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THE DETERMINATION OF ATMOSPHERIC WATER CONTENT FROM METEOROLOGICAL AND GPS DATA

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Abstract: The Global Positioning System (GPS) based on satellites and the networks of dual frequency receivers are actively used for geodetic and geophysical applications, as well as for studying the ionosphere and troposphere. The atmospheric water content is in the focus of research as a key parameter for determining of the accuracy of weather forecasting and hydrological monitoring. The precision of atmospheric water content calculations depends on the accuracy of determination of the delays of signals propagating from GPS satellites to ground-based GPS receivers when geodynamic measurements are conducted. This paper describes a technique that allows us to estimate the integrated water vapor (IWV) in the atmosphere from measurements of GPS satellite signal delays.

We consider remote sensing of the lower atmosphere by GPS measurements to detect the water vapor content in the conventional vertical column to the top level of the troposphere (up to 12 km above the Earth's surface). In studies of the propagation of signals from GPS satellites to ground receivers, the atmospheric water vapor is taken into account as a 'wet' component (ZWD) of the zenith tropospheric delay (ZTD). ZTD is the sum of ZHD (hydrostatic or 'dry' delay) and ZWD ('wet' delay). ZWD values can be converted with a very high confidence in integrated water vapor (IWV) values for each installed GPS receiver.

Key words: GPS; remote sensing; meteorological data; troposphere; tropospheric zenith delay; moisture content of troposphere; precipitable water

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ОПРЕДЕЛЕНИЕ АТМОСФЕРНОГО ВЛАГОСОДЕРЖАНИЯ ПО МЕТЕОРОЛОГИЧЕСКИМ И GPS-ДАННЫМ

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Аннотация: Система спутникового позиционирования GPS с использованием сетей двухчастотных приемников активно применяется не только для решения задач геодинамики, но и для исследования ионосферы и тропосферы. Особый интерес представляет оценка атмосферного влагосодержания, так как это один из ведущих параметров определения точности прогнозов погоды и гидрологического мониторинга. Точность оценки влагосодержания определяет точность оценки задержки GPS-сигнала при геодинамических измерениях. В работе описывается методика, позволяющая оценивать значение интегрального влагосодержания атмосферы по измеряемым фазовым задержкам сигнала спутников GPS.

Рассматривается дистанционное зондирование нижней части атмосферы посредством GPS-измерений с целью определения содержания водяного пара в условном вертикальном столбе до уровня верхней части тропосферы (до 12 км над поверхностью Земли). Атмосферный водяной пар учитывается в процессе распространения сигналов от GPS-спутников до наземных приемников в виде «влажной» компоненты полной тропосферной задержки (ZWD). Полная тропосферная зенитная задержка (ZTD) является суммой «сухой», или гидростатической (ZHD), и «влажной» (ZWD) компонент. Данные по ZWD могут быть преобразованы с очень высокой достоверностью в данные по суммарному водяному пару (IWV) над каждым установленным GPS-приемником.

Ключевые слова: GPS; дистанционное зондирование; метеорологические данные; тропосфера; тропосферная зенитная задержка; влагосодержание тропосферы; осаждаемая вода

1. Introduction

Permanent GPS stations in Irkutsk, IRKT and IRKM, are the base stations in the Baikal geodynamic network. High-precision geodetic measurements were conducted on the IRKT – ULAZ profile (from Irkutsk to Ulan-Ude) from 1999 to 2014 [*Sankov et al., 2014*]. In addition to the geodynamic parameters of crustal movements and deformations, the total tropospheric zenith delay data was collected. Changes in the refractive index with height in the lower neutral atmosphere cause tropospheric refraction or deviation of the rays of GPS signals. The index of radio wave refraction, *N* depends on temperature, pressure and aqueous tension. The zenith tropospheric delay (ZTD) is one of the most significant corrections [*Davis et al., 1985*] in high-precision geodetic calculations from GPS measurements [*Lukhnev et al., 2013*; *Dembelov et al., 2015*]. Then, using long term observations, it is also possible to study its changes in time (e.g., *Emardson et al., 1998; Nilsson, Elgered, 2008; Wang, Zhang, 2009*), which constitutes the beginning of its use in climate research. Water vapor is the most variable of all parameters of the troposphere and thus plays an important role in atmospheric processes [*Khutorova et al., 2012; Kunitsyn et al., 2015*]. The distribution of water vapor are closely related to the distribution of clouds and rain [*Eminov, Magerramov, 2012*]. The 'wet' component (ZWD) is practically proportional to the moisture content of clouds overlying a GPS station and can be estimated from GPS data on ZTD. Thus, GPS measurements can be useful for continuous remote sensing of the atmosphere. The emerging denser GPS networks, established mainly for studies of geodynamics [*Sankov et al., 2014*] and the ionosphere, offer the possibility of using GPS data for efficient weather forecasting [*Dembelov et al., 2015*].

GPS antennas on monitoring sites work with the cut-off angle of 10° relative to the horizon. Therefore, a satellite monitoring area is a cone with the base radius of 68 km, and the tropopause border altitude is 12 km. The tropospheric delay varies from about 6 to 8 ns in time (1.9–2.4 m), depending on weather conditions and location. With decreasing elevation angle α this parameter increases as the cosecant of the angle, so a delay at L1=1575.42 MHz with angle α of 20° can range from 30 to 36 cycles (5.71–6.85 m).

A real tropospheric delay is estimated as a zenith direction in the form of cosec α to consider ZTD. Surface weather data for Irkutsk are taken from www.rp5.ru. Meteorological vertical sounding data for Angarsk are provided by the Irkutsk Department of Hydrometeorology and Environmental Monitoring.

GPS site (IRKM) is located on a distance of 6 km from the Irkutsk meteorological station (WMO ID: 30710) and 43 km from the Angarsk meteorological station (WMO ID: 30715). The error of vertical meteorological data records in Angarsk for IRKM station does not exceed 5 %.

2. Tropospheric refraction index and zenith tropospheric delay

A tropospheric delay depends on refraction factor, *n*. Radio physics widely uses the refraction index from [*Smith, Weintraub, 1953*]:

$$N=(n-1)\cdot 10^6=\frac{k_1}{T}p+\frac{k_2}{T^2}e=N_T+N_e, \qquad (1)$$

where N_T is the refraction index of dry air, which depends on changes in air temperature and pressure; N_e is the refraction index of water vapour; k_1=77.6 is the first refraction constant, K/mbar (1 mbar=10^2 kg/m·s2); k_2=3.73·10^5 is the second refraction constant, K^2/mbar; *T* is absolute temperature, K; *p* is atmospheric pressure, mbar; *e* is aqueous tension, mbar. For average weather conditions in Irkutsk, *T*=288 K, *p*=960 mbar, *e*=19 mbar in summer, and *T*=255 K, *p*=975 mbar, *e*=1 mbar in winter.

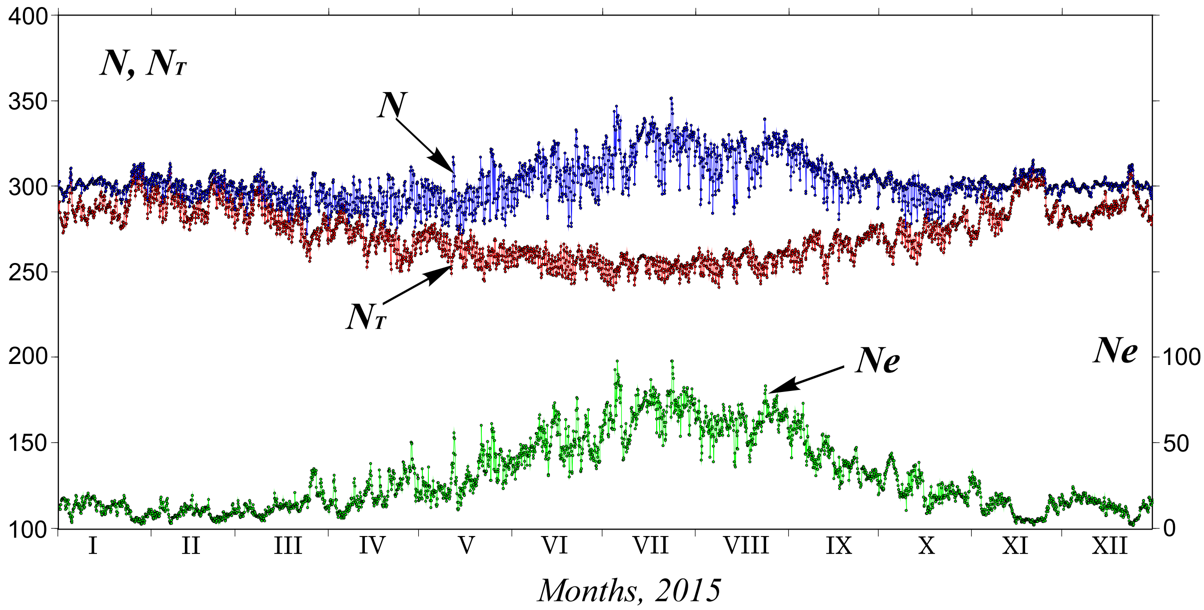

Fig. 1. Refraction indices N, N_T and N_e by months in 2015 (Irkutsk).

Рис. 1. Индексы рефракции N, N_T и N_e по месяцам 2015 г. для г. Иркутска.

Figure 1 shows the annual variations of parameters N, N_T and N_e in Irkutsk in 2015. In general, 'wet' component N_e makes a much smaller contribution to the determination of the refractive index, especially in the cold time of the year. The refractive index is predetermined by 'dry' component N_T. In the warm season, from the middle of April to the middle of October, the variations of the refractive index N correlate well with the changes in the refractive index of water vapor N_e (K=0.95).

The total tropospheric zenith delay (ZTD) is the sum of 'dry' (hydrostatic) and 'wet' components, i.e. ZHD and ZWD. By definition, the total delay of the signal path from the satellite to the GPS receiving antenna (ZTD) is equal to the difference of the real signal path in the atmosphere and the geometric distance:, $\mathrm{ZTD} = \int_{Atmosphere} n(h)dh - \int_{Vacuum} dh$, where h is height variable.

Using equation (1), components of the zenith delay can be expressed by integrating over the vertical profile of the corresponding refractive index values, $N_T(h)$ and $N_e(h)$:

$$\mathrm{ZHD} = 10^{-6}\int_0^{\infty} N_T\,(h)dh, \tag{2}$$

$$\mathrm{ZWD} = 10^{-6}\int_0^{\infty} N_e\,(h)dh. \tag{3}$$

In practice, the integration is limited for water vapor to the upper part of the troposphere, i.e. about 12 km, and for dry air may be continued in the stratosphere.

3. Vertical profiles of tropospheric refraction and formulas for ZTD

Given the atmosphere in the state of hydrostatic equilibrium, components ZHD and ZWD (depending on the height) are well modeled with reference to pressure near the ground data, air humidity and temperature. The vertical profile of the total refraction is well approximated by an exponential formula [*Moshkov, Pozhidaev, 2014*]:

$$N(h) = N_0\exp(-\beta h), \tag{4}$$

where N_0 is the refraction index at the Earth's surface; β, km^{-1} is the rate of decrease of the refraction index with changes in height h, km. Parameter β in formula (4) is estimated from N measurements at different heights by the least squares method. For the Angarsk station, parameter β is 0.125 in summer, 0.132 in winter, and 0.13 in spring and autumn. Figure 2 shows curves of altitude profiles obtained from weather sounding data and approximations using formula (4) for Angarsk on 03 January 2014 and 14 July 2014. Seasonal values of parameters N_0 and β in formula (4) allow obtaining reasonably reliable data on refraction index $N(h)$ through the year. For a specified observation point, values on parameter β can be tabulated by seasons of the year, which can allow with a sufficient accuracy to calculate height profiles of $N(h)$ without using the weather radio-sounding data.

Formula (4) for the vertical profile is also represented as the sum of the 'dry' and 'wet' components:

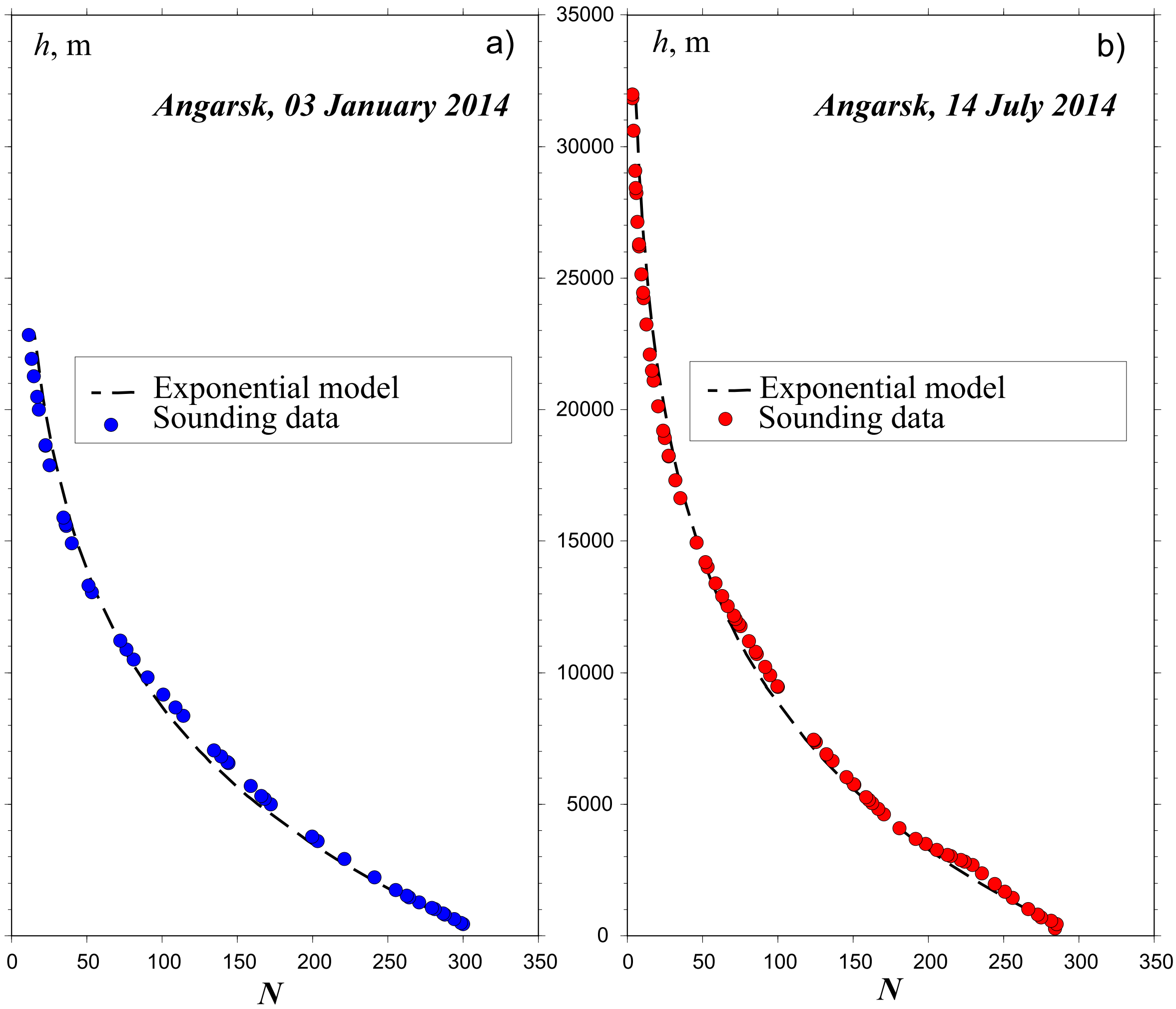

Fig. 2. Comparative height profiles of the refractive index based on sounding data and approximations over the Angarsk station in winter (*a*) and summer (*b*).

Рис. 2. Сравнительные высотные профили индекса рефракции по данным зондирования и их аппроксимации над пунктом наблюдения Ангарск для зимних (*а*) и летних условий (*b*).

$$N(h) = N_{T0}\exp(-\beta_D h) + N_{e0}\exp(-\beta_W h), \qquad (5)$$

where N_{T0} and N_{e0} are the near-surface refraction indices for dry air and water vapour, respectively; β_D and β_W are rates of decrease of the refraction index for dry air and water vapour, respectively. Values of β_D and β_W depend on the location of the monitoring station on the Earth. For the latitudes of the Baikal region, β_D is about $5/h_D$, and β_W is about 0.5 [*Dembelov et al., 2016*]. In this formula, $h_D = 40136 + 148.72 \cdot t$ is the effective height of the 'dry' (hydrostatic) component, m; t is surface temperature, °C [*Bevis et al., 1992*].

Representing ZTD according to formulas (2) and (3), given the components of the refraction indices according to formula (5), and performing the integration, the total tropospheric delay is given as the following sum:

$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD} = 10^{-6} N_T \frac{1}{\beta_D} + 10^{-6} N_e \frac{1}{\beta_W}. \qquad (6)$$

Formula (6) relates the refraction indices for dry air and water vapor with corresponding ZHD and ZWD. Hydrostatic delay ZHD can be estimated from meteorological data, using the well-known model described in [*Saastamoinen, 1972*], which, in its turn, was derived by transforming the integral (2) into the form convenient for use:

$$\mathrm{ZHD} = \frac{0.002277p}{f(\varphi, h_s)}. \qquad (7)$$

In this formula, $f(\varphi, h_s) = 1 - 0.00266\cos 2\varphi - 0.00028 h_s$ where φ is the geographical latitude of the station's location (degree); h_s is the receiver's height above the seal level (km). For all the monitoring stations in the Baikal region, value $f(\varphi, h_s)$ in formula (7) deviates from 1 by no more than 0.08 %. Thus, in formula (7), this value can be ignored. Actually, in formula (7), only the atmospheric pressure should be taken into account, which greatly simplifies the calculations of ZWD from GPS measurements by subtracting ZHD from ZTD.

4. Integrated water vapor in the troposphere

In formula (3), parameter ZWD is given with account of N_e as follows:

$$\mathrm{ZWD} = 10^{-6} k_2 \int_0^\infty \frac{e}{T^2} dh. \quad (8)$$

Weighted 'mean temperature' T_m over the reception station is introduced as the following ratio [*Bevis et al., 1992*]:

$$T_m = \frac{\int_0^\infty \frac{e}{T} dh}{\int_0^\infty \frac{e}{T^2} dh}. \quad (9)$$

With account of ratio (9), formula (8) can be given as follows:

$$\mathrm{ZWD} = 10^{-6} \frac{k_2}{T_m} \int_0^\infty \frac{e}{T} dh. \quad (10)$$

For normal atmospheric conditions, a ratio can be derived for the specific gas constant for water vapor R_W [*Bevis et al., 1992*]:

$$\frac{eV}{mT} = \frac{e}{\rho_{WV} T} = R_W, \quad (11)$$

where ρ_{WV} is the density of water vapor, kg/m³. With account of ratio (11) and the equation of the integrated vapor, $\mathrm{IWV} = \int_0^\infty \rho_{WV}\, dh$, formula (10) can be given as follows:

$$\mathrm{ZWD} = 10^{-6} \frac{k_2}{T_m} R_W \mathrm{IWV}. \quad (12)$$

Integrated water vapour (IWV) in the atmosphere over the measurement station is estimated as the vertically integrated mass of water vapor per unit area (kg/m²). The height of the precipitable water column (PW, m) corresponding to IWV can be calculated as $\mathrm{PW} = \mathrm{IWV}/\rho$, where ρ is the density of liquid water, kg/m³.

Fig. 3 shows the summer and winter high-altitude temperature profiles over Angarsk according to the vertical sounding data. The profiles have different heights (up to 23 km in winter, and up to 32 km in summer). Measurements taken at different heights may have errors and mistakes due to weather conditions, such as strong wind. Besides, in real conditions, it is quite difficult to accurately determine water vapor pressure (e) at different heights. Nonetheless, based on the available data, the relationship between the variations of parameter T_m and surface temperature is established.

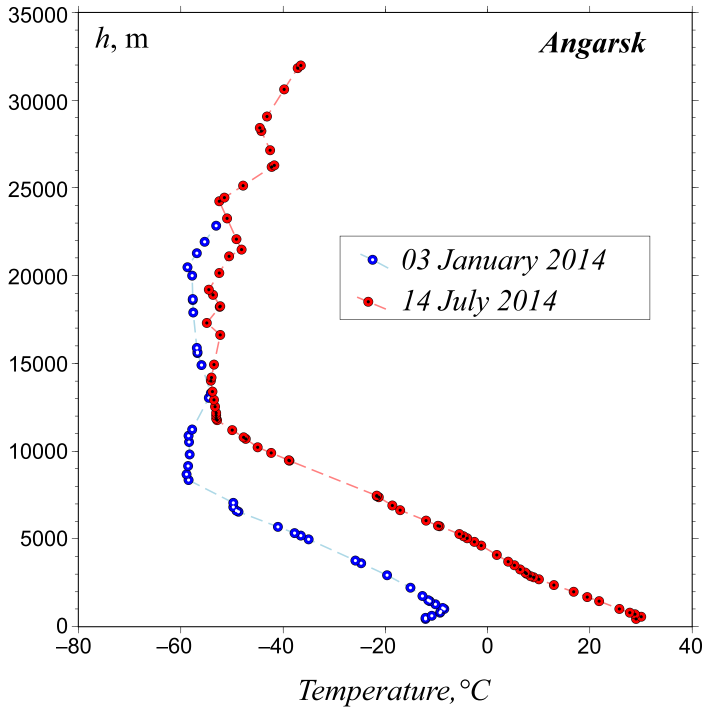

Fig. 3. High-altitude temperature profiles over Angarsk in winter and summer.

Рис. 3. Высотные температурные профили над г. Ангарском для зимних и летних условий.

Based on the vertical sounding data up to 35 km, average temperature T_m is calculated from formula (9). Figure 4 shows the linear regression relationships between surface temperature T and average temperature T_m for Angarsk in 2014 and 2015. Thus, the linear regression for Angarsk is T_m=70.27+0.73·T in 2014, and T_m=78.3+0.7·T in 2015. It is shown that the 'average temperature' up to the height of the lower stratosphere above the measurement station can be estimated from the surface temperature of air with the use of the regression equation.

Having processed the primary GPS data series [*Lukhnev et al., 2013*] by GAMIT software package precision, in addition to high-precision geodetic data, we obtained the atmospheric components in the form of the total zenith tropospheric delay (ZTD). Figure 5, *a*, shows the curve of annual ZTD variations for IRKM station. According to formula (7) from [*Saastamoinen, 1972*], taking into account the surface atmospheric pressure, the annual ZHD variations are estimated. From the difference of ZHD and ZTD values obtained by processing the GPS measurements, the annual ZWD variations are determined. Using formula (10), given the current temperature dependence of parameter T_m

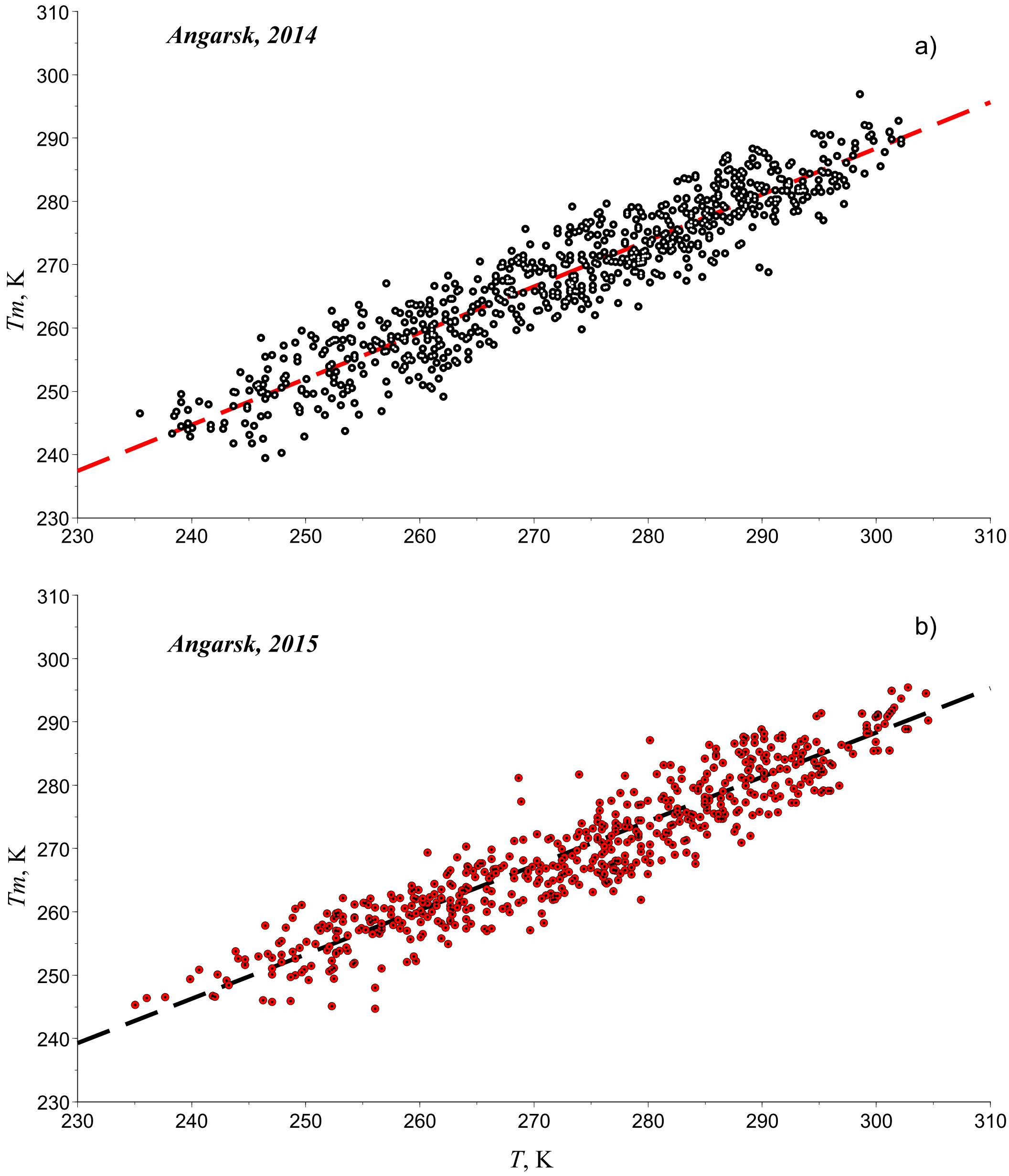

Fig. 4. Parameters T and T_m, estimated from the weather sounding data for Angarsk. The data for 2014 (*a*) and 2015 (*b*).

Рис. 4. Соотношение параметров T и T_m, выявленных по данным метеорологических зондирований в г. Ангарск в 2014 г. (*a*) и 2015 г. (*b*).

for Angarsk in 2015, the annual IWV variations over IRKM stations are estimated (Fig. 5, *b*). It should be noted that similar to the case for the refraction index and its components for water vapor, the cross-correlation coefficient of ZTD and IWV functions is quite high (0.92) in the warm period, from April to October.

5. Moisture content and precipitation

Using equation (12), it is possible to estimate an integrated water vapor (IWV) value over a permanent GPS station. During warm months, the measured ZWD value is practically proportional to the current humidity, and meteorologists can thus use the GPS network for remote sensing of the atmosphere.

In this paper, we consider variations in the humidity content of the troposphere in the warm season of 2015 (from April to October) over IRKM station (Irkutsk). According to the annual ZTD data obtained by processing the GPS data series (see Fig. 5, *a*), we estimate the 'wet' component of ZWD and the precipitable water (PW) levels that correspond to IWV. Figure 6 shows the humidity content of the troposphere on the scale of PW and the levels of precipitation accumulated during the

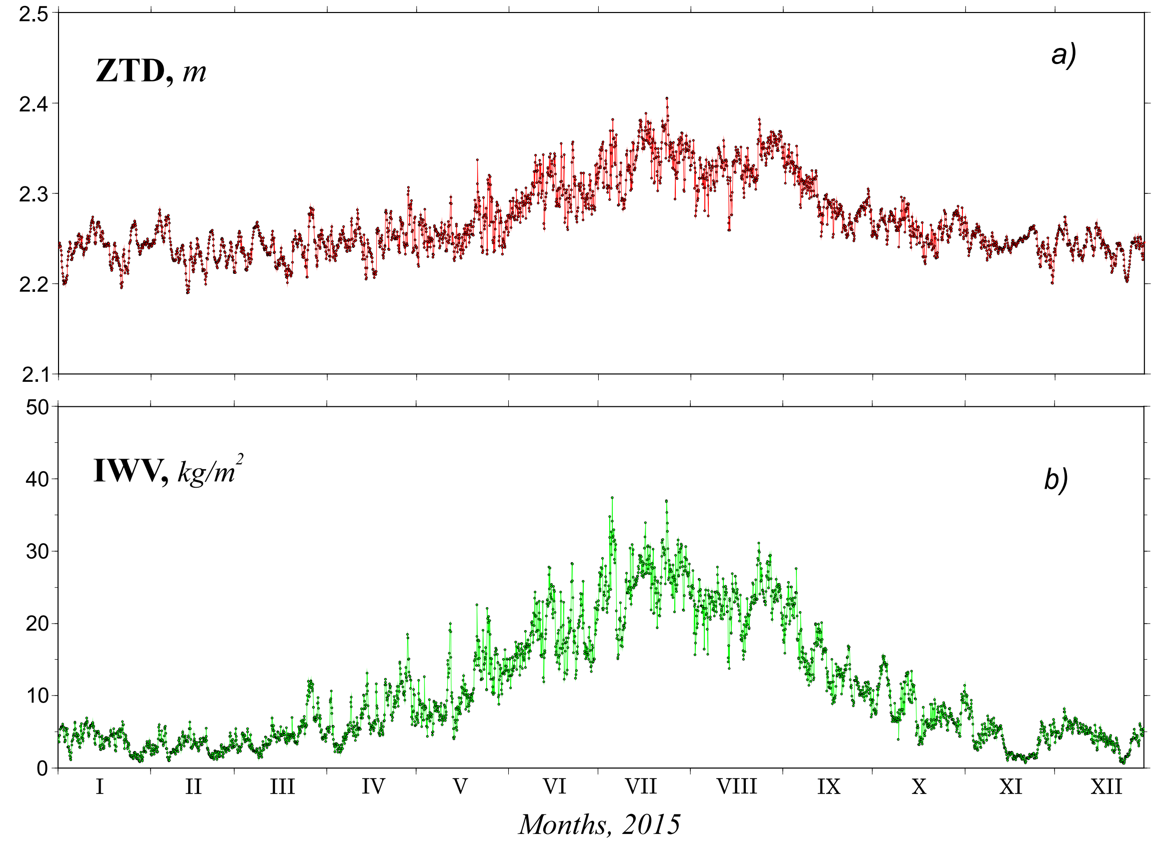

Fig. 5. Annual ZTD (*a*) and IWV (*b*) variations according to GPS measurements. The data for IRKM station (Irkutsk).

Рис. 5. Графики годового хода полной тропосферной зенитной задержки (*a*) и суммарного водяного пара (*b*) по данным GPS-измерений для пункта IRKM (Иркутск).

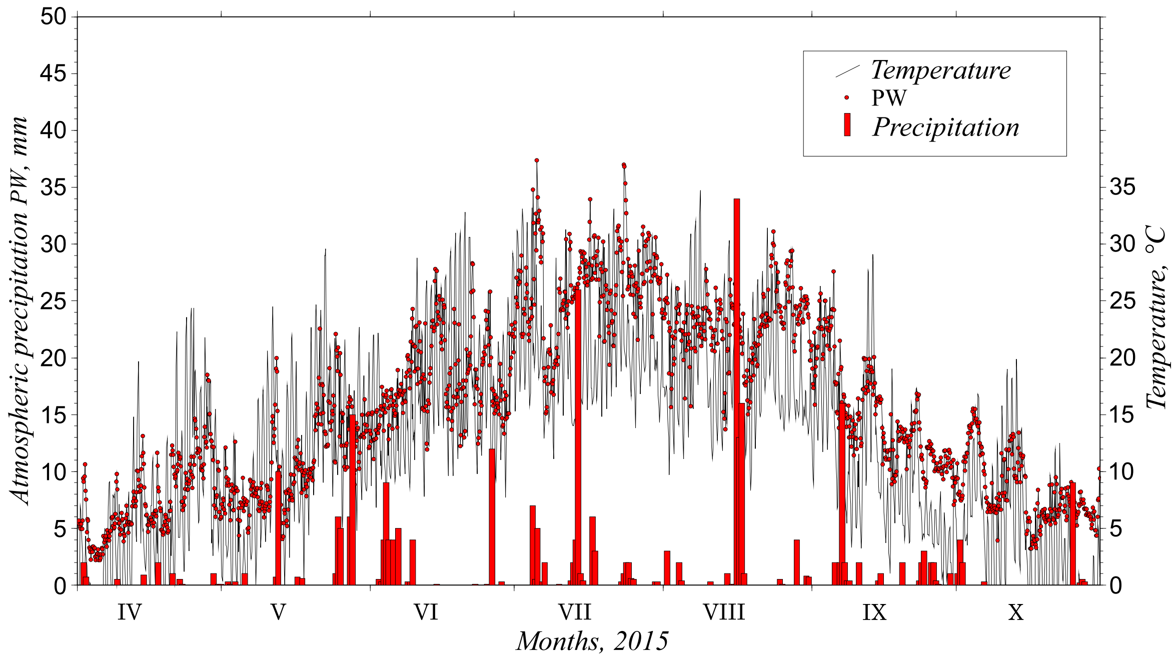

Fig. 6. Variations of the humidity content (PW) and the surface temperature in Irkutsk in the period from April to October 2015. Columns show the levels of accumulated precipitation during six hours.

Рис. 6. Вариации влагосодержания (PW) и приземной температуры в г. Иркутске за период апрель-октябрь 2015 г. Столбиками показаны уровни осадков, накопленных за 6 часов.

six hours of observation in Irkutsk. It should be noted that a high level of PW does not always correlate with precipitation due to the insufficient degree of vapour saturation at the given moment. An increase in the humidity content may be associated with precipitation, as a rule, in case of a sharp drop of air temperature and the presence of updrafts of air masses [*Marchenko et al.*, *2012*]. In Figure 6, precipitation correlated with the increase in the humidity content and a sharp decrease in surface temperature.

6. Conclusion

Based on the exponential model, the integrated refraction $N(h)$ is calculated to the altitude of 35 km, and the value of the zenith tropospheric delay (ZTD) is predicted on the basis of the analysis and processing of the surface meteorological data. In this paper, we have described the technique that allows estimating the integrated water vapour (IWV) from ZTD that is obtained by processing the primary GPS data series using GAMIT software package. The 'wet' component is the difference between ZTD and the 'dry' (hydrostatic) component calculated according to [*Saastamoinen*, *1972*].

The linear regressions between surface temperature (T) and weighted mean temperature (T_m) are established for the Angarsk station. Using dependences of parameter T_m from surface temperatures, it is possible to more accurately estimate the moisture content of the troposphere over the observation point.

Global Positioning Systems (GPS/GLONASS) provide for more efficient hydrological monitoring of the atmosphere and better forecasting of atmospheric precipitation.

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