the repeatability of the independent daily estimation for each baseline component. And finally, the multi session free network solution with loose constrain on position and fixed IGS orbits were established, and GLOBK Kalman filter method were applied to the analysis of solution vectors and associated covariance matrices generated during daily solutions. The coordinates were mapped in the ITRF solution of 2008 by constraining the IGS solutions included in the analysis to their positions in ITRF-2008. The displacement rates were computed by subtracting the ITRF-2008 mapped the campaign solutions.

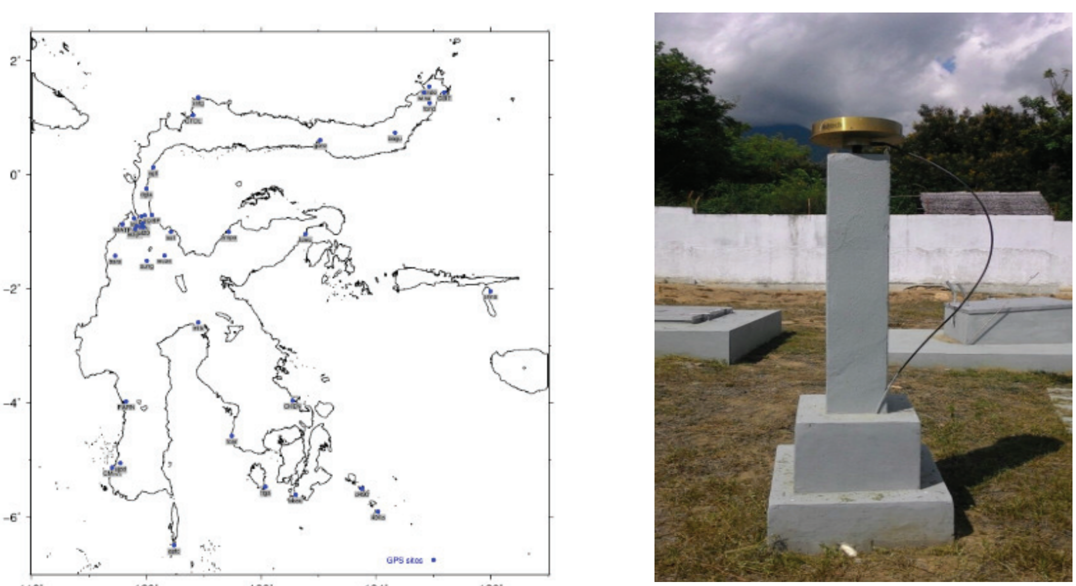

FIGURE 1. Station distribution at Sulawesi region (Left) and Continuous station type – PALP station (Right)

The daily repeatability (Figure 2) of coordinate solutions quality from multi-baseline computation are shown from its normalized root mean square (nrms):

$$nmrs = \sqrt{\frac{\sum_{i-1}^{n} residual_i^2}{\sigma * n}} \tag{1}$$

as a global estimate of differences between the observed phase and modeled phase. The nrms for daily solutions are required to have below 0.35; otherwise it will indicate incorrect values for orbit and station coordinate parameters. The nrms value for daily solution of Sulawesi observation gave consistency throughout the analysis between 0.1-0.2 mm. Besides the root mean square (rms) of the daily station coordinate residual with respect to the multi-day averaged campaign solution for the complete network, the rms statistics shown for the Sulawesi, transect and lGS stations only. The repeatability for the Sulawesi and IGS stations for horizontal components (table 1) are ranging between 1.3 to 4.6 mm and between 5.6 to 12.2 mm for vertical component. These values show a very high internal precision of Sulawesi network campaigns, but the transect shows rather poorer values due to data time coverage that less than 24 hours for each transect stations.

TABLE 1. Daily coordinate repeatability

Station	rms residual (mm)		
	North	East	Up
Sulawesi	1.3	2.6	5.6
Transect	2.0	4.6	12.2
IGS	1.2	2.5	6.8
Total	1.5	3.2	8.2

After inspecting daily repeatability and nrms values, multi session free network solution with loose constrain on position and fixed IGS orbits were established. GLOBK Kalman filter method was applied to the analysis of solution vectors and associated covariance matrices generated during daily solutions. The quality of fitting daily solution into overall solution in this step is represented by value (the weighted sum of the squared residuals).

$$\chi^2 = \frac{1}{n-u}\sum_{i=1}^{n}\frac{(residual)^2}{\sigma_i^2} \tag{2}$$

The values show the level of incompatibility between the newly added data and the solution data previously included are required smaller than 10. The   values of full analysis for all Sulawesi GPS campaign show good values for all session number with all values are under 10. Rather high values campaign type (above 4.5) probably due to small coverage of Sulawesi network compare to regional-global network. We used regional IGS site approach, but not all the nearby IGS stations (depend on the amount and quality of the data). The mapping in ITRF-2008 was done by transforming each campaign solution onto the ITRF-2008 coordinate set through the 7 parameters Helmert transformation (3 translations parameters, 3 rotation parameters and 1 scaling parameter).

The coordinate residual of all IGS stations are consistent and, with an rms values only 1 to 3.5 mm for the horizontal and 5 to 7 mm for the vertical position. The result of daily coordinate repeatability indicates that accuracy with respect to ITRF-2008 is better than 1 cm for both horizontal and vertical position. So, an accurate estimation of Sulawesi motions could be obtained during 1997-2015.

PRELIMINARY RESULT AND DISCUSSION

The displacement rates were computed by subtracting the ITRF-2008 mapped all observation solution and shown at Figure 3 (left). To get better view on the site motions in Sulawesi, the motion of the Eurasian-Sunda

Block was subtracted from the velocity field. This was done, by estimating the Sunda Block motion with the available IGS sites which are located in this block. The velocity estimates in this new reference frame are given in Figure 3 (right).

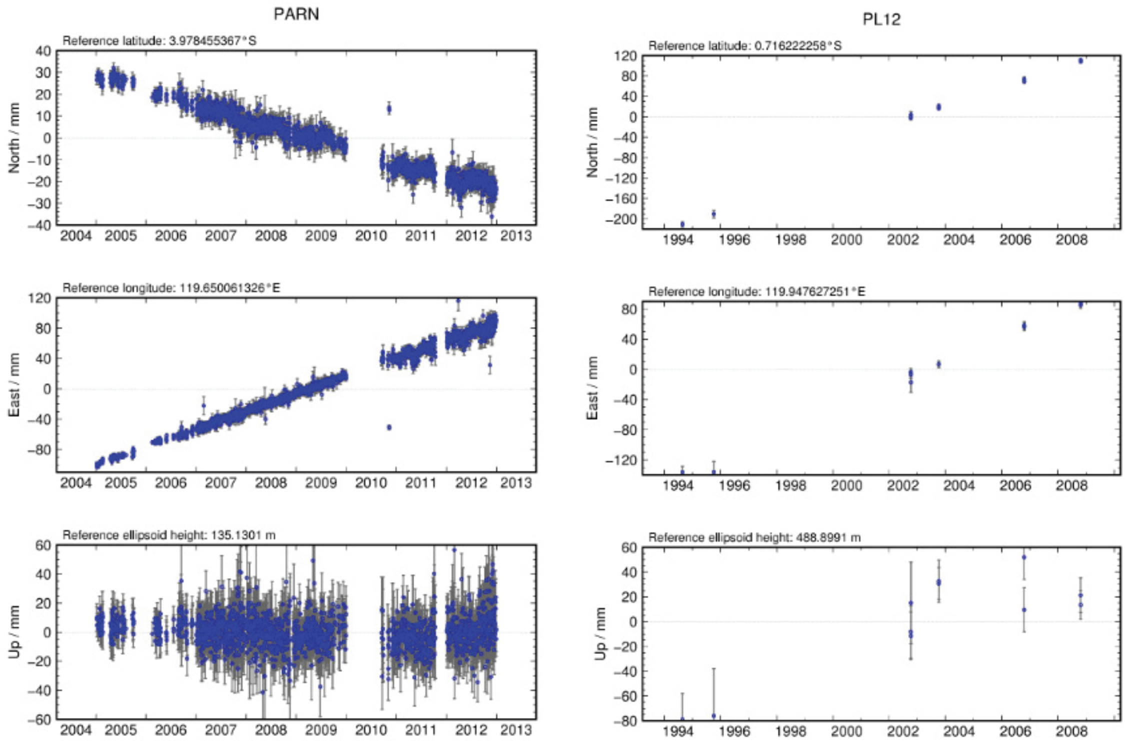

FIGURE 2. North-East-Up components for daily repeatibity of continuous station PARN (left) and campaign station PL12 (right)

From Figure 4, there are some phenomena can be identified. The velocities field estimate in the south-west of Sulawesi indicate that stations here move as part of Eurasian-Sunda Block with some compression taking place in Makassar Strait that can be seen from the decreasing baseline velocities to the southern part from northern part. By using a pair UJPD station (7.4 mm / yr) - PARE (5.7 mm / yr) relatif to BATU (0.6 mm / yr), the quantity of excess velocity movement is approximately 6 mm / yr for the southern region of Makassar Strait. As for the areas north of the Adang fault, the value of the excess velocity of Sulawesi at 6.5 mm / yr based on BLKP (4.0 mm / yr) - TNJB (5.9 mm / yr) - SNGK (7.3 mm / yr) in East Kalimantan to the station BARA (11.9 mm / yr) - LARA (13.1 mm / yr) and WATP (11.6 mm / yr) in Sulawesi. Thus along the Strait of Makassar happens pattern average compression 6.25 mm / yr to the west. Controversial to current hypothesis, that Makassar Strait is consider to be opening [6]. This compression from GPS observations needs more investigation, probably due to the activities of different block of Paternoster Fault at Makassar Strait.

Northward motion of South-east Sulawesi (TOAR, KEND, MAIX, BAUB) and AMBO to be influenced by Australian-plate motion to the north. Rather stable velocity at AMPA, KAMBA, WUAS, TOBO and TOMI have good fit with clockwise rotation 30/My from Sunda rigid block modeling with a rotation pole located east from Manado [7]. East Sulawesi velocity movement represented by LUWU, AMPA and KAMB with an average velocity of 32 mm / yr. In the eastern part of Central Sulawesi, which is in the Gulf of Tomini, visible pattern of rotation clockwise fast as represented by the velocity vector trending northwest of LUWU (38 mm / yr), AMPA (34.6 mm / yr) and and velocity vector SULI (42 mm / yr) were trending slightly to the north. The velocity difference is quite large (7.4 mm / yr) between the two stations of the latter indicates the strong involvement of the Tomini fault conveniently accommodate differences among them in this. LUWU itself showed unstable velocity during 1999-2000 that maybe caused by several nearby earthquakes (5.6 Mb – 25 November 1999, 5.5 Mb - 13 December 1999, 5.6 Mb - 19 February 2000, 6.7 Mb – 4 May 2000).

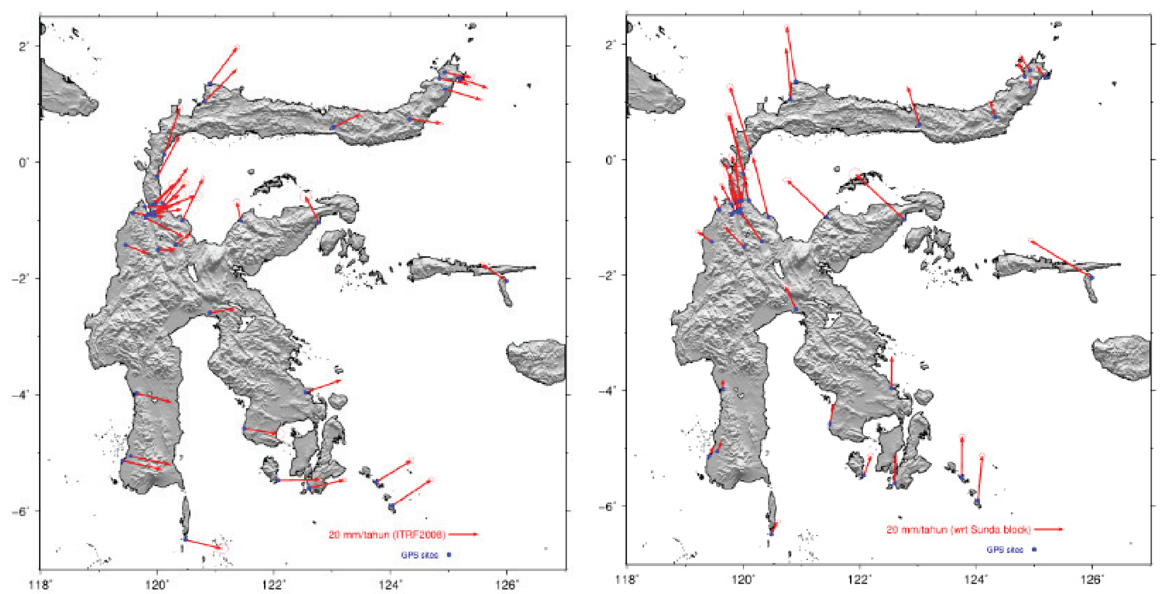

FIGURE 3. Velocity Rate of Sulawesi in ITRF-2006 (left) and with respect to Sunda Block (right)

Velocity at WUAS, KAMB and BARA exhibit an increased westward velocity component, and BARA together with REDO, MALI, KEND, BAUB and TOAR would suggest that the southern part of Sulawesi is also rotating counterclockwise around UJPD. The relative velocity about 3.3 cm/yr between TOMI and AMPA indicate an opening of the Tomini Gulf, which suggest a north-south extension in the Sula Block as it is pulled towards the subduction zone in the North Sulawesi Trench. The sites PALA and LING show big uncertainties during campaigns, but have rather similar direction of motion with surrounded area. This problem may be due to the short data available. North Sulawesi has a pattern of increasingly slow rate of velocity from west to east direction, which is indicated by a reduction in velocity of 39 mm / yr of TOLI to 9.8 mm / yr at KEMA. The northern part of Central Sulawesi, namely along the neck connecting with North SUlawesi, has a change velocity pattern from the station located at the south are DONG (41.5 mm / yr) which accelerated towards SGTI (43.7 mm / yr) and decreased again to 38 mm / yr in SNTG located in the most northern zone of the neck. This indicates subduction Minahasa role in curbing the rate of rotation of Tomini Gulf region.

In Central Sulawesi, to get better view on the site motions in Palu-Koro Transect, the motion of the PALU site was subtracted from the velocity field. The velocity estimates in this new reference frame and there are some phenomena can be indentified where small motion of BARA-WATA and large motion of WUAS-TOBO show a higher degree of deformation of the local area. The area is also show a pattern of velocity, though not as much in the North Sulawesi, which is of 12 mm / yr in WATP located at the westernmost tip of Palu-Koro transect lines to 39 mm / yr in TOBP located at the east, and time evolution of the WATA-TOBO baseline over the Palu Koro Fault show (left lateral) strike slip rates vary about 3,5 cm/yr.

CLOSING REMARKS

Processing and mapping all coordinate solutions on to ITRF-2008 system give accurate results based on all their quality parameters, but to get more and better regional IGS station coordinates in the future we will apply the latest ITRF-2014. Especially for processing and mapping after 2014 observations. The preliminary interpretation velocities can be classified into in agreement phenomena with previous results : clockwise rotation of the North Arm, Tomini Gulf opening and left lateral strike slip of Palu-Koro fault; further investigations of

Southwest Arm counterclockwise rotation and compression at Makassar Strait; Palu-Koro Fault still show a rapid strike slip fault with complex tectonic content and time evolution.

The ongoing works are: more detail interpretation of all velocities result, improve the Sulawesi network using new GPS permanent stations data and campaign stations and to compute the horizontal strain and spin rotation field of the area using discrete and collocation approach to get better information of stain region. The future work after done all the ongoing works as a continuation investigation are: improve and extent kinematic-dynamic model of Sulawesi region, for subduction zone at the North Arm, thrusting zone at southern of the North Arm, for transform faults at PaIu and Gorontalo, for Makkasar Strait and etc that can be detected from GPS observations. Studying the application of the permanent stations for monitoring the Palu-Koro Fault, especially to get the relations between earthquake occurrences and baseline statistics, and integrated modeling of the geodynamic of Sulawesi using more geophysical and seismicity contribution.

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