Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (41) No. (4) October, 2019

Precipitable Water Vapor Data Derived from GNSS and Radiosonde for Egypt.

Mohamed A. Abdelfatah[1], Nesreen M. Elhaty[1], Ashraf E. Mousa[2], and Gamal S. El-Fiky[1,3]

[1] Construction Department & Utilities, Faculty of Engineering, Zagazig University
[2] National Research Institute of Astronomy and Geophysics, Helwan

الملخص العربي

تم في هذا البحث تقديم اسلوب جديد لحساب هطول بخار الماء PWV داخل القطر المصري من خلال نظم الاقمار الملاحية GNSS بالاستعانة بدرجة الحرارة السطحية و مقارنتها بالارصاد الجوية لبلونات الهليوم علي مدار عام 2014 . تم استخدام عدد 3 محطات GNSS مصرية وهي (العريش ، أسوان ، مرسى مطروح). تتم معالجة بيانات هذه المحطات GNSS باستخدام خدمة التحديد الدقيق للنقطة (PPP) عبر صفحة خدمة CSRS-PPP حديثة لتقدير تباطؤ السمت للتروبوسفير (ZTD) تم تزويد هذه المحطات بتوزيع إقليمي تمثيلي لمواقع الشبكات العالمية لسواتل الملاحة ذات مناخات متفاوتة مع ضمان إتاحة الأرصاد الجوية التقليدية مثل البيانات المستندة إلى السطح لتحويل PWV بحيث يتم تحويلها لاحقًا إلى GNSS-PWV. أظهرت النتائج أن الفرق بين متوسط PWV من GNSS وبيانات الراديو radios هو 2.89 ، 2.48 و 0.6 مم على التوالي. بما يجعل هذا الاسلوب صالح للاستخدام.

Abstract

In this paper, as a first step, a comparison results of precipitable water vapour (PWV) data in Egypt derived from two techniques, radiosonde and Global Navigation Satellite Systems (GNSS) during a period of approximately 1 year (2014). Whereas radiosonde observations have a low temporal resolution and the observation interval is usually 12 h. GNSS can provide PWVs at a relatively high temporal resolution. Three of the GNSS stations were chosen nearby the radiosonde station(Al-Arish, Aswan, Marsa- Matrouh). These stations data processed by using the precise point positioning (PPP) service via a modernized CSRS-PPP service page to estimate the zenith tropospheric delay (ZTD). These stations were provided a representative regional distribution of GNSS sites with varying climates while ensuring conventional meteorological observations such as surface-based data are available for PWV conversion so as to be subsequently converted to GNSS-PWV.

The results have shown that the Mean difference between PWVs from GNSS and radiosonde data are 2.89, 2.48and 0.6mm respectively.

Keywords: Precipitable water vapour, GNSS, Radiosonde, *zenith tropospheric delay.*

1. Introduction:

perceptible water vapour (PWV) is defined as” the total atmospheric water vapour contained in a vertical column of the unit cross-sectional area extending between any two specified levels” (American Meteorological Society (AMS) 2000). PWV is the most greenhouse gas effects on our planet. Where increasing water vapour in the lower troposphere leads to greater warming, followed by a higher water vapour concentration, creating positive feedback. Mears et al. (2007) concluded that increasing the temperature of 1K would result in a 5-7% increase in PWV. Therefore, Knowledge of water vapour variations is essential for regional weather forecasting and global climate study.

Due to the importance of measuring the water vapour in the atmosphere many meteorological techniques have been used for decades to retrieve PW, such as radiosondes, water vapour radiometer, and infrared sounders. Among them, the most traditional water vapour observation technique is the radiosonde which is often used as an accuracy standard to evaluate the performances of other water vapour sensors with an accuracy of a few millimetres.

However, the scattered spatial distribution of radiosonde stations and the low temporal resolution is subject (Usually only two balloons are released daily). These limitations form the main source of error in short-term precipitation forecasts.

GNSS meteorology has successfully demonstrated its ability to retrieve PWV with high internal repeatability, all-weather capability, low cost and both high spatial and temporal resolutions. GNSS meteorology was first discussed in Bevis et al. (1992). They proposed that the atmospheric noise delay can be parameterized in terms of a time-varying total tropospheric delay. If surface temperature and pressure observations at the GPS receiver are known to sufficient accuracy, the tropospheric delay can be converted into accurate estimates of the total zenith column water vapour, termed precipitable water vapour (PWV). After that, many studies have worked on water vapour retrieval from GNSS data and research results show that GNSS-derived PWV can reach an accuracy of few millimetres [Ning et al (2011) and. Lee et al (2013)] Several studies have been conducted to compare the PWV measurements obtained from multiple techniques. For example, Niell et al. (2001) showed that PWV obtained from radiosonde, WVR, GPS and VLBI techniques agreed within 1 mm. Bokoye et al. (2003) Using the PWV measurements collected by GPS, radiosonde and WVR during the 8-years period at several locations in Canada and Alaska,. they revealed the differences between these three techniques (RMS) to be about 2 mm. Ning et al. (2011) compared water vapour data as derived from GPS, VLBI, WVR and re-analysis results of the European Center for Medium-Range Weather Forecasts(ECMWF) observations made over 10 years. They found that zenith wet delay ZWD was agreed within 7 mm. Finally, the availability of multi-GNSS sensors represents an opportunity to improve the precision and reliability of GNSS measurements, including the geometry, the processing time and the atmospheric water vapour sensing. [Li et al., 2015; Benevides et al, 2015].

The main motivation of this analysis work is to validate the GNSS data processing and conversion to PWV estimates given surface pressure and temperature readings and to understand the quality and characteristics of the water vapour data obtained from other technique.

2 .Illustration of Multiple Water Vapor Observations:

2.1 Ground-Based GNSS:

GNSS data, began to provide an alternative image of vertically integrated water vapour distribution (precipitable water vapour, PWV), which was found to contribute positively to the atmosphere analysis for weather forecast [Bevis et al., 1994; Seco et al., 2012]. GNSS radio waves are delayed due to the neutral atmosphere, leading to a positive bias in the range measurements. This delay is known as the “tropospheric delay”. This error must be dealt with to produce precise positioning results. The tropospheric delay can be computed as the zenith path delay (ZPD). Which is defined as the sum of the hydrostatic delays (ZHD) caused by the atmospheric gases such as nitrogen, oxygen, argon and carbon dioxide, and wet (ZWD) delays, contributed by water vapour in the atmosphere, as described in by:

$$\mathrm{ZPD} = \mathrm{ZHD} + \mathrm{ZWD} \qquad (1)$$

ZHD is generally very stable and is easily determined using an empirical model such as the Hopfield or Saastamoinen models [Hopfield. (1969) and Saastamoinen. (1972)] :

$$\mathrm{ZHD} = \frac{(2.2768 \pm 0.0005)\ \mathrm{P}_s}{1 - 0.00266 \cos 2\Theta - 0.00028\mathrm{h}} \qquad (2)$$

From ZPD, ZWD can be obtained by subtracting ZHD from ZPD. If the surface pressure (P_S), latitude (Θ) and height (h) of the station is known.

Given surface pressure measurements, it is usually possible to model and remove the hydrostatic delay with an accuracy of a few millimetres or less. On the other hand, the ZWD delay is more spatially and temporally variable and is more difficult to remove than the ZHD. The ZWD can be as small as a few centimetres or less in arid regions and as large as 35 cm in humid regions [Bevis et al., 1992]. After obtaining The ZWD the PWV (mm) can be retrieved from ZWD by using the conversion factor Π as follows [Bevis et al., 1994]:

$$\mathrm{PWV} = \Pi * \mathrm{ZWD} \qquad (3)$$

Where

$$\Pi = 10^{-6} \rho \mathrm{R}_v \left(\frac{\mathrm{K}_3}{\mathrm{T}_\mathrm{m}} + \mathrm{K}_2'\right) \qquad (4)$$

$$\mathrm{K}_2' = k_2 - m\mathrm{K}_1 \qquad (5)$$

K_2'= (17 ±10) Kmb^{-1}, K_3 = (3.776 ± 0.014) * 10^5 Kmb^{-1}, $\mathrm{K}_1 = 77.604\ \mathrm{Kmb}^{-1}$

ρ is the density of liquid water, R_v is the specific gas constant of water vapour, m is the ratio of the molar mass of water vapour and dry air and $\mathrm{T}_\mathrm{m}$is the weighted mean temperature of the atmosphere defined by [Askne and Nordius, 1987]. Π is approximately 0.15– 0.16 and it may vary by about 20% depending on the weighted mean temperature [Byun et al.2009]. T_m can be approximated from station temperature observations (T_S). For the Egyptian region, $\mathrm{T}_\mathrm{m}$is computed by [Elhaty et al., 2019] using the least square fit of 3600 radiosonde profile as:

$$\text{Regional; } T_m = 0.73\ Ts + 69.68 \qquad (6)$$

With an RMS scattering of about 3.95 K. Equation (6) is almost similar to the original linear regression equation derived by [Bevis et al.1992]. To illustrate the impacts of the Tm error on the resultant PWV, the relative error observed during GPS-PWV retrieval can be used:

$$\frac{\Delta PWV}{PWV} = \frac{\pi(\Delta T_\mathrm{m} + T_\mathrm{m}) - \pi(T_\mathrm{m})}{\pi} = \frac{1}{1 + \frac{K_2'}{K_3}(T_\mathrm{m} + \Delta T_\mathrm{m})} * \frac{\Delta T_\mathrm{m}}{T_\mathrm{m}} \approx \frac{\Delta T_\mathrm{m}}{T_\mathrm{m}} \qquad (7)$$

From the above equation, the relative error of the PWV is approximately equal to the relative error for T_m. Because $\frac{K_2'}{K_3}$ is very small (~5.9 ×$10^{-5} k^{-1}$). This means that uncertainty when converting ZWD to PWV is an estimate of the mean weighted average temperature of the troposphere. However, On the basis of Eq(7), Wang et al. (2005) shows that for Tm ranging from 240 to 300 K, the 1 and 2% accuracies in GPS-PWV require errors in Tm less than 2.74 K and 5.48 K on average, respectively.

2.2 Radiosonde :

The radiosonde observation was built to measure meteorological data by using a sensor to measure the pressure (P_s), temperature (Ts), dew point and geo-potential height. This observation is usually carried out by releasing a helium gas balloon into the upper atmosphere, allowing measurement of meteorological parameters. A region-specific model for T_m in terms of surface temperature (Ts) was developed. (Elhaty et al., 2019).By using these meteorological parameters, PWV (unit: mm) in a layer is calculated by [Böhm and Schuh, 2013; Bock et al., 2005]:

$$\mathrm{PWV} = \frac{1}{g_s}\int_{p_s}^{p_t} q\,dP \qquad (8)$$

Where Ps and Pt are the pressures (hPa) on the troposphere, g_s is the average gravitational acceleration (m/s2) in the tropospheric air column.

$$g_s = 9{:}784(1 - 0.00266\cos 2\emptyset - 0.00028\ H) \qquad (9)$$

$\emptyset$ is the latitude; H is the average geodetic height (km).

$$q = \frac{621{,}98e}{P - 0.378e} \qquad (10)$$

q is the specific humidity of the air, and e is the water vapour pressure (hPa). PWVRS(priciptable water vapor of radiosonde) is often used as a precision standard for evaluating water vapour data from other I dependent sensors. But their expensive operating costs have low time data that restrict their applications to short-term weather forecasting.

3. GNSS Processing Strategy:

GNSS radio signals are delayed by the ionosphere and troposphere layers. The troposphere is the lowest portion of the atmospheric layer between the surface of the earth and the ionosphere. The delay caused by the neutral Atmosphere. It consists of two components: the hydrostatic or dry component (HZD) which was estimated by using the modeling of Tropospheric corrections, and wet delays (ZWD), which is mainly contributed by water vapour contained in the atmosphere. The wet component is, in fact, more difficult to estimate compared to the dry component. In GNSS processing, the tropospheric delay can be computed as zenith path delay (ZPD). Referring to equation (1), ZWD can be determined from two ways. First one by subtracting HZD from the (ZPD)model and the second is from Saastamoinen wet model Eq.(11).

$$\mathrm{ZWD}_{\mathrm{Saastamoin}} = \left(\frac{1255}{T_S} + 0.05\right) e_S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(11)$$

In this study, GNSS data from three Egyptian stations were processed for the year 2014. Locations of the three GNSS stations used are depicted in Figure (1). These stations were chosen to provide a regional distribution of GNSS sites in Egypt with good meteorological observations near these stations, from other PWV sensors; for example, Upper-air data from radiosonde stations are available for verification.

As in equation (3) Converting ZWD to PWV needs metrological data. Such as the surface temperature to obtain a good temperature profile and surface pressure is needed to evaluate. The surface temperature and the pressure was determined from the radiosonde database of the department of atmospheric science of Wyoming. These soundings were available at http:/weather.uwyo.edu/upperair/sounding. HTML.

The radiosonde stations in Egypt are situated at three stations (Aswan, Mersa-Matrouh and Al-Arish) shown in Fig. (1). It was collected at 00:00 and 12:00 UTC for all days in year's 2005 to2016.

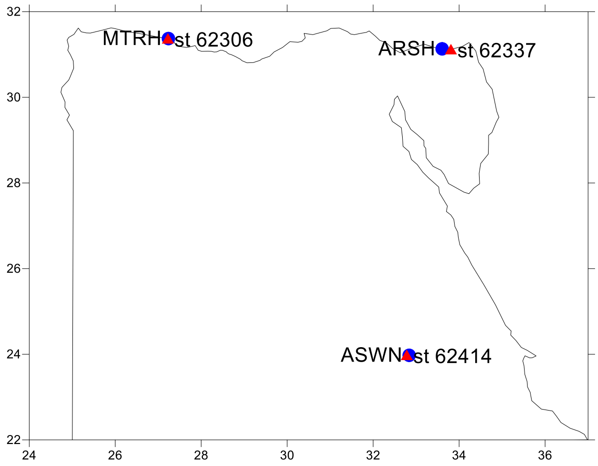

Figure 1: Locations of the GNSS and radiosonde stations in Egypt.
▲ radiosonde stations. ● GNSS stations.

Figure 2 shows the flowchart of processing to get PWV. Where the observational dataset consists of surface meteorological data and GNSS RINEX files. First, Three GNSS stations were selected to provide Regional distribution of GNSS sites on Egyptian region, with good quality conventional Meteorological observations, in addition to radiosondes stations nearby providing data for surface temperature and pressure, available for validation. In this study, the processing of the ZPD estimation was carried out using the precise point positioning (PPP) service via The Canadian Geodetic Survey of Natural Resources modernized CSRS-PPP service page.

From ZPD, ZWD can be obtained by subtracting ZHD from ZPD. Where ZHD constitutes more than 80% of the total path delay but by a given surface pressure measurements and using an empirical model such as the Hopfield or Saastamoinen models it can be easily model and remove the hydrostatic delay with an accuracy of a few millimetres or less. Since ZWD was estimated the PW amount can be calculated referring to equation (3).

To validate the accuracy of the PWV computed from GNSS, it is compared with the precipitable water directly extracted from the radiosonde data. Where the PWV amount calculated independently from radiosonde data profiles.

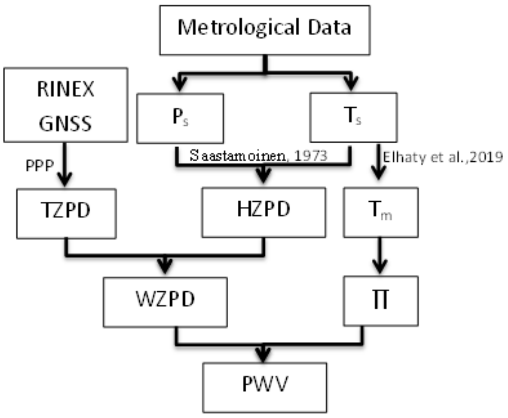

Figure 2: Flowchart of GNSS Processing Strategy to estimate PWV.

4.Comparisons between GNSS and Radiosonde PWV results:

For comparison there are a total of 142 GNSS and radiosondes observations, only obtained at 12 h UTC cover approximately one year period. The radiosonde data used as a reference to evaluate water vapour data retrieved from other techniques.

Table 1 provides a summary description for the three GNSS stations located close to the radiosonde stations. Also, it shows the horizontal distances from the locations of GNSS sites to the corresponding radiosonde sites.

Table (1) Horizontal distances difference from GNSS to Radiosonde stations.

GNSS			Radiosonde			distance (km)
Station	φ (deg)	λ (deg)	Station	φ (deg)	λ (deg)	
ARSH	31.11	33.62	62337	31.08	33.81	18
ASWN	23.97	32.85	62414	23.96	32.78	7

FigureS, (3 and 4) displays a comparison between PWV obtained from GNSS Meteorological data and PWV from Saastamoinen wet model in Eq.(11). With radiosondes observations. In the first station with 18 km distance difference between the two stations,

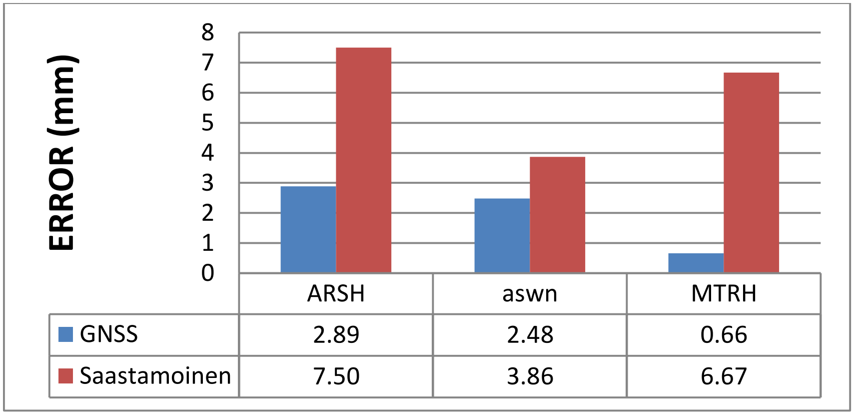

Figure 3: PWV mean difference.

The mean PWV difference was 2.89 with 0.98 root mean square (RMS). These mean difference in PWV decreases with the distance decreasing to 2.48, 0.66 respectively in the other two stations with RMS 0.49, 0.58.

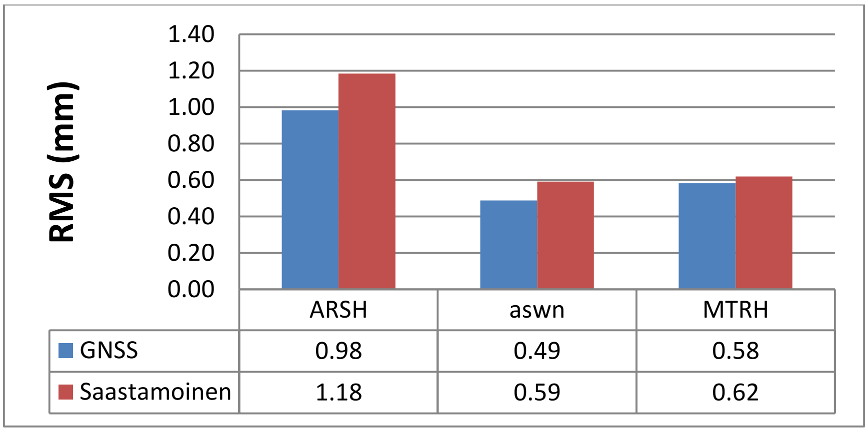

Figure 4: PWV root means square.

5. Conclusions

It has been demonstrated that GNSS technique has the potential to measure column abundance of water vapour. The result shows that there is good agreement between the PWV amounts estimated from GNSS signal delay measurements and those derived from radiosondes data with RMS 0.35 mm.

Comparisons between the PWV values derived from GNSS data and radiosonde data were performed using the same atmospheric parameters to achieve advantageous when comparing different instruments.

In this research, comparisons of three GNSS data station with the three corresponding radiosondes by using one-year data set (2014) for both technique. The PPP technique was adopted to estimate ZTD, which were converted to GPS-PWV by using two key parameters: Tm and Ps.

This effort is intended to compute the PWV, improving both the spatial and temporal resolutions required for estimating the PW in this country, to help for developing accurate weather prediction and global climate models and to fill the observation data gaps and knowledge related to water vapour contrast in this part of the world.

Furthermore, GNSS data can be used for tropospheric delay monitoring with high accuracy. This can be achieved by using PPP online service webpage. Where the result shows that the desired accuracy of the PWV can be achieved. Such that, PPP is much quicker than the network approach, especially with scientific software like Bernese and GAMIT.

References

- **Askne J. and Nordius, H.**(1987): "Estimation of tropospheric delay for microwaves from surface weather data," Radio Science, vol. 22, no. 3, pp. 379–386.
- **Benevides, P., Nico, G., Catalao, J., and Miranda, P. M. A.** (2015): "Can Galileo increase the accuracy and spatial resolution of the 3D tropospheric water vapour reconstruction by GPS tomography? IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 26–31 July 2015, 3603–3606 doi:10.1109/IGARSS.2015.7326601.
- **Bevis M, Businger S, Herring TA, Rocken C, Anthes RA, Ware RH** (1992): "GPS meteorology: remote sensing of atmospheric water vapour using the Global Positioning System. J Geophys Res Atmos 1984–2012 97(D14):15787–15801.
- **Bevis, M., Businger, S., Chiswell, S., Herring, T. A., Anthes, R. A., Rocken, C., and Ware, R. H**(1994): " GPS meteorology: Mapping zenith wet delays onto precipitable water, J. Appl. Meteorol., 33, 379– 386.
- B**ock, O., C. Keil, E. Richard, C. Flamant, and M. Bouin** (2005): "Validation of precipitable water from ECMWF model analyses with GPS and radiosonde data during the MAP SOP, Q. J. R. Meteorol. Soc., 131(612), 3013–3036, doi:10.1256/qj.05.27.
- **Bokoye AI, Royer, A, O'Neill NT, Cliche P, McArthur LJB, Teillet PM** (2003): "Multisensor analysis of integrated atmospheric water vapour over Canada and Alaska. J Geophys Res 108(D15). Available from: http://doi.wiley.com/10.1029/2002JD002721.
- **Böhm, J., and H. Schuh** (2013): "Atmospheric Effects in Space Geodesy, pp. 9–10, Springer, Berlin Heidelberg.
- **Byun, S. H and Bar-Sever, Y. E**(2009): "A new type of troposphere zenith path delay product of the international GNSS service," Journal of Geodesy, vol. 83, no. 3-4, pp. 367–373.

- **Elhaty, N. Abdelfatah, M., Mousa, and El-Fiky, G.**(2019): "GNSS Meteorology in Egypt: Modeling Weighted Mean Temperature from Radiosonde data. Alexandria Engineering Journal, May 2019,DOI: 10.1016/j.aej.2019.04.001,License CC BY-NC-ND 4.0.
- **Hopfield, H. S. (1969)**: "Two-quartic tropospheric refractivity profile for correcting satellite data," Journal of Geophysical Research, vol. 74, no. 18, pp. 4487–4499.
- **Lee S-W, Kouba J, Schutz B, Kim DH, Lee YJ** (2013): "Monitoring precipitable water vapour in real-time using global navigation satellite systems. J Good 87(10–12):923–934.
- **Li, X., Dick, G., Lu, C., Ge, M., Nilsson, T., Ning, T., Wickert, J., and Schuh, H.** (2015.): "Multi-GNSS meteorology: Real-time retrieving of atmospheric water vapour from BeiDou, Galileo, GLONASS and GPS observations, IEEE T. Geosci. Remote, 53, 6385–6393,doi:10.1109/TGRS.2015.2438395,.
- **Mears, C., Santer, B. D., Wentz, F. J., Taylor, K., and Wehner, M.**(2007): "Relationship between temperature and precipitable water changes over tropical oceans, Geophys. Res. Lett., 34, L24709,doi:10.1029/2007GL031936.
- **Niell AE, Coster AJ, Solheim FS, Mendes VB, Toor PC, Langley RB et al** (2001): "Comparison of measurements of atmospheric wet delay by radiosonde, water vapour radiometer, GPS, and VLBI. J Atmos Ocean Technol 18:830–850.
- **Ning T, Haas R, Elgered G, Willén U** (2011): "Multi-technique comparisons of 10 years of wet delay estimates on the west coast of Sweden. J Geod 86(7):565–575.
- **Seco, A., Ramírez, F., Serna, E., Prieto, E., García, R., Moreno, A., Cantera, J. C., Miqueleiz, L., and Priego, J. E**.(2012): "Rain pattern analysis and forecast model based on GPS estimated atmospheric water vapour content, Atmos. Environ., 49, 85–93.
- **Saastamoinen, J,**(1972): "Contributions to the theory of atmospheric refraction," BulletinG- eod´esique, vol. 46, no. 3, pp. 279–29.
- **Wang J, Zhang L, Dai A** (2005): "Global estimates of the water-vapour weighted mean temperature of the atmosphere for GPS applications. J Geophys Res 110: D21101.