Investigation of Vertical Displacement due to Ocean Tide Loading Based on GNSS Positioning in Indonesia

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Key words: Ocean Tide Loading (OTL), IERS model, GNSS Measurement, Kinematic Precise Point Positioning

SUMMARY

This study aims to investigate the vertical displacement due to OTL based on GNSS positioning in Indonesia. The GNSS data used are BAKO, CCLP and CPKL station located on Java Island, CBKT and SAMP station located on Sumatera Island, CPON and CBAL station located on Kalimantan Island, CMAK and CBIT station located on Sulawesi Island, and CUKE station located in Papua Island. The data length is a year data, from January 1st until December 31st 2011. Data processed using Kinematic Precise Point Positioning (KPPP) method. OTL effect in Indonesia is dominated by semi-diurnal and diurnal phenomena, with the highest component are K1 and M2. the amplitude at each station also varies between 0.5 - 1.6 cm, with the lowest values found in BAKO station and the highest value at CBIT station. The results of the comparison with the four IERS OTL models, namely FES2004, OSU12, NAO99.b and TPXO.7.2, improve vertical accuracy of GNSS positioning, between 0.2 - 0.9 cm, with an applicable model for each stations are different. This study suggests that GNSS positioning affected by OTL effect and needed the right model to improve the positioning accuracy, especially for the vertical component.

RINGKASAN

Penelitian ini bertujuan untuk mempelajari pergerakan vertikal karena efek OTL berdasarkan penentuan posisi menggunakan GNSS di Indonesia. Data GNSS yang digunakan adalah stasiun BAKO, CCLP dan CPKL yang berada di Pulau Jawa, CBKT dan SAMP yang berada di Pulau Sumatera, CPON dan CBAL yang berada di Pulau Kalimantan, CMAK dan CBIT yang berada di Pulau Sulawesi dan CUKE yang berada di Pulau Papua. Panjang data yang digunakan adalah satu tahun data mulai dari 1 Januari sampai 31 Desember 2011. data diproses dengan menggunakan metode KPPP. Efek OTL di Indonesia didominasi oleh fenomena semi-diurnal dan diurnal, dengan komponen tertinggi adalah K1 dan M2. amplitude pada masing-masing stasiun bervariasi antara 0.5-1.6 cm, dengan nilai terendah di stasiun BAKO dan tertinggi di stasiun CBIT. Hasil dari membandingkan empat model OTL, yaitu FES2004, OSU12, NAO99.b daan TPXO7.2, meningkatkan akurasi posisi vertikal antara 0.2 sampai 0.9 cm, dengan model yang sesuai di masing-masing stasiun berbeda beda. Penelitian ini memperlihatkan bahwa penentuan posisi menggunakan GNSS terimbas oleh efek OTL dan membutuhkan model yang paling cocok untuk meningkatkan ketelitiannya, khususnya pada posisi vertikal.

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1. INTRODUCTION

In 2013, Indonesia launched a geospatial reference system, namely the Indonesian Geospatial Reference System 2013 (*Sistem Referensi Geospasial Indonesia* [SRGI2013]) that set out in the Rule of Head (*Peraturan Kepala*) Geospatial Information Agency (*Badan Informasi Geospasial* [BIG]) Number 15 Year 2013. The concrete manifestation of SRGI2013 in the field is a reference coordinate frame in the form of Geodetic Control Network (*Jaring Kontrol Geodesi* [JKG]). With this regulation, JKG must have high accuracy as a reference for the implementation of IG in Indonesia (Perka BIG 15/2013).

A year after, Indonesia set out Rule of Head Geospatial Information Agency (BIG) Number 15 Year 2014 about Technical Guidelines of Topographic Maps. In this rule, the largest scale for generating topographic maps, especially Indonesian Topographic Map (*Peta Rupabumi Indonesia* [RBI]), is 1:1000. The standard of geometric accuracy for RBI map on a scale of 1: 1000 is 0.2 meters for horizontal and vertical position (Perka BIG 15/2014). To fulfill this, the accuracy of SRGI 2013, which is realized by JKG, must achieve the accuracy in the level of ~ 1 cm, but to connect SRGI 2013 to the international or global network the accuracy is ~ 1 mm (Subarya, 2015).

As a single Indonesian geospatial reference, SRGI 2013 must fulfill the standard of accuracy following the existing regulations. To obtain high accuracy for JKG coordinates, the positioning should use satellite based technology, i.e. by using Global Positioning System (GPS). GPS, now familiar with Global Navigation Satellite Systems (GNSS), is a constellation of satellites that transmits signals to provide accurate Position, Velocity and Time (PVT) information that is accessible to anyone with a receiver (Zheng, 2006).

As positioning technology, GNSS is also has error sources, one of them error due to Ocean Tide Loading (OTL) effect. Ocean tides cause a temporal variation of the ocean mass distribution and the associated load on the crust and produce time-varying deformations of the Earth (McCarthy et al., 2004). To improve the positioning accuracy, models for correcting the OTL have to be applied. Currently a global model issued by McCarthy has been recommended the IERS Convention 2003 (McCarthy, 2004). Unfortunately, the global models might not be accurate to be applied in Indonesia. Therefore, assessment of relational of global models and also vertical displacement of OTL in Indonesia are necessary.

2. OCEAN TIDE LOADING (OTL) MODEL

Ocean tides are caused by a temporal variation of the ocean mass distribution and the associated load on the crust and produce time-varying deformations of the Earth (McCarthy, 2004). The OTL correction is computed using the coefficients made by Scherneck (1991). Which is consists of the diurnal waves K1, O1, P1, Q1, the semi diurnal waves M2, S2, N2, K2 and the long term waves Mf, Mm and Ssa. The different tidal constituents are computed and combined to accurately predict the future tides (Yeh, 2011). OTL also influences crust movement, explaining why GPS positioning coordinates vary slightly with the tides. The model of ocean loading is given as follows (McCarthy, 1996; IERS, 2003):

$$\Delta c = \sum_j f_j A_{cj} \cos(w_j t + \chi_j + u_j - \phi_{cj})$$

Where, is displacement caused by ocean loading; j is represents 11 tidal waves (K1, O1, P1, Q1, M2, S2, N2, K2, Mf, Mm and Ssa); is depends on the longitude of lunar node (at 1-3 mm precision fj =1); uj is depends on the longitude of lunar node (at 1-3 mm precision uj =0); is an angular velocity at time t = 0h; is an astronomical argument at time t = 0h; is a station specific amplitude; is a station specific phase.

In this study, four models are chosen to conduct surveys: FES2004, OSU12, NAO.99b, and TPXO.7.2 (**Table 1**). The OTL models were computed using Hans–Georg Scherneck's web tool (http://www.holt.oso.chalmers.se/~loading/).

3. DATA AND METHOD

3.1 Data

GNSS permanent station in Indonesia, particularly in BIG, is also called Indonesian Permanent GNSS Station Network (IPGSN). The main purpose of IPGSN is to maintain the accuracy and precision level of national control network in Indonesia and also to help many activities, both scientific and practical activities, such as geodynamics and deformation surveys, ionosphere and meteorology study, surveying and mapping-based real time, and other applications.

In this study, the data used is GNSS data that connected to IPGSN. The data used are RINEX observations that have 30 seconds observation interval.

Table 1 The ocean tidal models used in this study

Name of Model	***Resolution***	***Area***	***Input***
FES2004	$1/8^0 x 1/8^0$	Global	Computed by numerical model, improved by assimilating tide gauge and altimetry data (*T/P* and *ERS-*2).
OSU12	$1/4^0 X 1/4^0$	Global	Pure empirical tide model based on satellite altimetry data from TOPEX, Jason-1/-2, Envisat, and GFO that have been interpolated using least-squares collocation.
NAO.99b	$1/2^0$ x $1/2^0$	Global	Based on the same hydrodynamics model as the Schwiderski model, but has TOPEX/Poseidon data incorporated into it.
TPXO.7.2	$1/4^0 X 1/4^0$	Global	Computed using inverse theory using tide gauge and

	TOPEX/Poseidon data, also includes GRACE data.

Table 2 List of IPGSN stations

Station Name	*Location*	*Receiver*	*Antenna*	*Coordinate*	
				Longitude	**Latitude**
CBKT	Bukit Tinggi	LEICA GRX1200GGPRO	LEIAT504GG	100.37109	-0.30898
SAMP	Sampali	Ashtech UZ-12	ASH700936A_M	113.25194	-7.19544
BAKO	Cibinong	LEICA GRX1200GGPRO	LEIAT504GG	106.84891	-6.49105
CCLP	Cilacap	LEICA GRX1200+GNSS	LEIAR25	109.01016	-7.73763
CPKL	Pekalongan	LEICA GRX1200+GNSS	LEIAR25	109.66944	-6.88701
CPON	Pontianak	TOPCON Net-G3	TOPCON CR.G3	109.32904	-0.00361
CBAL	Balikpapan	TOPCON Net-G3	TOPCON CR.G3	116.83971	-1.25614
CMAK	Makasar	TOPCON Net-G3	TOPCON CR.G3	119.40801	-5.13480
CBIT	Bitung	TOPCON Net-G3	TOPCON CR.G3	125.18675	1.44312
CUKE	Merauke	LEICA GRX1200+GNSS	LEIAR25	140.39416	-8.48985

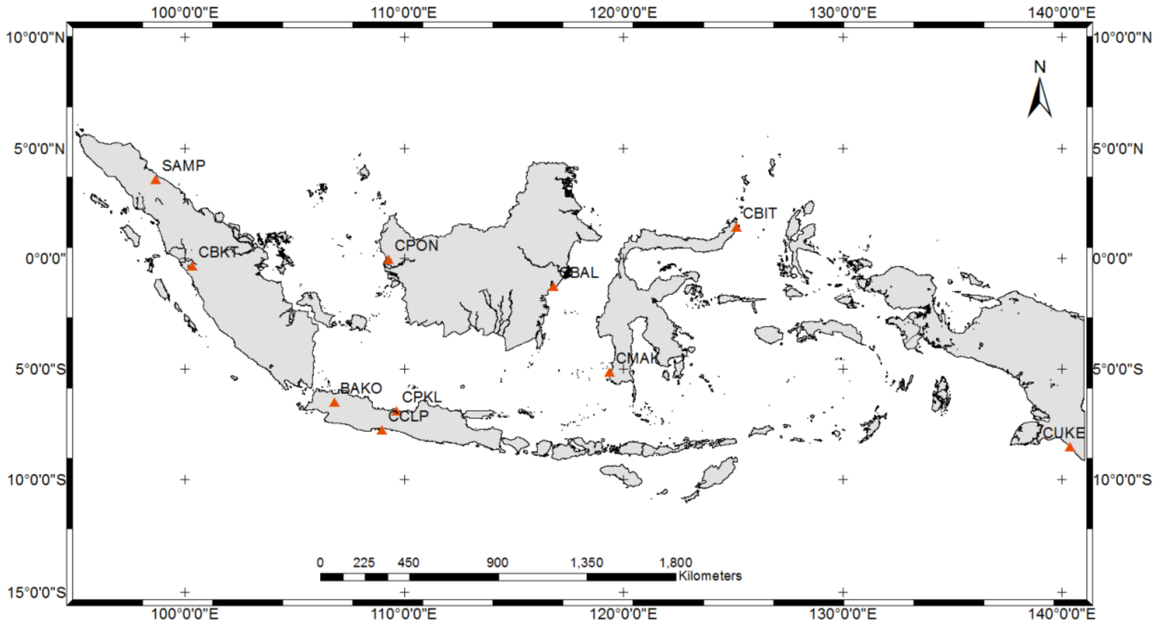

Figure 1 IPGSN stations that used in this study

3.2 Method

We processed 10 stations data from the beginning of 1st January 2011 through in the 31st December 2011, 1 year in total, using free software that called RTKLib with Comment User Interface (CUI) in Kinematic Precise Point Positioning (KPPP) method. OTL have temporal characteristic. Temporal characteristic that are commonly seen are semidiurnal, diurnal and long-period (Weber, et al.,2011).

The former can be monitored very precisely by satellite techniques like GNSS (Weber, et al.,2011). GNSS processing mode that can process data epoch wise is Kinematic Precise Point Positioning (KPPP) mode (Zumberge et al., 1997; Allison et al.,2004). KPPP utilizes precise satellite orbit and clock data from a previous global network solution to allow coordinates of GNSS receivers to be obtained on an individual basis, typically with few-mm precision, from 24-hour datasets (Bar-Sever et al.,1998; Allison et al.,2004).

Figure 1 shows the stations that used in this study. The stations represent big island in Indonesia and located close to inland waters and/or Open Ocean. We used 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 receiver and satellite antennas (Schmid et al. 2007). Troposphere correction using estimate ZTD+Grad and Ionospheric correction using iono free LC. In our solutions, we used a 7^0 elevation mask. Carrier phase ambiguities were not resolved. For align to reference frame, we are not specified reference frame. The result is height variation time series from GPS observation data. Vertical displacement are obtained from height variation time series

To assessment the characteristics of vertical displacement in each station, then performed spectral analysis using a Fast Fourier Transform (FFT). Spectral analysis is done to see the most dominant frequency of each phenomenon and variation and Also its accuracy/standard deviation. The spatial pattern and characteristic that are dominant in the vertical displacement can be obtained from this analysis from, whether the diurnal, semidiurnal or long period.

4. RESULT AND ANALYSIS

4.1 Vertical Displacement Time Series

Vertical displacement time series produced by RTKLib with KPPP method is a three-dimensional (3D) coordinate toposentric. The resulting time series, there are have missing or gap data. To produce the analysis in the frequency domain (spectral domain) using Fast Fourier Transform (FFT) it takes time series intact and should not be interrupted. Therefore, if there are gaps data, to fill in the gaps, then the methods used are interpolating the data or fill in the blanks with the model (Variandy, 2014). In this study, the method of filling the gap data is spline interpolation. The average amount of gaps data at each station in one year is 19 days of data, so that the percentage of data lost in one year was 5.2%, the biggest percentage is in CPON station with 15.61% and the smallest is in CPKL station 0.27%. This percentage is small, so it does not interfere with the overall data when filling the gaps data using interpolation method.

Figure 2 shows the vertical displacement time series from GPS observation data of BAKO station located in the Bogor district. In that figure, there are many outliers, so we need to detect outliers and eliminate outliers. Detecting outliers is to calculate the gross-error then discard data beyond the gross-error range (Elgazooli, 2012). Gross-error was detected using the following formula:

$$\left.\begin{aligned} UCL &= \bar{x} + 3\sigma \\ CL &= \bar{x} \\ LCL &= \bar{x} - 3\sigma \end{aligned}\right\}$$

UCL is Upper Control Limit, CL is Control Limit, and LCL is Lower Control Limit. $\bar{x}$ is mean and σ is standard deviation. After discard data that beyond gross-error range, the steps taken to remove the outlier using moving average filtering. Moving average is a low pass filter with filter coefficients equal to the reciprocal of the span. Span or window that is used in this step is 119, assuming the smallest phenomena that wants to be seen in this study is a daily phenomenon, so that the smallest interval of data can still be used to see daily phenomena is 1 hour. Interval data used in this study is 30 seconds, so in one hour there are 120 data, because the moving average span must be odd, therefore the span used is 119.

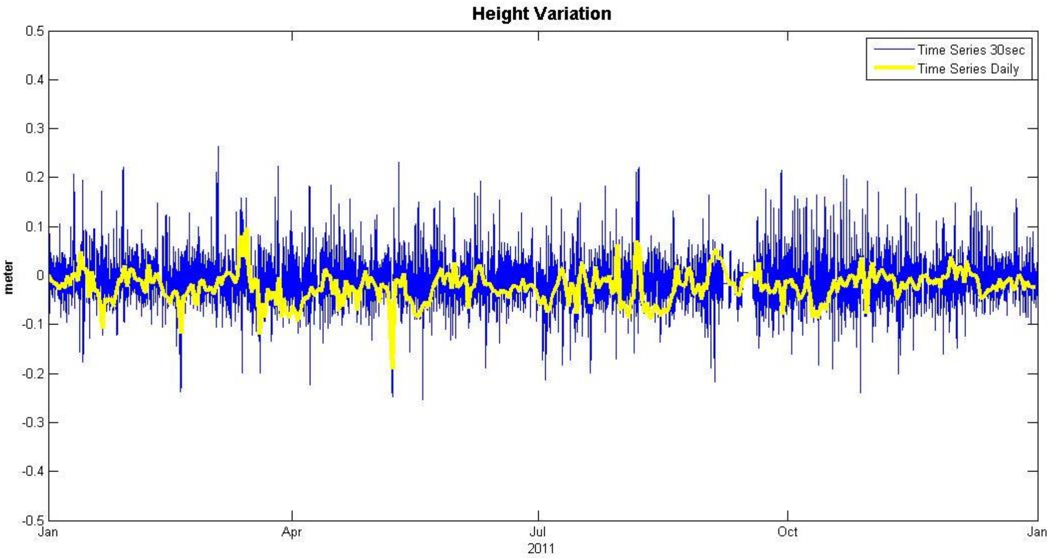

Figure 2 Vertical displacement time series in BAKO station before outlier removed

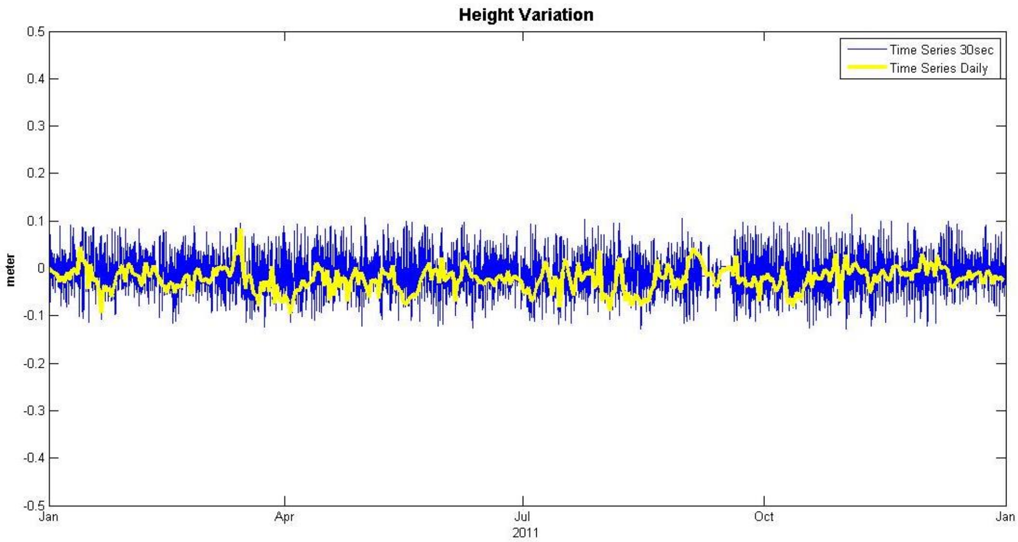

Figure 3 Vertical Displacement time series in BAKO station after outlier removed

Table 3 Maximum, minimum and displacement value for each stations

Station	*Min Value (m)*	*Max Value (m)*	*Average (m)*	*Displacement (m)*	*RMS Error (m)*
BAKO	-0.1	0.0787	-0.0113	0.1787	0.0338
CBAL	-0.2172	0	-0.1172	0.2172	0.0365
CBIT	-0.2204	0.0878	-0.0663	0.3082	0.0629
CBKT	-0.1228	0.0409	-0.04	0.1637	0.031
CCLP	-0.1568	0.0304	-0.0645	0.1872	0.0408
CMAK	-0.1242	0.0728	-0.026	0.197	0.0439
CPKL	-0.1801	0.0164	-0.0841	0.1965	0.0398
CPON	-0.1504	0.0625	-0.0434	0.2129	0.0454
CUKE	-0.0977	0.0947	0.0011	0.1924	0.0364
SAMP	-0.1068	0.1161	0.0034	0.2229	0.0412

Before outlier removed the maximum and minimum values is 0.2645 and -0.2544 meters. After outlier removed the maximum and minimum values is 0.0787 and -0.1 meters. The maximum and minimum values is a vertical displacement value. For more details, **Table 3** shows the vertical displacement of all stations.

Table 3 and **Figure 4** shows that CBIT station (Bitung) has the largest vertical displacement with the value is 0.3082 meters, and CBKT station (Bukit Tinggi) has the smallest vertical displacement with the value is 0.1637 meters. Each station has a different displacement value, to further strengthen the results and also to assess the pattern and characteristic of OTL effects it is necessary to analyze the spectral domain.

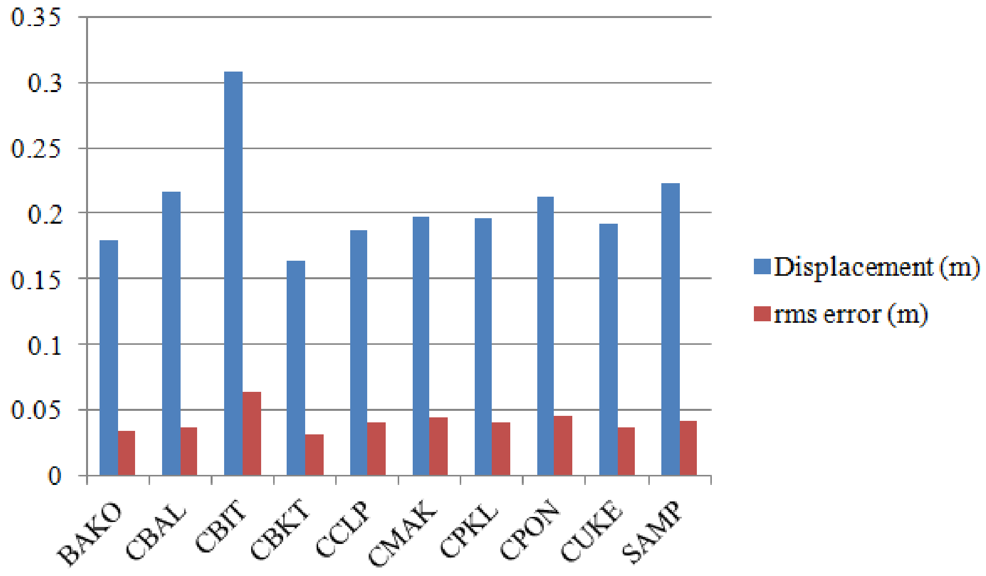

Figure 4 Displacement and RMS error value for each station

4.2 Patterns and Characteristics OTL Displacement for each station

To know a phenomenon in each station it is necessary to change the time series in the spatial domain into the spectral domain using Fast Fourier Transform (FFT). **Figure 5** shows the amplitude variation of the spectral domain phenomenon. Power spectrum variation of vertical displacement dominated by Diurnal and Semi-diurnal phenomena. The largest phenomena are K1 and M2 phenomena, K1 is Luni-solar diurnal tide and M2 is lunar semi-diurnal tide. The largest power spectrum is in CBIT station, located in Bitung, North Sulawesi Province with amplitude value in M2 phenomena is 0.016 meters. The smallest power spectrum value is BAKO station, located in Bogor, West Java Province with amplitude value in M2 phenomena is 0.0059 meters.

Similarly its displacement, pattern and characteristic in spectral domain of OTL also influenced by the location of the station. From amplitude variation, CBIT, CCLP, CPON, CUKE, SAMP and CBAL station, has amplitude value more than 0.01 meters or more than 1 cm. While, BAKO, CBKT, CMAK and CPKL station has amplitude value less than 1 cm. From the calculation results in the spatial domain, displacement at each station is directly proportional to the amplitude value in spectral domain. Indonesian seas are mostly shallow water, the topography and depth distributions of the ocean floors around Indonesia affects the amplitude value of OTL (Yeh, et al, 2011). Problem areas are mostly shallow seas with large tidal amplitude.

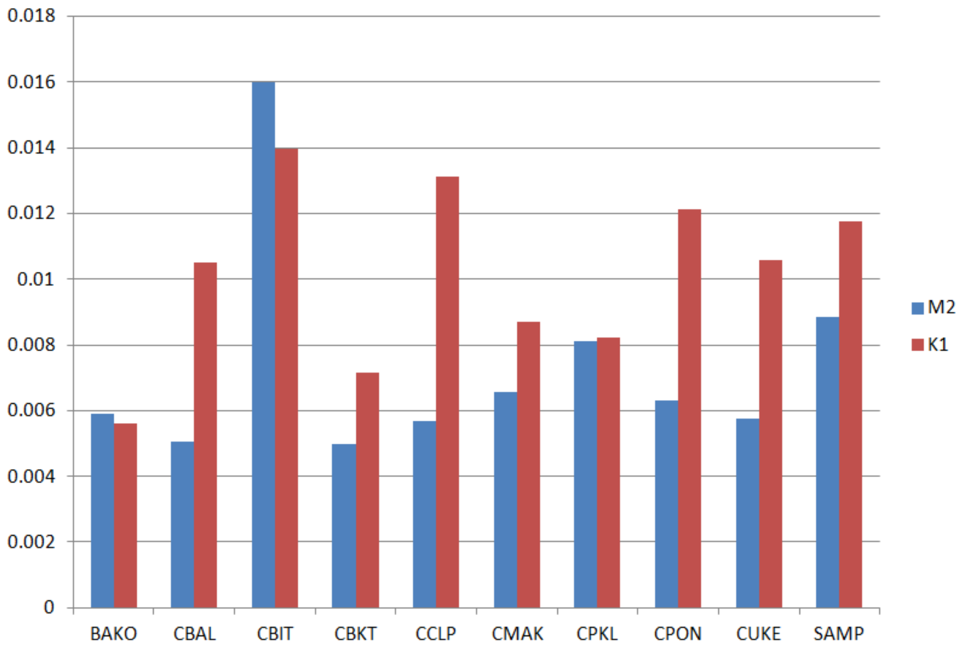

Figure 5 The amplitude variation of K1 and M2 phenomena

4.3 Relation of modeled and observed OTL

This section describes how OTL model affects GNSS positioning. After time series processing without OTL corrections, corrections derived from ocean tide models were applied to evaluate their effect on the resulting site coordinates. The OTL models that used in this study are FES2004, OSU12, NAO99.b and TPXO.7.2. Because of GNSS satellite are gravitationally attracted by the mass of the whole Earth system, so their trajectories are physically relative to Center of Mass (Fu, 2011).

Figure 5 shows the height variation or vertical displacement with no OTL correction and using OTL correction in BAKO station at daily time series for a year. Average rms error before using OTL correction is 0.0338 meters, using FES2004 correction the average rms error is 0.03144 meters, using OSU12 model the average rms error is 0.0319 meters, using NAO99.b the average rms error is 0.0315 meters, and using TPXO.7.2 the average rms error is 0.03142 meters. For BAKO station, TPXO.7.2 model have the smallest average rms error value with no OTL correction vertical displacement. That mean, TPXO.7.2 applicable for use in BAKO station. Respectively, demonstrating improvements of 0.19 - 0.24 cm in the vertical positioning precision in BAKO station. In other station, OTL correction improves 0.2 – 0.9 cm in vertical positioning precision.

Figure 6 shows the average rms error value for each station. For each station, have different fit models. At the station CBAL, TPXO.7.2 also has the smallest RMS error average value. In CBKT, CCLP and CPON station, FES2004 OTL is a model that has the smallest RMS error average value. Unlike the CBIT and CPKL, on both stations, OSU12 model have the smallest RMS error average value. While at the SAMP station, NAO99.b has the smallest RMS error average value. This means that each station has a different characteristic so that the most applicable model to be used to correct for the OTL effects is also different.

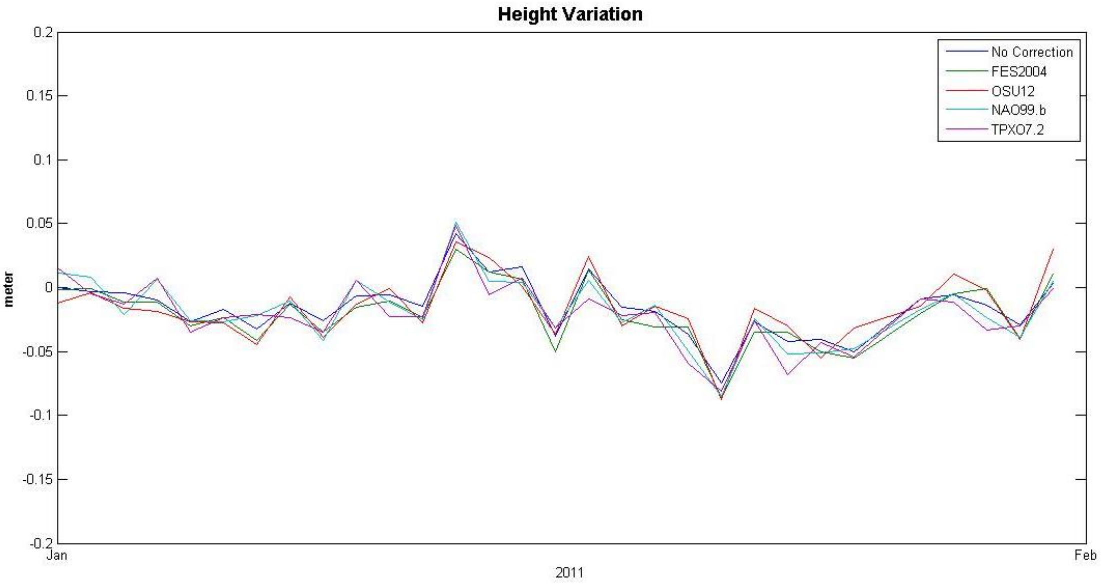

Figure 6 Height variation with and without OTL correction in BAKO station

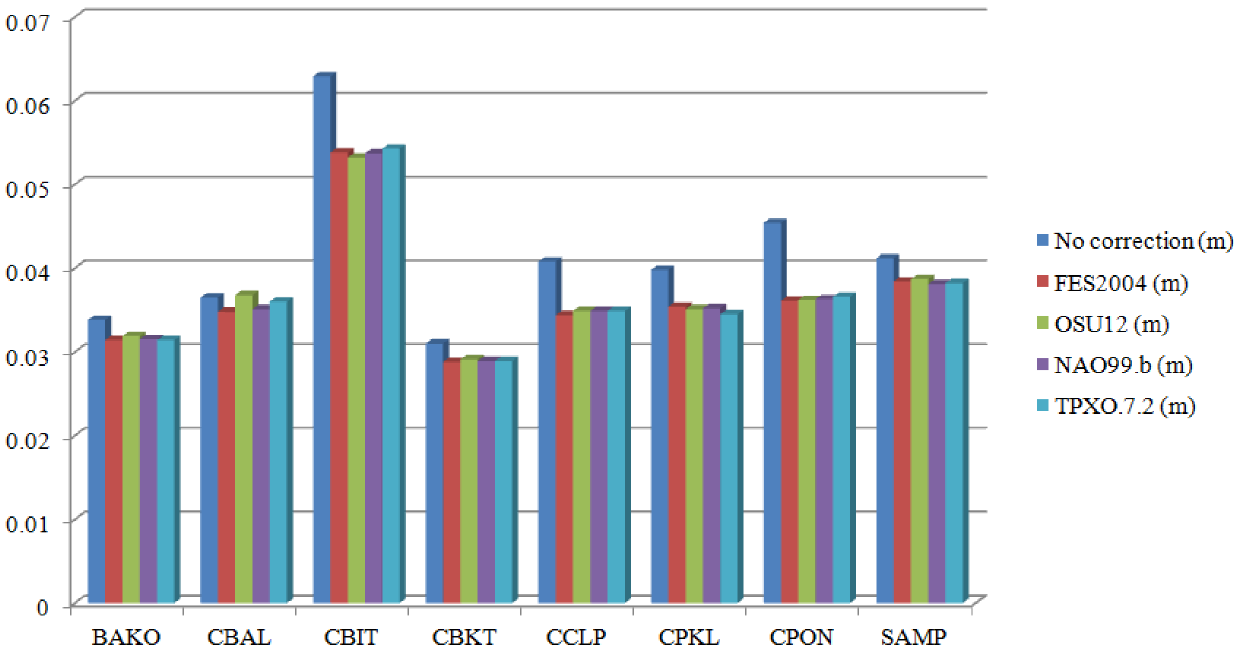

Figure 7 Average rms error value for each station

5. CONCLUSIONS

Based on the results of GNSS data processing, the vertical displacement as a result of OTL effect have different values at each station. Vertical displacement range between 0.16 - 0.3 meters with rms error value between 3-6 cm. The results of spectral domain analysis, phenomena that occur in Indonesia is dominated by the semi-diurnal and diurnal, with the highest component are K1 and M2. the amplitude at each station also varies between 0.5 - 1.6 cm, with the lowest values found in BAKO station and the highest value at CBIT station. The results of the comparison with the four OTL models improve vertical accuracy of GNSS positioning, between 0.2 - 0.9 cm, with an applicable model for each stations are different.

The accuracy of GNSS data processing using software RTKLib unsatisfactory, for the next study, suggested using scientifics software and improve the other models that affect the accuracy of GNSS positioning. To ensure OTL amplitude value of each station need to be checked by using the tidal station. the tidal amplitude from tidal station can be used as a validator of the model OTL. By using 10 stations GNSS, less cover all areas of Indonesia, which consists of thousands of islands, therefore it is highly advisable to increase the number of stations so that the conclusions could be more comprehensive. However, as a first step of the study, this study suggests that GNSS positioning affected by OTL effect, especially for the vertical component.

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