Sensing of the atmospheric variation using Low Cost GNSS Receiver

Brian Bramanto, Irwan Gumilar, Teguh P. Sidiq, Wedyanto Kuntjoro, Daniel A. Tampubolon
Geodesy Research Group, Institut Teknologi Bandung, LABTEK IX-C, Jalan Ganesha 10 Bandung, Indonesia
E-mail: brian.bramanto@s.itb.ac.id

Abstract. As the GNSS signals transmitted through the atmosphere, they are delayed by interference of TEC (Total Electron Content) in the ionosphere and water vapor in the troposphere. By using inverse-problem, name GNSS Meteorology, those parameters can be obtained precisely and several researches has approved and supported that method. However, the geodetic GNSS receivers are relatively high cost ($30,000 to $70,000 each) to be established on a regular and uniform network. This research aims to investigate the potential use of low cost GNSS receiver (less than $2,000) to observe the atmospheric dynamic both in ionosphere and troposphere. Results indicated that low cost GNSS receiver is a promising tools to sensing the atmospheric dynamic, however, further processing is needed to enhance the data quality. It is found that both of ionosphere and troposphere dynamic has diurnal periodic component.

1. Introduction

Atmosphere consists at least two layers, like ionosphere and troposphere. The ionosphere can be described as the upper layer (20 to 2,000 km) of atmosphere where the thickness of free elections and ions is sufficiently high to interfere the electromagnetic waves propagation [1]. The troposphere can be defined as the lower layer (up to 20 km) of the atmosphere where consists of water vapor and aerosol [2]. Nowadays, atmospheric study is important for the communication and the climate change issues.

Atmospheric can be monitor by using ionosonde (for ionosphere) and Automatic Weather Station (for troposphere), however, in accordance with the emergence and the development of GNSS (Global Navigation Satellite System) technology and methods, it leads to diverse application of GNSS, such as ionosphere and troposphere monitoring. As the GNSS signals transmitted through the atmosphere, the GNSS signals are interfered by the TEC (Total Electron Content) in the ionosphere, while water vapor in the troposphere.

In ionosphere and troposphere monitoring, the geodetic GNSS receiver (high cost $30,000 to $70,000 each) leads to a problem, especially in Indonesia. As seen on Figure 1, at about 1.9 million square kilometers, Indonesia needs a lot of atmosphere monitoring stations. Assumed that there will be at least one monitoring station every 20 kilometers, Indonesia demand at least 4,000 monitoring stations. Recently several researches on low cost GNSS receiver (less than $2,000) had been done by many researchers, such as precise point positioning [3], landslide monitoring [4-5] and UAV applications [6]. Those researches indicate the accuracy and the potential use of the low cost GNSS receiver for a wider applications. Furthermore, as mentioned before, by replacing those geodetic GNSS receivers with low cost GNSS receiver, it lead to a cost efficiency for the site monitoring establishment itself. Therefore, this research aims to investigate the potential use of low cost GNSS receiver to observe the atmospheric
dynamic both in ionosphere and troposphere. The data and method are presented in detail in Section 2. In section 3, the ionosphere and troposphere parameter derived from low-cost GNSS will be evaluated.

![Map of Indonesia produced by Badan Informasi Geospasial (BIG).](image1)

**Figure 1.** Map of Indonesia produced by Badan Informasi Geospasial (BIG).

2. **Data and Method**

An experimental observation points was established in Bandung, by using Astech ProFlex 500 as the reference geodetic GNSS receiver and Tersus BX305 as the low cost GNSS receiver (Figure 2). Figure 3 shows the basic flowchart used in this research. This research includes several steps, such as data observation and satellite navigation collection, data quality assessment, ionospheric parameter determination and tropospheric parameter determination.

![Astech ProFlex 500 (left) and Tersus BX305 (right).](image2)

**Figure 2.** Astech ProFlex 500 (left) and Tersus BX305 (right).
2.1. Data Quality Assessment Method

GNSS data quality can be determined by evaluating the Signal to Noise (SNR) ratio and the multipath error of GNSS signal propagation. SNR indicates the degree of distorted GNSS signal propagation which is affected by surrounding environment. The high value of SNR (in dBHz) indicates that noise is significantly low compared with the signal strength and vice versa. In simplified, SNR can be defined as follows:

$$SNR = \frac{Signal\ Strength}{Noise}$$ (1)

The multipath of GNSS signal can be investigate by applied the Multipath Combination (MPC) algorithm. The MPC can be expressed as [7]:

$$MP1 = P_1 - \frac{f_1^2 + f_2^2}{f_1^2 - f_2^2}L_1 + \frac{2f_2^2}{f_1^2 - f_2^2}L_2$$ (2)

Figure 3. Basic flowchart used in this research.
\[ MP2 = P_2 - \frac{f_2^2}{f_1^2 - f_2^2} L_1 + \frac{f_2^4 + f_2^2}{f_1^2 - f_2^2} L_2 \]  

where \( P \) and \( L \) are the pseudorange and carrier phase range respectively and \( f \) is the frequency of the carrier phase. By using these combinations, the first order of ionospheric delay and geometric range from satellite and receiver are eliminated, while noise are assumed to be negligible due to the accuracy of the pseudorange observation.

2.2. **GNSS Signal Propagation and Error**

GNSS observation data is consist of carrier phase and pseudorange code data observation. Error and other noises are also contained within the GNSS observation data. Mathematically, GNSS data observation, as well as the error and noise can be defined as follows [8]:

\[ P_i = \rho + d\rho + d_{\text{mp}} + d_{\text{am}} + c(dt - dT) + MP_i + \theta_P \]  

\[ L_i = \rho + d\rho - d_{\text{am}} + c(dt - dT) + ML_i + \lambda_i N_i + \theta_L \]  

where \( P_i \) and \( L_i \) are pseudorange and carrier phase range on selected frequency \((i = 1, 2)\), \( \rho \) is related to geometrical range from receiver to satellite, \( d\rho \) is the orbital error, \( d_{\text{mp}} \) and \( d_{\text{am}} \) are troposphere and ionosphere biases, \( c \) is the speed of light \((299,729,458 \text{ m/s})\), \( dt \) and \( dT \) are time error of receiver and satellites, \( MP_i \) and \( ML_i \) are related to multipath error of pseudorange and carrier phase range, \( \lambda_i \) and \( N_i \) are related to wavelength and ambiguity number, while \( \theta_P \) and \( \theta_L \) are related to noise error.

**Table 1.** Error in GNSS signal propagation [9].

| Error Source       | Magnitude |
|--------------------|-----------|
| Satellite orbital error | ~ 100 m   |
| Satellite clock error     | ~ 500 m   |
| Ionospheric bias                  | ~ 50 m    |
| Tropospheric bias                   | ~ 5 m     |

By understanding the GNSS signal propagation, TEC and water vapor can be estimated. Geometrical linear combination of GNSS signal is used to determine the TEC, while PPP (Precise Point Positioning) method is used to determine the tropospheric delay which lead to water vapor estimation.

2.3. **GNSS Ionospheric Algorithm**

The Slant TEC is defined as the line integral of the electron density from all GNSS-Satellites visible from each of these receiver above a user-specified elevation cut-off angle (usually 15°). Mathematically, slant TEC can be defined as follows [10]:

\[
STEC = \int Ne(r)dr = \frac{[P_1 - P_2] - [RCB - SCB]}{C_x \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)}
\]  

where \( C_x \) is the constant \(80.62 \text{ (m}^3/\text{s}^2)\), \( RCB \) and \( SCB \) are receiver code bias/receiver clock bias and satellite code bias/satellite clock bias respectively.

2.4. **GNSS Tropospheric Algorithm**

Tropospheric parameter can be determined by Precise Point Positioning (PPP) algorithm. PPP uses both of pseudorange and carrier phase GNSS observation data from a single dual-frequency receiver. PPP...
uses ionospheric-free linear combination in order to eliminate the ionosphere biases. Ionospheric-free linear combination can be described as follows [11]:

\[ P_{IF} = \frac{f_1^2 p_1 - f_2^2 p_2}{f_1^2 - f_2^2} = \rho + d\rho + c(dt - dT) + d_{trop} + MP_{IF} + \partial P_{IF} \]  
(7)

\[ L_{IF} = \frac{f_1^2 l_1 - f_2^2 l_2}{f_1^2 - f_2^2} = \rho + d\rho + c(dt - dT) + d_{trop} + \frac{c f_1 N_1 - c f_2 N_2}{f_1^2 - f_2^2} + ML_{IF} + \partial L_{IF} \]  
(8)

where \( MP_{IF} \) and \( ML_{IF} \) are multipath error due to linear combination, while \( \partial P_{IF} \) and \( \partial L_{IF} \) are noise error due to linear combination. To eliminate the satellite orbital error and satellite clock error, precise orbit and clock correction are needed. Multipath error can be reduced by using a proper antenna. As a result, PPP can be simplified as follows:

\[ P_{IF} = \frac{f_1^2 p_1 - f_2^2 p_2}{f_1^2 - f_2^2} = \rho + cdt + mf\cdot ztd + \partial P_{IF} \]  
(9)

\[ L_{IF} = \frac{f_1^2 l_1 - f_2^2 l_2}{f_1^2 - f_2^2} = \rho + cdt + mf\cdot ztd + \frac{c f_1 N_1 - c f_2 N_2}{f_1^2 - f_2^2} + \partial L_{IF} \]  
(10)

where \( mf \) is refer to tropospheric mapping function and \( ztd \) is refer to zenith troposphere delay. The PPP estimates four types of parameters, the receiver position \((X, Y, Z)\), the receiver clock \((dt)\), the troposphere delay \((ztd)\) and the ambiguity \((N_1 \text{ and } N_2)\).

3. Result and Discussion

3.1. Data Quality Assessment

Figure 4 shows the SNR and multipath for both Astech Proflex 500 (geodetic GNSS) receiver and Tersus BX305 (low-cost GNSS) receiver. Both observed the same satellites in the same observation time. It could be seen that SNR for low-cost GNSS receiver is almost the same as the reference geodetic GNSS receiver which vary from 30 dbHZ to 50 dbHZ. On the other hand, Low-cost GNSS receiver gives worse performance in code multipath analysis. Low-cost GNSS receiver code’s multipath is vary from -3 meter to 3 meter, while the multipath for geodetic GNSS receiver is vary from -1 meter to 1 meter. This condition leads to a worse code point positioning accuracy in low-cost GNSS receiver rather than geodetic GNSS receiver.
3.2. Ionosphere Parameter Estimation

Figure 5 shows the estimated relative slant TEC from code pseudorange data for both of low-cost GNSS receiver and geodetic GNSS receiver for each observed satellite. Both of them show similar magnitude of slant TEC which is up to 120 TECU, however, the estimated slant TEC from low-cost GNSS receiver showed a significant noise compared with the estimated slant TEC from geodetic GNSS receiver. According to equation (4), possible caused that lead estimated slant TEC has significant noise is there receiver clock bias. Receiver clock bias is related with the effect of oscillator instability. That factor may also be the main factor of the high deviation of code multipath error [12].

To improve the quality of the data observation, further data processing is needed. Data smoothing is applied in this research. Data smoothing is conducted in several steps [13]:

![Figure 4. SNR and multipath over elevation for geodetic GNSS receiver (upper) and low-cost GNSS receiver (below).](image-url)
- Checking the receiver clock consistency
- Data screening based on Melbourne-Wübbena linear combination
- Data screening based on Geometry-Free linear combination
- Data screening based on Ionosphere-Free linear combination
- Code smoothing

Figure 6 shows the estimated slant TEC from smoothed low-cost GNSS data. It could be seen that the estimated slant TEC has small biases. Slant TEC has maximum magnitude around 3:00-7:00 UTC or 10:00-14:00 at local time and minimum at the 12:00-00:00 UTC or 19:00-7:00 at local time. These diurnal variation is related to the sun occurrence [14,15]

![Relative Slant TEC (pseudorange)](image1)

![Relative Slant TEC (pseudorange)](image2)

**Figure 5.** Relative slant TEC that is estimated from low-cost GNSS receiver (upper) and geodetic GNSS receiver (bellow).
3.3. Troposphere Parameter Estimation
Figure 7 shows the zenith wet delay (ZWD) from three days observation by subtracting the zenith tropospheric delay with zenith hidrostatic delay using Saastamoinen model. ZWD is vary from 0.22 meter to 0.34 meter. Similar with TEC, ZWD also indicates diurnal variation. Precitable water vapor (PWV) can be estimated from zenith wet delay as follows:

$$ PWV = \Pi ZWD $$  \tag{11}

where $\Pi$ is 0.15 as constant. Figure 8 shows the PWV that is vary from 35 mm to 50 mm.

4. Conclusion
It is now possible to accurately observe variations of atmospheric parameters using a single ground-based low cost GNSS receiver, however, further processing is needed to enhance the data quality. As the implications, atmospheric monitoring using dense low-cost GNSS receiver can provide continuous regional/global monitoring of the ionosphere and troposphere parameters with various spatio-temporal scales (even in real-time).
Figure 7. Tropospheric delay (upper) and zenith wet delay (bellow) from 17 April 2017 with 30 second of interval observation.
Figure 8. Estimated precitable water vapor from 17 April 2017 with 30 second of interval observation.

References
[1] Zolesi B and Cander L R 2004 Ionospheric Prediction and Forecasting (UK: Springer Geophysics)
[2] Bevis M, Businger S, Chiswell S, Herring T, Anthes R, Rocken C, Ware R 1994 GPS meteorology: Mapping zenith wet delays onto precipitable water Journal of Applied Meteorology 33 379–386
[3] Bramanto B, Gumilar I, Sidiq T P, Abidin H Z, Hernawan M D A, Wijayanto B M 2016 On the Performance of a Single-Frequency Low-Cost GPS (Yogyakarta :FIT-ISI and CGISE 2016)
[4] Cina A, Piras M 2015 Performance of low-cost GNSS receiver for landslides monitoring: test and results Journal of Geomatics Natural Hazards and Risk 6 497-514
[5] Biagi L, Grec F C. and Negretti M 2016 Low-cost GNSS receivers for local monitoring: experimental simulation, and analysis of displacement Sensor 16 2140
[6] Stempfhuber W, Buchholz M 2011 (Zurich: Proceeding of ISPRS volume XXXVIII-1/C22)
[7] Estey L H, Meertens C M 1999 TEQC: the multi-purpose toolkit for GPS/GLONASS data GPS Solutions 3 42-49
[8] Xu G 2010 GPS Theory, Algorithms and Application (Berlin: Springer)
[9] Seeber G 2003 Satellit geodesy, 2nd edition (Berlin: de Gruyter)
[10] Cabrera M A, Ezquer R G, and Radicella S M 2005 Predicted and measured slant ionospheric electron content J. Atmos. Terr. Phys. 67 1566–1577
[11] Gao Y and Chen K 2004 Performance Analysis of Precise Point Positioning Using Real-Time Orbit and Clock Products Journal of Global Positioning Systems 3 95-100
[12] Gaggero P O 2008 Effect of oscillator instability on GNSS signal integration time Master thesis (Neuchâtel: University of Neuchâtel)
[13] Dach R, Lutz S, Walser P, Fridez P 2015 Bernse GNSS Software Version 5.2 (Bern: Astronomical Institute, University of Bern)
[14] Bramanto B, Rudin O and Wijaya D D 2013 Sensing of the Ionosphere Dynamics over the Indonesian Region using GNSS Observations (Bali: Asian Conference of Remote Sensing 2013)
[15] Pastrav A, Puschita E, Palade T 2017 Ionospheric propagation monitoring and TEC measurements using GPStation-6 GNSS receiver European Conference on Antennas and Propagation 11th