ISSN 1024-8560, Atmospheric and Oceanic Optics, 2015, Vol. 28, No. 4, pp. 303–307. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © V.V. Bychkov, Yu.F. Nepomnyashchii, A.S. Perezhogin, B.M. Shevtsov, 2015, published in Optika Atmosfery i Okeana.

REMOTE SENSING OF ATMOSPHERE, HYDROSPHERE, AND UNDERLYING SURFACE

Lidar Returns from the Upper Atmosphere and Possible Causes of Their Generation

V. V. Bychkov, Yu. F. Nepomnyashchii, A. S. Perezhogin, and B. M. Shevtsov
Institute of Cosmophysical Research and Radio Wave Propagation, Far Eastern Branch, Russian Academy of Sciences, ul. Mirnaya 7, Paratunka, Kamchatskii krai, 684034 Russia
e-mail: vasily.v.bychkov@gmail.com, vicecam@gmail.com, d72156@gmail.com, bshev@ikir.ru

Received October 3, 2014

Abstract—New experimental data which confirm episodic occurrence of the correlation of light backscattering lidar signals from a 150–300 km altitude region with the plasma content in the nighttime F_2 layer of the ionosphere are presented. Analysis results of lidar observation data for 2008–2014 are given. A conclusion is drawn that these correlations occur when additional sources for ionosphere ionization appear. A hypothesis is discussed that the resonance scattering by excited atomic nitrogen ions is a possible cause of generation of these signals.

Keywords: sounding, atmosphere, lidar, scattering
DOI: 10.1134/S1024856015040041

INTRODUCTION

It is commonly accepted that lidar backscattering signals from altitudes higher than 100 km are absent during Rayleigh lidar sensing of the atmosphere. It is shown in [1], based on lidar data and ionosphere observations on March 28, 2008, that that day the difference between the total signal from the 200–300 km altitude region and the independently measured background signal correlates with the plasma content in the region of maximal nighttime F_2 layer of the ionosphere. A possible physical mechanism is proposed which explains these correlations, namely, the formation of scattering by electron-excited atoms [1].

Additional experiments carried out in April–May, 2014, have stated that the frequency of returns from the upper atmospheric region is close to the sensing radiation frequency and has a spectrum no wider than 1 nm. This suggests the existence of resonance scattering. A correlation of the lidar returns with the plasma density in the nighttime F_2 layer of the ionosphere means that scattering by ions can take place. The aim of this paper is to find a possible component among ions of the upper atmosphere and to justify its role in the generation of lidar returns.

INSTRUMENTAL COMPLEX

We used experimental data from lidar and ionosphere stations located in Kamchatka (Paratunka settlement, 52.9° N, 158° W). The instrumental complex is described in [2]. A Hamamatsu H8259-01 PMT and a Hamamatsu M8784 photon counter were used in the receiving system. Also, we used light filters with transmission bandwidths of 3 and 1 nm at half maximum and identical transmission $T > 65\%$. In order to exclude signals of the near zone, we used the electron blocking of PMT by a 140-ms pulse. A signal was recorded during 4 ms with a step of 10 ms, which corresponded to the altitude region 21–600 km with a step of 1.5 km.

The magnitude of the background signal was measured from the 20th to the 24th ms with a step of 10 μs after sending each laser pulse. During measurements of the background signal the sensing pulse is in the altitude region 6000–6600 km, the background signal is free of cutoff pulses and is provided by good data accumulation. The background measurement is software initiated and, as the practice has shown, can be specified by any pulse from the 10–95 ms region. Application of this method for noise measurements allowed us to detect weak returns from the upper atmosphere against a well-averaged background.

OBSEVATION RESULTS

The detail analysis of observation results and geophysical situation on March 28, 2008, is described in [1]. Figure 1 shows the basic experimental result taken from [1]. At nighttime from 13:00 to 14:30 UT, a small but sharp increase in the critical frequency of layer F_2 was noted, which was accompanied by an increase in the F_2 layer depth by approximately 40 km. Simultaneously, a spike is observed on the lidar return summed over the altitude region 200–300 km, which coincides in time and shape with the burst of the critical frequency of F_2 layer of the ionosphere.

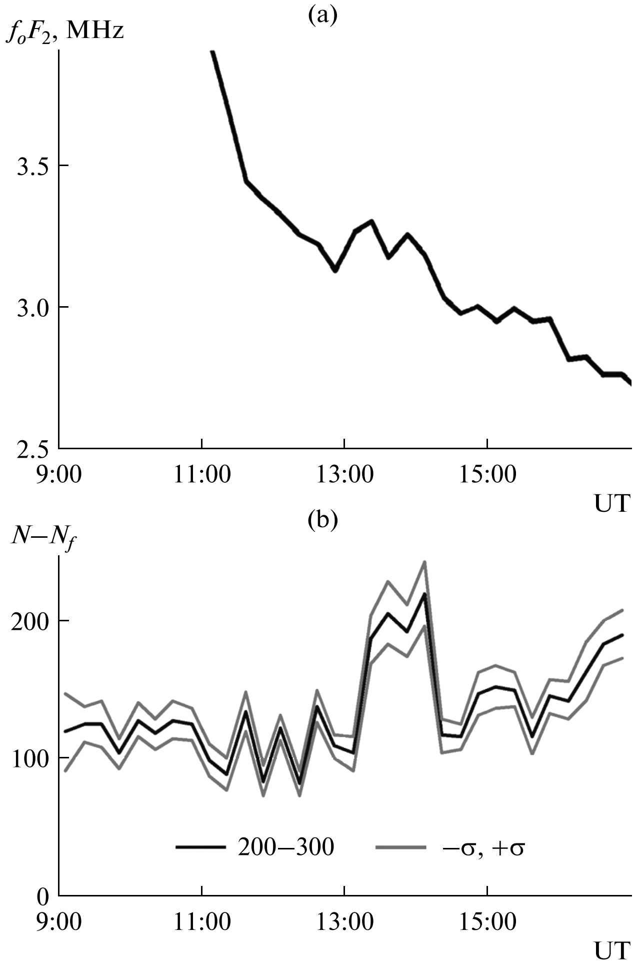

Fig. 1. (a) Critical frequency of the F_2 layer of the ionosphere f_oF_2 and (b) lidar signal $N–N_f$ summed over the 200–300 km altitude region. The middle line shows the lidar signal; top and bottom lines show root mean square deviations.

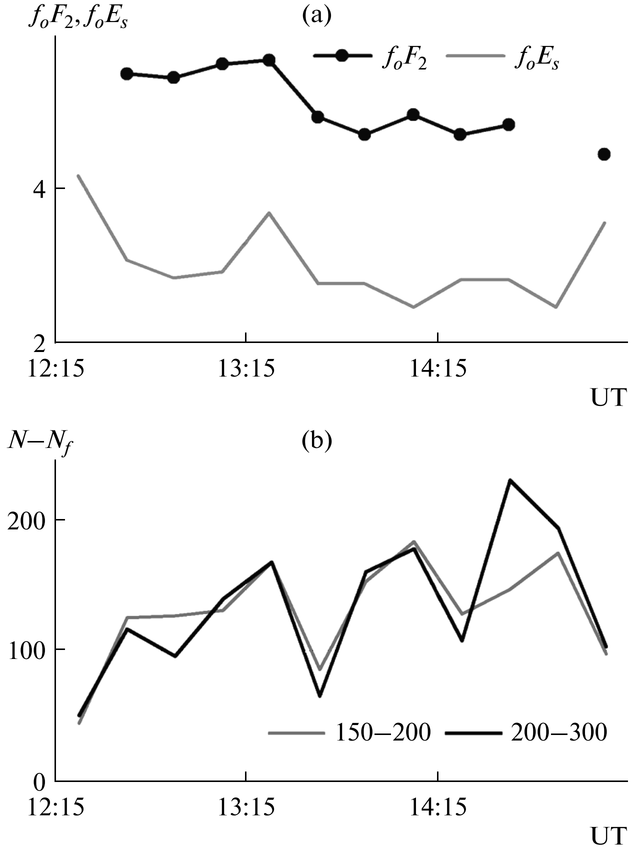

Fig. 2. (a) Critical frequencies f_oF_2 and f_oE_s on July 1, 2010, and (b) lidar signal minus background from the altitude regions 150–200 and 200–300 km.

The geophysical situation of this night was characterized by a residual geomagnetic disturbance after a storm, the maximum of which fell on March 26. During observations, local geomagnetic K indices were equal to four. According to data of the ionosphere station, sporadic E_s layers of corpuscular type were simultaneously recorded at altitudes of 130–150 km with the critical frequency f_oE_s equal to1.5–1.6 MHz.

Examples of similar correlations in September and November, 2008, are given in [2]. Observations of lidar returns from the upper atmosphere require good weather, absence of the moon, which guarantees a minimal level of the background signal, and precipitation of soft electrons in the ionosphere above the observation point. Such conditions are not frequent at the midlatitude Kamchatka lidar station.

As an example, Fig. 2 shows observation results for July 1, 2010. Layers E_s at altitudes of 100–110 km were recorded that day throughout all three hours of observations. The increase in f_oF_2 at nighttime can be explained by precipitation of particles with energies of hundreds of electron volts (eV). The ionization increases in the 100–150 km region with the content of particles of units of keV in energy [3], and E_s layers are formed near its maximum. Night corpuscular E_s layers differ from plane E_s layers of the wind origin in their somewhat larger thickness and horseshoe-shaped trace in ionograms, which is typical for the regular daytime E layer.

Maxima at 13:15, 14:00, and 14:45 UT (Fig. 2b) are well pronounced on the lidar return plot. The first two of them coincide in time with f_oF_2 maxima (Fig. 2a). At 14:45 UT, the value of f_oF_2 is undetermined because of diffusivity of the F_2 layer. The ionogram shows that the magnitude of f_oF_2 at least did not noticeably decrease at 14:45 UT. We may think that the correlation of f_oF_2 with lidar returns took place throughout the 12:30–15:00 UT time interval.

At 13:15 UT, a correlation of a lidar return with both f_oF_2 and f_oE_s is observed. This circumstance additionally confirms the corpuscular nature of E_s layers. The decrease in f_oE_s (at E_s layer altitude of 100–110 km) at 14:00 and 14:45 UT is explained by a decrease in the number of precipitating electrons with energies of units of keV in flows. At altitudes of the E region, the precipitating electrons form sufficiently narrow regions with noticeably decreased ionization. In this case, a correlation between f_oE_s and f_oF_2 is not obligatory; this is determined by the energy spectrum of the precipitating particles.

Weather conditions at the Kamchatka lidar station allow about 40–50 sessions of lidar observations per year. The data analysis for 2008–2013 has shown that correlations of f_oF_2 with lidar returns from the F layer of the ionosphere can be successfully observed from two to five times every year, i.e., in 5–10% of observations. The cases of electron precipitation in the atmosphere at midlatitudes occur comparatively seldom; they differ in duration, intensity, and spectrum of precipitating electrons. When the moon is in the sky, the background signal can increase by an order of magnitude; and it is impossible to detect a lidar return from ionosphere altitudes. Both these factors determine a possibility of finding correlations between lidar returns and f_oF_2. The found ratio of the number of cases of correlation to the total number of sensing events, equal to 5–10%, approximately corresponds to observation conditions.

It follows from 2008–2013 observations that the increased light scattering from the upper atmosphere can be observed both during magnetic disturbances and under magnetically-quite conditions [2]. In most cases, an increase in lidar returns was accompanied by appearance of corpuscular E_s at altitudes of 100–150 km. This testifies the precipitation of soft electrons (hundreds of eV—units of keV) in the air of Kamchatka during lidar observations. A cause of increased scattering in the upper atmosphere should be sought in the increased ionization of the 150–300-km region by precipitating electrons.

Starting from April, 2014, lidar observations were conducted with the use of a YG-982E laser (wavelength of 532 nm, pulse energy of 1.0–1.1 J). The receiver signal, cut in two, came to two PMT tubes through light filters with transmission bands at a half maximum of 1 and 3 nm and equal transmission coefficients $T > 65\%$, which allowed the estimation of the signal spectral width.

Figure 3 shows results obtained on May 14, 2014. That day, sporadic E_s layers were observed at 11:15, 12:30, and 12:45 UT with critical frequencies of 2, 1.8, and 1.55 MHz, respectively. The type of all observed E_s layers in night conditions can be classified as corpuscular. Maxima on the lidar signal curve (Fig. 3b) correspond to those time points, as well as local increases in f_oF_2.

According to Fig. 3b, there is a good coincidence between signals received by receivers with narrow and wide light filters. This allows us to assume that lidar signals have frequencies in the spectrum of sensing pulse, and the spectrum width does not exceed 1 nm.

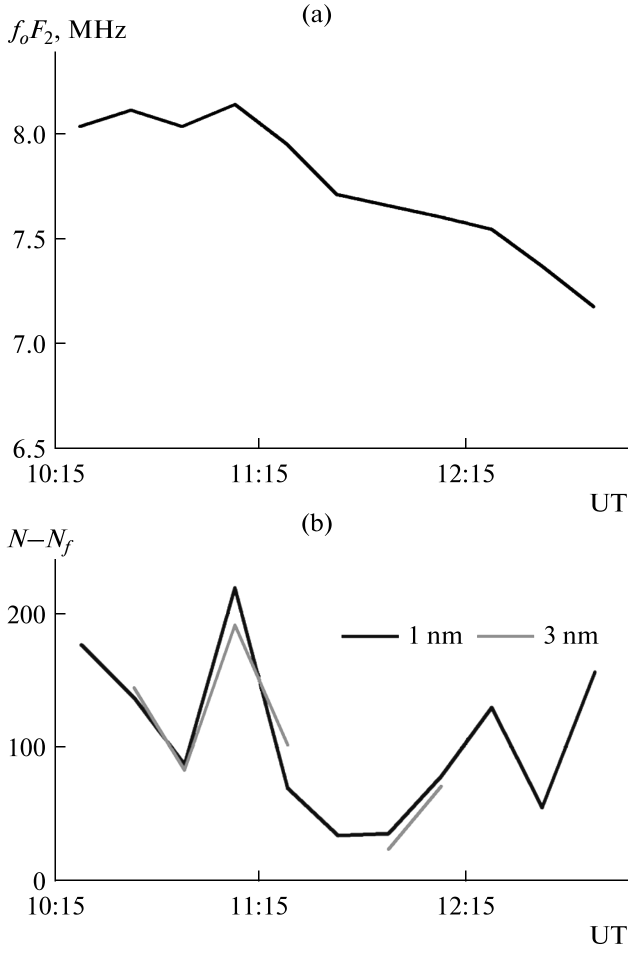

Fig. 3. (a) Critical frequency of the F_2 layer of the ionosphere f_oF_2 and (b) lidar signals with different grades of filtration summed over the 200–300 km region.

The testing of the atomic oxygen radiation spectrum and its ions, which dominate at F_2 altitudes, has shown that the nearest radiation lines of oxygen are located near 533 nm, and the atomic oxygen fails to affect noticeably the backscattering signal generation.

DISCUSSION

The second harmonics of an Nd:YAG laser has the radiation band (532.08 ± 0.07) nm. The search in database [4] has shown that three lines of dipole transitions of the atomic nitrogen ions from excited states with basic quantum number $n = 3$ fall in this band.

In [5], observation results on resonance scattering by N_2^+ ions within the 100–300 km altitude region are given. At an altitude of 200 km, $[N^+]$ (N^+ ion concentration) is approximately equal to $[N_2^+]$, and at an altitude of 300 km, $[N^+]$ exceeds $[N_2^+]$ by more than an

Dipole transitions of excited atomic nitrogen ions in the Nd:YAG laser radiation band

Component	Wavelength in air, nm	A_{ki}, s^{-1}	Lower level	Term	J	Upper level	Term	J
NII	532.0202	4.20e + 07	$2s2p^2(^4P)3p$	$^5P^0$	2	$2s2p^2(^4P)3d$	^5P	1
NIII	532.0870	5.68e + 07	$2s2p(^3P^0)3p$	^2D	5/2	$2s2p(^3P^0)3d$	$^2F^0$	7/2
NII	532.0958	2.52e + 07	$2s2p^2(^4P)3p$	$^5P^0$	1	$2s2p^2(^4P)3d$	^5P	2

A_{ki} is the probability of spontaneous transition, s^{-1}; J is the total moment of state.

order of magnitude [6]. Parameters of the lidar system [5] (mirror diameter of 100 cm, laser frequency of 20 Hz, summing over 5-km layers) differ little from our lidar (corresponding parameters are 60 cm, 10 Hz, 50- and 100-km layers, respectively). The same order of values of accumulated backscattering signals allows us to think that the scattering by atomic nitrogen ions within the 200–300 km range is quite possible.

The table shows frequencies of radiation lines of the atomic nitrogen ions within the radiation band of the Nd:YAG laser. The following standard designations are used [4]: NII denotes the single-ionized ion N$^+$, and NIII, twice-ionized ion N^{++}.

Figure 4 shows the upper half (starting from the spectrum half-height level) of the scheme of radiation lines of an atomic nitrogen ion relative to the radiation spectrum of the laser. The ion radiation bandwidth was calculated taking into account the Doppler broadening of lines at a temperature of 800 K.

The first of these lines is at the edge of the band (532.08 ± 0.07) nm, and two others fall in its center. All three transitions can claim the role of resonance scatterers; however, the first one will be excited less effectively than the third one, and the concentration of NIII (line *2*, N^{++}) is significantly lower than of NII (N$^+$).

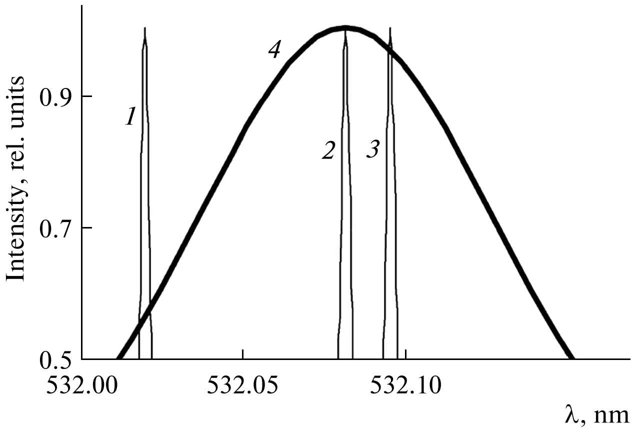

Fig. 4. Scheme of radiation lines of nitrogen ions relative to YAG:Nd laser spectrum: 532.0202 (*1*), 532.087(*2*), and 532.0958 nm (*3*); YAG:Nd (*4*).

The contribution of the third transition in the scattering observed can be maximal.

At altitudes of 200–300 km, atomic oxygen prevails. The O$^+$ concentration can be estimated as 10^4 cm^{-3} from the electron concentration of nighttime F_2 layer of the ionosphere. Main source of a N$^+$ ion is the reaction of O$^+$ with a N(^2D) atom, which is formed from dissociation of molecular nitrogen. Therefore, we can think that the concentration of N$^+$ is proportional to that of O$^+$ at altitudes of 200–300 km. It makes about 1% of the O$^+$ concentration [6] and can be accepted equal to 10^2 cm^{-3}. In this case, the cross-section of resonance scattering at a wavelength of 532 nm is proportional to the squared wavelength equal to 0.25×10^{-12} m^2. The estimates, taking into account the lidar system parameters, show that they correspond in order of magnitude to the signal observed [7].

CONCLUSIONS

A hypothesis about the participation of highly excited atoms and molecules in the generation of lidar returns from ionosphere altitudes was discussed in [1, 2]. No specific mechanisms of scattering by these objects were proposed. Following the additionally conducted studies, this hypothesis should be changed and specified. The conclusion should be drawn that the scattering of laser radiation with a wavelength of 532 nm in the upper atmosphere can be conditioned by the resonance scattering by excited atomic nitrogen ions with the main quantum number $n = 3$. The participation of highly excited atomic nitrogen ions in this process can be considered only under the condition that they will pass through the state with $n = 3$, including states shown in the table, during the cascade relaxation to the ground state.

This scattering takes place always, but it is weak under standard conditions. The constant signal component (about 100 photons per 15 min, see Fig. 1) can be stipulated among others by cutoff pulses as well. Signals accumulated for15 min were not corrected for aftereffects in order to conserve the reliability of the initial data. The scattering increases by several orders of magnitude during precipitation of soft electrons and can be detected from correlations with plasma content in the nighttime F_2 layer of the ionosphere.

ACKNOWLEDGMENTS

This work was financially supported by of the Far Eastern Branch of the Russian Academy of Sciences (Project no. 12-I-OFS-16), Siberian Branch of the Russian Academy of Sciences (Integration Project no. 106), and the Russian Foundation for Basic Research (grant no. 13-05-01036a).

REFERENCES

1. V. V. Bychkov and B. M. Shevtsov, "Dynamics of lidar reflections of the Kamchatka upper atmosphere and its connection with phenomena in the ionosphere," Geomagn. Aeron. (Engl. Transl.) **52** (6), 797–804 (2012).
2. V. V. Bychkov, Yu. A. Nepomnyashchii, A. S. Perezhogin, B. M. Shevtsov, and N. M. Polekh, "Lidar returns from the upper atmosphere of Kamchatka according to observations in 2008," Atmos. Ocean. Opt. **27** (4), 297–302 (2014).
3. M. G. Deminov, "Earth's ionosphere," in *Plasma Heliophysics*, Ed. by L.M. Zelenyi and I.S. Veselovskii (Fizmatlit, Moscow, 2008), Vol. 2 [in Russian].
4. http://physics.nist.gov/PhysRefData/ASD/lines_form.html
5. R. L. Collins, L. Su, D. Lummerzheim, and R. A. Doe, "Investigating the auroral thermosphere with N_2^+ lidar," in *Proc. of the Meeting "Characterising the Ionosphere"* (RTO, Neuilly-sur-Seine, 2006), pp. 2-1–2-14.
6. P. G. Richards, "Reexamination of ionospheric photochemistry," J. Geophys. Res., A **116** (08307) (2011).
7. V. V. Bychkov, Yu. A. Nepomnyashchiy, A. S. Perezhogin, and B. M. Shevtsov, "Lidar returns from the upper atmosphere of Kamchatka on observations in 2008–2014," Earth, Planets Space **66** (150) (2014). doi 10.1186/s40623-014-0150-6

Translated by S. Ponomareva