Lidar investigations of the scattering of the upper and middle atmosphere

Vasily V *Bychkov; Andrey S Perezhogin; Ilya N Seredkin; Boris M Shevtsov;*

Institute of Cosmophysical Research and Radio Wave Propagation FEB RAS, Paratunka, Elizovskii raion, Kamchatskii krai, Russian Federation

ABSTRACT

The results of two-frequency lidar investigation of the atmosphere scattering are presented. The observations were carried out at the wavelength of 561 and 532 nm. The radiation band of lasers covers two emission lines of atomic oxygen (561.106 and 561.346 nm) and three emission lines of atomic nitrogen (532.020, 532.087 and 532.095 nm). The lines correspond to the transitions between the exited states of ions of atomic oxygen or nitrogen. The possibility of application of the lidar method for ionosphere investigations is discussed. The physical basis of such method may be the resonance scattering on upper atmosphere ions. The authors discuss the conditions when the impact of the resonance scattering into the lidar signal at the mesosphere heights is observed.

Keywords: atmosphere, ionosphere, lidar, sounding, scattering.

1. INTRODUCTION

According to the data of ionospheric and lidar observations at the wavelength of 532, nm it was shown in the papers[1-3] that during the precipitations of super-thermal (0.1-10 keV) electrons into the atmosphere the total lidar signal from the upper atmosphere height region (150-300 km) may correlate with foF2 of the ionosphere. Analysis of the geophysical conditions accompanying the phenomenon allowed us to make the conclusion that the possible physical mechanism explaining these correlations is the resonance scattering on excited ions of nitrogen atom forming during electron precipitations into the ionosphere. The content of nitrogen atom ions at ionospheric heights is units of percentage by day and it is neglectfully small by night. The paper presents the results of registration of resonance scattering at exited ions of atomic oxygen which is the main charged component in ionosphere F2 layer.

2. HARDWARE COMPLEX

The lidar observations of 2015 applied two-frequency lidar with Brilliant-B laser to generate 532 nm radiation and TDL-90 dye laser with YG982E pumping laser to generate 561 nm radiation. The both lasers have the frequency of 10 Hz. The pulse energy at the wavelength of 532 nm is ~ 400 mJ and about 150 mJ at the wavelength of 561 nm. The laser emission spectrum width at the half height measured by monochromator is 0.5 nm for laser Brilliant-B and 1 nm for laser TDL-90.

The receiving telescope of the lidar has a parabolic mirror with the diameter of 60 cm. The receiver angle of view is 0.1-1 mrad. A signal received by the telescope is sent to a light guide in the form of a parallel beam through the lens of the receiving device. A beam splitter is mounted in the light guide at an angle of 45 degrees to the direction of beam propagation. Radiation with the wavelength of more than 532 nm is passed by the splitter. Radiation with the wavelength of 532 and less is reflected at the angle of 90 degrees into another light guide. Both streams are directed to the photocathodes of two photomultipliers Hamamatsu H8259-01, connected to photon counters Hamamatsu M8784.

The background signal value was measured from the 20th to the 24th ms with the step of 10 μs after each laser pulse sending. A signal measured by such a way does not contain aftereffect pulses and is provided by good data accumulation.

Control of the ionosphere state was carried out according to “Parus” ionosonde data which replaced the Automatic Ionospheric Station in August 2015.

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3. OBSERVATIONS RESULTS

First probing results applying a receiving system for radiation registration at the wavelength of 561 nm are shown in Fig. 1. It is clear from Fig. 1 that high correlation is observed between the resultant signal from the layers of 150-200, 200-300 and 300-400 km, which is not typical for signals at high altitudes.

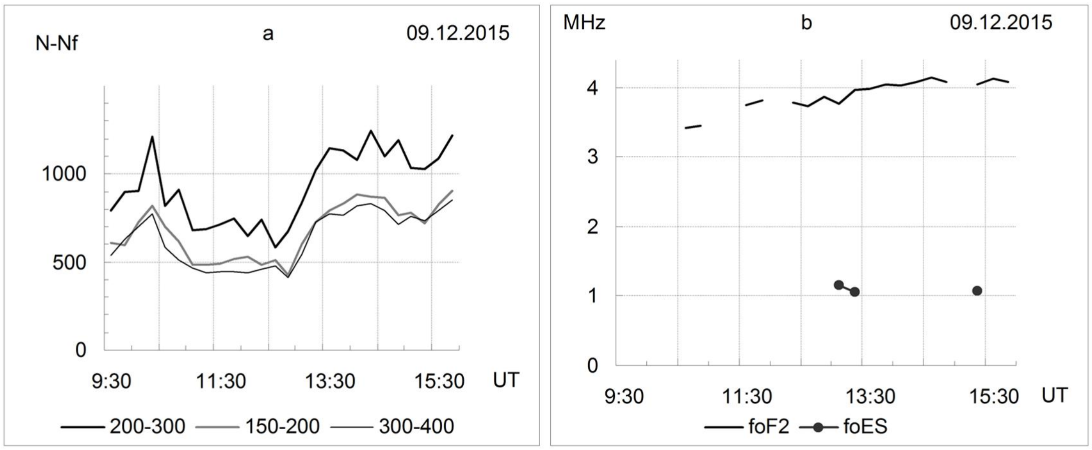

Fig. 1. Lidar “signal-background” from the layers of 150-200, 200-300 and 300-400 km (a) and critical frequencies of F2 and Es layers (b) during lidar observations on December 9, 2015

According to the data of Fig. 1a, synchronous increase of the lidar signal within the whole height region of 150-400 km is observed before 10:15 UT and after 12:45 UT. The correlation coefficient between the signals summed according to the layers in Fig. 1 exceeds the value of 0.9.

According to the ionospheric data for F2 layer high diffuseness (F-scattering) was characteristic during the whole period of lidar observations on December 9, 2015. In most cases it was impossible to determine the exact value of foF2. The diffuseness of F2 layer is explained by the presence of inhomogeneities in the layer, the cause of which among the others may be precipitations of ionizing particles. On the whole, increase of foF2 is observed at nighttime which also indicates additional ionization. Weak nighttime Es were displayed on ionogramms from 12:30 till 15:15 UT (Fig. 1b). The layer at 15:15 UT differs by standard intensity which corresponds to the time of increase of the lidar and background signal within the mentioned period of time.

There are no noticeable correlations for the lidar signals at the wavelength of 532 nm.

Geomagnetic state on December 9, 2015 was calm during the whole period of observations.

4. DISCUSSION OF THE RESULTS

Fig. 2a shows a resultant signal S for a night (curve 1) minus the measured background. Fig. 2b shows a background signal attributed to the interval 10 μs (which corresponds to the time of passage of the layer with the height of 1.5 km and the counter gate width). Number 1 indicates the signal measured from the 20^{th} to the 24^{th} ms after each laser pulse sending, number 2 indicates the signal measured from the 3^{rd} to the 4^{th} ms, i.e. the middle signal from the region of 450-600 km. Comparison of curve 2 of Fig. 2b with Fig. 1a shows that the signal from the region of 450-600 km repeats the form of the signal from the layers in the region of 150-400 km, contains a signal of resonance scattering and can not be used as a background one. In usual conditions, the difference of the signals obtained by such ways is very small.

Curves 2 and 3 in Fig. 2a show the “signal-background” resultant over a night, normalized to the value $(H/100)^2$, where H is the height in kilometers. The normalization was chosen according to the idea that the optical view to the mirror decreases from heights as ~ $1/R^2$. The decrease of beam intensity of laser radiation with height is compensated by the increase of light-stuck volume.

Curve 3 in Fig. 2a was calculated taking into account the background values illustrated on curve 1 in Fig. 2b. Increase of the normalized signal with height means that the difference “signal-background” contains some additional component. This additional component of a signal may be composed of aftereffect pulses with the characteristic time of attenuation of few milliseconds. Such an order of attenuation time has, for example, an aftereffect of ion feedback type.

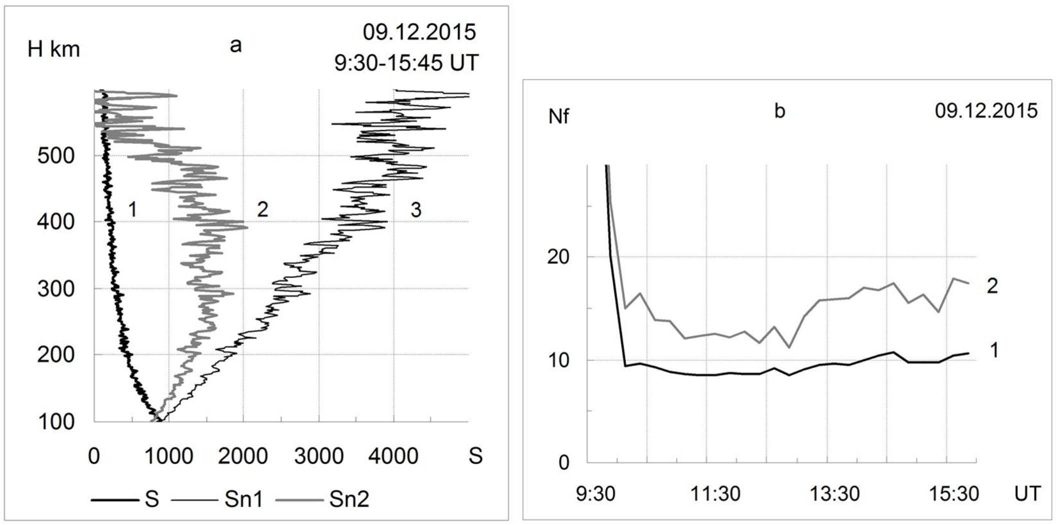

Fig. 2 a – resultant lidar signal S (1) and normalized lidar signals Sn (2,3), b - background signal measured within 20-24 ms after signal sending (1) and average signal value measured within 3-4 ms (2).

The aftereffect processes are described in the paper[4], they may be grouped according to the character of a process and the time of action relatively the main pulse. The typical times of the processes are within the interval from nanoseconds to milliseconds and even seconds.

An aftereffect is a decaying process. Since there are no signals of molecular and aerosol scattering at the heights of more than 100 km, we may distinguish a residual signal in the form of an exponent. In the lidar data on December 9, 2015, an exponent was detected in the height region of 100-400 km by least square method. Calculations showed that the exponential part of the dependence A*exp(B*H) + C of the residual effect is small and affects weakly the result. The signal drops slowly and only a constant may be used as a residual effect for this height region. The constant C value significantly affects the curve, but its value obtained by least square method is overrated which results in negative values of the normalized signal. The latter is due to the fact that the initial data contain resonance scattering signal besides the residual pulses. Thus, the constant C value was chosen so that the normalized signal would be close to zero at the height of 600 km.

The result is shown in Fig. 2a, curve 2. Curve 2 initial data are smoothed by the moving average method with the window of 4.5 km. Curve 2 corresponds to the profile of distribution of O^+ ion concentration in the ionosphere. But in fact, this curve corresponds to the average content of oxygen ion excited states $2s^22p^2(^1S)3s$ and $2s^22p^2(^3P)3s$, the lifetime of which is parts of microsecond. A profile is composed of 213 200 measured values and contains the data of ionization function history for 6.5 hours of observations. Based on the location of local maximums in the signal profile, it is possible to estimate the energy of precipitated electrons and their spectrum.

5. MESOSPHERE OBSERVATIONS

The paper[5] presents the data on the correlations between the relation of the scattering R = (βa+βm)/βm by the layers with the thickness of ~5 km in the height region of 60-77 km with the ionospheric parameter f_{min}. Here βa, βm are the coefficients of aerosol and molecular scattering. According to the data of ionospheric and lidar observations at the wavelength of 532 nm on January 18 and 23 and February 19, 2008, correlation coefficients were obtained as 0.68, 0.77 and 0.5, respectively.

The paper[5] estimates the possibilities of water condensation in the mesosphere. Pressure for the dew point was calculated by Magnus formula, and the water vapor content and temperature in the mesosphere was estimated from the measurement data of Aura satellite. It was obtained that during average temperature conditions, water vapor content in the mesosphere is two orders less than it is necessary to reach the dew point. Even during the lidar experiments carried out on December 7, 2009, when at the height of 73.5 km the temperature was 168º K and was lower than that of the model NRLMSIS-00 by 56º, there was not enough water vapor content for reach the dew point by more than one order. Nevertheless, we observed aerosol formations in the mesosphere on January 18, 2008 and on other days in the heights region of 60-80 km.

According to the data of Demeter satellite, flying to the East and to the West from Kamchatka during the lidar observations, increased fluxes of relativistic electrons with the energies of more than 100 keV were observed during this three days. Ionization rate was calculated from the spectrum measured on Demeter satellite. The obtained values of ionization rate is more than one order exceed the values generally accepted in D layer simulation. As an example, Fig. 3 shows the data from the paper[5].

Fig. 3a shows the values of f_{min} and the average in the region of 64.5-70.5 km, scattering coefficient relation R. Correlation coefficient between the curves is equal to 0.68. Fig. 3b illustrates ionization rate by relativistic electrons calculated from the data of Demeter satellite. Calculations were made by the method described in the paper[6].

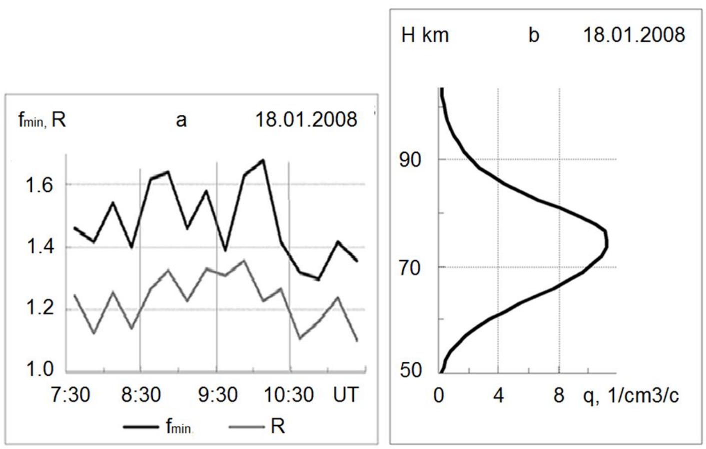

Fig. 3 Values of f_{min} and of lidar signal form the region of 64.5-70.5 km on January 18, 2008 (a) and ionization rate by precipitated electrons measured on Demeter at 10:10 UT (b)

Results of the papers[1-3] allow us to suggest a mechanism of formation of additional lidar signals from the mesosphere region. Changes of f_{min} are associated with the change of free electron content in the upper layers of ionosphere D region. Thus, increase of f_{min} denotes the increase of ionization rate. Ionization by energetic electrons is accompanied by the processes of atmosphere molecule dissociation. The main component of the atmosphere at these heights is the molecular nitrogen. Thus, increase of the lidar signal at mesospheric heights during relativistic electron precipitation may be explained by the appearance of atomic nitrogen excited ions and the conditions for resonance scattering at the wavelength of 532 nm.

6. CONCLUSIONS

Analysis of the obtained results allows us to make the following preliminary results:

- during the electron precipitation into the ionosphere at the heights of 150-250 km, the lidar signal at the wavelength of 561 nm many times exceed the values of the lidar signal at the wavelength of 532 nm from the scattering on atomic nitrogen ions. It corresponds to the estimates which had been made before[1, 2].

- lidar observations of the upper atmosphere may give us the information on the distribution of charged components in the ionosphere with significantly better space resolution than ionospheric radars.

- in the analysis of the results of mesosphere sounding at the wavelength of 532 nm, we should take into account the possibility of occurrence of an additional lidar signal caused by additional ionization.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Bychkov, V. V., Nepomnyashchiy, Y. A., Perezhogin, A. S., Shevtsov, B. M., "Lidar returns from the upper atmosphere of Kamchatka and possible causes of their generation" Atmospheric and Oceanic Optics, 28(3), 210-214 (2015), DOI: 10.1134/S1024856015040041

[2] Bychkov, V.V., Nepomnyashchiy, Y.A., Perezhogin, A.S., Shevtsov, B. M. "Resonance scattering at excited atoms and ions of the upper atmosphere as a possible mechanism for ionosphere investigations" Proc. SPIE 9680, 21st International Symposium Atmospheric and Ocean Optics: Atmospheric Physics, 968073 (2015); DOI: 10.1117/12.220596

[3] Bychkov, V. V., Nepomnyashchiy, Y. A., Perezhogin, A. S., Shevtsov, B. M., "Lidar returns from the upper atmosphere of Kamchatka on observations in 2008-2014," Earth Planets and Space 66, 1-4 (2014)

[4] Zuev, V.V., [Lidar monitoring of the stratosphere], Nauka, Novosibirsk, 307(2004)

[5] Bychkov, V. V. , Perezhogin, A. S., Perezhogin, A. S, Shevtsov, B. M., Marichev, V. N., Matvienko, G. G., Belov, A. S.and Cheremisin, A. A. "Lidar Observations of Aerosol Occurrence in the Middle Atmosphere of Kamchatka in 2007–2011" Atmospheric and Oceanic Optics, 25(3), 228–235(2012)

[6] Deminov, M. G., "Earth's ionosphere" in: [Plasma heliogeophysics] Ed. Zelenyi L. M. and Veselovskii I. S., Fizmatlit, Moscow, 559(2008)