Prospective research on modeling of GNSS tropospheric delays for improving the accuracy of weather forecast in Indonesia

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Abstract. This paper overviews the prospect of utilizing Global Navigation Satellite Systems (GNSS) tropospheric delays to improve the accuracy of weather forecasts as well as environmental models toward effective management and decision-making. As well reports the application of GNSS technique for investigation of space weather and meteorological applications that have been conducted in the South Pole (Antarctica) and North Pole (Arctic). The revelation of the previous research provides further direction, what is the best approach that can be done to solve local problems but can give global impacts. In this case highlighted the application of GNSS technique for monitoring the volcanic activity in the Special Region of Yogyakarta, Indonesia.

1. Introduction
Tropospheric delays is an element of weather systems which highly correlated with atmospheric dynamics. The Global Navigation Satellite Systems (GNSS) is a promising technique to model the tropospheric dynamics for improving the accuracy of weather forecasts as well as improving numerical weather predictions. The precise point positioning with GNSS remote sensing is important in the estimation of the precipitable water vapor (PWV) [1,2]. PWV is the basic concept of the weather systems; the engine of the weather and is ones of the indicator in determining changes in global warming [3]. Thus, understanding of water vapor transport and their feedback to atmospheric phenomena are a crucial such as for meteorological applications.

Since the GNSS such as Global Positioning System (GPS) is cost-effective technique, powerful and with better accuracy, and provides good spatial and temporal resolution, much work has been done using this technique. For example, correlating the solar activity with PWV variation for Antarctica [2]; analysis of the influence of terrestrial winds on the PWV variations [4], correlation between GPS total electron content (GPS TEC) with aurora activity [5], katabatic wind detection using GPS meteorology [6], tropical thunderstorm estimated using GPS in Borneo [7]. Other utilizations of GNSS signals such as monitoring for flash floods in Peninsular Malaysia [8], volcano ash (pollution) [9] and deformation activities [10], landslides [11], etc. have been successfully implemented. In particular for modeling of tropospheric delays, Suparta and Alhasa [12, 13] has developed the model using the adaptive neuro-fuzzy inference system (ANFIS) technique. The tropospheric delays model with ANFIS is then used to develop a new system of PWV measurements [14]. Basically, modeling the tropospheric delays can be found in Hofmann-Wellenhof et al. [15].
This paper overviews the prospective modeling of GNSS tropospheric delays for Indonesia in an effort to enhance the accuracy of weather forecasts as well as utilizing the GNSS signals towards the advancement of regional climate models. First, a short modeling of tropospheric delays will be enlightened and followed by the introduction of GPS data processing in the methodology section. Secondly, the legacy of achieving GPS applications in Antarctica and the Arctic will also be highlighted. Based on previous achievements, new insights to enhance weather forecasts in Indonesia include the development of monitoring system for volcanic ash in the Special Region of Yogyakarta, Indonesia is proposed. The most fundamental effort of monitoring with GNSS is to provide data that will be useful for analysis and other decisions.

2. Modeling of Tropospheric Delays

The presence of free electrons in the ionosphere and the refractivity of gases, hydrometeors, and other particulates in the troposphere will retards and affects significantly the travelling of radio signals to receiver on the Earth. During the propagation, the pseudorange from GNSS will be delayed. Figure 1 shows the difference between the actual path of the carrier (S) and the straight-line (rectilinear) path in a free-space (G) of the radio signal to obtain travel time dt.

\[ dt = \frac{1}{v} \int_{S} \frac{1}{c} \int_{G} dS - dG, \text{ with } S = \frac{P_1}{P_2} n(s) dS = G + D_{\text{Trop}}, \text{ and } G = \frac{P_1}{P_2} \int dG \]

(1)

where \( v \) and \( c \) are speed of the radio signals in medium and in free space, respectively.

![Figure 1. GNSS signals travel through Earth’s atmosphere and atmospheric path delay geometry [16]](image)

Let \( D \) is the delay of radio wave, \( \theta \) is the satellite elevation angle, \( S \) is the true path along which the radio wave propagates, and \( G \) the shortest geometric path along which the signal would transverse, assuming as \( n = 1 \). Then

\[ D = c dt = \frac{1}{S} \int_{S} n(s) dS - G = \left[ n(s) - 1 \right] dS + [S - G] \]

(2)
From (2), there are two effects on a ray path: bending and retarding, which produce an excess path length with respect to propagation in a free space. Excess path length due to signal retarding is called tropospheric path delay [17], as expressed

$$\Delta D = \int_2^n [n(s) - 1]dS = 10^{-6} \int_n^h N(s)dS$$

(3)

where \(\Delta D\) is the difference delay between \(S\) and \(G\). With assuming the atmosphere to be spherically symmetric, the atmospheric will vary only with geometric radius. In this way, the electromagnetic ray represent the refractive index as a function of geocentric radial distance only, \(n(h)\) and for \(S\), it can written as

$$G + D^{Trop} = \int_2^n [n(h)\sec\beta_z(h)]dh = \int_2^n [n(h) - 1]\sec\beta_z(h)dh + \int_2^n \sec\beta_z(h)dh$$

(4)

where the refractive index is integrated along the path between point \(h_0\)-the geocentric distance of the user’s antenna and \(h_1\)-the geocentric distance of the ‘top’ of troposphere, respectively. Angle \(\beta\) is the actual (refracted) zenith angle of the ray path at distance \(h\) (see Fig. 1). The path delay is caused by variation of \(n\) from unity.

To obtain the total tropospheric delay, the delay in free-space is subtracted to get the following integral equation:

$$D^{Trop}_s = \int_2^n [n(h) - 1]\sec\beta_z(h)dh + \left[ \int_2^n \sec\beta_z(h)dh - \int_2^n \sec\alpha_d(h)dh \right]$$

(5)

where the first integral accounts for the difference between the electromagnetic distance and geometric distance along the ray path and the bracketed integrals account for curvature of the ray path: i.e. the difference between the refracted and rectilinear geometric distances. The total tropospheric delay, can be simplified as in (6), which contain the hydrostatic and wet components (\(\delta\) is the tropospheric correction and \(\delta = 0\) if the asymmetric components are neglected).

$$D^{Trop}_s = 10^{-6} \int_{\text{actual}} N(h)dh + \delta = 10^{-6} \int N_{\text{hyd}} dh + 10^{-6} \int N_{\text{wet}} dh + \delta$$

(6)

Tropospheric delays increase with decreasing satellite elevation angle. This is accounted for multiplying the zenith delays by a correction factors, \(m\). In general, total tropospheric delay from (6) following Davis et al. [17] can be rewritten as

$$ZTD = m_{\text{hyd}}(\theta) \cdot ZHD + m_{\text{wet}}(\theta) \cdot ZWD$$

(7)

where \(ZTD\) is zenith tropospheric delay or equal to the total tropospheric delay (\(D^{Trop}_s\)), \(ZHD\) is the hydrostatic zenith delay, \(ZWD\) is the wet zenith delay, and \(m_{\text{hyd}}(\theta)\) and \(m_{\text{wet}}(\theta)\) are hydrostatic and wet mapping functions respectively. The mapping function can be developed in order to track the GNSS signals with respect to the hydrostatic and wet components. Details modeling of tropospheric delays can be found in Suparta and Alhasa [13].
The ZTD is eq. (7) will be more benefits for meteorological applications if it converted to water vapor parameter. The direct computation of ZTD is now based on the Modified Hopfield model as expressed as \([2, 15]\),

\[
ZTD_{j}^{\text{Trop}}(x) = 10^{-12} N_{j,0}^{\text{Trop}} \left( \sum_{k=1}^{9} \beta_{k,j} T_{j}^{k} \right) 
\]

where \(N_{j,0}^{\text{Trop}}\) is the total refractivity at the surface of the Earth, subscript \(j\) is replaced by \(h\) and \(w\) for hydrostatic and wet component, respectively. \(\beta_{j}^{k}\) is a series expansion of \(k\) tropospheric layer and \(r_{j}\) is the dry and wet refractivity components as a function of tracking station height \(h\) above the Earth's surface. The input to compute ZTD is the elevation angle and surface meteorological data \((P, T, \text{and} H)\). A Vienna mapping function (VMF1) was used to reduce atmospheric bias in the ZTD estimation \([18]\). The ZHD is calculated using Saastamoinen model \([19]\). The ZWD is estimated from the GPS measurements, \(\text{ZWD}_{\text{GPS}} = \text{ZTD} – \text{ZHD}\). PWV now can be calculated as given by Bevis et al. \([20]\).

\[
PWV = \pi(T_{m}) \cdot \text{ZWD}_{\text{GPS}}, \text{ where } \pi(T_{m}) = \left[ \rho_{w} R_{v} \left( \frac{k_{1}}{T_{m}} + k_{2} \right) \right]^{-1} \times 10^{6}
\]

where the dimensionless \(\pi(T_{m})\) parameter is a conversion factor that vary with the summation on the local climate and is depend on a weighted mean temperature \(T_{m}\) as given by

\[
T_{m} = 0.83663 \cdot T_{s} + 48.103
\]

where \(\rho_{w}\) and \(R_{v}\) are the density of the liquid water and specific gas constant for water vapor respectively. The mean temperature \(T_{m}\) is estimated linearly from Radiosonde data over 15 sites in the tropical region as done by Suparta and Iskandar \([21]\).

3. Methodology and Experimentation

The purpose of doing research in Antarctica is deal with the global climate change. Climate change is the most daunting collective challenge that humanity has ever faced. The installation of GPS receiver for monitoring the meteorological aspects as well space weather parameter that has been done by the author is compiled in Table 1. The GPS receiver reported in the table does not include the installation of the similar system in Peninsular Malaysia and Sabah (Malaysia). For Sabah, it was installed at Universiti Malaysia Sabah, Kota Kinabalu (UMSK) in 2011 for monitoring the El Nino Southern Oscillation (ENSO) activities along the South China Sea \([22]\). While the GPS and meteorological systems at Peninsular Malaysia was installed at Universiti Kebangsaan Malaysia, Bangi, Selangor (UKMB) in 2004 \([23]\).

| Station       | ID  | Latitude (deg) | Longitude (deg) | Height (m) | Types of GPS receiver and year installed | Country     |
|---------------|-----|----------------|-----------------|------------|----------------------------------------|-------------|
| Scott Base    | SBA | 77.85°S        | 166.76°E        | 15.85      | Trimble TS5700 (2002)                   | Antarctica  |
| Husafell      | HUSA| 66.67°N        | 338.97°E        | 220.20     | LEICA GRX1200 Pro (2008)               | Iceland     |
| Carlini Base  | CARL| 62.23°S        | 58.63°W         | 48.48      | Trimble TS5700 (2017)                  | Antarctica  |
| Sleman        | YOG3| 7.75°S         | 110.44°E        | 200.35     | TOPCON Net-G3 (2014)                   | Indonesia   |

Table 1. The geographical position for installation of the GPS receivers
The measurement of GPS and meteorological data is collected and processed following the scenario presented in Figure 2. The PWV is calculated based on the equations 9 and 10 which consist of satellite elevation angle and surface meteorological data (pressure ($P$), temperature ($T$), and relative humidity ($H$)) as input. Pre-processing was conducted for the GPS data such as RINEX-level data pre-processing and implemented the TEQC (translation, editing, and quality check) procedures to produce observation (*.obs), navigation (*.nav), and meteorology (*.met) data. The strategy of GPS data processing to produce PWV is conducted by a Tropospheric Water Vapor Program (TroWav) written in MATLAB [24]. Meanwhile, the algorithm for determination of vertical total electron content (VTEC) has been presented in [23].

![Diagram](image)

**Figure 2.** Data processing techniques for the determination of PWV based on the ground-based GPS measurements [16].

**4. Results and Discussion**

**4.1. Research activities in the South of Antarctica**

Since Antarctica is compromised as a privileged position and a unique laboratory for sciences, tourism and other explorations, the amount of carbon emissions is raised the global warming. In scientific perspective, Antarctica provide boundary conditions for understanding the changes in ocean circulation flow to the space phenomena that can affect communications systems. For the first idea to expand the prospective for utilizing the tropospheric delays for monitoring the atmospheric dynamics via PWV and TEC is depicted in Figure 3. The figure brief overview of research in South part of Antarctica (“Southern Land”) that was started in 2002. The monitoring system was installed at Scott Base station (SBA). The base is managed by the Antarctica New Zealand (ANZ). The big station around 3 km from SBA is American base, McMurdo station on the south tip of Ross Island.

The major finding for the research at South of Antarctica from 2002 to 2011 are listed as below. First, the measurement of PWV and total electron content (TEC) using GPS sensing [2]. Secondly, a developed of the data processing and analysis programs, namely TroWav program to produce the PWV data [24]. Third, utilization of GPS and meteorological data together with the ancillary data over the Antarctica to study the coupling process between the Sun activities and Earth’s surface via GPS sensing, so-called the upper-lower atmospheric coupling, which is used the relationship between TEC and PWV. Fourth, some works on GPS for meteorological applications such as Katabatic winds [6], ice deep movement in Ross Island, GPS applications for space weather such as geomagnetic storms,
solar eclipse, and all sky cameras for monitoring the aurora. The last work as in the figure is monitoring the lightning activity with moving the GPS antenna from SBA to Crater Hill and all the GPS system during the winter season was destroyed by the lightning in 2011.

![Image of GPS system installation](image)

**Figure 3.** Installation of GPS system at Scott Base station, Antarctica and the research activities started from 2002 to 2011. The system was for monitoring the precipitable water vapor, total electron content, and lightning detection for studying the Sun-Earth coupling.

4.2. Research activities in North Pole

To expand the coupling studies between the pole via conjugate point is by the installation of GPS system at Husafell, Iceland (HUSA). HUSA is located in the west of Iceland ~100 km from Reykjavik center which is at the circle of Arctic (66 degrees). HUSA has a strategic position or conjugate point with Syowa station in Antarctica. The systems at HUSA consist of a permanent GPS receiving system and broadband meteorological sensors [25]. The GPS was installed on 6 September 2008 under collaboration between Universiti Kebangsaan Malaysia (the National University of Malaysia, UKM) and National Institute of Polar Research (NIPR) Japan and between UKM and Science Institute of University of Iceland (SIUI). Both GPS and meteorological system and other activities are depicted in Figure 4.

The major finding for the research at North Pole (Iceland) from 2008 to 2014 such as first, measurement of PWV and TEC for the coupling studies through the conjugate point between HUSA and one another station in Iceland managed by NIPR is Tjornes [25]. Examples of PWV and TEC results are presented in Figure 5. Secondly, using the TEC data to monitor the aurora occurrence, where during the aurora activity, the GPS signal is delayed a few cm and this finding is confirmed with magnetometer data in Iceland and Syowa [5]. Third, GPS meteorology applications for investigation of dust storms in Iceland and the volcanic eruption of Eyjafjallajökull in 2010 that was disrupted the air travel activities (resulting largest air-traffic shutdown) in Europe more than a week [9]. The dust storms in 2008 destroyed the GPS antenna at HUSA and it was rectified. One more dust storms occurred in 2014 make the system totally ground-down until now and we cannot rectify due to the constraint in the budget.
Figure 4. Installation of GPS and meteorological system at Husafell, Iceland in the North Pole on September 6, 2008 for monitoring the atmospheric effects toward space weather advancement.

Figure 5. Comparison measurement of TEC and PWV based on the ground-based GPS between Northern and Southern Hemispheres on September 26, 2003.

4.3. Research activities in the West of Antarctica (Antarctica Peninsula)

As introduced in Section 3 and Section 4.1, the continuation of monitoring the weather systems such as lightning activities is expanded to the West of Antarctica, i.e. Antarctic Peninsula. Figure 6 shows the number of instruments installation at Carlini Base which located inside the Potter Cove, King George Island, Antarctic Peninsula. The base is managed by Argentinean. GPS tracking satellite, TEC results and thunderstorm occurrence that was captured by the lightning sensor (EFM-100) is shown on the right side of Figure 6.
Figure 6. Installation of lightning detector (a) LD-350 lightning detector, (b) GPS, (c) EFM-100 sensor, and meteorology sensors (d) at Carlini Base of Argentina in the Antarctica Peninsula

The expedition carried out during the summer campaign from 21 January to 28 February 2017 in collaboration with Instituto Antártico Argentino (IAA) was with the project to develop “Thunderstorms Forecasting Model for Antarctica”. The main finding from two lightning sensors installed in Carlini Base found that thunderstorms had occurred in Antarctica. Secondly, the frequent lightning activity is the Intra-cloud (IC) type, particularly the -IC type which is potential to penetrate the Earth’s surface when sufficient energy from space to push it to Earth. The most frequent of lightning detected emerged from the South Pacific Ocean (Northwest direction) and Weddell Sea (Southeast direction) and the lightning is more active during the summer. The pending investigation is how the GPS receiver capable to detect lightning activities. The preliminary result showed that PWV is positively correlated with Cloud-to-Ground (CG) and the opposite relationship with IC lightning.

4.4. Research activities in the Special Region of Yogyakarta, Indonesia

Water vapor is a natural greenhouse gas that can spit out by a cloud of volcanic ash into the atmosphere and potentially increase the global warming and can be regarded as attenuation in communication systems, especially in the GPS signals. The cloud volcanic ash can be correlated with the measurement of PWV from GPS. Monitoring the PWV variation in space and time leads to improvement of the traditional early warning system. Figure 7 shows the recent development of GPS systems for monitoring the atmospheric activity of the Merapi Mount (7.54°S, 110.44°E) in Sleman, Yogyakarta, Indonesia. The distance of GPS position is estimated ~23.30 km the to the peak of Merapi (Google Maps). Since the Merapi Mount is a legendary volcano that is regularly erupted since 1548 at every 2 ~ 7 years on average, early predictions and anticipations should be done more directed and structured so that loss of life and damage to property can be minimized.

At the current stage, the system in Figure 7 consisted of a GPS antenna and a TOPCON receiver which capable connected to the internet. The system will be improved from time to time by adding the analog to digital converter (ADC) embedded with Arduino (24-bit ADC TI ADS1220). This Arduino will replace the GPS receiver and the computer (laptop or desktop) in the near future. By using the Arduino, this enables the connection of Tilt sensors and other gauge sensors to monitor the deformation of volcanoes. The challenge of this work with Arduino is the development of GPS data processing like GPS Base station and Bernese.
Figure 7. Installation of smart GPS system at Sleman, Yogyakarta, Indonesia on August 26, 2014, for monitoring the Merapi volcanic eruption toward an accurate development of early warning systems

5. Summary and recommendation for future work

From the overview and successful GPS applications implemented, it will be highly motivated to develop new prospective research in other locations such as in Indonesia. By utilizing the GNSS technology for monitoring the weather systems as well volcano deformation and its volcano ash pollution in Indonesia is a good initiative to improve traditional early warning systems. The GNSS system with good geographic coverage in spatial and temporal resolutions and at low cost are promising to modernize existing systems. The political will government in providing the facilities and competitive grant to improve this system as well as empowering human capabilities in line with technological developments are very much expected.

For future work reports the result of weather systems as well as space weather monitoring in Yogyakarta, Indonesia in respect to the Merapi activities. The priority of the work enhances the system to become smart remote control and provides a database system for those who require data to be accessible everywhere.

Acknowledgements
The author would wish to thank the Antarctica New Zealand (ANZ) for their full support and kind hospitality during our stay at Scott Base station in Antarctica, the National Institute of Polar Research (NIPR) Japan and Science Institute of University of Iceland (SIUI) for the collaboration and maintaining the GPS system at Husafell, Iceland, the Instituto Antártico Argentino (IAA) for the hospitality and collaboration during the summer campaign in 2017 at Carlini Base of Antarctica Peninsula, Universiti Kebangsaan Malaysia and Malaysia Government for providing the research grant, and all those who have assisted to carry out the expedition to Antarctica and Iceland.

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