Estimation of the relative humidity in the troposphere using GNSS signals

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Abstract. The report presents the relative air humidity in the troposphere retrieved from signals of global navigation satellite systems. The estimate is based on information on the moisture retrieved from the value of the wet tropospheric delay. The wet delay is converted into the humidity. The results are compared with the data of direct measurements. The discrepancy between the calculated and measured humidity values is about 12 percent.

1. Introduction
The idea of determining the parameters of the Earth’s atmosphere using satellite radio signals is not new [1]. Recently, signals from global satellite navigation systems (GNSS) are widely used for sensing of the atmosphere [2–5]. The influence of the atmosphere on radio signals is manifested through an additional delay of navigation signals. The delay is caused by the difference between the velocities of radio wave and light propagation along paths having different curvatures. As a rule, the curvature of the trajectory is neglected due to its small effect on the time delay. The radio wave propagation velocity depends on the atmospheric refractive index that is determined by the parameters of the atmosphere. Two atmospheric layers have a significant effect on the radio wave propagation. They are the neutral ionized layer of the atmosphere (including the troposphere and the stratosphere) and the ionosphere. The refractive index $n$ in the neutral layer of the atmosphere is determined by the meteorological parameters, including the atmospheric temperature $T$ (K), the atmospheric pressure $P$ (hPa), and the water vapor partial pressure $e$ (hPa):

$$n = 1 + \frac{77.6}{T} \left[ P + \frac{4810 \cdot e}{T} \right] \cdot 10^{-6}. \tag{1}$$

The refractive index of the ionosphere depends on the radio wave frequency $f$ (Hz). It is determined by the electron content in the ionosphere $N_e$ (the number of electrons per cubic meter) [6]:
\[ n = 1 - 40.3 \cdot N_f f^{-2} \cdot 10^{-6}. \]  \hspace{1cm} (2)

The additional signal delay \( \tau \) in the atmosphere, expressed in meters, is determined by integrating the refractive index along the signal propagation path \( S \) [6]:

\[ \tau [m] = \int_{S} (n-1) ds. \]  \hspace{1cm} (3)

The frequency dependence of the ionospheric delay permits obtaining information on the state of the ionosphere from double- or triple-frequency measurements of the GNSS parameters [6, 7], in particular, from measurements of the pseudorange defined as the difference between the reception time (in the time frame of the receiver) and the transmission time (in the time frame of the satellite) of the GNSS signal.

The tropospheric delay is frequency independent (in the frequency band up to 30 GHz [6]). This does not allow the methods of determining the parameters of the ionosphere to be used for reconstructing the parameters of the troposphere. At present, the problem of determining the vertical profile of the tropospheric refractive index is conventionally reduced to a solution of the inverse problem [4, 8, 9]. In this case, a system of equations (3) is compiled for the tropospheric delays of navigation signals received from different directions at spatially separated points, and the refractive index profile is subdivided into several layers of fixed thicknesses. Within each layer, the refractive index is assumed constant or described by a known deterministic function. A disadvantage of this method is its relatively low accuracy, because it is impossible to consider changes in the refractive index within layers whose thickness is less than several hundred meters, and the temperature and humidity profiles cannot be reconstructed separately.

2. Determination of the integrated water vapor

When analyzing the influence of the troposphere on the navigation signal delay, it is customary to consider separately the influence of the dry (hydrostatic) and wet components of the refractive index [7, 10–12]. The high stability and the monotonic character of the altitude dependence of the dry component (determined by the atmospheric pressure) make it possible to determine the Integrated Water Vapor (IWV) of the troposphere:

\[ IWV[mm] = ZWD[mm] \left( 0.10631 + \frac{1732.83}{T_m} \right)^{-1}, \]  \hspace{1cm} (4)

where \( IWV[mm] \) is the integrated water vapor expressed in terms of the thickness of the deposited water layer (mm); \( ZWD[mm] \) is the Zenith Wet Delay (mm) defined as the difference between the Zenith Total Delay (ZTD) and the Zenith Hydrostatic Delay (ZHD); \( T_m \) is the weighted mean temperature of water vapor [12]:

\[ T_m = 50.4 + 0.789 T_s, \]  \hspace{1cm} (5)

and \( T_s \) is the surface temperature. The numerical coefficients in Eqs. (4) and (5) are empirical. The procedure of their derivation was presented in [12].

The ZTD is estimated from the GNSS signals, and the ZHD is determined from the following formula [6]:

\[ ZHD = 0.002277 P_s, \]  \hspace{1cm} (6)

where \( P_s \) is the surface atmospheric pressure. The above formula was derived for the Saastamoinen model [6] by separating the expression for the ZTD into the dry and wet components using gas laws and simplifying assumptions on altitude dependences of the pressure, temperature, and humidity. At present, the Saastamoinen model is the most accurate ZTD model [13].

The IWV estimated from GNSS signals is shown in Figure 1. The ground-based values of air temperature and atmospheric pressure used to obtain the IWV estimate were measured by an autonomous Weather Station “AMK-03”.

\[ n = 1 - 40.3 \cdot N_f f^{-2} \cdot 10^{-6}. \]  \hspace{1cm} (2)

\[ \tau [m] = \int_{S} (n-1) ds. \]  \hspace{1cm} (3)

\[ IWV[mm] = ZWD[mm] \left( 0.10631 + \frac{1732.83}{T_m} \right)^{-1}, \]  \hspace{1cm} (4)

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The IWV estimated from GNSS signals is shown in Figure 1. The ground-based values of air temperature and atmospheric pressure used to obtain the IWV estimate were measured by an autonomous Weather Station “AMK-03”.
In Figure 1, a peak in the \( IWV \) was observed from 10 a.m. to 6 p.m. on October 1, 2018. This peak corresponded to the rain observed at the Tomsk Weather Station from 3 to 6 p.m. During rain, the moisture content in the atmosphere decreased. This was because the water accumulated in the atmosphere condensed and fell on the ground. On October 3, it rained lightly. In this case, a general increase in the \( IWV \) by 2...4 mm was observed. The local decrease in the \( IWV \) during this period corresponded to an increase in the precipitation intensity. In the rest of the observation time, no precipitation occurred.

An increase in the \( IWV \) before rain can be used as a sign of impending rain. The faster the \( IWV \) rises, the more intense precipitation can be expected.

3. Determination of the relative humidity
In addition to assessing the \( IWV \), estimation of the relative humidity is of practical interest, since meteorological instruments for direct humidity measurements have significant inertia and cannot measure rapid humidity variations. The relative humidity is determined by the saturated water vapor pressure which in turn can be estimated through the \( ZWD \) and the surface temperature using the formula derived for the Saastamoinen model:

\[
e = ZWD \cdot \frac{439.17T_s}{1255 + 0.05T_s}.
\]

The water vapor pressure is recalculated into the relative humidity using the formula [14]

\[
U = \frac{e}{6.112 \exp \left( \frac{17.61T_s}{243.12 + T_s} \right)} \times 100%,
\]

where \( T_s \) is the surface temperature, in degrees Celsius.

Figure 2 shows a comparison of the relative humidity calculated from the GNSS signals with the results of direct humidity measurements with the Weather Station “AMK-03” and with the data taken from the weather archive (Internet resource www.rp5.ru).
Figure 2. Relative humidity calculated from the GNSS signals

Figure 2 shows that the daily course of the humidity calculated from the GNSS signals corresponds to the direct measurements, but at some points in time, the difference in values exceeds 20 percent. The mean square error of the relative humidity estimate and direct measurements is 12 percent. A significant discrepancy was observed after the end of rain on October 1. This was caused by increased humidity at the ground surface: the Weather Station was located at a height of 2 m above the ground surface, while the GNSS receiving antenna was located at a height of 15 m above the ground surface.

4. Summary
The results obtained allow us to conclude the following. The use of GNSS signals makes it possible to accurately measure the relative humidity and allows rapid changes in the humidity to be detected which does not allow modern sensors with significant inertia. The disadvantage of this method is the need to measure atmospheric pressure and air temperature at the GNSS receiver location.

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