INVESTIGATION OF THE SOLID EARTH TIDE BASED ON GPS OBSERVATION AND SUPERCONDUCTING GRAVIMETER DATA

(Investigasi Pasang Surut Bumi Berdasarkan pada Data Pengamatan GPS dan Data Superconducting Gravimeter)

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ABSTRACT

According to previous study, vertical displacements caused by the solid earth tide often reach at the range of 20 cm and can exceed 30 cm at some stations. Solid earth tide can be measured by using satellite system or sensitive gravimeters. This paper aims to investigate the patterns of the solid earth tide based on Global Positioning System (GPS) data compare with Superconducting Gravimeter (SG) data and solid earth tide global model. Processing GPS data using Kinematic Precise Point Positioning (KPPP) method within a year data from 1st January – 31st December 2011. The data used are BAKO GPS Permanent station data and Cibinong SG Station data. The location of BAKO station is close to Cibinong SG station, which is about 50 meters. The result of this paper are solid earth tide which is derived from both devices have the different pattern but it is dominated by same type of tidal, namely semi-diurnal components. Applicability global models with SG observations has smaller residue with standard deviation is 0.0031 mgal, this result is equivalent with 0.0098 meter. Comparison between the results of GPS observations to global models which have a standard deviation residue for vertical component is 0.0360 meters.

Keywords: solid earth tide, GPS permanent station, Kinematic Precise Point Positioning, Superconducting Gravimeter

ABSTRAK

Menurut penelitian sebelumnya, perubahan posisi vertikal yang disebabkan oleh pasang surut bumi mencapai 20 cm dan dapat mencapai 30 cm pada beberapa stasiun. Pasang surut bumi bisa diukur menggunakan alat ukur berbasis satelit atau gravimeter teliti. Tujuan penelitian ini adalah untuk menyelidiki pola dari pasang surut bumi berdasarkan data dari dua alat yang berbeda yaitu Global Positioning System (GPS) dibandingkan dengan Superconducting Gravimeter (SG) serta model pasang surut global. Pengolahan data GPS menggunakan metode Kinematic Precise Point Positioning (KPPP). Panjang data yang digunakan adalah satu tahun data dari 1 Januari – 31 Desember 2011. Stasiun GPS yang digunakan dalam penelitian ini adalah stasiun BAKO dan stasiun SG Cibinong. Lokasi kedua stasiun berdekatan yaitu sekitar 50 meter. Hasil penelitian ini adalah pasang surut bumi yang dihasilkan kedua alat mempunyai pola yang berbeda tetapi didominasi oleh tipe pasang surut yang sama yaitu komponen semi-diurnal. Kesesuaian model global dengan data SG mempunyai residu yang lebih kecil dengan standar deviasi 0,0031 mgal, atau setara dengan 0,0098 meter. Sedangkan kesesuaian model global dengan data GPS mempunyai standar deviasi 0,0360 meter.

***Kata Kunci**: pasang surut bumi, stasiun tetap GPS, Kinematic Precise Point Positioning, Superconducting Gravimeter*

INTRODUCTION

Solid earth tides are caused by the gravitational force imposed by the moon, sun and other bodies of the solar system, hence there is a displacement caused by it (Vanicek, 1973). Because the earth is not plastic, it does not reach the same shape and conform only partially to the equipotential (Vanicek, 1973). Displacement is strongly influenced by the potential on the earth, therefore whose value is dependent on the position and location of the site (Cai, 2009; Zheng, 2006). Displacement caused by the solid earth tide often reaches in range 20 cm and can exceed 30 cm in some stations (Zheng, 2006).

Solid earth tides are easily measured only with satellite systems or sensitive gravimeters (Ito, Okubo, & Sagiya, 2009). One of satellite system is GPS. In GPS processing data method, differential positioning, such as differential carrier phase GPS, can frequently ignore solid earth tide effects, because it is a very smooth function around the Earth. But for GPS carrier phase, Precise Point Positioning (PPP), must include the effect of solid earth tide, because this effect cannot be removed if used PPP. PPP is stand-alone point positioning techniques (Cai, 2009). In the other hand, there is SG. SG is ground-based gravity measurements, which describe the elastic response of the earth to the gravitational of the nearby space object due to its high stability and sensitivity (Neumeyer, 2010). Therefore, in the long term, SG can be used to detect solid earth tide (Variandy, 2014).

By using both data from different tools, how correlation of the solid earth tide patterns generated from both and its comparison with theoretic global models that have become international agreement (McCarthy & Petit, 2004) initiation by McCarthy (1996). Global models are developed by considering global characteristics of the earth using global data. However, Indonesia has unique local characteristics. Therefore, investigation of solid earth tide are necessary.

METHOD

Solid Earth Tides and Global Model

Earth rotates affect the dynamics of the Earth. Dynamic phenomena of the Earth causes the Earth's shape changed so that the position of the objects on the Earth's surface also changes. This change is called deformation and deformation of the Earth caused by fluid in the Earth's mantle (Vanicek, 1973).

The deformation or displacement caused by the solid Earth tides that is dependent on station latitude, tide frequency and sidereal time can reach about 30 cm in the height component and 5 cm in the horizontal plane (Kouba & Héroux, 2001; Zheng, 2006).

According to Vanicek (1973), beginning with Newton's law of gravitation, the geophysical potential can readily be derived by the expression:

$$W_t^m(P) = \frac{G.m}{d_M^m}\sum_{n=2}^{\infty}\left(\frac{r_p}{d_M^m}\right)^n P_n(\cos Z_p) \quad \text{.......} (1)$$

Where, *m* is the mass of the Moon 7,38 x 10^{22} kg; *G* is the universal constant of gravitation 6,673 x 10^{-11} m ^{3}/(kg s^2); is average distance between centre of the Earth and centre of the Moon; Z_P the zenith angle of the Moon at P; P_n associated with a series of the Lagendre's functions; r_P the distance from centre of mass of the Earth to point P.

McCarthy (1996) has been issued the model of solid earth tides and recommended in the IERS Convention 2003 (McCarthy & Petit, 2004). The implementation of the model consists of two steps. First step, the degree 2 and 3 in phase corrections are computes in the time domain as well as out-of-phase corrections of degree 2 and contributions from the latitude dependence for diurnal and semi-diurnal tides. Second step, corrections are computed in the frequency domain for the diurnal, semi-diurnal and long term tides (Zheng, 2006).

Vector displacement due to degree 2 tides is given by:

$$\Delta r = \sum_{j=2}^{3}\frac{G M_j R_e^4}{G M_e R_j^3}\left\{h_2\hat{r}\left(\frac{3}{2}(\hat{R}_j.\hat{r})^2-\frac{1}{2}\right)+3l_2(\hat{R}_j.\hat{r})[\hat{R}_j-(\hat{R}_j.\hat{r})\hat{r}]\right\} \quad \text{.......}(2)$$

Where, Δr is vector displacement of the station; $G M_j$ is gravitational parameter for the Moon (j=2) or the Sun (j=3); $G M_e$ is gravitational parameter for the Earth; $\hat{R}_j, R_j$ is unit vector from the geocentre to the Moon or the Sun, and its magnitude; R_e is Earth's equatorial radius in (m); $\hat{r}, r$ is unit vector from the geocentre to the station, and its magnitude; h_2 is nominal degree 2 Love number, h_2 = 0.6090; l_2 is nominal degree 2 Shida number, l_2 = 0.0852.

Vector displacement due to degree 3 tides is given by:

$$\Delta r = \sum_{j=2}^{3}\frac{G M_j R_e^5}{G M_e R_j^4}\left\{h_3\hat{r}\left(\frac{5}{2}(\hat{R}_j.\hat{r})^3-\frac{3}{2}(\hat{R}_j.\hat{r})\right)+l_3\left(\frac{15}{2}(\hat{R}_j.\hat{r})^2-\frac{3}{2}\right)[\hat{R}_j-(\hat{R}_j.\hat{r})\hat{r}]\right\} \quad \text{.......}(3)$$

Where, h_3 is nominal degree 3 Love number, h_3 = 0.292; l_3 is nominal degree 3 Shida number, l_2 = 0.015.

GPS Data and Processing Method

Deformation due to geophysical effects, especially solid earth tide is because the reference marker of geodetic control networks located on the crust. Models describing the displacements of reference points due to various effects are provided (McCarthy & Petit, 2004). In this paper, the data used is BAKO GPS permanent station data, which located in Cibinong, Bogor (6,490 S; 106,840 E; 159,81 m), operated by Geospatial Information Agency for Indonesia (Badan Informasi Geospasial, BIG).

Length of data is one year, from 1st January – 31st December 2011. The GPS data used are RINEX observations that have 30 seconds observation interval. The data processed use free software that called RTKLib with Comment User Interface (CUI) in Kinematic Precise Point Positioning (KPPP) method. To obtain coordinates and covariance, KPPP method has satellite clocks and orbits fixed. For satellite errors correction used correction from IGS satellite clocks and orbits, this file can be obtained via Internet access from IGS website http://igscb.jpl.nasa.gov which were determined using a consistent set of models over the entire time span, including absolute antenna phase center models for both GPS receiver and satellite antennas (Services, 2009). For signal propagation correction, used GMF (Global Mapping Function) tropospheric mapping function and adopted a priori dry tropospheric delay estimates from the Global Pressure and Temperature (GPT) model (Boehm, Heinkelmann, & Schuh, 2007). In our solutions, the elevation mask used 7^0 and carrier phase ambiguities were not resolved.

For align to reference frame, there was no specified reference frame, and for ocean tide models used FES2004 to calculate OTL corrections for GPS stations (Allinson et al., 2004). The OTL model amplitudes and phases from the FES2004 tide model (including the tidal components M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM and SSA) were computed using Hans–Georg Scherneck's web tool (Scherneck & Bos, 2006).

The data processed by entering all corrections; there are tropospheric, ionospheric, ocean tide loading, pole tide, antenna correction, phase windup and corrections related relativity effects, without entering solid earth tide correction.

SG Data and Processing Method

Length of SG data is same with length of GPS data; there is a year data from from 1st January – 31st December 2011. the data used cibinong SG station data, which located in Cibinong, Bogor (6,490 S; 106,840 E; 159.81 m), closed to bako GPS permanent station, which is about 50 meters (**Figure 1**). This station operated by Geospatial Information Agency of Indonesia.

To process SG data is necessary to determine the scale factor (calibration) to change the signal from electrical voltage (volt) to µgal unit (Bramanto, 2014; Variandy, 2014). Then proceed with separation of SG data into its components using modeling with help of other supporting data such as polar coordinates data of the International Earth Rotation and Reference Systems service (IERS) to calculate atmospheric pressure effect, pole movement effect, groundwater level data, air pressure data and ocean loading data using baytap-g software. Then, generated SG data accuracy with smaller than 1 µgal (Bramanto, 2014; Variandy, 2014).

Figure 1. Location of GPS and SG station (the triangle mark is GPS station and the square mark is SG station).

RESULT AND DISCUSSION

Time Series

Time series coordinate generated from kinematic data processing according to the interval data used and generate three-dimensional (3D) topocentric coordinates. The interval data used is 30 seconds. GPS data used for processing is not filled completely, there are some not recorded raw data, so there are gaps in RINEX data, there are 10 days RINEX missing, namely doy 42, 100, 180, 192, 250, 251, 253, 258, 259 and 260. The percentage of data lost is 2.74%. To fill the data gap used spline interpolation. This method was chosen because it can generate continuous data, so that make it easier to transfer from the spatial or time domain to the frequency domain. Before fill in the gap, the data should be clear from outlier. Detecting outliers could be calculated using gross-error, then discard data beyond the gross-error range (Elgazooli & Ibrahim, 2012). The data outlier could be removed using moving average filtering.

Figure 2 shows the GPS time series including solid earth tide signal. From **Figure 2**, there are gap data and outlier. Before edited, solid earth tide variations for N-S component are -24,630 to 14,182 meters with the average value is 0,043 meters, for E-W component solid earth tide variations are -14,944 to 21,192 meters with the average value is -0,0627 meters, for U-D component the variations are -14,065 to 34,334 meters with the average value is -0,0374 meters.

Figure 3 Shows solid earth tide signal that have been outlier removed and filled by spline interpolation. After edited, solid earth tide variations for N-S component are -0,0614 to 0,1399 meters with the average value is 0,0314 meters, for E-W component, solid earth tide variations are -0,139 to 0,0512 meters with the average value is -0,0475 meters, for U-D component the variations are -0,2928 to 0,288 meters with the average is 0,0283 meters.

Solid earth tide time series from SG data obtained from SG signal reduced by all components. The components are: (1) atmospheric pressure effect have been calculated using BAYTAP-G. The resulting of atmospheric pressure effect is smaller than the range of SG raw data, that is 4-5 μGal (Variandy, 2014); (2) pole movement effect have been calculated using TSOFT. The resulting of pole movement effect is between 0,8 - 1,9 μGal, with an average value 1,4126 ± 0,6778 μGal (Variandy, 2014), this effect is negligible, because the magnitude is small; (3) Ocean Tide Loading (OTL) effect. To calculate this effect, we use NAO99.b OTL model. The model is based on assimilating about 5 years of TOPEX / POSEIDON altimeter of data into a numerical barotropic hydrodynamical model (Matsumoto, Sato, Takanezawa, & Ooe, 2001). Ocean loading effects ranging from -6 to 10 μGal with an average value of 0,0106 ± 5,1837 μGal (Variandy, 2014); (4) hydrology effect. From the calculation of regression between ground water level and SG data, resulted in admittance value of 1,7061 nms-2/m, or about 0,17061 μGal/m (Variandy, 2014).

By reducing all components, components of the solid earth tides produced variation -350 until -50 μGal with average value -108,6667 ± 15,1085 μGal (Variandy, 2014). One μGal of gravity change is equivalent to about 3,2 mm of relative height change (Ito et al., 2009), that mean the variation of solid earth tides -1,12 to -0,16 meters with average value of solid earth tides are -0,347733 ± 0,048347 meters.

Comparison of the Solid Earth Tide from GPS and SG Data

Comparison of the solid earth tide between GPS and SG data by comparing patterns obtained from both signal. The component that could be compared is only the vertical component, because SG only detects vertical signal. Pattern compared apart from the spatial domain, also the spectral domain. Spectral analysis was conducted using Fast Fourier Transform (FFT). Time series results from the GPS data and time series data from SG can be seen in **Figure 3**. The pattern result that occurs is semi diurnal pattern, but there is a difference patterns between the two time series. The different patterns between SG and GPS is because SG record gravity force signal (Neumeyer, 2010), while GPS record distance. According to newton's law of gravity, force inversely proportional to the square of the distance. If the signal in GPS is growing up, then the signal in SG is growing down.

In the spectral domain (**Figure 4**), solid earth tide signal obtained from the SG data are ter-diurnal, semi-diurnal, diurnal component and also long-term components. Likewise, solid earth tide signal obtained from the GPS data are ter-diurnal, semi-diurnal, diurnal component and also long-term components.

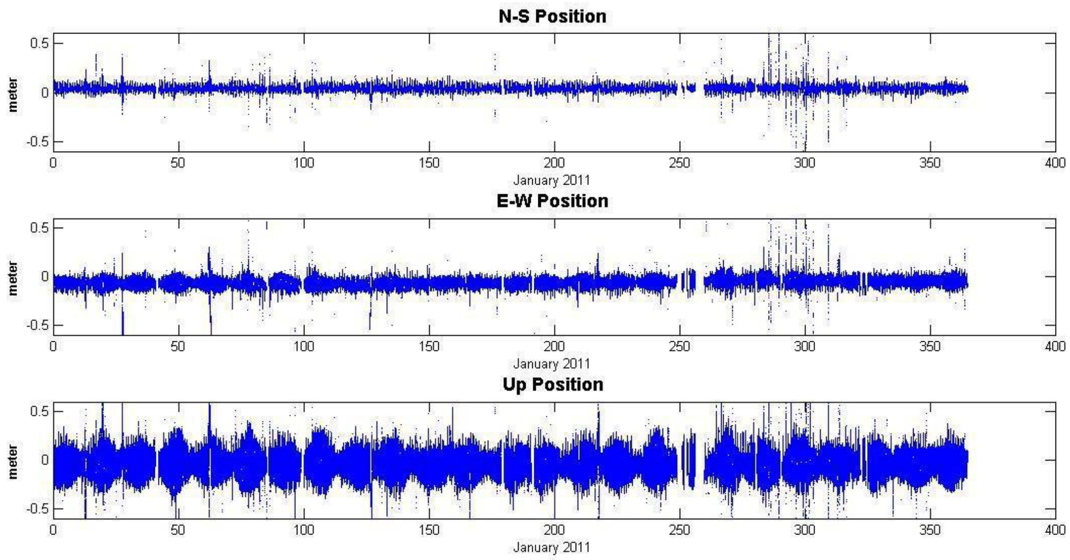

Figure 2. GPS time series including solid earth tide signal.

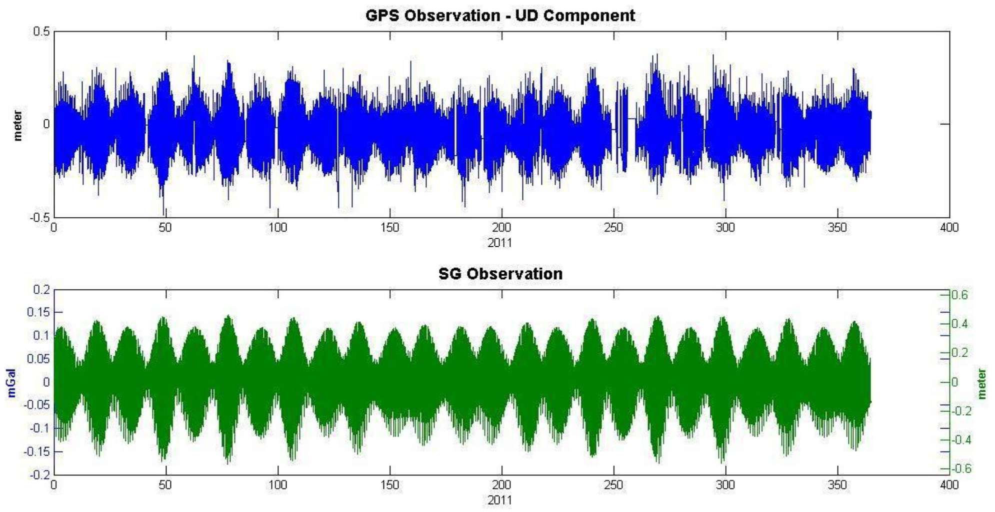

Figure 3. Time series of solid earth tide signal that have been filled by spline interpolation.

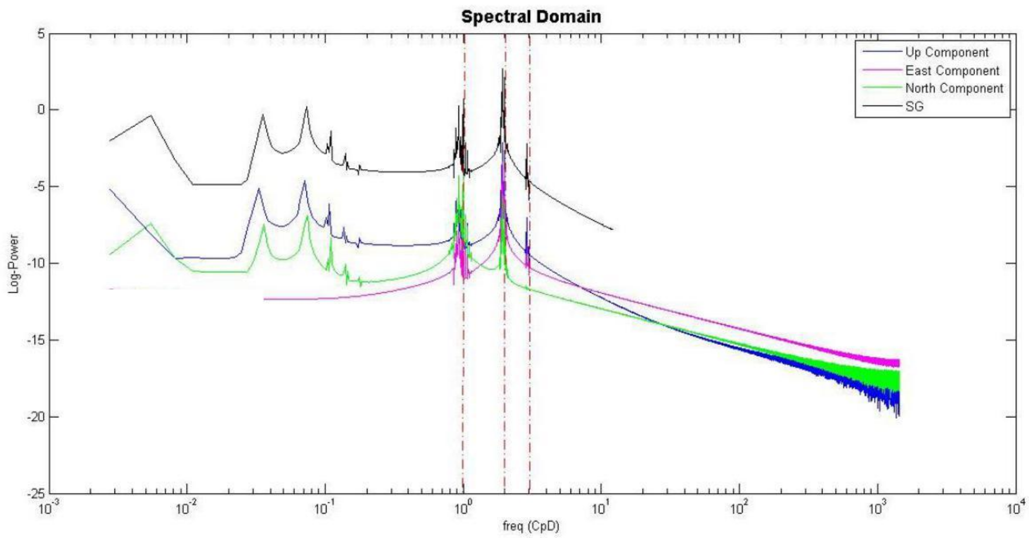

Figure 4. Spectral domain analysis for solid earth tide.

Based on **Figure 4**. It can be seen that semi-diurnal components, have the highest power value, then diurnal component and long-term component has a lower value. This indicates that the solid earth tide variation is dominated by semi-diurnal.

The signal of the solid earth tide between two devices cannot be compared quantifiably, because the unit result from both device is different, although there is a number of conversion, but that number contains many assumptions (Ito et al., 2009), so comparison between both device can only be done qualitatively.

To know correlation between GPS and SG solid earth tide signal, a simple linear model is applied to get the correlation SG data against GPS data (Hinderer, Crossley, & Warburton, 2007):

$$y_i = \alpha x_i + \beta \quad (4)$$

where x is the SG data, y is GPS data, α is the multiplication factor, β is the shifting and i = 1, n where n is the total number of combined data.

Figure 5 shows the plot of the x-axis SG data against y-ordinat GPS data. The linear least square fitting model is obtained as following:

$$y_i = -0.48x_i - 0.018 \quad (5)$$

From the scatter plot result GPS observation data have negative correlation with the SG data and the correlation is -0,91186.

Applicability of Global Model

Global models obtained from the global data. To see at the applicability of global model and observations then compared the results of GPS data processing, SG data processing and global model. A global model used was WDD model. For comparison the GPS pattern, WDD model that used is in metric (meter), while for comparison the SG pattern WDD model that used is in force (mgal). **Figure 6**. Shows a comparison between the solid earth tide observations from GPS data to models, to clarify the difference then take a sample of 7 days of data on vertical component. Green color is a model, while the blue color is solid earth tide observation.

Figure 7. shows a comparison between solid earth tide from SG observation to model from Whar Dehant model. To clarify the differences then take a sample of 7 days of data. Green color is a model, while the blue color is solid earth tide observation.

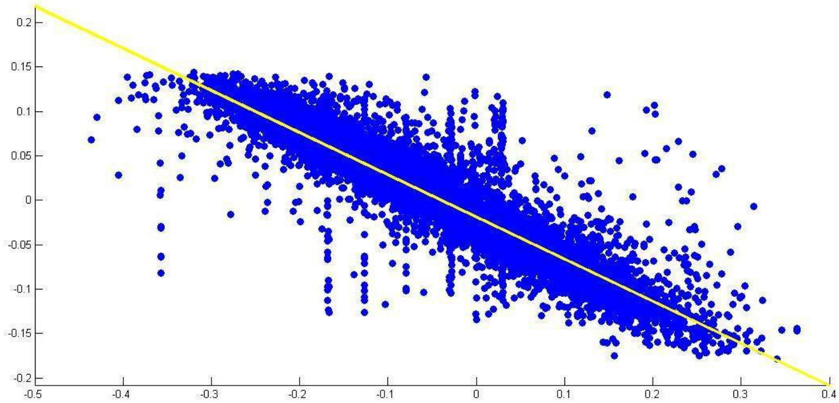

Figure 5. Scatter plot GPS observation data and SG data.

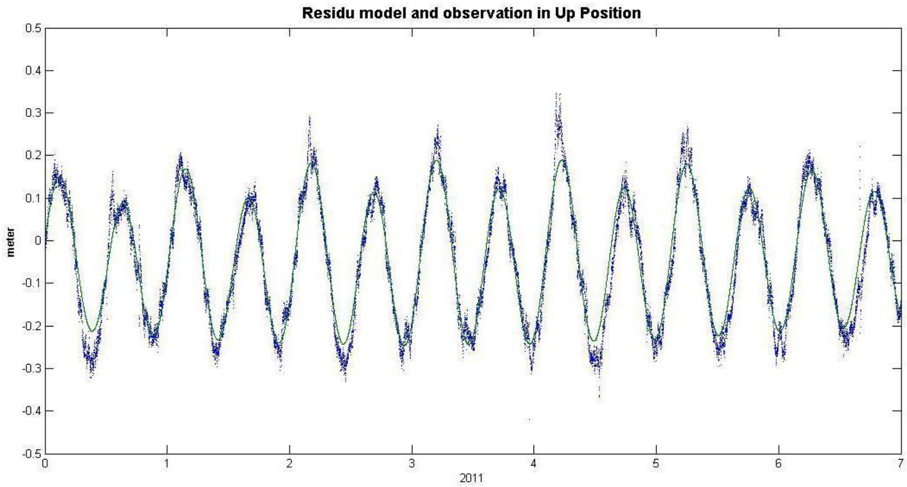

Figure 6. Comparison GPS observation for 7 days in U-D component.

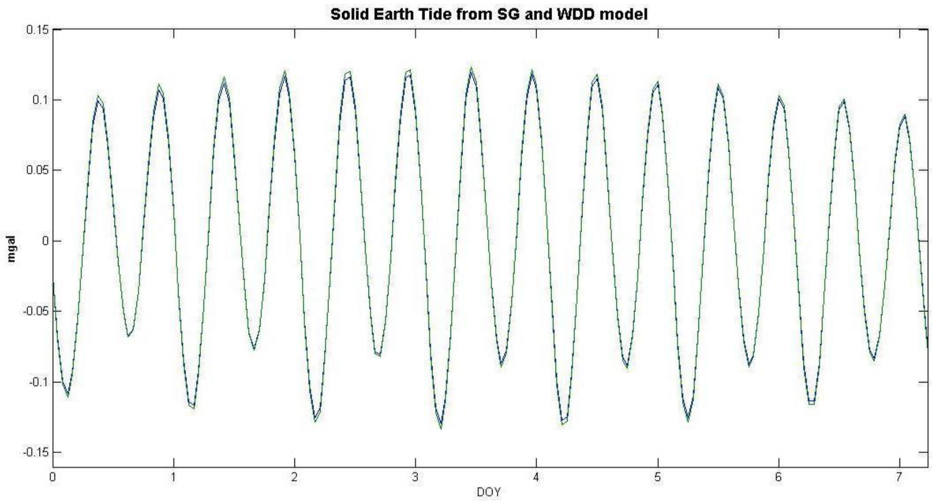

Figure 7. Comparison SG observation with model.

The standard deviation residue in models and observations for vertical component is 0,0360 meters. The standard deviation residue between models and data SG observation is 0,0031 mgal, this result is equivalent with 0,0098 meter.

The residue between GPS data and model is 2,6 centimetres larger than the residue between SG data and model. The amount of residues between GPS data and model is caused by the effects which affect the GPS observation data, namely the presence of noise, which are local effects such as hydrological effect, multipath and non tidal errors.

CONCLUSION

This paper discussed about the pattern of the solid earth tide derived from two different devices that GPS station and SG stations. Solid earth tide signal generated by these two devices have different pattern and dominated by the same component that is semi-diurnal. Based on the results of GPS data, solid earth tide have more influence on the vertical component than the horizontal component. While the results of the comparison with global models. SG processing residue results have smaller compared with the results of the processing of GPS. This is caused the signal from the GPS processing is still affected by noise, outliers, which are local effects such as hydrological effect, multipath and other errors.

Although it has larger residues, GPS observation data are quite conform and consistently used to detect geophysical effects phenomena, because there is only one SG station in Indonesia, and it is not sufficient to determine the pattern and characteristics of geophysical effects throughout the region. Therefore using GPS observation data is a solution.

From the results of this processing, despite having a larger residue, solid earth tide is detected using GPS data with KPPP processing methods. The global models put forward in IERS2003 conventions, fit with the observations. Observations proved that the residual values between SG and global model are small.

For the futher research to improve the accuracy of the investigation of the solid earth tide using GPS data, should be used scientific GPS software that accommodate KPPP method, such as Gypsy or Bernese. Geophysical and environemental parameters introduced in the scientific software is relatively more accurate that that of the RTKLib.

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