

# Peculiarities of Stratospheric Temperature Stratification Measurements by the Microwave Radiometry Method<sup>1</sup>

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**Abstract**—In this paper, we consider the peculiarities of using the microwave radiometry method for remote sensing of the thermal stratification of the high layers of the atmosphere: the stratosphere and the lower mesosphere in comparison with other high-altitude layers, the troposphere and the atmospheric boundary layer. Such peculiarities are a special choice of spectral channels and bandwidths, the use of limb geometry of measurements along with the nadir in satellite instruments, as well as taking into account the influence of the Zeeman effect. Characteristics for first-generation satellite microwave sounders that measure temperature profiles up to an altitude of 30 km, as well as for more modern ground-based and satellite instruments, the sounding altitude of which reaches 50 km with a nadir-measurement geometry and 100 km with a limb one, are given. The results obtained in experiments with high-altitude balloons and using experimental setups for measuring the absorption coefficient of molecular oxygen at nearly 60 GHz are presented. The capabilities of ground-based instruments for microwave remote sensing of the stratosphere temperature and the results of complex comparisons are also analyzed.

**Keywords:** stratosphere, mesosphere, thermal stratification, microwave radiometry method

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## INTRODUCTION

Thermal stratification is a key parameter for describing a number of stratospheric processes (the thermal mode, circulation, waves, and stratospheric warming), analyzing the temperature-dependent characteristics of photochemical processes occurring in the ozone layer of the stratosphere, and making the impact estimate of volcanic eruptions on the climate of our planet [1, 2]. It is no coincidence that the most common is the stratification of the atmosphere according to the features of the thermal mode: the troposphere (0–16 km), stratosphere (16–55 km), mesosphere (55–85 km), thermosphere (85–400 km), and exosphere (above 400 km). Traditionally, the thermal stratification of the lower stratosphere has been measured using radiosondes (the maximal ascent is 30–40 km), while the upper stratosphere and mesosphere have been measured using meteorological rockets (with a maximal ascent of 100 km) [1]. However, the number of radiosondes produced in Russia has sharply decreased in recent years, and meteorological rockets have ceased to be used for 5 years already. This gave impetus to the development of remote methods for

monitoring the thermal stratification of the stratosphere using measurements in the optical (lidars), infrared (IR radiometers), and radio (microwave radiometers) wavelengths [3, 4]. In the radio range, two main methods for measuring the thermal stratification of the atmosphere are used: microwave radiometry and the radio-occultation method. In the radio-occultation method, the restoration of atmospheric thermal stratification is possible by measuring the phase and amplitude of radio signals emitted by a highly stable transmitter located on one satellite and received by a receiver located on another satellite [5]. The microwave radiometry method has specific requirements for sensing the thermal stratification of various layers of the atmosphere [4, 6, 7]. For example, ground-based instruments for measuring the temperature profiles of the atmospheric boundary layer mainly use single-channel instruments with elevation scanning [3, 8]. In this case, it is possible to use a wide bandwidth of up to 2 GHz and a frequency near the absorption center of molecular oxygen (60 GHz) [7–10]. In the troposphere, multichannel microwave radiometers are mainly used since it is necessary to take into account the radiation of water vapor and liquid water in clouds [3, 4, 11, 12]. This paper is devoted to the peculiarities of the construction of ground-based and satellite microwave radiometers for measuring the temperature profiles of the stratosphere and lower

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mesosphere in comparison with instruments for other high-altitude layers of the atmosphere (the troposphere and atmospheric-boundary layer) [3, 6, 13–15]. Such peculiarities take the form of a special choice of spectral channels and bandwidths and, taking into account the influence of the Zeeman effect, the use of our proposed so-called “convolution” of lines, which allows the measurement of temperature profiles from the tropopause to the stratopause. The accuracy of measuring or calculating the absorption coefficient of molecular oxygen on spectral lines near 60 GHz (the wavelength is 5 mm) affects the altitude range of measurements [16–18]. A brief history of the evolution of microwave instruments from the point of view of increasing the altitude of sounding to the stratosphere and mesosphere is given.

PHYSICAL BASES OF MEASUREMENTS  
OF TEMPERATURE PROFILES  
OF THE STRATOSPHERE  
IN THE MICROWAVE RANGE.  
ACCOUNTING FOR THE INFLUENCE  
OF THE ZEEMAN EFFECT

The microwave (MW) range is understood as the range of radio waves in the range from 3 to 300 GHz or wavelengths from 100 to 1 mm or 10 to 0.1 cm<sup>-1</sup>. Devices that measure this radiation are called “MW radiometers” [4, 19]. The possibility of measuring atmospheric temperature profiles by radiophysical methods is based on the propagation features of radio waves in the mm and cm ranges in the Earth’s atmosphere. The methods that allow using these features are called “passive radar,” “radio-thermal location,” “MW radiometry,” or “radio-thermal imaging” [3, 4]. A feature of the microwave radiation of the Earth’s atmosphere is the sensitivity of its characteristics to a large number of physicochemical parameters: temperature, humidity, cloud water content, pressure, gas composition, and turbulence parameters [4]. In comparison with the visible and IR ranges, the microwave method has a number of advantages in remote sensing of atmospheric thermal stratification: it is possible to perform sensing even in the presence of clouds; there is practically no the aerosol effect; sounding can be performed both at night and during the day. Although the intensity of atmospheric radiation in the microwave range is 10<sup>5</sup> times lower than in the IR, microwave equipment has a much higher spectral resolution (about 5000 times) [4]. Sounding is based on the receiving of molecular oxygen radiation, which has a high concentration in the atmosphere (21%) and the highest stability of the O<sub>2</sub> percentage up to the upper boundary of the mesosphere. This possibility was first substantiated in [6]. Absorption by molecular oxygen in the microwave range appears as individual lines or bands of a simple structure, and so the calculation of absorption functions is simpler than that in the IR range. The oxygen molecule does not have an electric-

dipole moment (unlike the water-vapor molecule), but has a permanent magnetic moment. The change in the orientation of the electron spin of the O<sub>2</sub> molecule with respect to the vector of the rotation moment of the molecule forms a series of spectral lines (48) in the region of 60 GHz (the wavelength is 5 mm) and a single line at 118.7505 GHz (2.53 mm) [3, 6]. The presence of such a large number of spectral lines allows choosing the most optimal frequencies for measuring the thermal stratification of the stratosphere. By selecting the appropriate measurement frequencies for microwave radiation, it is possible to measure the intensity of radiation generated by various atmospheric layers. Unfortunately, there is no direct relation between radiation and temperature at some fixed altitude, since radiation for a given frequency is generated in a sufficiently extended layer of the atmosphere. In this regard, remote methods are inferior to contact methods (radiosonde and meteorocket) in vertical resolution. The higher the layers to be measured, the narrower must be the bandwidths of the corresponding channels of the radiometer [6]. For example, in microwave profilers, to measure the temperature profiles of the atmospheric boundary layer, single-channel microwave radiometers scanning in the elevation angle with a bandwidth of up to a few gigahertz are used; for sounding the thermal stratification of the troposphere, multichannel radiometers with a bandwidth of hundreds of megahertz are used; and for the stratosphere, multichannel radiometers with a bandwidth of units of megahertz and even less are used [3]. An important parameter for increasing the sounding height to stratospheric altitudes is also the accuracy of calculating the O<sub>2</sub> absorption coefficient for the corresponding frequencies [3, 6]. Unlike the IR range, when calculating radiation in the radio range, it is possible to use not the Planck formula, but its long-wave approximation (the Rayleigh–Jeans formula), which simplifies the calculations [4]:

$$I(\nu, T) = 2k_{\text{B}}T \left( \frac{\nu}{c} \right)^2, \quad (1)$$

where  $I(\nu, T)$  is the radiation intensity,  $\nu$  is the radiation frequency,  $T$  is the thermodynamic temperature,  $k_{\text{B}}$  is the Boltzmann constant ( $k_{\text{B}} = 1.38066 \times 10^{-23}$  J/K), and  $c$  is the speed of light.

Therefore, the intensity of blackbody radiation in the microwave range is directly proportional to temperature. In this case, the concept of radio-brightness (radiation) temperature  $T_{\text{b}}$ , which is defined as the temperature of such an absolute black body, the radiation intensity of which is equal to  $I$  at frequency  $\nu$ , is introduced [4]. The calculations used in data processing are based on the well-known equation of microwave radiation transfer in the atmosphere, from which equations are obtained for radio-brightness temperatures measured both from the Earth’s surface and from satellites [4]. Usually, so-called “direct” and “inverse”

problems are distinguished [3, 4]. The calculation of the radiation intensity or other quantitative characteristics of the radiation field using specified absorption functions and known distributions of atmospheric state parameters is called a “direct problem.” The inverse problem is understood as a cycle of problems consisting in determining the distributions of meteorological parameters of the atmosphere, for example, temperature [18], using the specified absorption characteristics of atmospheric gases and the measured radiation characteristics.

The equation for radio-brightness temperature in the case of measuring the downward microwave radiation of molecular oxygen in the atmosphere (from the Earth’s surface) can be written as follows [4]:

$$T_b = \frac{1}{\cos \theta} \int_0^\infty T(h) \gamma_v(h) \times \exp\left(-\frac{1}{\cos \theta} \int_0^h \gamma_v(h') dh'\right) dh + T_{\text{bkg}} \exp\left(-\frac{\tau_0}{\cos \theta}\right), \quad (2)$$

where  $\gamma(h)$  is the absorption coefficient at the corresponding frequency,  $h$  is the altitude,  $\theta$  is the angle of deviation from the nadir,  $T(h)$  is the required thermodynamic temperature profile, and  $T_{\text{bkg}}$  is the temperature of the cosmic-background radiation (2.7 K). In the case of measuring the upward radiation of the stratosphere from a satellite, the expression has the following form [4, 6]:

$$T_b(v, \theta) = \varepsilon T_r \exp\left(-\frac{2\tau_0}{\cos \theta}\right) + (1 - \varepsilon) T_s \exp\left(-\frac{\tau_0}{\cos \theta}\right) + \left[\varepsilon \exp\left(-\frac{\tau_0}{\cos \theta}\right)\right] \times \frac{1}{\cos \theta} \int_0^\infty T(h) \gamma(h) \exp\left[-\frac{1}{\cos \theta} \int_0^h \gamma(h') dh'\right] dh + \frac{1}{\cos \theta} \int_0^\infty T(h) \gamma(h) \exp\left[-\frac{1}{\cos \theta} \int_h^\infty \gamma(h') dh'\right] dh, \quad (3)$$

where  $\varepsilon$  is the surface emissivity,  $T_s$  is the surface temperature,  $\tau_0 = \int_0^\infty \gamma(h) dh$  is the optical thickness of the atmosphere, and  $\varepsilon T_r$  is the radiation reflected from the Earth.

The first three terms of this equation are very insignificant [4]. The fourth term of Eq. (3) characterizes the upward radiation of the atmosphere, which will be recorded by a satellite device. Therefore, with minimal assumptions for satellite measurements, Eq. (3) can be written as follows [3, 4, 6]:

$$T_b(v, \theta) = \frac{1}{\cos \theta} \times \int_0^\infty T(h) \gamma(h) \left[ \exp\left(-\frac{1}{\cos \theta} \int_h^\infty \gamma(h') dh'\right) \right] dh. \quad (4)$$

A microwave radiometer actually measures not the radio-brightness temperature, but the so-called “antenna temperature,” which is measured in voltage units [19]. The radio-brightness temperature in Kelvin degrees is obtained through calibrations. To put it in a simplified way, in the case of measuring the thermal stratification of the stratosphere from a satellite, the radiometer antenna is pointed into outer space (“cold” spot,” 2.7 K), and at a microwave target (“hot spot,” usually 300 K). By connecting these two points, we obtain a straight line, along which the antenna temperatures are converted into radio-brightness ones. In fact, calibration is one of the most complex and critical aspects of radiometric measurements [19]. If losses in the antenna-feeder path are neglected, then the sensitivity of a microwave radiometer, which is one of its main characteristics, is usually expressed in Kelvin degrees and is written as follows [19]:

$$\Delta T = k \frac{T_n + T_{\text{atm}}}{\sqrt{\Delta f \tau}}, \quad (5)$$

where  $k$  is a coefficient depending on the type of the radiometer circuit ( $k = 0.7-1.0$ ),  $T_n$  is the intrinsic noise temperature of the radiometer,  $T_{\text{atm}}$  is the ambient temperature ( $T \approx 300$  K),  $\Delta f$  is the bandwidth of the radiometer, and  $\tau$  is the time constant.

This seemingly simple formula shows ways to improve the quality of measurements by improving the radiometer circuit (low-noise microwave amplifiers have appeared up to frequencies of 100 GHz, which allows using direct amplification receivers with the lowest possible noise characteristics, on the order of 200 K, for measurements in the stratosphere). However, at the same time, the bandwidth must be of the order of only 1 MHz and even less, which is provided by current multichannel microwave filters with minimal losses. For ground-based measurements of the stratosphere temperature, the integration time increases up to 1–2 h (which is impossible for stratospheric satellite measurements, where it is 1–2 s [6, 15]). In addition, we proposed another way related to taking into account the features of absorption in the stratosphere, where individual spectral lines do not actually overlap [20]. In this case, the addition of two closely spaced absorption lines of approximately equal amplitude and shape is possible. There are several such doublets of absorption lines in the molecular oxygen spectrum near 60 GHz, for example, lines with transition numbers  $7^+$  and  $9^+$ ,  $15^+$  and  $17^+$  (Fig. 1) When probing the temperature profiles of the atmosphere in microwave oxygen absorption bands, function (5) has the form of an inte-

gral Fredholm equation of the first kind and is generally written as follows [6]:

$$T_b = (\Theta, \nu) = \int_0^H K(h, \nu) T(h) dh + \Delta(\Theta, \nu), \quad (6)$$

where  $K(h, \nu)$  is the kernel of the integral equation and  $T(h)$  is the desired solution.

As can be seen, the desired parameter is under the integral; this is a classical inverse problem that has only approximate solutions. There are several methods for solving this kind of problems: statistical regularization, using basis functions, using least-squares regression, Tikhonov regularization, the nonlinear iterative method, Shahin’s method, the regression method, the neural-network method, etc. [3, 4]. We mainly use the statistical regularization method. The neural-network method is ideally good with current stratospheric and mesospheric rocket-sounding data. However, now there are practically none and only radiosonde data (lower stratosphere) can be used. There are also various models for calculating the  $O_2$  absorption coefficient in the microwave range: Van Vleck–Weisskopf, Lorentz, Gross, Gordon, Zhevakin–Naumov, Kalmikov–Titov, Blio–Konst, Bhatnagar–Gross–Krook, Liebe, Lam, and Rosenkranz [3]. There are also experimental data. However, in connection with the problem of increasing the accuracy of determining temperature at stratospheric and mesospheric altitudes, much attention is currently paid to improving calculation models and obtaining more accurate experimental data. The Rosenkranz formula is currently most widely used [16, 17]. It is attractive due to its relative simplicity and rather high degree of agreement with the results of experimental measurements. The Rosenkranz model considers a first-order approximation that takes into account only the bonds between adjacent rotational states, which corresponds to the case in which the states of oxygen molecules are weakly coupled in most collisions. Mathematically, this is expressed in the fact that only the diagonal and near-diagonal elements in the interaction matrix are not equal to zero. According to Rosenkranz, the expression for the  $O_2$  absorption coefficient is written as follows [16]:

$$\gamma(\nu, T, P) = 0.330P^2 \frac{\nu^2}{T^2} \left\{ \sum_N \Phi_N [f_N^+(\nu) + f_N^+(-\nu) + f_N^-(\nu) + f_N^-(-\nu)] + \frac{0.70W_B}{\nu^2 + (PW_B)^2} \right\}, \quad (7)$$

with dimensions  $[\gamma] = \left[ \frac{H_s}{\text{km}} \right]$ ,  $[P] = [\text{mbar}]$ , and  $[T] = [\text{K}]$ .

In (7), quantum transitions with  $N = 1–39$  are taken into account,  $\nu$  is the radiation frequency,  $\Phi_N$  is the probability of population of the  $N$ th rotational level of the molecule,  $f_N^\pm(\pm\nu)$  is the shape factor of the  $O_2$  emission line, and  $W_B$  is the width of nonresonant

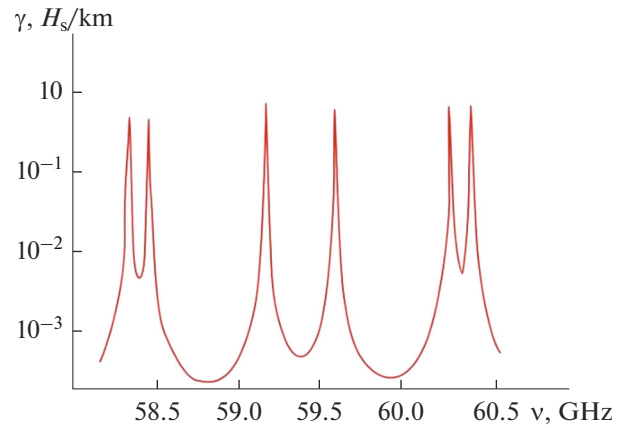


Fig. 1. Frequency dependence of the absorption coefficient of molecular oxygen that we calculated using the Rosenkranz method at  $H = 40$  km for the upper atmosphere model at  $15^\circ$  N.

absorption lines. The absorption also depends on the polarization of the radiation.

We set a specific task: to measure the  $O_2$  absorption coefficient by the direct spectrometric method at low pressures of 0.1–10 mm Hg in the frequency range of 54–65 GHz used in thermal sounding of the atmosphere and compare the obtained data with the results of Rosenkranz’s theoretical calculations and Liebe’s experimental data [21–23]. The experimental setup developed jointly with employees of RPA Etalon (Irkutsk) allowed measuring the shape of each spectral line [21]. The  $O_2$  absorption intensity at low pressures was determined by measuring the attenuation of microwave radiation in the waveguide cell. The setup for measuring the absorption coefficient was assembled according to the scheme of a microwave spectrometer with molecular modulation and with a microwave receiver [21]. For molecular modulation, the Zeeman effect is used: an alternating magnetic field acts on the analyzed gas in the cell. In addition, the signal is recorded at the modulation frequency. The sensitivity of the setup is 0.01  $H_s/\text{km}$ , and the relative measurement error is 15%. Some results are presented in Table 1. Sufficiently good agreement with the results of calculations using the Rosenkranz formula [22] was obtained. It should be noted that our results obtained both in terms of conducting an experiment with a high-altitude balloon and in terms of experimental measurements of the  $O_2$  absorption coefficient and our invention on the use of convolution of spectral lines remain relevant and are reflected in current devices for microwave sounding of thermal stratification of the stratosphere.

Unlike the troposphere, it is necessary to take into account the influence of the Zeeman effect when measuring the thermal stratification of the stratosphere. Due to the presence of a magnetic-dipole

**Table 1.** Values of the O<sub>2</sub> absorption coefficient at the resonant frequencies of lines with quantum numbers 1<sup>+</sup>–23<sup>+</sup> and 3<sup>–</sup>–23<sup>–</sup>

Line quantum number	Resonance frequency, MHz	Calculations based on the Rosenkranz model, H <sub>s</sub> /km	Liebe measurement data, H <sub>s</sub> /km	Our measurement data, H <sub>s</sub> /km
1 <sup>+</sup>	56265	0.52	0.37	0.47
3 <sup>+</sup>	58447	1.42	1.15	1.20
5 <sup>+</sup>	59591	2.08	1.80	1.70
7 <sup>+</sup>	60435	2.45	2.21	2.67
9 <sup>+</sup>	61151	2.51	2.34	2.18
11 <sup>+</sup>	61800	2.32	2.22	2.39
13 <sup>+</sup>	62411	1.96	1.94	1.99
15 <sup>+</sup>	62998	1.53	1.55	1.03
17 <sup>+</sup>	63569	1.10	1.15	0.85
19 <sup>+</sup>	64128	0.75	0.79	0.77
21 <sup>+</sup>	64679	0.47	0.52	0.61
23 <sup>+</sup>	65224	0.28	0.31	0.27
3 <sup>–</sup>	62486	1.60	1.26	1.54
5 <sup>–</sup>	60306	2.12	1.81	1.67
7 <sup>–</sup>	59164	2.35	2.08	1.83
9 <sup>–</sup>	58324	2.28	2.10	1.80
11 <sup>–</sup>	57612	2.01	1.92	1.83
13 <sup>–</sup>	56968	1.63	1.59	1.77
15 <sup>–</sup>	56363	1.22	1.24	1.14
17 <sup>–</sup>	55784	0.85	0.88	0.80
19 <sup>–</sup>	55221	0.55	0.59	0.52

moment in the O<sub>2</sub> molecule, the absorption lines under the effect of the Earth's magnetic field will be split into separate components due to the Zeeman effect, which begins to manifest itself at altitudes above 40–45 km [24]. Under the effect of the Earth's magnetic field (~0.5 G), individual absorption lines experience splitting: each N<sup>±</sup> line splits into 3(2 + 1) Zeeman components. Each of these components is characterized by number M<sub>J</sub> (the projection of the total moment onto the direction of external field H or the magnetic quantum number). The energy of this splitting for the O<sub>2</sub> molecule can be written as follows [24]:

$$\Delta W^Z(N, J) = \mu_B H \frac{N(N+1) - J(J+1) - 2}{J(J+1)} M_J, \quad (8)$$

where μ<sub>B</sub> is the Bohr magneton equal to 0.92712013 × 10<sup>-20</sup> erg/G and J is the line intensity.

Then, the Zeeman frequency shift will be equal to [24]

$$\Delta \nu^3 = \frac{\Delta W_{J+1} - \Delta W_J}{h}. \quad (9)$$

Taking into account the influence of the Zeeman effect, an accurate choice of operating frequencies and the type of polarization can raise the altitude of temperature sounding by microwave nadir satellite sounders up to 70 km.

#### USE OF HIGH-ALTITUDE BALLOONS FOR TESTING THE METHOD OF SATELLITE MEASUREMENTS

The first attempt to measure the temperature of the stratosphere with a microwave radiometer was made in 1966 in the United States by installing it onboard a balloon with a lifting altitude of 30–35 km [25]. The radiometer had a noise temperature of about 15000 K, measured radiation at the 9+ line frequency (61.151 GHz), and had three channels with bandwidths from 200 to 20 MHz. The measured radio-brightness temperatures were compared with the calculated ones, and the discrepancies were 3°–8°. The experiment confirmed the possibility of measuring the thermal stratification of the atmosphere by measuring the upward radiation

in the region of 60 GHz. In 1989, we continued further studies of the possibility of measuring the thermal stratification of the stratosphere by this method [26–29]. The installation of a microwave radiometer on a high-altitude balloon provides a unique opportunity to work out the method of stratospheric measurements and to choose the optimal frequencies of the measuring channels. Unlike a satellite, the high-altitude balloon is equipped with high-precision contact temperature sensors, which provides a unique opportunity to compare the results of contact and remote measurements in all phases of flight ascent, drift at an altitude of ~40 km, and descent. In this case, at the beginning of the ascent, the data coincide, and, as the altitude of the maximal weight function of the corresponding radiometer channel is reached, the data of this channel remain unchanged during further ascent, unlike contact sensors, which confirms the correctness of the theory of remote measurements. Together with specialists from the Space Research Institute of the Russian Academy of Sciences, we performed three launches of a high-altitude balloon (with a ceiling of 40 km) at the field experimental base of the Central Aerological Observatory (Rylsk, Kursk oblast) in 1989–1990. The microwave radiometer was installed in a special container, the information was transmitted via a radio telemetry line, and coordinate tracking was carried out by a radar. Characteristics of the microwave radiometer: six measuring channels with bandwidths from 3 to 250 MHz and sensitivities from 0.65 to 0.09 K with an integration time constant of 1 s. The effective noise temperature of the radiometer is 850 K; a convolution of two O<sub>2</sub> spectral lines of 11<sup>-</sup> (57.6125 GHz) and 9<sup>+</sup> (61.1506 GHz) was used. The measurements were carried out in the nadir, and in one run, they were carried out in the horizon, which made it possible to measure the O<sub>2</sub> absorption coefficient in the real atmosphere in an original way (some results are presented in Table 2) [27, 28]. The first domestic satellite microwave sounder, MTVZA, launched in 2001 to measure the thermal stratification of the lower stratosphere had temperature channels with approximately the same main characteristics [14].

#### SATELLITE MICROWAVE INSTRUMENTS FOR MEASURING THE THERMAL STRATIFICATION OF THE STRATOSPHERE AND MESOSPHERE

##### *Instruments with Nadir Measurement Geometry*

The advent of artificial Earth satellites has opened up new possibilities for measuring the temperature of the atmosphere using microwave radiometers. From the satellite, it is possible to obtain global patterns of temperature fields. Measurements from outside the atmosphere also allowed to get rid of the strong influence of the variable radiation of the lower layer, i.e., the troposphere. The first satellite microwave instru-

**Table 2.** Comparison of the values of absorption coefficient  $\gamma_{\text{air}}$  obtained from the balloon experiment data with the values calculated using the Rosenkranz model

Channel	Altitude, km	$\gamma_{\text{air}}, H_s/\text{km}$	$\gamma_{\text{theory}}, H_s/\text{km}$	$\Delta\gamma/\gamma, \%$
4	25	0.385	0.402	4
5	21	0.307	0.330	7
6	19	0.221	0.234	6

ment that made it possible to measure the temperature of the atmosphere was the NEMS instrument installed on the *Nimbus-5* satellite in 1972 [15]. It consisted of five Dicke superheterodyne receivers at fixed frequencies: 22.235, 31.4, 53.65, 55.9, and 58.8 GHz [3, 15]. The first two channels were intended for measuring the concentration of water vapor, and the other three channels were intended for temperature sounding. The device was not scanning. Its further development was the SCAMS instrument launched in 1975 on the *Nimbus-6* satellite. Unlike NEMS, this device had a scanner, which significantly increased the field of view and, consequently, the horizontal resolution. The first satellite radiometer intended only for temperature measurement was the microwave sounding unit (MSU) radiometer [3, 15] developed for the TIROS-N/NOAA system of operational meteorological Earth satellites. The MSU instrument was first launched in 1979 on the *NOAA-6* satellite. The instrument provided independent information on the atmospheric temperature in the altitude range of 0–25 km. Measurements are carried out in four spectral channels at 50.30, 53.74, and 57.95 MHz. Almost simultaneously with the development of the MSU, the United States created the sounder system microwave temperature (SSM/T) satellite device designed to operate on military meteorological satellites of the defense meteorological satellite program (DMSP) system [15]. This is a seven-channel radiometer that measures the temperature of the atmosphere in the altitude range of 0–30 km under any weather conditions. It was first launched on the Block-5D satellite in 1979. A serious breakthrough in the field of satellite sounding of the thermal stratification of the atmosphere, including the stratosphere, was the creation of the AMSU microwave sounder. Table 3 presents the main characteristics of the first microwave instruments for measuring the thermal stratification of the atmosphere [3]. Particular interest is presented by the consideration of the measuring channels of the AMSU instrument (Table 4) [15]. Channels 1 and 2 are designed to estimate the total content of water vapor and the water content of clouds (mainly over the oceans). Channel 3 is designed to measure the temperature of the Earth's surface. Channels 4–8 are for measuring temperature profiles of the

**Table 3.** Microwave satellite instruments for remote thermal sensing of the atmosphere (nadir measurement geometry)

Characteristic	Characteristic values				
	NEMS	SCAMS	MSU	SSM/T	AMSU
Total number of channels	5	5	4	7	20
Number of temperature-sounding channels	3	3	47	7	12
Frequency range, GHz	53.7–58.8	52.9–55.5	50.3–55.5	50.5–59.4	50.3–57.6
Bandwidth, MHz	100	100	200	115–400	3–400
Reduced sensitivity, K	0.4	0.4	0.25	0.4–0.6	0.25–1.2
Antenna RP width	10°	10°	7.5°	11°	3.3°
Scanning	–	±40°	±47.35°	±36°	±40°
Altitude range	0–20	0–20	0–25	0–30	0–38
Satellite	Nimbus5	Nimbus6	NOAA6	DMSP	ATN

**Table 4.** AMSU: basic characteristics of all channels

Channel number	Center frequency, GHz	Number of used bands	Bandwidth, MHz	Reduced sensitivity, K	Central frequency stability, MHz	Absolute calibration error, K
1	23.800	1	380	0.3	10	2.0
2	31.400	1	180	0.3	10	2.0
3	50.300	1	200	0.35	10	1.5
4	52.800	1	400	0.25	5	1.5
5	53.330	1	400	0.25	5	1.5
6	54.400	1	400	0.25	5	1.5
7	54.940	1	400	0.25	5	1.5
8	55.500	1	400	0.25	10	1.5
9	57.290344 = $f_{10}$	1	330	0.25	0.5	1.5
10	$f_{10} \pm 0.217$	2	78	0.4	0.5	1.5
11	$f_{10} \pm 0.3222$ $f_{10} \pm 0.48$	4	36	0.4	0.5	1.5
12	$f_{10} \pm 0.3222$ $f_{10} \pm 0.22$	4	16	0.6	0.5	1.5
13	$f_{10} \pm 0.3222$ $f_{10} \pm 0.10$	4	8	0.80	0.5	1.5
14	$f_{10} \pm 0.3222$ $f_{10} \pm 4.5$	4	3	1.20	0.5	1.5
15	89.0	1	6000	0.5	50	2.0
16	89.0	1	6000	0.60	50	2.0
17	166.0	1	4000	0.60	50	2.0
18	183.31 ± 1.00	2	1000	0.8	30	2.0
19	183.31 ± 3.00	2	2000	0.8	30	2.0
20	183.31 ± 7.00	2	4000	0.8	30	2.0

troposphere and lower stratosphere, channels 9–14 are for measuring temperature profiles in the altitude range of 20–38 km, channels 15–17 are for observing land and oceans, and channels 18–20 are for measuring water-vapor profiles in the troposphere. In addition, a whole galaxy of ultramodern hyperspectral satellite devices appeared. We list them briefly: ATMS (22 channels in the frequency range from 23 to 183 GHz for the JPSS satellite series—JPSS-1 (2011), JPSS-2 (2021), JPSS-3 (2026), and JPSS-4 (2031) [3, 15]. On the Aqua satellite (2002) (United States, Japan, Brazil), besides the unique infrared instrument AIRS (having 2378 spectral channels), AMSU-A1 and AMSU-2 modernized microwave sounders are installed. To reconstruct temperature and humidity profiles, as well as measure cloudiness and precipitation, ATMS uses measurements in 22 operating bands with spaced bandwidths and frequencies with 38 channels allocated in the operating band from 23 to 184 GHz. A further development concerning U.S. military meteorological satellites (DMSP) is the SSMIS onboard instrument, which overrides the capabilities of all previous sounders. In particular, it includes channels with frequencies in the range of 60–64 GHz with narrow bands (0.8–2.7 MHz) that provide measurement of profiles of stratospheric temperatures in the altitude range of 15–55 km. A hyperspectral microwave device using an antenna array was developed on U.S. geostationary satellites in the framework of the GeOMAS project. It has 72 frequency channels near a separate O<sub>2</sub> spectral line (118.75 GHz). Another new U.S. project (STAR) involves the creation of a 900-channel microwave device (of which 300 channels are near the maximal absorption frequency of molecular oxygen at 60 GHz) [3, 14, 15]. It is also planned to develop a large number of microwave satellite devices in the EU countries, as well as in Japan and China. In Russia, the most modern microwave satellite instrument for measuring atmospheric thermal stratification is the MTVZA-GYa instrument installed on the *Meteor-M-2-2* satellite, which is not inferior in its characteristics to the AMSU instrument. It is also planned to develop a more modern device, MTVZA-MN (2024) [3, 14].

#### *Instruments with Limb Measurement Geometry*

The need to use limb geometry of measurements, i.e., scanning across the limb of the atmosphere perpendicular to the satellite's velocity vector (in the foreign literature, "field-of-view" (FOV)), is due to the fact that the concentration of molecular oxygen in the stratosphere is significantly lower than that in the troposphere, and, to increase the intensity of the received signal, the amount of absorbing substance along the measurement path increases due to this measurement geometry [30]. From the point of view of creating such measuring complexes, namely, satellite–instrument ones, limb geometry leads to a significant complication and hence an increase in cost.

The radio-brightness temperature measured from the satellite in the limb mode can be expressed by the formula [30]

$$T_b(\nu, h_t) = T_{bs} e^{-\tau_\nu(-\infty, \infty)} + \int_{-\infty}^{\infty} T(s) k_\nu(s) e^{-\tau_\nu(-s, \infty)} ds, \quad (10)$$

where  $T_{bs} = 2.7$  K is the brightness temperature of space,  $T(s)$  is the temperature of the atmosphere at a point at distance  $s$  from the aiming point,  $k_\nu(s)$  is the absorption coefficient, and  $\tau_\nu(s, \infty)$  is the optical depth between specified point  $s$  and the satellite position.

The first microwave limb sounder (MLS) was launched on a special heavy geophysical satellite upper-air research satellite (UARS) [30]. The launch took place on September 12, 1991, the weight of the satellite was 6540 kg, and the orbit altitude was about 600 km. The satellite was in orbit until 2005 and had a Sun-synchronous orbit with an apogee of 575 km and a perigee of 574 km. The device was mainly developed for the analysis of minor gas components (MGCs) of the free atmosphere, which affect the Earth's ozone layer [30]. The temperature profiles of the stratosphere and mesosphere were also measured. For this purpose, a channel at 61 GHz was used. The opening of the antenna scanning along the limb of the atmosphere was 1.6 m, which provided a vertical resolution of 6 km and a horizontal resolution of 15 km in terms of atmospheric temperature profiles. The altitude range of temperature profiles: 20–100 km. Certainly, for such characteristics, an onboard spectrum analyzer was used in the MGS measurements. The successor of the UARS-MLS instrument was the more advanced MLS limb instrument, which was launched on July 15, 2004, on the *Aura* (air) satellite of the Earth-Observing System (EOS) mission. Usually, this instrument is referred to as the EOS MLS (unlike UARS MLS) [3, 15, 30]. The EOS MLS device had three measuring modules: the "GHz" module included an antenna with a mirror diameter of 1.6 m, calibration targets, a scanning system, an optical multiplexer, and radiometers at 118, 190, 240, and 640 GHz. The "TGz" module included a special THz scanner, an antenna and a switching mirror, a telescope, and a 2.5-THz radiometer with two polarizations. The "Spectrometer" module included spectrum analyzers, a data-acquisition and control system, and power supplies. The satellite was in a Sun-synchronous orbit with an altitude of 705 km, and the weight of the satellite was 2970 kg. In addition to the temperature and geopotential profiles in the altitude range of 20–100 km, the EOS MLS instrument measured the following MGCs in the atmosphere: OH, HO<sub>2</sub>, H<sub>2</sub>O, O<sub>3</sub>, HCL, CLO, HOCl, BrO, HNO<sub>3</sub>, N<sub>2</sub>O, CO, HCN, CH<sub>3</sub>CH, volcanic SO<sub>2</sub>, and ice particles. In total, the instrument includes 29 spectrometers: 19 Standard, 5-Midband, 4-DAC, and 1 spectrometer in Wide. The vertical reso-



lution of the temperature profiles is 5.8 km, and the horizontal resolution is 12 km [23], although some data on the Internet give the vertical resolution as 2.5 km.

### MEASUREMENT OF STRATOSPHERIC TEMPERATURE PROFILES WITH GROUND-BASED MICROWAVE SPECTRORADIOMETERS

If measurements are performed from the Earth's surface in narrow bands near the resonant frequencies of O<sub>2</sub> absorption in the range of 52–54, then having a high sensitivity (due to the long signal accumulation time of ~1 h or more), it is possible to measure the increase in radio-brightness temperatures of individual lines over the general absorption background and reconstruct the temperature profiles of the stratosphere. Such unique measurements were first described in [31]. The measurements were performed near resonant frequencies of 54.130, 53.596, 53.067, 52.542, and 52.021 GHz. The radiometer had a noise temperature of 1800 K, a spectral resolution of 0.16 MHz, and a local oscillator frequency stability of 0.01 MHz. Temperature profiles were obtained in the altitude range of 20–70 km with a vertical resolution of 20–30 km.

A microwave measuring complex for measuring the temperature profiles of the stratosphere from the Earth's surface was developed at the Institute of Applied Physics, Russian Academy of Sciences (Nizhny Novgorod), in 2010 with a partial upgrade in 2017 [32]. The substantiation for the need to create such an instrument was the fact that satellite instruments do not provide continuous data acquisition over a region with a diameter of 10–100 km, which is necessary for studying fast local processes. The heterodyne receiver with a microwave amplifier at the input, the frequency of the local oscillator is 52.39709 GHz, and the noise temperature of the receiver is 1400 K [32]. An AC 240 Acquiris spectrum analyzer operating with the fast Fourier transform mode is used. It has 16384 spectral channels in the 1-GHz band with a frequency resolution of 61.04 kHz. Two spectral lines of molecular oxygen at 52.542 and 53.066 GHz are used. Of foreign instruments, there is the TEMPERA instrument, which measures the temperature profiles of both the troposphere and the stratosphere [33]. It provides two blocks of filters: the first tropospheric one for the wings of the lines and the second stratospheric one for the central part of the lines. An Acquiris AC 240 Fourier digital spectrometer (Fourier transform spectrometer) is also used. Measurements on two spectral lines of molecular oxygen (52.5424 and 53.0669 GHz) are used. The analysis bandwidth is 960 MHz, and the resolution is 30.5 kHz. The noise temperature of the receiver is 480 K. The range of stratospheric altitudes is 20–50 km. The antenna is a scalar horn and a parabolic reflector. The half-power beamwidth is 4°. Stratospheric measurements were performed at an ele-

vation angle of 60°. The spectrum-analyzer integration time is 15 s. Data are integrated in half an hour or an hour [33]. The absorption coefficient of molecular oxygen is calculated according to the Rosenkrantz method [16, 17], and the temperature profiles are reconstructed according to the Rogers method [3].

### RESULTS OF COMPARISONS OF DATA FROM COMPLEX MEASUREMENTS OF THERMAL STRATIFICATION OF THE STRATOSPHERE

From January 2014 to September 2016, international comparisons of various instruments for measuring stratospheric temperature profiles were carried out at the Payerne aerological station (Switzerland) [3]. Comparisons involved the TEMPERA instrument, the microwave limb sounder (MLS) limb satellite instrument operating onboard the *Aura* satellite ("Air") (118-GHz channel data), and the Rayleigh stratospheric lidar at the Hohenpeißenberg station (Germany, 400 km from the aerological station) with only night data. Over 2 years, 192 stratospheric temperature profiles were compared in the altitude range of 20–50 km. In this case, the discrepancies with MLS were  $2.4 \pm 0.6$  K at the bottom of the altitude range and  $2.0 \pm 0.4$  K at the top of the altitude range. The discrepancies with the lidar data were  $2.3 \pm 0.9$  K at altitudes above 35 km and  $3.2 \pm 1.1$  K below this altitude, which is explained by the parasitic effect of aerosol on the lidar data at lower altitudes. Besides, the TEMPERA data were compared with the data of the SD-WACCM global climate model (this is part of the Community Earth System Model), and the discrepancies were from 1.7 to 4.7 K [3].

### CONCLUSIONS

Over the past 10–20 years, alongside the rather rapid development in the 21st century of ground-based and satellite remote instruments for measuring the thermal stratification of the troposphere, a clear trend became observed towards the development of methods and instruments in the radio range for measuring temperature profiles in high layers: the stratosphere and mesosphere. This is due both to the need to control the state of the Earth's ozone layer and to the possible impact of these layers on global climate change, including control of the effects of volcanic eruptions and, possibly, greenhouse gases on the state of the high layers of the atmosphere. At present, there is some warming in the temperature of the troposphere and some cooling of the middle and lower layers of the stratosphere, which also require further monitoring and research. Current satellite microwave temperature sounders with nadir measurement geometry already reach altitudes of ~50–60 km and with limb geometry reach altitudes of 90–100 km, while ground-based spectroradiometers can provide local continuous data

on the dynamics of temperature stratification of the stratosphere. Radio-occultation instruments also allow tracking various wave processes [5]. It is also very useful to compare data from satellite instruments with ground-based microwave radiometers, stratospheric lidars, and climate models.

#### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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