Ground-based Microwave Radiometry for measurements of Atmospheric Water Vapour and Cloud Liquid Water Contents

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Abstract. The method of ground-based microwave radiometry for determining the integral parameters of atmospheric moisture content, such as integrated water vapor and cloud liquid water content is considered. Some results of experimental studies of integrated water vapor and integrated cloud liquid in different regions by means of ground-based and ship-based of microwave radiometers are given. The microwave radiometric measurements of integrated water vapor were found to be in agreement with independent radiosonding data (rms is ~1 kg/m²). Microwave radiometric measurements of integrated cloud liquid of stratified clouds are consistent with empirical models of cloudy atmosphere based on aircraft data sensing of clouds. The capabilities of the novel microwave water vapor radiometer for studying variations in atmospheric moisture content on micro and meso scales were demonstrated. Histograms of the moisture content are obtained, and an approximation for the temporal structural function of the integrated water vapor in a wide range of time scales is discussed.

1. Introduction
The method of ground-based microwave radiometry allows to get unique information about the physical state of the atmosphere in real time, so this method is used in various fields in atmospheric and cloud physics, applied meteorology, radio astronomy and radio navigation. Research in the field of microwave radiometry for meteorological purposes has been continuing since the early 60s of the last century [1]. The method of microwave radiometer allows to determine important meteorological variables of the atmosphere, such as profiles of temperature, humidity, and cloud water content [2]. One of the tasks that is effectively solved using ground-based microwave radiometry is related to the measurement of integral characteristics of atmospheric moisture content, which include the integrated water vapor and cloud liquid water content. Interest in studying the characteristics of atmospheric moisture content is associated with the huge role played by atmospheric water vapor in the formation of atmospheric processes, the formation of clouds and precipitation, the development of weather hazards associated with clouds, the need to improve methods for forecasting weather hazards.

There is a lack of research and modeling of difficult to predict small-scale (micro and mesoscale variations) of changes in atmospheric humidity and cloud water content. Data on the temporal variability of atmospheric moisture content parameters can be considered as predictors for predicting cloud cover and precipitation. Current research for radio navigation problems is related to the improvement of the method for measuring the variable wet component of the tropospheric delay [3].

The purpose of this work is to improve the method of microwave radiometry and analyze the results of experimental studies of temporal variations of atmospheric moisture and cloud water storage in a wide range of time scales based on ground-based microwave radiometers.
2. Microwave radiometry for moisture sounding of the atmosphere

Microwave radiometry method are based on measuring the thermal emission of the atmosphere and then extracting from it the information on atmospheric development [2,4]. Relation between target atmospheric parameters and characteristics of the radio thermal emission of atmosphere are defined by the radiation transfer equation. In clear sky, emission is mainly determination by oxygen and water vapor. The oxygen absorption lines are centered at frequencies at 118 and 60 GHz (are used for temperature sounding). The water vapor absorption lines, at 22.235 and 183.16 GHz (interesting for humidity sounding of the atmosphere). The atmospheric “windows” at 30-38 and 75-100 GHz, as well as spectral region of weak emission at 6-15 GHz are used for cloud sounding.

Simple variant of the experiment is based on the use of two or three-frequency radiometric sounding near the center line of the water vapour at 22.235 GHz and in transmission “window” of atmosphere near 35 GHz, which allows to measure atmospheric integrated water vapor and integrated cloud liquid [5-9]. Optimal frequencies sensing are selected in the ranges of 20.6 -23.9 GHz as well as 31.0-37.0 GHz. For example, a frequently used combinations of frequencies of 23.9 GHz (or 20.6 GHz) and 31.50 GHz (or 36.5 GHz).

In the case of a cloudy atmosphere (no rain) radiometric measurements the characteristics of radiothermal emission of the atmosphere are carried out on two frequencies \( \nu_1, \nu_2 \). Then integrated water vapor and integrated cloud liquid are determined from the equations:

\[
IWV = a_0 + a_1 \tau(\nu_1) + a_2 \tau(\nu_2)
\]

\[
ICL = b_0 + b_1 \tau(\nu_1) + b_2 \tau(\nu_2),
\]

where \( a_i, b_i \) - regression coefficients calculated for different models of atmosphere based on radiosonde and aircraft data obtained in Leningrad region.

Optical thickness of the atmosphere associated with the measured brightness temperature:

\[
\tau(\nu) = \ln \left( \frac{T_{\nu,\nu}(\nu) - T_{\cos}}{T_{\nu,\cos} - T_{\nu}} \right),
\]

where \( T_{\cos} \) - cosmic background brightness temperature, 2.75 K; \( T_{\nu} \) - mean effective temperature of the atmosphere. Theoretical accuracy of determining the integrated water vapor of the atmosphere (in the absence of precipitation) is about 10%. Accuracy of determining the integrated cloud liquid is about 30%.

Integrated cloud liquid estimation can be obtained from microwave radiometric measurements at one frequency:

\[
ICL = K_w(\nu, T_{\nu})^{-1} \left[ \tau(\nu) - \tau_d(\nu) - K_q(\nu)IWV \right],
\]

where: \( \tau_d(\nu) \) - absorption of atmospheric oxygen; \( K_q, K_w \) - specific absorption coefficients of water vapor and cloud liquid, respectively. Two-frequency microwave radiometric sounding are used for effective investigations of convective clouds. Frequency range 30-38 GHz are used in the early stages of the development of convective clouds. Frequency range 6-14 GHz are used for studies of convective clouds (Cu cong, Cb) and supercooled zones cumulonimbus. Error estimating of integrated cloud liquid is 20-40%.

3. Microwave radiometers for investigation of the atmosphere

The principles of microwave radiometry are given in [1]. Some examples of a ground-based microwave radiometers for the study of meteorological parameters of the atmosphere are discussed in works [4]. The MP - 3000A Radiometrics Corporation (USA), HATPRO Radiometer Physics GmbH (Germany), AWVR-2 JPL (USA) radiometers are known among microwave radiometers that allow us to solve the problem of determining the moisture content and profiles of temperature of the atmosphere. Also known are ground-based microwave radiometers for atmospheric research developed recently in Russia, such as:
8 channel (from 22 to 58 GHz) microwave radiometric system “Microradcom”, designed by The Central Aerological Observatory, Moscow [10].

The microwave radiometers at 18-26 GHz and 31-36 GHz for atmospheric humidity sounding developed by Kotelnikov Institute of Radioengineering and Electronics of Russian Academy of Sciences, Moscow.

The microwave water vapor radiometer at 20.7 and 32.0 GHz designed by Institute of Applied Astronomy of Russian Academy of Sciences (IPA RAS), Saint Petersburg [11].

Characteristics microwave water vapor radiometer of IPA RAS are shown in Table 1. The microwave radiometer is built according to the classical scheme of a two-frequency full-power radiometer with a superheterodyne receiver. The radiometer includes two independent radiometric channels. Each channel receives atmospheric radiation on a separate horn-lens antenna, the beam width of the antenna’s directional diagram is about 6-7° (3 dB).

Table 1. Characteristics of microwave water vapor radiometer.

| Parameter                      | Channel 1 | Channel 2 |
|--------------------------------|-----------|-----------|
| Centre frequency, GHz          | 32.0      | 20.7      |
| Bandwidth, GHz                 | 0.50      | 0.50      |
| Sensitivity, K/sec^0.5          | 0.1       | 0.1       |
| Beamwidth, level 3 dB, deg.    | 7         | 7         |
| Sampling time, sec             | 5         | 5         |
| Absolute accuracy, K           | 1         | 1         |

The system of temperature control and "internal" calibration of the radiometer provides the possibility of long-term continuous measurements in automatic mode. According to preliminary estimates, the error in determining the moisture content of the atmosphere is about 0.5 kg/m², and the water content of clouds is about 0.03 kg / m². Modern microwave radiometers allow us to study the features of variation of the parameters of atmospheric moisture content in a wide range of spatial and temporal scales, including micro, meso and synoptic scales.

4. Some results of microwave radiometric experiments
The first experiments performed in 1966 in the Leningrad region with the use of microwave radiometers operating near the water vapor absorption line of 22.235 GHz demonstrated the possibility of determining the moisture content of the atmosphere based on measurements of its own radiothermal radiation of the atmosphere. In the future experimental research of the atmosphere using microwave radiometers are conducted in different regions: over the ocean in the North Atlantic and over land in the Leningrad region Russian Federation [5]. Tasks that were handled in experiments: a study on temporal variability of atmospheric integrated water vapor and integrated cloud liquid at different weather conditions; error estimation of determining the integrated water vapor and integrated cloud liquid; investigations of integrated water vapor and integrated cloud liquid in the period of development convective clouds and thunderstorms. Some examples of microwave radiometric measurements of integrated water vapor and integrated cloud liquid are given in this paper.

4.1. Water vapor and cloud liquid over Ocean
As an example, figure 2 presents time-series of atmospheric integrated water vapor and integrated cloud liquid over the ocean, obtained in the North Atlantic in the period Atlantex-90 (coordinates: 48 N, 46 W). The observations were carried out with the ship-based dual-channel microwave radiometer (21.0 GHz and 36.5 GHz) installed on board the research ship "Volna". The figure also shows the values of integrated water vapor, obtained according to the simultaneous radiosounding of the atmosphere. The ship-based microwave radiometric measurements are in good agreement with the data radiosonde (r.m.s is 2.0 kg/m²). In figure 1 for comparison also shows data of satellite microwave
radiometer SSMI/DMSP [12]. Atmospheric integrated water vapor data qualitatively consistent. Total 25 spatial SSMI/DMSP maps of integrated water vapor and integrated cloud liquid were used for analysis of meteorological parameters in region of Atlantic Ocean. A histograms was used to analyze the data on integrated cloud liquid obtained independent methods.

![Figure 1](image1.png)

**Figure 1.** Time series of cloud liquid (a) and water vapor (b) over ocean

The histograms of cloud liquid shows satisfactory agreements between satellite and ship-based microwave radiometer measurements in the observation period of homogeneous clouds.

Temporal variability of atmospheric integrated water vapor and integrated cloud liquid reflects the synoptic processes in the atmosphere. Maximum values of integrated water vapor for period of measurements amounted to about 35 kg/m$^2$. Atmospheric integrated water vapor changes in the field of atmospheric fronts may be about 20 kg/m$^2$. Speed of integrated water vapor changes in the field of atmospheric fronts over the Ocean can be about 0.2 kg/m$^2$ min.

4.2. *Water vapor and cloud liquid in Leningrad region*

Microwave radiometric measurements of integrated atmospheric water vapor are compared with values obtained from radiosondes (Voeikovo). The agreement between measured and calculated values is typically about 1 kg/m$^2$ during no rain conditions, when atmospheric water vapor varied from 4 to 45 kg/m$^2$ and integrated cloud liquid water content less 1 kg/m$^2$. Ground-based microwave radiometric measurements of integrated cloud liquid of stratified clouds are consistent with empirical models of cloud atmosphere based on aircraft data for the Northwest region of the Russian Federation. In winter period in the Leningrad region integrated cloud liquid did not exceed 0.28 kg/m$^2$ in 95% of cases and estimating values of integrated cloud liquid, exceeding 0.52 kg/m$^2$, registered only in 1% of cases. Integrated cloud liquid in summer to exceed 0.5 kg/m$^2$ in 5% of cases. As an example, Figure 2 shows a histograms of integrated water vapor for July (figure 2a) and February (figure 2b) in Leningrad region.
Figure 2. Histogram of IWV, Leningrad region: a) – July, b) - February.

Figure 3 shows an example of the time variability of cloud liquid and atmospheric water vapor measured by the water vapor radiometer of the IPA RAS on June 12, 2018 in Lekhtusi, Leningrad region. Qualitatively, microwave radiometric measurements of atmospheric moisture content are consistent with independent observations of aerological sounding station in Voëikovo. The decrease in atmospheric moisture content according to radiosonding data on June 12 was about 14.3 kg / m². Changes in the moisture content of the atmosphere are caused by the passage of a system of atmospheric fronts in the cyclone area.

Figure 3. Time series of ICL and IWV during June 12 2018 in Leningrad region.

4.3. Model of water vapor variations
A semi-empirical model for the structural function [13,14] of the atmospheric moisture content is used as a hypothesis to describe the time variations of the atmospheric moisture content at various spatial intervals. According to this model, three different regions of changes in the time structural function are distinguished:

- If \( t_0 < t < t_1 \), \( D_V(t) = C_i^2 t^{5/3} \).
- If \( t_1 < t < t_2 \), \( D_V(t) = C_2^2 t^{2/3} \).
- If \( t_2 < t \), \( D_V(t) = C_3^2 t_2^{2/3} \).

Where, \( C_i \) – mean structural coefficients; \( t \) – time interval; \( t_1, t_2 \) – the time scales.
5. Appendices

Experimental studies of moisture parameters of atmosphere performed in different regions over the ocean and over land using microwave radiometers have confirmed the possibility of microwave radiometry to measuring integrated water vapor and cloud liquid water content. Microwave radiometric measurements of atmospheric integrated water vapor consistent with the radiosounding data (RMS is approximately 1 kg/m²). Ground-based microwave radiometric measurements of integrated cloud liquid of stratified clouds are consistent with empirical models of cloudy atmosphere based on aircraft data sensing of clouds. Ship's microwave radiometric measurements of atmospheric integrated water vapor and integrated cloud liquid the ocean are consistent with those of satellite microwave radiometers SSMI/DMSP.

Further studies related to development in the practice of meteorological observations methods of network microwave radiometric temperature and humidity sounding of the atmosphere for nowcasting and short-range forecasts of severe weather associated with clouds and precipitation. Promising areas of application of ground-based microwave radiometry are also related to improving methods for operational control and accounting for tropospheric delay of radio navigation signals in radio navigation tasks and performing satellite experiments for calibration and validation of satellite data for temperature and humidity sensing of the atmosphere.

6. References

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