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Lidar for atmospheric transparency monitoring

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Abstract. The transparency of the atmosphere affects the quality of astronomical observations and optical communications, but above all, it directly controls the fluxes of radiation, which is of particular interest for the study of weather and climate changes. The transparency of the atmosphere also affects the success of observing thermospheric lidar reflections. Since they are a consequence of the high transparency of the atmosphere, the reflections can be used as characteristics of atmospheric transparency.

1 Introduction

The thermospheric lidars were created to determine the concentration of the components of the upper ionosphere of molecular nitrogen, atomic helium, nitrogen and oxygen and their ions. But the successful implementation of the thermospheric lidar is known only for the ions of atomic nitrogen and oxygen [1], and these are the components of the upper ionosphere with the lowest concentrations. Perhaps this result is due to low concentrations, at which giant resonant scattering cross sections are realized [2]. And at high atomic concentrations, scattering appears as in a continuous medium on fluctuations of the refractive index, but this is a less effective scattering mechanism.

In the ionosonde version, the thermospheric lidar can also be used as a detector of precipitations of charged particles into the ionosphere [3], as a result of which additional gas ionization occurs to the level determined by the ultraviolet fluxes. Here we will consider another application of the thermospheric lidar for atmospheric transparency measurements. This value affects the quality of astronomical observations and optical communications, but above all it directly controls the radiation flux, which is of particular interest for the study of weather and climate changes.

The transparency of the atmosphere also affects the success of observing thermospheric lidar reflections. Since thermospheric lidar reflections are a consequence of the high transparency of the atmosphere, they can be used as characteristics of this transparency.

The occurrence of thermospheric lidar reflections can serve as an indicator of the high transparency of the atmosphere. Below we will consider the features of lidar reflections at the heights of the thermosphere.

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2 Thermospheric lidar reflections

In the exploration of great heights, the following stages can be distinguished. After the start of the lidar station in 2006, the first resonant lidar reflections in the thermosphere were obtained in 2008 [4], figure 1.

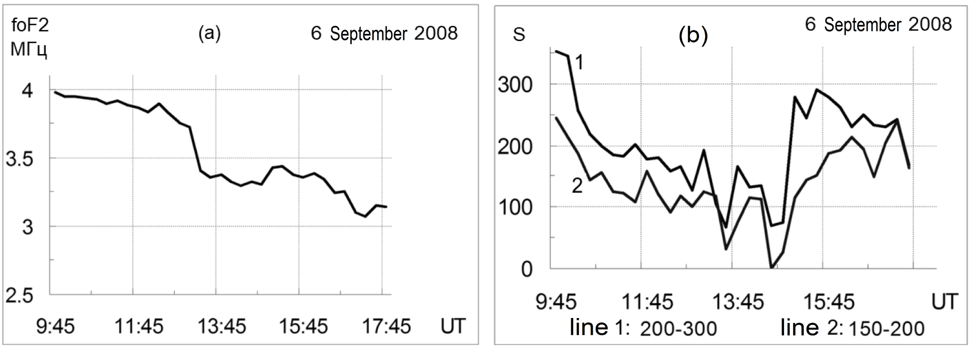

Figure 1. Critical frequency F2 of the ionospheric layer (a) and reflection signals at a wavelength of 532 nm from layers 200-300 and 150-200 km (b).

Note that with the departure of the thermosphere into the shadow, the concentration of electrons decreases, and, accordingly, the lidar signal also decreases. From this we can conclude that the reflected signal was mainly determined by the ionization of the thermosphere; however, after midnight local time, fluctuations in the signals begin to increase, which cannot be explained by changes in ionization alone. This is better seen in figure 2.

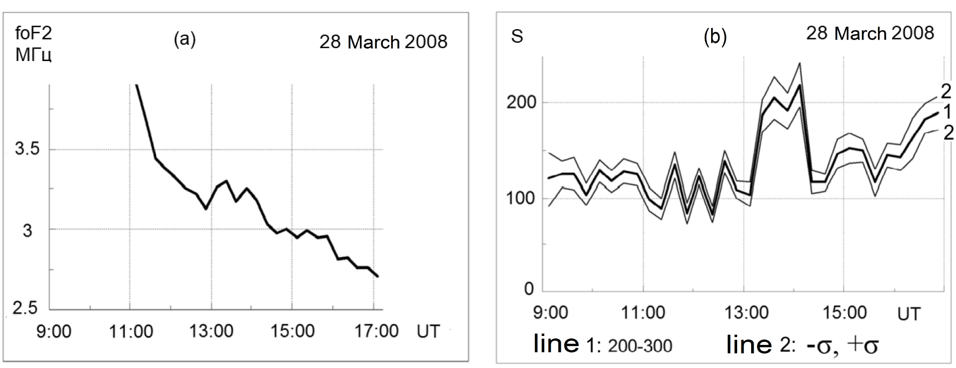

Figure 2. Critical frequency F2 of the ionospheric layer (a) and the signal of reflections at a wavelength of 532 nm from a layer of 200-300 km (b).

In 2014, it was concluded that reflections in the thermosphere are resonant scattering by excited ions of atomic nitrogen [4], and in 2017, simultaneous reflections in the thermosphere were obtained at wavelengths 561 and 532 nm, corresponding to resonance scattering by excited ions of atomic oxygen and nitrogen [1], figure 3.

In figures 3a and 3b, the dependence of lidar reflections on the ionization of the thermosphere is visible as in figures 1 a and b. In figure 3c, lidar signals oscillate with a two-hour pe-

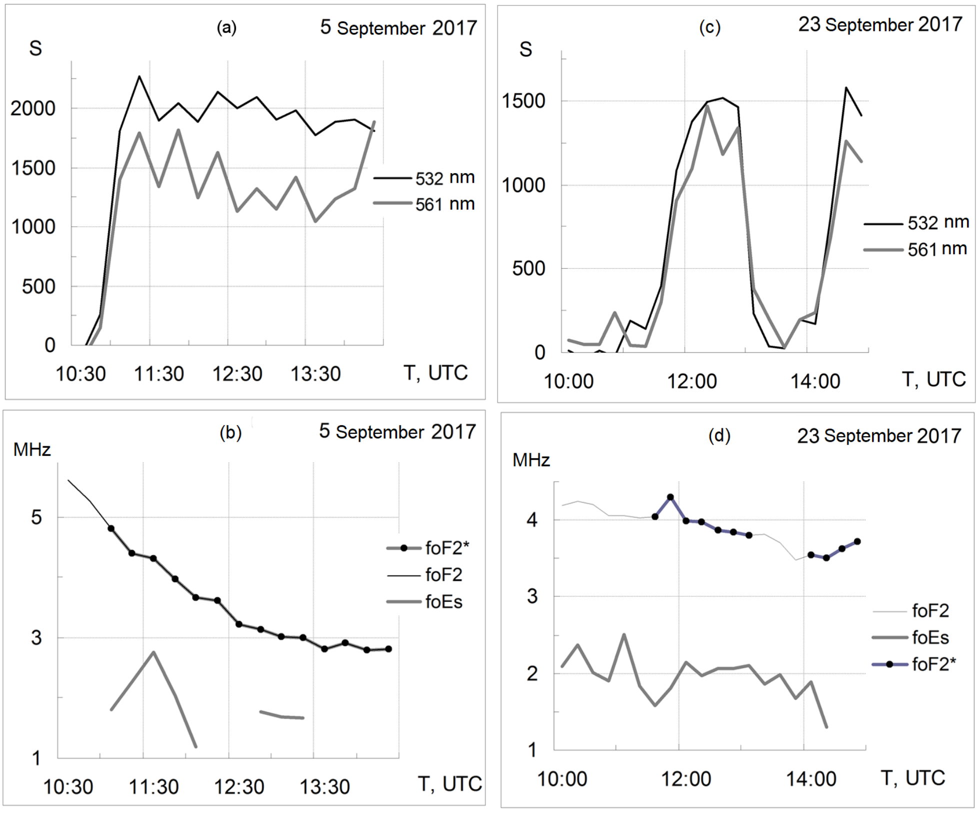

Figure 3. Reflection signals from a layer 200–400 km (top) and $foF2$ and $foEs$ (bottom).

riod corresponding to the frequency range of internal gravitational waves in the atmosphere. This can explain the reason of oscillations in figures 1 and 2.

The significant oscillations of lidar signals in figure 3c give an understanding of how high-altitude observations depend on the state of the lower atmosphere. Perhaps this explains the extreme rarity of thermospheric observations. To start work at high altitudes, it is necessary to determine the state of the lower layers of the atmosphere, figure 4.

Obviously, with such an ionization environment in the middle atmosphere, high-altitude lidar observations become impossible. These data can be used to assess the transparency of the atmosphere and predict the stability of the operation of communication optical systems.

It is noteworthy that the cases of successful sounding of the thermosphere took place during the decline of solar activity, when its radiation effect on the neutral atmosphere reaches a minimum, which creates favorable conditions for high-altitude observations.

Strong fluctuations in the amplitude of lidar reflections due to changes in the conditions of signal transmission along extended paths are of a multiplicative nature. This explains the wide range of changes. Before the start of thermospheric lidar observations, the influence of atmospheric transparency on the fading of lidar signals was not known, so it took a long time to understand why resonantly reflecting layers in the thermosphere are observed so rarely.

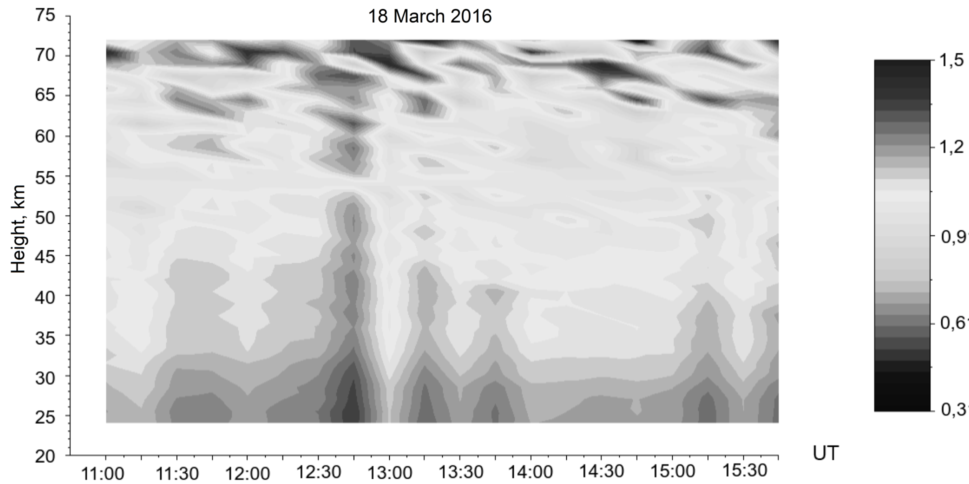

Figure 4. Hours of lidar observations in the lower and middle atmosphere.

The radiative effect of solar activity on various layers of the atmosphere is of interest in studies of weather and climatic changes. And lidar observations provide an opportunity for an integral estimation of this influence.

3 Lidar calibration

There is a problem with the calibration of the lidar. In figure 3, we see that the signal of atomic oxygen ions is slightly less than the signal of atomic nitrogen ions, while the concentration of atomic oxygen ions is two orders of magnitude higher than the concentration of atomic nitrogen ions. This is inconsistent with the theory of resonant scattering, in which the density of scatterers is decisive.

With an increase in the average density of scatterers, the relative density fluctuations decrease, the medium becomes weakly inhomogeneous. In homogeneous media, the scattering also becomes relatively weak. With an increase in the density of scatterers, the statistical characteristics of the scattering change [2]. Perhaps this explains the absence of scattering signals from neutral plasma components, which are five orders of magnitude more than ions.

But there is one more very important circumstance, ions participate in recombination processes, the frequency of which is many orders of magnitude higher than the collision frequency, and this significantly affects the width of resonance lines and reduces the requirements for the coherence of radiation generators.

According to Langevin's theory, the rate of recombination of an atomic oxygen ion depends on the electron concentration, which coincides with the concentration of atomic oxygen ions where atomic oxygen prevails over all other neutrals. This relationship takes place at the operating altitudes of the thermospheric lidar.

The nonlinear effect in recombination must be taken into account, first of all, when we explain the anomalously low lidar signal on atomic oxygen ions. Thanks to it, the dependence of the scattering coefficient on the density of the scatterers changes.

Atomic oxygen of the thermosphere plays an important role in the calibration of a high-altitude lidar due to the fact that the concentration of its ions can be compared with the density of electrons, which is measured by an ionosonde.

And the nonlinear effect in recombination makes it possible to compare the signals of atomic oxygen and nitrogen ions. The atomic oxygen ion signal can be used to calibrate the lidar and determine the recombination parameters. To obtaine the characteristics of the medium, one can use the solutions of the problem of non-stationary reflections [5] which take into account the dispersion properties of the medium and are presented in figure 5.

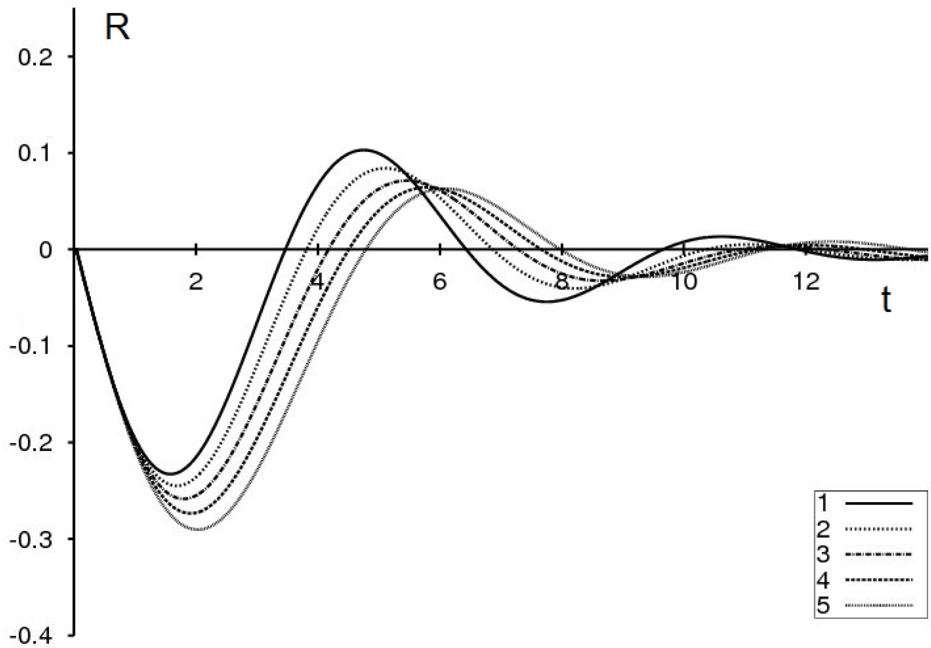

Figure 5. Reflections $R(t)$ in the case of fractional oscillations at different values of the resonance curve parameter b: 0.3 - 1; 0.4 - 2; 0.5 - 3; 0.6 - 4; 0.7 - 5.

The last three years have been decisive in understanding the physical principles of thermospheric lidar operation. This was largely facilitated by multifrequency lidar observations [1].

Conclusions:

1. Thermospheric lidar reflections can be used as an indicator of high transparency of the atmosphere. This will find application for assessing the astroclimate and the efficiency of communication systems.

2. Resonant reflections occur under the usual conditions for the thermosphere, the level of its ionization is quite sufficient. Charged particle precipitation assumptions are not required. They can be considered as a source of additional ionization.

3. Strong fluctuations and difficulties in the detecting of resonant reflections in the thermosphere are caused by unfavorable conditions for signal transmission in the underlying atmosphere.

4. The differences in resonance scattering on neutrals and ions are determined by a significant difference in their concentrations and ion recombination processes.

5. The anomalously weak signal of scattering by atomic oxygen ions can be explained by the nonlinear recombination effect.

6. The signal of atomic oxygen ions can be used to calibrate the lidar and determine the recombination parameters.

7. The obtained solutions for non-stationary reflections can be used for diagnostics of the thermosphere.

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