Retrieval of Weather Information for Climate Change Monitoring Using Ground-based GPS Network

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Abstract

Global Positioning System (GPS) is a multi-satellites positioning system that consists of 24 satellites, arranged in nearly circular orbital planes at an altitude of about 22,000 km above the earth surface. Denoted as an efficient satellite-based positioning tool yet available, GPS provides real time three-dimensional positioning, velocity information and time in common reference system 24 hours a day. In spite of its appreciable applications in navigation, surveying and mapping, petrology, open-pit mining, precision farming and earth deformation study, there has been a resurgence of interest among European countries and other developed nations towards the use of GPS as an effective yet practical tool for meteorological applications. Taking the advantage of existing GPS tracking networks worldwide, this paper highlights the retrieval of the least understood weather information namely precipitable water vapour (PWV) for climate change monitoring. Given that appropriate strategies are employed during data acquisition and data processing, it is noted that there are lots of advantages using ground-based GPS network for the purpose of retrieving the highly variable PWV. It is suggested that through the aspect of accuracy and practicality, ground-based GPS network is sufficiently adequate to satisfy the demands of in-depth understanding on the spatial and temporal variability of weather information, contributing to the aftermath of climate changes.

Introduction

Climate change is among many challenges experienced by the world today. It refers to a statistically significant variation either in the mean state of the climate or in the variability of weather information i.e. temperature, precipitation and wind, persisting over an extended period. According to Corvalan (2003), climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic activities in the composition of the atmosphere. Given that the life cycles, human well-being, economic growth and societal activities are greatly affected by their local climate, the need for an in-depth understanding on the spatial and temporal variability of weather information, contributing to the aftermath of climatic changes is highly demanded.

Arises from global awareness on the abovementioned issues, a wide variety of meteorological instruments have been developed throughout the past decades. Amongst them include weather satellites, aircrafts, weather balloons (i.e. radiosonde and rawinsonde), LIDAR and water vapour radiometers. Apparently, due to the rapid growth of the GPS continuously operating reference stations worldwide, it is noted that there is also a strong interest among European countries and other developed nations towards the use of ground-based GPS network for meteorological applications. As monitoring long-term changes in water vapour, which are closely linked to other climate variations and trend, is needed to both detect and predict climate changes, this paper therefore highlights examples of ground-based GPS network yet available for the retrieval of precipitable water vapour (PWV). In addition to GPS-PWV retrieval modeling and strategies on data acquisition and data processing, further discussions on advantages of ground-based GPS network for climate change monitoring will also be presented.

Ground-based GPS network

In brief, GPS is a space-based radio navigation satellite operated by the United States (U.S.) Department of Defense (DoD). Denoted as an efficient satellite-based positioning tool yet available, GPS consists of nominal constellation of 24 operational satellites inclined at 55˚ with an orbital radius of 26,560 km. To extend the use of positioning services (i.e. navigation, surveying and mapping, open-pit mining and earth deformation study) rendered by GPS, there is a significant and rapid growth of GPS continuously operating reference stations (GPS-CORS) worldwide. GPS-CORS has become an important element of enhancements in GPS works and applications. The use of a reference stations network in GPS measurement allows minimizing distance dependent errors in differential positioning. Taking the benefit of existing GPS tracking networks, there has been a resurgence of interest among European countries and other developed nations towards the use of GPS technology as a precursor for rainfall, thunderstorm, flash flooding and seasonal monsoon event (Rocken et al. 2000).

Mostly integrated with radiosondes or surface meteorological observations, these ground-based GPS networks include U.S. National Oceanic and Atmospheric Administrations (NOAA) Ground-Based GPS Integrated Precipitable Water (GPS-IPW) Network (Wolfe and Gutman 2000; Gutman et al. 2004). In addition, there are also studies been made in France through the integration of RGP (Nationwide permanent GPS network from Institut Geographique National) and REGAL (Alpine region GPS geodetic network) (Champollion et al. 2004); Canada through the Westford Water Vapor Experiment (WWAVE) (Coster et al. 1996); Sweden through its Goteborg GPS network (Nilsson and Gradinarsky 2006); Australia through the use of Australian Regional GPS Network (ARGN) (Feng et al. 2001); Japan through the establishment of GPS Earth Observing Network (GEONET) (Iwabuchi et al. 2000); India through GPS stations developed by Center for Mathematical Modeling and Computer Simulation (C-MMACS) (Jade et al. 2005); and Africa through the use of African IGS Network (Walpersdorf et al. 2007). Figure 1 depicts the overview of NOAA Ground-Based GPS-IPW Network.

GPS-PWV Retrieval

The Modeling

One of the most significant yet poorly described weather information is water vapour. Often considered as a nuisance among GPS practitioners, water vapour is the link between the surface and the atmosphere in the water or hydrology cycle. Being one of the plentiful greenhouse gases, water vapour plays crucial role in a variety of atmospheric processes which include not only for fog and clouds formation but also as the main source of precipitations such as rain and snow events. Appreciable water vapour contents are almost entirely confined to the troposphere. Compared to only 75% in the mid latitude region, the troposphere in the tropics (or equator) contains nearly 90% of the atmospheric mass (Weisberg 1976). Troposphere is the first layer of the earth atmosphere. Bounded above by tropopause, troposphere has differences in its layer thickness around the globe. According to Mendes et al.

(1998), this non dispersive medium is twice time thicker above the equatorial region compared to the poles with an approximate of 16 km above the earth surface. Figure 2 illustrates the differences in layer thickness of the troposphere

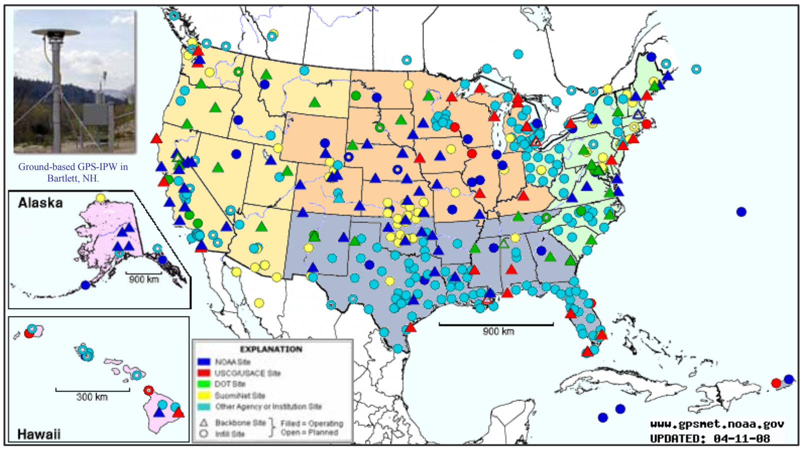

Figure 1. Distribution of NOAA Ground-Based GPS-IPW Network

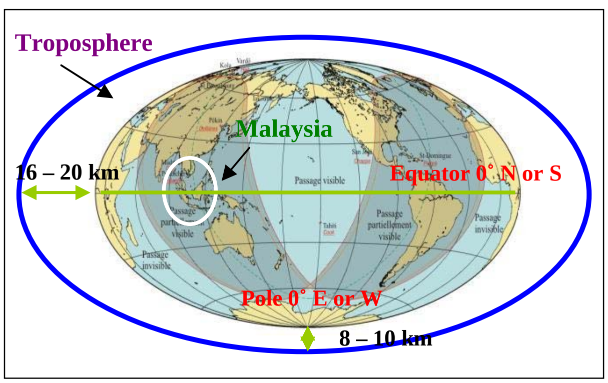

Figure 2. Differences in Layer Thickness of the Troposphere

The vertically integrated amount of water vapour above a location, when scaled to its equivalent liquid amount (in mm), is called PWV. PWV is principally derived from the precise modeling associated with GPS signal propagation delay induced from the troposphere. Often referred to as Zenith Tropospheric Delay (ZTD), it is a function of temperature, pressure, and water vapour. The general mathematical modeling for ZTD is given by Thayer (1974) as:

$$ZTD = \underbrace{\left(k_1 \cdot \left(\frac{P_d}{T}\right) \cdot Z_d^{-1}\right)}_{1^{st}\text{ term}} + \underbrace{\left(k_2 \cdot \left(\frac{e}{T}\right) + k_3 \cdot \left(\frac{e}{T^2}\right)\right) \cdot Z_w^{-1}}_{2^{nd}\text{ term}} \tag{1}$$

where:
$k_{1..3}$ are refraction constants
$Z_{d/w}^{-1}$ is the inverse compressibility factors for dry and wet air
P_d is dry pressure; P_d = p – e with p being the total pressure (measured quantity)
T is the temperature in Kelvin
e is partial pressure of water vapour in mbar

Based on Equation 1, the 1st term characterizes the effect of the induced dipole moment of the dry constituent usually referred to as ZHD. The 2nd term in which characterizes the dipole moment of water vapour, along with the orientation effects of the permanent dipole moment of water molecules is often called as ZWD. As $k_{1..3}$ are empirically determined refraction constants, Table 1 summarizes the most significant evaluations of the refractivity constants.

Table 1. Refractivity Emperical Constant

Reference	k_1 (Kmb^{-1})	k_2 (Kmb^{-1})	k_3 (10^5 K^2mb^{-1})
Essen and Froome (1951)	77.64	-12.96	3.718
Boudouris (1963)	77.59 ± 0.08	72 ± 11	3.75 ± 0.03
Thayer (1974)	77.60 ± 0.01	64.79 ± 0.08	3.776 ± 0.004
Hill et al. (1982)	-	98 ± 1	3.583 ± 0.004
Hill (1988)	-	102 ± 1	3.578 ± 0.03
Bevis et al. (1994)	77.60 ± 0.09	69.4 ± 2.2	3.701 ± 0.012

According to Dodo et al. (2007); Yahya and Kamarudin (2007), ZTD is a distance-dependent error that that increases when the baseline length between two GPS stations increases. Similarly, ZTD induces discrepancies in the GPS derived positions and varies with changes on meteorological condition. Based on series of investigations made within Johore RTK network, it is noted that maximum residuals in Easting, Northing and Height components due to tropospheric effect are 68.880 cm, 68.970 cm and 119.100 cm respectively. Reaching to the minimum and maximum RMS value of 16.8 and 29.2 respectively, GPS Height component is by far the most affected component compared to the Horizontal components (Easting and Northing)(Yahya and Kamarudin 2008).
According to Janes et. al. (1989), ZHD contributes to about 90% of the ZTD whereas ZWD is only contributing to the remaining 10% of the effect. Given that the ZWD is entirely due to the presence of water vapour and that liquid water and ice does not contribute to the effect, PWV is basically the conversion of ZWD precise modeling. Based on Equation 1, the retrieval of PWV can therefore be made using the following derivation:

$$PWV = k \times \left[\left(k_2 \cdot \left(\frac{e}{T} \right) + k_3 \cdot \left(\frac{e}{T^2} \right) \right) \cdot Z_w^{-1} \right] \quad (2)$$

where:
k as according to Bevis et al. (1994) is given by:

$$k = \left[10^{-6} \cdot \left(k_2 + \frac{k_3}{T_M} \right) \cdot R_w \cdot \rho_w \right]^{-1}$$

(3)

where:

ρ_w is the water density

R_w is the specific gas constant of water vapour (461.495 $Jkg^{-1}K^{-1}$)

T_m is atmospheric weighted mean temperature in which can be referred to Table 2

Table 2. Atmospheric Weighted Mean Temperature

Model	Mean Temperature
Bevis et al. (1994) Eq. 4	T_m=70.2(˚K) + 0.72 T_o(˚K)
Mendes et al. (2000) Eq. 5	T_m=50.4(˚K) + 0.789 T_o(˚K)
Solbrig (2000) Eq. 6	T_m=54.7(˚K) + 0.77 T_o(˚K)

The Strategies

The accuracy of GPS-PWV measurement depends on the accuracy of the ZWD measurement. Providing that errors in ZWD measurements are reduced, it is suggested that ground-based GPS network can be used as a very comprehensive tool for meteorological purposes. For an effective retrieval of weather information using ground-based GPS network, there are several consideration that need to taken care of. These considerations can be divided into two phases, i.e. data acquisition and data processing.

Data Acquisition

During data acquisition, there are several considerations need to be taken care of. These include the type of GPS receivers, inter-station spacing, quality of integrated surface meteorological measurement and site suitability. Given that signal refraction error due to the ionospheric medium (atmospheric layer ranging from 50 km to 1000 km above the earth surface) is a frequency-dependent error, ground-based GPS network needs to be equipped with dual-frequency receivers. Similarly, it is estimated that inter-station spacing between GPS receivers should not be more than 50-70 km for the purpose of PWV retrieval (MacDonald and Xie 2000). As far as the quality of integrated surface meteorological measurement may concern, it is noted that surface pressure measurements with accuracy of about 0.5 hPa and surface temperature measurements with accuracy of about 2˚ are sufficient to keep the PWV retrieval error budget below 0.5 mm (Gutman et al. 2003).

As GPS signals can also be corrupted by strong electrical interference, it is important to ensure that these stations are far from electrical storms, power lines, 2-way radios, nearby electric motors, cellular phones, microwave towers and pulsed interference from airport communication radar signals (Akib and Low 2003). In order to avoid GPS signal refraction (and diffraction) due to the nearby obstructions or surfaces, it is also important to let alone any reflecting surfaces (i.e. trees, water, high-rise buildings, bridges) near the GPS receiver. To further minimize the effect of reflecting surfaces, it is suggested that good quality antenna equipped with antenna ground plane or choke-ring assembly is used for data acquisition. According to Gutman et al. (2004), it is also a good practice to locate ground-based GPS sites in area that maximize sky visibility. Local sky coverage varies as a function of tracking station latitude. At low latitude region, it is found that local GPS coverage is well distributed at all quadrants, representing the most desirable configuration compared to the high latitude and mid latitude region. Figure 3-5 depicts the GPS sky plot near Helsinki, Finland (N 60˚ 9’, E 24˚ 52’), Tokyo, Japan (N 37˚ 15’, E 138˚ 27’), and Johore, Malaysia (N 1˚ 33’, E 103˚ 38’) on 21 February 2008.

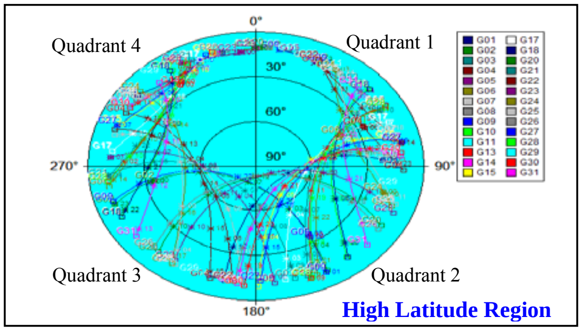

Figure 3: GPS Sky Plot for Helsinki, Finland on 21 February 2008

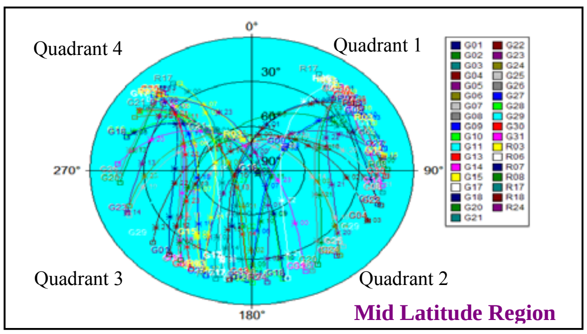

Figure 4: GPS Sky Plot for Tokyo, Japan on 21 February 2008

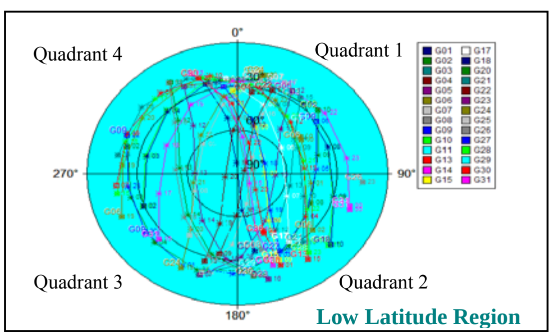

Figure 5. GPS Sky Plot for Johore, Malaysia on 21 February 2008

Data Processing

For data processing, there are several considerations need to be taken care of. These include the orbital error, ocean loading, ionospheric effect and ZWD mathematical modeling. As far as orbital error and ocean loading may concern, it is a must to acquire precise orbits and ocean loading parameters prior data processing. To mitigate the effect of the ionosphere, it is suggested that ionosphere free double-differencing method is used during data processing. According to Jade et al. (2005), there is also a need for an accurate assumption and/or mathematical modeling of ZWD. Serious attention on T_m determination is as well crucial due to the varying accuracy levels in relative to the site geographical location.

Advantage of GPS-PWV Retrieval

There are lots of advantages using ground-based GPS network for the retrieval of weather information for climate change monitoring. Some of these advantages include high measurement accuracy; arbitrary temporal resolution; all weather operability; no requirement for calibration; high reliability; and low acquisition and maintenance cost (Gutman et al. 2004). GPS-PWV retrieval can also overcome the cloud problem associated with weather satellites. Unlike radiosonde in which is typically launched every 6 to 12 hours, Feng et al. (2001) asserts that a network of continuously operating GPS receivers provides unprecedented spatial coverage and continuous PWV retrieval at highly temporal resolution of 30 seconds to 30 minutes. Providing that other sources of error (associated with GPS carrier phase observables and ZWD modeling) are properly mitigated during data acquisition and data processing, it is suggested that ground-based GPS retrieves PWV at a comparable level of accuracy to radiosonde (RMS ≤ 1.5 mm) (Collins et al. 2002).

Conclusion

Given that the life cycles, human well-being, economic growth and societal activities are greatly affected by their local climate, the need for an in-depth understanding on the spatial and temporal variability of weather information, contributing to the aftermath of climatic changes is highly demanded. Taking the benefit of existing GPS tracking networks worldwide, there has been a resurgence of interest among European countries and other developed nations towards the use of ground-based GPS network for the retrieval of weather information (i.e. precipitable water vapour) for climate change monitoring. It is noted that there are lots of advantages using ground-based GPS network for the retrieval of weather information for climate change monitoring. Providing that appropriate strategies being employed during data acquisition and data processing, it is suggested that ground-based GPS network can be further used as a very comprehensive tool for climate change monitoring.

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