Cross-calibration of ground-based measurement of rotational temperature of OH(3-1) at altitude ~87 km in Maimaga (63° N, λ = 129.5° E) and SABER/TIMED satellite data

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Abstract. Maimaga (63° N, λ = 129.5° E) is a base point in the meridional station network that we create in East Siberia to monitor changes in the upper mesosphere. Therefore, the comparison of measurements obtained by ground-based instruments and satellite data are relevant. It is known that the rotational temperature of hydroxyl (OH) corresponds to the temperature of the neutral atmosphere at the height of its radiation (~87 km). The night spectrum of OH(3-1) is measured by a new Shamrock 303i spectrograph since January 2013. The rotational temperature, estimated from the ratio of the P - branches, is compared with the kinetic temperature of the atmosphere at an altitude of 87 km measured with the SABER radiometer installed aboard the TIMED satellite. The v2.0 version of the SABER temperature profiles was used (http://saber.larc.nasa.gov). The SABER measurements obtained within the area (55°N-70°N)×(115°E-135°E) have been selected. The angle of view of the ground-based spectrograph is almost in the center of the selected area. The satellite overpasses the selected area only in September-November and January-March. The spectrograph measurement is considered if the difference in time from the satellite measurement does not exceed a half of hour. The analysis of 328 cases of coincident measurements has shown that the difference in temperatures obtained from the satellite and ground-based spectrograph lies within the errors of both instruments. The correlation coefficient between two databases is equal 0.8. Based on the performed analysis, it has been concluded that a series of hydroxyl rotational temperatures can be used to study temperature variations of different time scales including long-term trends at the OH emission altitude (~87 km).

1. Introduction
One of the available and inexpensive methods allowing tracking climatic changes in the upper atmosphere is a measurement of temperature using the emission of nightglow. A mesopause is the atmosphere region where the mesosphere borders the thermosphere (80-100 km), in which the temperature minimum is located. The radiating layer of excited hydroxyl (OH) is located at a distance of about 87 km in the mesopause region. The activated hydroxyl molecule executes $2 \cdot 10^4$ s$^{-1}$ collisions before the radiation which is sufficient for thermalization with the surrounding medium. Therefore, the OH rotational temperature calculated from the night sky spectrum indicates to the neutral atmosphere.
temperature at the radiation height [1]. Recently, with the development of satellite methods, it has become possible to compare ground-based measurements of upper atmosphere temperature with satellite temperature measurements [2, 3]. As noted by Scheer et al. in [4], a comparison of ground-based instruments scattered around the globe with data from a single instrument with known characteristics located aboard a satellite can facilitate mutual calibration of the entire world network of instruments. Since January 2002, the TIMED satellite with a polar orbit equipped with a complex of instruments for studying the state of the atmosphere is successfully operating. One of the instruments is the SABER radiometer [5]. Among the many parameters measured with the radiometer there are vertical profiles of the kinetic temperature and radiation at wavelengths of 1.6 µm and 2.0 µm.

In this paper, the rotational temperatures OH (3-1) measured from January 2012 to May 2017 with the infrared Shamrock 303i spectrograph installed at the high-latitude Maimaga optical station (φ = 63° N, λ = 129.5° E) are compared with the kinetic temperature at a distance of an altitude of ~87 km obtained by the SABER.

2. Instruments
The infrared digital spectrograph consists of the Shamrock SR-303i monochromator equipped with the infrared iDus InGaAs detector. The spectrograph records the strongest emission OH(3-1) occurring near 1.5 µm wavelength. In this paper, we compare the rotational temperature OH(3-1) with the kinetic temperature of the atmosphere at the height of the hydroxyl emission measured from the satellite. The angle of view of the spectrograph is ~14° and is directed to the west at a zenith angle of 49° (the field of view of the spectrograph at an altitude of 87 km is an ellipsoid with a size 38x32 km). The transfer function of the spectrograph has an approximately Gaussian form, and its half-width is ~1 nm. The method for estimating the rotational temperature of molecular emissions is based on fitting the model spectrum, convoluted with a transfer function of the spectrograph for various predetermined temperatures, to the actually measured spectrum using the least-squares method [6]. The model spectrum, whose deviation from the real one does not exceed the noise of registration, is considered to be the most appropriate to the reality and that its rotational temperature corresponds to the temperature at the height of the mesopause. As the estimations show, a random error in the temperature measurement does not exceed 2 K if the signal-to-noise ratio is greater than 20. The transition probabilities calculated by Mies [7] were used to derive the rotational temperature. Observations were made at night, when a zenith angle of the Sun was >9°. The geographical location of station makes it possible to conduct observations only from the end of July up to the middle of May, because in the summer at the latitude of Maimaga the mesopause is constantly illuminated by the Sun. For the analysis, the data obtained during the moonless time without aurorae have been selected. The spectrum of OH(3-1) was exposed with a time resolution of 1 min.

SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) is an infrared radiometer probing the atmosphere from the troposphere up to 350 km. It is installed aboard the NASA's TIMED satellite [5]. The vertical profile of kinetic temperature is calculated using the emission of 15 µm CO2 under the condition of non-local thermodynamic equilibrium (non-LTE) in this altitude region. The algorithm for calculating the temperature profile, which takes into account the non-LTE effect, including all collisional and radiative processes, is described in detail in [8]. In our work, the v2.0 version of the SABER database was used (http://saber.larc.nasa.gov). The random error in measuring the temperature with SABER at an altitude of 87 km is 5 K; the systematic error is estimated by 2 K.

In this work, we have selected those SABER data that were obtained when scanning the emitting layer of OH within the area (55°N-70°N) × (115°E-135°E) with the radiometer. The ground-based spectrograph’s sight line intersects almost the center of this area. Because of the orbital characteristics, the SABER overpasses the station Maimaga only in September-November and January-March.

3. Results and discussion
The ground-based spectrograph integrates the radiation along the field of view and the rotational temperature reflects the average atmosphere temperature weighted in thickness of the emission layer. It
is necessary to distinguish that part of the SABER vertical temperature profile that would be equivalent to the hydroxyl rotational temperature. The convolution of the vertical profile of volume emission of OH with the kinetic temperature profile is equivalent to the temperature measured with the ground-based instrument. The SABER radiometer two channels are intended to carry out a vertical scanning of airglow: in the 1.6 µm wavelength region, where the OH(5-3) and OH(4-2) bands are emitted, and in the 2.0 µm wavelength region where the OH(9-7) and OH(8-6) band are emitted. The radiation vertical profile in the 1.6 µm region has been chosen as a weight function since OH(3-1) radiates approximately at the same wavelength. To reduce the effect of solar illumination, the data obtained at the zenith angle of the Sun of less than 115 degrees, we have excluded these data from analysis. For comparison, the time difference between SABER and the ground-based measurements should not to be greater than 1 hour. Since 17 January 2013, 328 nights of measurements coinciding in time and space were found. During night, the SABER radiometer scanned the limb above Maimaga three–four times, and the scanning results have been averaged. A scatter plot of OH(3-1) rotational temperatures versus SABER kinetic temperature is shown in Figure 1 a. A correlation coefficient between two data sets is equal 0.8.

The time series of OH(3-1) rotational temperatures and the equivalent SABER temperatures are shown in Figure 1 b. The open blue squares and red triangles are the nighttime rotation temperature of OH(3-1) and the SABER temperature, respectively. The solid large squares and triangles connected with lines correspond to the average temperature during the observation period from September to March, except December, when the SABER data are absent. As can be seen, the temporal temperature changes in the measurements of two independent devices are in good agreement. However, the mean rotational temperature is approximately 3 - 4 K higher than the mean temperature measured with the SABER radiometer.

![Figure 1. Left panel – the comparison of OH(3-1) rotational temperature measured at st. Maimaga with the equivalent kinetic temperature obtained with the SABER. Right panel - the OH(3-1) temperature series (red triangles), and SABER temperatures (blue squares) measured from 2013 to 2017. The solid large black squares and triangles are the annual mean temperatures. Vertical bars show the standard deviations.](image-url)

The difference in the measurements of two independent devices can depend on various reasons. The first works devoted to inter-comparison of ground-based and satellite-borne measurements of the mesospheric temperature indicated that such a comparison is associated with some difficulties. A ground-based spectrograph receives emission from the entire emitting layer, the half–width of which is about 8–10 km. There is usually no information on the change of the height of emission layer and shape of the layer itself. The satellite device scanning the limb integrates the light horizontally at a certain fixed height. As a result, both instruments measure the temperature of different volume of air, even if the angles coincide precisely. Under quiet conditions, the measured temperatures should be close,
however, with strong wave disturbances, the measured temperatures can differ greatly. On the other hand, the spectrograph and the radiometer measure the temperature at the radiation height of the hydroxyl bands from different vibrational levels. The difference in altitude between them is about 2 km and the average temperature can be different. Finally, a systematic error can consist of systematic errors with two different devices. Nevertheless, it can be concluded that a series of rotational temperatures can be used to study temperature changes at different time scales at the altitude of OH emissions (~ 87 km), including long-term trends.

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