The influence of clouds on atmospheric radiation fluctuations in the resonance absorption band of water vapor 18 - 27.2 GHz

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Abstract. The results of processing new experimental data on brightness temperature of atmospheric downwelling radiation near the resonance absorption line of water vapor 22.235 GHz are presented. The experiment was carried out by means of special 47-channel microwave radiometer-spectrometer. In this article the observations of stable clear sky and also cumulus cloud cover of various vertical extent for summer 2018-2019 measurement periods are considered. Due to assess the dynamics of brightness temperature fluctuations, the apparatus of Kolmogorov’s structural functions is used. Spectra of square root of structural function for wide range of temporal interval values under clear sky and cumulus cloud cover conditions are obtained. The two-frequency method of integral atmospheric moisture content evaluation is discussed. Experimental dependencies of cloud liquid water content on square root of structural function are shown.

1. Introduction

The spatial and temporal fluctuations in the microwave emission of atmosphere are known to be directly related to the tropospheric turbulence [1]. That is a subject of special attention to atmospheric physics, since such a relation allows one to remotely evaluate statistical characteristics of turbulence [2]. On the other hand, the radiation fluctuations are only a nuisance in many areas, for example, in radio astronomy. They also need to be taken into consideration when developing navigation systems and various remote sensing systems. The frequency band 18 - 27 GHz, in turn, is interesting in that these frequencies are located near a sufficiently powerful resonance of water vapor, the rotational line of 22.235 GHz, and can be used to obtain atmospheric humidity characteristics. Together with other frequency ranges, including those related to the influence of atmospheric oxygen, it is possible to carry out full-fledged monitoring of the meteorological situation, to predict the weather, precipitation, and dangerous weather phenomena.

The first experimental studies of fluctuations in microwave radiation of atmosphere were performed in 1976 by means of RT-22 radio telescope for two wavelengths of 0.8 and 1.35 cm [3]. Measurements of spatial fluctuations were further continued on IL-18 laboratory airplane, and temporary ones from ground-based observation points [4]. The results confirmed that fluctuations in the absorption of atmosphere and its brightness temperature are caused by the
variability of the humidity and wind speed fields. The new data are obtained through the use of modern equipment [5] multichannel radiometer-spectrometer (47 channels in the 18 – 27.2 GHz band) with improved fluctuation sensitivity and high temperature stability of the gain coefficient. Such a radiometer allows for long-term (from 2 to 5 hours) sessions of continuous measurements to be performed. It becomes possible to calculate structural functions for larger temporal intervals and to study in more detail the influence of water vapor and liquid water fields variability on fluctuations in microwave emission.

2. The experiment
The observations of downwelling atmospheric radiation in the 18 – 27.2 GHz band were carried out at Kotel’nikov Institute of Radio Engineering and Electronics since 2016, were started at the Moscow part of the Institute and continued since 2017 at its branch in Fryazino, Moscow Region. The radiometer-spectrometer [5] measures spectra of brightness temperature around the clock from the laboratory room window at zenith angle 51°. The data of measurements are stored on the disk space of the remote server. As additional information, a 2.0-megapixel camera HI3516C makes video recording of current weather conditions. Two Vantage Pro2 meteo stations located at a distance of about 300 m from the radiometer-spectrometer measure near-surface (15 meters above the Earth’s surface) air temperature, atmospheric pressure, absolute humidity, wind speed and precipitation amount [6]. The main characteristics of the radiometer-spectrometer are listed in table 1.

| Feature                        | Value            |
|--------------------------------|------------------|
| Frequency range                | 18 – 27.2 GHz    |
| Frequency resolution           | 200 MHz          |
| The number of spectral channels| 47               |
| Fluctuation sensitivity        | 0.02 K           |
| Full spectrum acquisition time | about 11 sec.    |
| Angular resolution             | 5-7°             |

The angular resolution of the radiometer-spectrometer is from 5 to 7 degrees depending on frequency. As known, the characteristic height of water vapor distribution is 2.1 km. At this height, the spatial resolution of the considered radiometer will be than from 183 up to 256 meters. Thus, assuming Taylor’s hypothesis of frozen turbulence, this radiometer allows one to study inhomogeneities which linear size is both smaller and larger than the external scale of turbulence.

3. Structural function
The apparatus of structural functions was invented by A.N. Kolmogorov in 1941 to describe statistically the locally homogeneous and isotropic turbulence in media. In its most general form, the structural function is an averaged squared modulus of change in fluctuation component of a certain field considered at two different points in space. As to the atmosphere, it makes sense to talk about structural function of such fields as the air temperature field, the wind speed field e t.c. The value of the structural function calculated for two taken points in space located inside the inertial interval of turbulence, according to Kolmogorov-Obukhovs two-thirds law, turns out to be proportional to the distance between them (spatial interval) raised to the
power of 2/3. However, the coefficient of proportionality will be different for fields of different physical quantities. An analogue of structural function may also be introduced for the brightness temperature $T_b(\nu)$ observed at a fixed frequency $\nu$ [7]. One has to replace spatial intervals with temporal ones, which can be done on the basis of the frozen turbulence hypothesis and the assumption, that the drift velocity of inhomogeneities is much greater than the rate of change in their shapes. Let $l$ be the spatial interval, then, based on the Taylors hypothesis, $l = u_h \cdot \tau$, where $u_h$ is the horizontal component of wind speed and $\tau$ is the temporal interval. Let also the radiometers antenna occupy a fixed position throughout the entire observation time, then the structural function of brightness temperature can be written as

$$D_{T_b}(\nu, \tau) = \left\langle \left| T_b(\nu, t + \tau) - T_b(\nu, t) \right|^{2} \right\rangle,$$  

(1)

where $\nu$ is the radiation frequency, $l$ is the spatial interval, $\tau$ is the temporal interval, and $T_b(\nu, t)$ is the brightness temperature of radiation at frequency $\nu$ and at the certain moment of time $t$.

The square root of structural function (1) provides a native measure of the intensity of radiation fluctuations [7]

$$S_{\nu}(\tau) = \sqrt{D_{T_b}(\nu, \tau)}$$  

(2)

4. Clear sky

Consider a session of measurements of a stable summer clear sky in the absence of clouds and precipitation. Based on the data on brightness temperatures measured in August 23, 2019, from 18:30 to 20:30 Moscow time UTC+3 (near-surface air temperature $T_0 = 19.65^\circ C$, atmospheric pressure $P_0 = 755.66$ mmHg, absolute humidity $\rho_0 = 10.57$ g/m$^3$), calculations of the square root of structural functions $S_{\nu}(\tau)$ for temporal interval values $\tau = 33, 55, 99, 154$ sec. were performed. The values of $\tau$ are always multiples of the full spectrum acquisition time 11 sec.

In figure 1 the frequency spectra of $S_{\nu}(\tau)$ (curves 1-4) and the spectrum of water vapor attenuation coefficient $\gamma_{\rho}$ (curve 5) are shown for comparison. The $\gamma_{\rho} = \gamma_{\rho}(T_0, P_0, \rho_0)$ coefficient is calculated in accordance to the ITU P.676 recommendations.

From figure 1 one can see, that values of $S_{\nu}(\tau)$ (and hence the structural function itself) increase with enlargement of temporal interval $\tau$. The maximum of $S_{\nu}(\tau)$ is observed in the range of 22-24 GHz frequencies, that is, close to the resonance line of water vapor. On both sides of the maximum frequency, $S_{\nu}(\tau)$ decrease markedly. Note, that the shape of spectral curves

![Figure 1. Spectra of fluctuations in brightness temperature at temporal intervals $\tau = 33, 55, 99, 154$ sec. (left) and the frequency spectrum of water vapor attenuation coefficient $\gamma_{\rho}$ (right). Session on August 23, 2019, clear sky, 18-27.2 GHz.](image-url)
$S_{\nu}(\tau)$ reminds the spectrum shape of water vapor attenuation coefficient $\gamma_{\rho}$. This confirms the fact, that spatial and temporal variability of water vapor field causes fluctuations in the microwave emission of a cloudless atmosphere.

5. Cumulus clouds

In the presence of cloudiness, the intensity of fluctuations in brightness temperature is influenced not only by water vapor, but also by liquid water content in clouds [8]. Since the nature of absorption in water vapor and small drops of water is very different, both the spectra of brightness temperature and spectra of structural function undergo significant changes (comparing to the clear sky case). Clouds of vertical development or cumulus clouds with powerful flows of air masses are of the greatest interest here [9, 10].

Figure 2. Spectra of fluctuations in brightness temperature at temporal interval $\tau = 66$ sec. (curve 1 – clear sky, curve 2 – Cu Fra, curve 3 – Cu Hum, curve 4 – Cu Hum goes into Cu Med).

Figure 3. Spectra of fluctuations in brightness temperature (curve 5 – Cu Med, curve 6 – Cu Cong, curve 7 – Cb). Temporal interval $\tau = 66$ sec.

In figure 2, 3 the frequency spectra of square root of structural function $S_{\nu}(\tau)$ (curves 1-7) at temporal interval $\tau = 66$ sec. are shown. These spectra were obtained on the data of measurement sessions during which the cloudiness of one of the following types was observed: cumulus fractus (Cu Fra), cumulus humulis (Cu Hum), mediocris (Cu Med), congestus (Cu
Cong) and cumulonimbus (Cb). The spectrum of $S_\nu(\tau)$ for clear sky is shown for comparison (curve 1). During the observations of cumulonimbus (curve 7) non-zero precipitation was observed (8.25 mm/hour).

It is noticeable that clouds of greater vertical development have a greater effect on the intensity of fluctuations in brightness temperature. This is true for any value of temporal interval $\tau$. The resonance absorption line is visible in cases of clear sky, cumulus fractus and cumulus humulis. In cases of cumulus mediocris and cumulus congestus the maximum of structural function shifts toward the highest frequency of 27.2 GHz. The frequency spectrum of $S_\nu(\tau)$ for cumulonimbus clouds should be considered separately due to precipitation effects.

6. Structural functions and liquid water content in clouds

The two-frequency microwave radiometric method for determining the integral atmospheric moisture content parameters is described in [2]. This method allows one to estimate the values of total water vapor mass $Q$ and liquid water content in clouds $W$ from brightness temperatures measured at two frequencies. The method consists in solving a system of linear equations for unknown $Q$ and $W$.

$$\tilde{\gamma}(\nu_i) = \tilde{\gamma}_{O_2}(\nu_i) + k_p(\nu_i) \cdot Q + k_w(\nu_i, t_w) \cdot W, \quad i = 1, 2$$

where $\nu_i$ is the radiation frequency, $\tilde{\gamma}(\nu_i)$ is the total absorption of atmosphere, $\tilde{\gamma}_{O_2}(\nu_i)$ is the total absorption in oxygen, $k_p(\nu_i)$ and $k_w(\nu_i, t_w)$ – weight functions (see [2, 11]), $t_w$ is the effective cloud temperature. The total absorption $\tilde{\gamma}(\nu_i)$ can be estimated from the value of brightness temperature $T_\nu$, if $\tilde{\gamma}(\nu_i) \ll 1$ for $i = 1, 2$. The values of $\tilde{\gamma}_{O_2}(\nu_i)$ and $k_p(\nu_i)$ can be obtained by a model calculation (for example, according to ITU P.676 recommendations).

The time courses of total water vapor mass $Q$ and liquid water content in clouds $W$, as well as average, minimum and maximum (per session) values of these parameters were calculated for all measurement sessions performed under cumulus cloud cover. The set of frequency pairs $[21.4, 21.6, ..., 23.6] \times [26.4, 26.6, ..., 27.2]$ (60 combinations) was selected [12]. The required integral parameters were calculated for each pair of frequencies, and then the obtained values were averaged for each moment of time in order to achieve better accuracy.

In figure 4 the results of regression of square root of structural function $S_\nu(\tau)$ at $\nu = 18.0, 22.2$ and 27.2 GHz and at certain temporal interval $\tau = 99$ sec. versus maximum per session integral liquid water content in clouds $\langle W \rangle_{\text{max}}$ are shown under the following restrictions: 0.33
K < S_{22.2}(99) < 25 K, \langle W \rangle_{\text{max}} > 0.022 \text{ kg/m}^2. \text{ A relatively stable relationship between} \ \langle W \rangle_{\text{max}} \text{ and} \ S_{\nu}(99) \text{ is visible, both for} \ \nu = 22.2 \ \text{GHz and for other frequency channels. Thus, for example,} \ S_{22.2}(99) \approx 0.5591 + 5.6224 \cdot \langle W \rangle_{\text{max}}. \text{ When considering temporal intervals} \ \tau = 66 \text{ and 110 sec., one would notice the similar picture. At the same time, no similar relationships between} \ \langle W \rangle_{\text{max}} \text{ and brightness temperature} \ T_b(\nu) \text{ were detected.}

7. Conclusion
The new experimental data on fluctuations in downwelling radiation of atmosphere in the band of resonance absorption of water vapor 18–27.2 GHz were processed. Long-term observation sessions (ranging from 2 to 5 hours) were considered. It is shown that fluctuations in brightness temperature are caused by spatial and temporal variability of the water vapor field. In the absence of cloudiness (clear sky), the spectral curves of square root of structural function \ S_{\nu}(\tau) \text{ repeat the shape of the absorption spectrum in water vapor. In the case of cumulus clouds, a strong growth in the intensity of fluctuations is observed. If clouds have a powerful vertical development (large vertical extent), then the shape of} \ S_{\nu}(\tau) \text{ spectrum undergoes significant changes: the maximum of fluctuation intensity shifts toward the highest frequency of 27.2 GHz, which is associated with the absorption of radiation by small droplets of water. Experimental regression dependences of fluctuation intensity} \ S_{\nu}(\tau) \text{ at temporal intervals} \ \tau = 66, 99 \text{ and 110 sec. on the maximum of integral liquid water content in clouds} \langle W \rangle_{\text{max}} \text{ are obtained.}

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References
[1] Tatarksy V I 1967 Wave Propagation in a Turbulent Atmosphere (Moscow, Russia: Science Publ.)
[2] Kutuza B G, Danilychev M V and Yakovlev O I 2016 Satellite Monitoring of the Earth: Microwave Radiometry of Atmosphere and Surface (Moscow, Russia: Lenand Publ.)
[3] Gagarin S P and Kutuza B G 1976 The Influence of Fluctuations in the Atmospheric Thermal Radiation on the Sensitivity of a Radio Telescope Izv. Vuzov, Radiophysics vol 17 no 11 p 1636
[4] Gagarin S P and Kutuza B G 1977 Aircraft Measurements of Spatial Characteristics of Fluctuations in the Atmospheric Microwave Emission at 0.8 and 1.35 cm Izv. USSR Academy of Sciences, Atmospheric and Oceanic Physics vol 13 no 12 p 1307
[5] Danilychev M V, Kazaryan R A, Kalinkevich A A, Kutuza B G and Turgyin S Yu 2016 Ground-based Microwave Radiometer for Atmospheric Researches and Ensuring Ground Truth Experiments Proc. of ARMMIP-2016, Acoustooptic and Radar Methods for Information Measurements and Processing (Moscow, Russia) pp 203-207
[6] Egorov D P, Kutuza B G and Smirnov M T 2019 Web Portal for a Databank of Microwave Radiometric Measurements of the Atmosphere in Resonant Band of Water Vapor 18–27 GHz Proc. of PhotonIcs & Electromagnetics Research Symposium (PIERS-Spring) (Rome, Italy) pp 3421-3427
[7] Kutuza B G 2003 Spatial and Temporal Fluctuations of the Atmospheric Microwave Emission Radio Science vol 38 no 3 pp 12-1 – 12-7
[8] Akvilonova A B and Kutuza B G 1978 Cloud Thermal Radiation Soviet Journal of Communications Technology and Electronics vol 23 no 9 pp 1792-1806
[9] Basharinov A E, Kutuza B G 1968 Investigation of Radiation and Absorption of Cloudy Atmosphere in Microwave Range Bulletin of the American Meteorological Society vol 49 no 5 p 2
[10] Basharinov A E and Kutuza B G 1968 Studies of Radiation and Absorption of Cloudy Atmosphere in the Millimeter and Centimeter Ranges Proc. of Main Geophysical Observatory vol 222 pp 100-110
[11] Kutuza B G 1995 Spectral and Temperature Dependencies of the Millimeter and Centimeter Wave Absorption in Clouds Microwave Radiometry and Remote Sensing of the Environment ed D Solimini (VSP, Utrecht, Netherlands) pp 175-184
[12] Egorov D P and Kutuza B G 2019 On the Accuracy of Determining the Moisture Content During Microwave Radiometric Sensing of the Atmosphere in the Resonant Band of Water Vapor Attenuation 18–27 GHz Proc. of RWP-26, All-Russian Open Scientific Conference on Radiowave Propagation vol 2 (Kazan, Russia) pp 254-257.