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# Diagnostics of Atmospheric Water Vapor Content according to GPS Measurements

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**Abstract**—A continuously operating GPS network, comprising seven permanent observation sites, is created to study the geodynamic processes in the Baikal region. Processing of the initial GPS data provides continuous atmospheric data in the form of total zenith tropospheric delay, which can be used for meteorological and climatological studies. The total delay is the sum of "dry", or hydrostatic, and "wet" components. The wet component determines the total water vapor amount and amount of precipitable water over the measurement site. Thus, GPS measurements make it possible to obtain initial data for creating new numerical models of zenith tropospheric delay and total precipitable water vapor for meteorological applications.

*Keywords*: GPS measurements, zenith tropospheric delay, meteorological data, refractive index, atmospheric water vapor

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## INTRODUCTION

An urgent problem in modern radiophysics is to develop radio wave methods for studying the radio climate and stratified structures in the Earth's atmosphere with the help of high-stability radio signals of satellite navigation systems (GPS, GLONASS, GALILEO, etc.). The tropospheric effect enters through refraction of propagating radio waves. The radio wave refractive index $N$ is determined mainly by the temperature, pressure, and water vapor pressure. Global Positioning System (GPS) signals are also affected by the inhomogeneous troposphere, and propagation in the troposphere is accounted for by tropospheric signal delay. The total zenith tropospheric delay (ZTD) is one of the most substantial corrections, which are taken into consideration in high-accuracy geodetic calculations according to GPS data using the GAMIT software package [1, 2]. The use of the exact ZTD estimation technique [3] showed its utility in atmospheric and climatological applications.

Water vapor content rapidly changes in the atmosphere, giving rise to complex distributions of clouds and rainfall. The temperature and humidity usually vary nonmonotonically with height [4]. Water vapor plays an important role as a key climate parameter in the dynamics of thermal processes and in local- and global-scale atmospheric and hydrological cycles. The atmospheric water vapor content was estimated quantitatively in the diurnal behavior according to the zenith wet delay (ZWD) parameter retrieved from GPS measurements. The ZWD parameter can be extracted from ZTD, taking additionally into account only atmospheric pressure. The ZWD values are minimal (maximal and more variable) during winter (summer) season, when the water vapor content and air temperature are low (high). The amount of water vapor in the atmosphere over a given ground point is determined as vertically integrated water vapor (IWV) mass per unit area. The precipitable water (PW), corresponding to the parameter IWV, is determined as liquid water column.

The purpose of the paper was, using ULAZ (Ulan-Ude) and IRKT (Irkutsk) observations, to compare ZTD values obtained according to GPS measurements and on the basis of meteorological data. The ZWD value is nearly proportional to tropospheric water vapor content, allowing GPS network to be used for atmospheric remote sensing in meteorology and climatology applications.

## 1. REFRACTIVE INDEX AND ZENITH TROPOSPHERIC DELAY

The refractive index $N$ in the troposphere, which is used in radio meteorology, obeys the additivity law and is represented as the sum of "dry" and "wet" components:

$$N = (n-1)\times 10^6 = \frac{k_1}{T}p + \frac{k_2}{T^2}e, \tag{1}$$

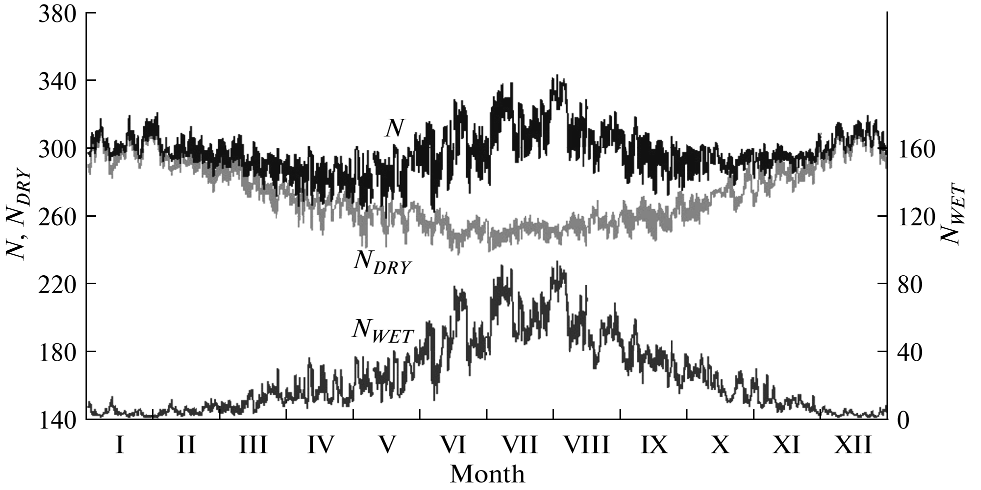

**Fig. 1.** Values of $N$, $N_{DRY}$, and $N_{WET}$ in different months of 2012 for Ulan-Ude.

where $n$ is the refractive index; $k_1 = 77.6$ is the first refraction constant in K/mbar (1 mbar = $10^2$ N/m$^2$); $k_2 = 3.73 \times 10^5$ is the second refraction constant in K$^2$/mbar; $T$ is the absolute temperature in K; $p$ is the atmospheric pressure in mbar; and $e$ is the water vapor pressure in mbar [5, 6].

Formula (1) can be rewritten as $N = N_{DRY} + N_{WET}$, where $N_{DRY} = \frac{77.6}{T} p$ is the refractive index for dry air, which depends on temperature and air pressure variations; and $N_{WET} = \frac{3.73 \times 10^5}{T^2} e$ is the refractive index for water vapor. Figure 1 shows the annual behaviors of the parameters $N$, $N_{DRY}$, and $N_{WET}$ for Ulan-Ude during 2012. On the whole, the "wet" component $N_{WET}$ makes a much smaller contribution to the refractive index, especially during the winter season. The "dry" component $N_{DRY}$ dominates in the refractive index.

Formula (1) can be used to determine the refractive index $N$, if we know the temperature, pressure, and water vapor pressure over the GPS signal reception site. From the formula for $N$, it follows that ZTD is also the sum of "hydrostatic" (ZHD) and "wet" (ZWD) components. The total delay on the signal path from the GPS satellite to receiver antenna is equal to the difference between geometrical distance and real signal pathlength in the atmosphere: $\mathrm{ZTD} = \int_{\mathrm{Atmosphere}} n(h)dh - \int_{\mathrm{Vacuum}} dh$. Therefore, the zenith delay components can be obtained through integration over the vertical profiles of the corresponding refractive indices [3]:

$$\mathrm{ZHD} = 10^{-6} \int_{h_S}^{\infty} N_D(h)dh; \tag{2}$$

$$\mathrm{ZWD} = 10^{-6} \int_{h_S}^{\infty} N_W(h)dh, \tag{3}$$

where $h_S$ is the antenna height above sea level in km; $N_D$ and $N_W$ are the height-dependent refractive indices of dry air and water vapor. We note that the integration for water vapor can be bounded by the upper part of the troposphere, i.e., up to approximately 11000–12000 m; while the integration for dry air can be extended into the region of the tropopause.

## 2. FORMULAS FOR DETERMINING THE TOTAL VAPOR AND PRECIPITABLE WATER

The ZHD parameter is well modeled under the assumption that the atmosphere is at hydrostatic equilibrium state. This modeling can be performed with the use of data on near-ground pressure and temperature. In work [7] it is theoretically suggested to express the hydrostatic refraction profile via the following model:

$$N_D = N_{DRY}\left(1 - \frac{h}{h_D}\right)^4. \tag{4}$$

Here, $h_D = 40136 + 148.72t$ is the effective height of hydrostatic component in m; and $t$ is the near-ground air temperature in °C. The height $h$ may vary from 0 to $h_D$. Substituting equation (4) to formula (2) and integrating yields a formula for the zenith dry delay

$$\mathrm{ZHD} = 2 \times 10^{-7} N_{DRY} h_D. \tag{5}$$

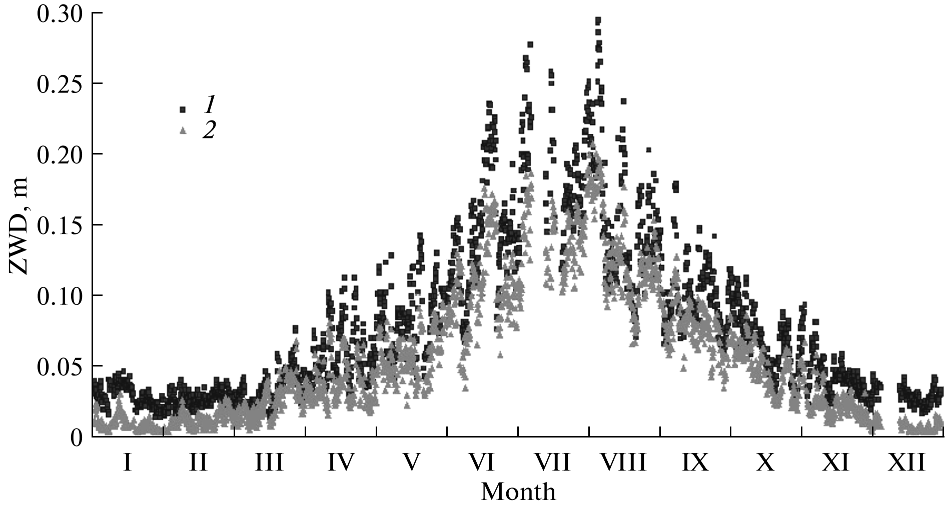

**Fig. 2.** Annual behavior of parameter ZWD at ULAZ station: according to GPS measurements accounting for near-ground atmospheric pressure (*1*); and according to meteorological data which take into account the near-ground temperature and water vapor pressure (*2*).

The formula for the refractive index of water vapor is written analogously as $N_W = N_{WET}\left(1-\frac{h}{h_W}\right)^4$, which we substitute under integral in (3) and finally obtain

$$\text{ZWD} = 2\times 10^{-7} N_{WET} h_W \qquad (6)$$

(the parameter $h_W$ is the maximal height above sea level, at which water vapor may be present, i.e., it is the height of the troposphere).

Formulas (5) and (6) relate the refractive indices for dry air and water vapor to the parameters ZHD and ZWD, respectively. At present, these parameters are calculated according to meteorological data using most common and sufficiently exact model of Saastamoinen [6, 8, 9]:

$$\text{ZHD} = \frac{0.002277p}{f(\varphi, h_S)}; \qquad (7)$$

$$\text{ZWD} = \frac{0.002277e}{f(\varphi, h_S)}\left(\frac{1255}{T} + 0.05\right), \qquad (8)$$

where $f(\varphi, h_S) = 1 - 0.00266\cos 2\varphi - 0.00028h_S$, and $\varphi$ is the geographic latitude for the receiver location in degrees. For the ULAZ and IRKT sites, the denominator $f(\varphi, h_S)$ in formulas (7) and (8) is approximately 1.00054, error due to its neglect in the ZHD and ZWD calculations does not exceed 0.08%, and, as such, it can be ignored. We note that, in contrast to formula (5), formula (7) is devoid of the temperature dependence, which substantially simplifies the ZWD determination from GPS measurements by accounting only for near-ground atmospheric pressure at the reception site according to the formula ZWD = ZTD – ZHD.

For ULAZ site in 2012, Fig. 2 compares the annual behavior of ZWD, retrieved from GPS measurements taking into account the near-ground atmospheric pressure, against the ZWD record calculated from formula (6). The cross correlation coefficient for data in Fig. 2 was 0.955.

To determine how accurately do the models calculate ZTD as the sums of ZHD and ZWD according to formulas (5)–(8), we evaluated the differences between model-based ZTD values according to meteorological data and ZTD values obtained according to GPS measurements at ULAZ and IRKT sites.

Figure 3 shows the time series of $\text{ZTD}_\text{C}$ – ZTD and $\text{ZTD}_\text{X}$ – ZTD for 2012, where $\text{ZTD}_\text{C}$ is the model-based total zenith tropospheric delay according to Saastamoinen's formulas (7) and (8), and $\text{ZTD}_\text{X}$ is the model-based total zenith tropospheric delay according to formulas (5) and (6). The average deviations are, respectively, –2.76 and –2.29 cm for ULAZ site and– 0.26 and 0.75 cm for IRKT site. In summer season, the maximal dispersion of deviations reaches 10 cm for both measurement sites and, at the same time, is within 4.2% relative to ZTD values according to GPS data. It can be concluded that the formulas for calculating the ZTD parameter on the basis of meteorological data ensures quite a satisfactory accuracy, with the cross correlation of $\text{ZTD}_\text{C}$ and $\text{ZTD}_\text{X}$ data being almost unity for both measurement sites.

Taking into account the formula for $N_{WET}$, equation (3) for the ZWD parameter can be written as

$$\text{ZWD} = 10^{-6} k_2 \int_{h_S}^{\infty} \frac{e}{T^2}\, dh. \qquad (9)$$

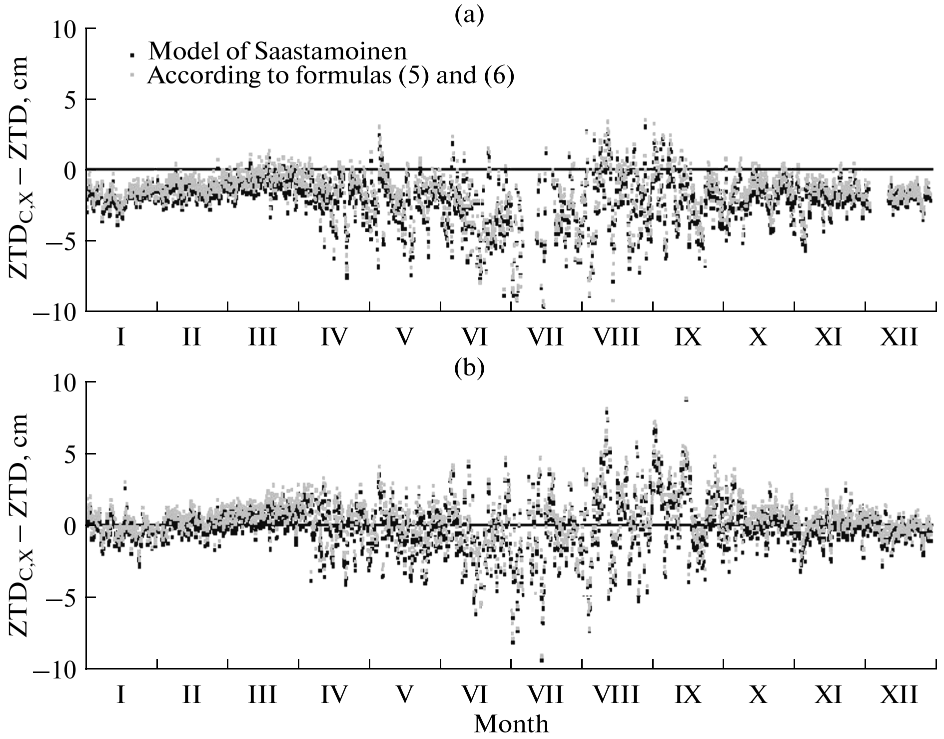

**Fig. 3.** Time series of the differences $ZTD_C - ZTD$ and $ZTD_X - ZTD$ for the (a) ULAZ and (b) IRKT sites.

Authors of works [3, 6, 8] consider parameter of "weighted mean temperature" $T_m$ over a signal reception site as the ratio

$$T_m = \int_{h_S}^{\infty} \frac{e}{T} dh \Bigg/ \int_{h_S}^{\infty} \frac{e}{T^2} dh.$$

Taking into account the parameter $T_m$ and relationship for normal atmospheric conditions $\frac{e}{\rho_{WV} T} = R_W$, where $\rho_{WV}$ is the water vapor density in kg/m$^3$; $R_W \approx 4.6$ is the gas constant for water vapor in J K$^{-1}$ kg$^{-1}$, formula (9) will be written as

$$\mathrm{ZWD} = 10^{-6} \frac{k_2}{T_m} R_W \mathrm{IWV}. \tag{10}$$

Here, $\mathrm{IWV} = \int_{h_S}^{\infty} \rho_{WV} dh$ is the total water vapor per unit area. The precipitable water (PW in m) is determined as liquid water column. We have the relationship $\mathrm{PW} = \frac{\mathrm{IWV}}{\rho}$, where $\rho$ is the liquid water density in kg/m$^3$.

Authors of work [6] present an empirical formula for the parameter $T_m$ in the form $T_m = 70.2 + 0.72T$ after analysis of 8718 profiles from meteorological radio sondes to determine the altitudinal dependence of parameters $e$ and $T$ in a wide latitudinal band from 27 to 65°. Therefore, the "weighted mean temperature" up to the altitude of the upper troposphere over the measurement site can be identified only according to the data on near-ground air temperature.

The amount of water vapor in the atmosphere over a given ground location is determined as vertically integrated water vapor mass per unit area. Thus, formula (10) makes it possible to determine IWV over a GPS site, which corresponds to cloud liquid water, as well as to the potential level of cloud-contained precipitable water. In the warm season, ZTD is proportional to precipitating cloud amount over the GPS site, so that data from GPS/GLONASS network can be used in meteorology for remote sensing of the atmosphere.

## 3. NUMERICAL RESULTS

Figure 4 shows the time series of ZTD and PW measurements for the ULAZ and IRKT sites in 2012, as well as the amounts of precipitation, accumulated for the preceding 6 h at each observation site. The coefficient of cross correlation between ZTD and PW data for the ULAZ site during the period from early May to late September is 0.86. As can be seen from Fig. 4, high-rate rainfall is accompanied by increases in ZTD and PW levels, which are propor-

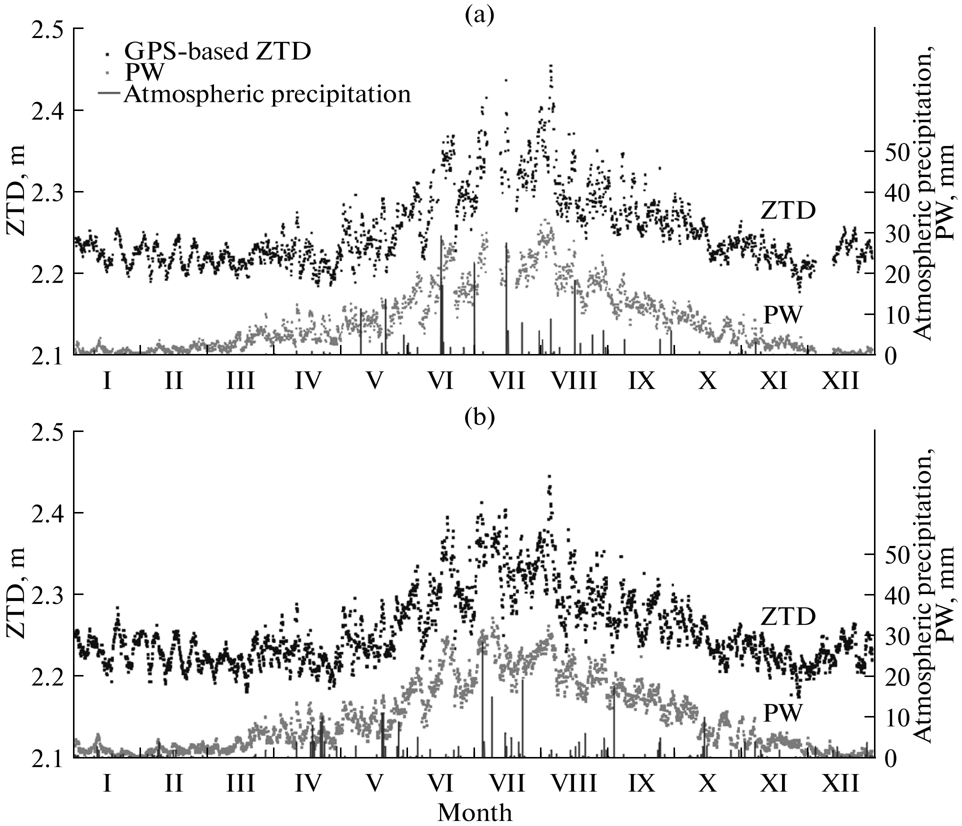

**Fig. 4.** The ZTD and PW time series for GPS measurements at (a) ULAZ and (b) IRKT sites and the amounts of 6-hour atmospheric precipitation for 2012.

tional to water vapor content in the troposphere. We note that increases in ZTD and PW values are not always associated with rainfall. This may be, in particular, because high ZTD levels, especially at summertime, signify abundant liquid water in the troposphere, which may result in rainfall; however, vapors are still insufficiently saturated. Nonetheless, there is a certain correspondence between increased ZTD and PW levels and rainfall.

## CONCLUSIONS

Quantitative characteristics, ZTD and PW, are determined for ULAZ and IRKT GPS stations. It is found that these data are closely correlated (with a correlation coefficient of 0.86) during the warm season (May–September). During the colder period of the year (October–April), the ZTD level starts to depend more strongly on atmospheric pressure, showing more vigorous variations at this time. Using data on near-ground pressure, which is determined at the meteorological station located close to a GPS receiver, the ZTD values are readily recalculated to ZHD and ZWD values. Comparison of variations in ZTD, PW, and atmospheric precipitation during the entire 2012 at the ULAZ and IRKT sites showed that the ZTD and PW levels had regularly increased prior to precipitation events. Wide use of GPS data helps to improve the short-range weather forecasting system and carry out fundamental research into the field of atmospheric circulation, the hydrologic cycle, and global climate change. A denser network of permanently operating GPS stations is now created for these purposes in the south of Eastern Siberia [2, 10].

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