Hardware-software system for monitoring of atmospheric water vapor structure in the city of Kazan

V V Dementev, O G Khutorova, V E Khutorov, A R Nizameev and G E Korchagin¹

Institute of Physics, Kazan Federal University, Kremlin st. 18, Kazan, Russian Federation, 420008

Abstract. Methodology and software to reconstruct the spatial-temporal structure of water vapor in the troposphere by GNSS signals measured by ground-based receivers is developed. In this paper, measurements of a satellite navigation system receiver network located near the city of Kazan are used. It is shown that using a tomographic approach it is possible to reconstruct the altitude profile of the refractive index in the lower atmosphere and its space-time variations. The tomography method gives less smoothed results than Tikhonov’s method.

1. Introduction
Water vapor has a huge impact on climate and atmospheric radiation, and on precipitation and chemical transformations of atmospheric impurities [1]. Therefore, taking into account its fine spatial structure helps improve the quality of weather forecasts and atmospheric pollution. This paper presents a method to research the spatio-temporal structure of water vapor in the troposphere with high temporal and spatial resolution.

To improve the quality of the forecast of the fine structure of meteorological parameters, it is necessary to rely on a dense network of means of monitoring the atmosphere with a high temporal resolution. Such a network can be created by using a modern, highly efficient and promising method of GPS meteorology, whose development was started in the 1990s. High-orbit (GPS / GLONASS) satellite navigation systems and a network of ground-based receivers make it possible to probe the atmosphere and the ionosphere and to apply tomographic methods, i.e. allow one to reconstruct the spatial structure of the atmosphere and ionosphere with high temporal resolution. Most atmospheric monitoring programs currently being developed by the international scientific community include the use of GPS signals, which also indicates the need for the development of this technology [2]. An automated high-performance software and hardware complex for continuous measurements and forecasting of atmospheric dynamics was deployed in Kazan. The complex includes a network of GPS-GLONASS receivers and weather stations.

It was shown that using the tomographic approach it is possible to reconstruct the altitude profile of the refractive index in the lower atmosphere and its space-time variations [3, 4]. The spatial fields of the refraction index allow one to quickly obtain the weather conditions in various areas where receiving antennas of global navigation systems are installed. It was shown that assimilation of GPS monitoring data in numerical atmospheric models improves the quality of forecast of meteorological parameters [5, 6].
2. Hardware and software system
The complex consists of a distributed net of GPS/GLONASS receivers, a data storage server, and a computing server. The satellite receivers are located at different points of Kazan. Each node includes a GPS/GLONASS receiver, small antennas, and an amplifier. The device generally calculates the geographic coordinates and the world time (UTS) itself. Data from the receivers is collected every second and accumulated on the local data storage. Then the data is automatically converted to the RINEX format. These data with meteorological data are involved in further calculations.

3. Algorithm and methods
The atmosphere affecting signals of global navigation satellite systems (GNSSs) with a frequency of 1.2 - 1.5 GHz causes their time delay. This delay taking into account the slope of the radio paths and reduced to the zenith direction is called the zenith tropospheric delay (ZTD). Physically, it displays the refraction in the atmosphere caused by atmospheric gases:

$$ZTD = \int_{Atmosphere} \left( n(h) \right) dh - \int_{Vacuum} dh,$$

where $h$ is the height of vertical integration; and $n$ is the refractive index of radio waves, which is calculated by formula (2).

$$n = \frac{77.6}{T} \left( p + \frac{4810 e}{T} \right) \times 10^{-6} + 1$$

$$N = (n-1) \times 10^6$$

The refraction index in the troposphere and stratosphere depends on the pressure $p$, the temperature $T$, and the humidity $e$. The vertical profile of the total refraction is approximated by the exponential,

$$N(h) = N_0 \exp(-\beta h),$$

where $N_0$ is the index of refraction on the Earth's surface; $\beta$ [km$^{-1}$] is the rate of decrease of the refraction index at altitude.

The zenith tropospheric delay usually consists of a dry (hydrostatic) zenith delay (ZHD) and a wet tropospheric delay (ZWD):

$$ZTD = ZHD + ZWD.$$
$$\rho = -\frac{1}{g} \frac{dp}{dh} 10^2,$$

where \( p, \rho \) are the pressure [mbar] and air density [kg/m\(^3\)] at height \( h \) [m], and \( g \) is the acceleration of gravity [m/s\(^2\)].

The tropospheric delay of GLONASS and GPS satellite radio signals reflects only the integral value of the refractive index. To solve the problem of spatial distribution of the refraction index of radio waves in the troposphere, we have investigated and applied the method of radiotomography.

The method for reconstructing the altitude structure of water vapor has two stages. At the first stage, the altitude profile of the refractive index \( N(h) \) with a high spatial-temporal resolution is reconstructed [4].

In this method, atmospheric sampling is used for elementary volumes in the form of a parallelepiped on which the entire region of the troposphere radiating by radio paths is divided. For each elementary volume, a constant refraction index is entered as an unknown value.

Solving the system of equations (1), where each equation corresponds to one radio path of the satellite, relative to \( N \), we obtain the spatial structure \( N \) which characterizes the variations of the atmospheric parameters in space.

The second stage of the reconstruction methods is the spatio-temporal structure of water vapor in the troposphere along the refractive index profile and the values of surface meteorological parameters obtained from the weather stations. By subtracting the hydrostatic components we obtain an array of reconstructed spatio-temporal structure of water vapor.

4. Results and Analysis

Figure 1 shows the altitude-time structure of the partial pressure of water vapor in the troposphere. The restoration of the altitude distribution of the water vapor concentration was carried out for the period from 18.08.17 to 22.08.17 using the results of the profile of the refraction index and the meteorological parameters for this period.

Our hardware and software system is used to investigate the water vapor profile and to consider its variations in time.

![Figure 1](image_url)

**Figure 1.** Altitude distribution of water vapor concentration in the troposphere.

5. Conclusions

The high frequency of the measurements allowed us to obtain variations in the partial pressure of water vapor due to daily dynamics of the meteorological parameters. For example, in the middle of each day there is an increase in the level of moisture content in the troposphere. A comparison with the results of [3] showed that the tomography method gives less smoothed results than Tikhonov’s
method. Thus, the above methodology and software was developed to reconstruct the spatial-temporal structure of water vapor in the troposphere by GNSS signals measured by ground-based receivers.

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