Resonance scattering at excited atoms and ions of the upper atmosphere as a possible mechanism for ionosphere investigations

Vasily V *Bychkov; Yuri A Nepomnyashchiy; Andrey S Perezhogin; Boris M Shevtsov;*

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

ABSTRACT

According to the results of lidar observations in 2014, new experimental data are presented. They confirm the possibility of correlation of lidar signals backscattering at the wavelength of 532 nm with the parameters determining plasma content in the nighttime ionospheric F2 layer. The possibility of application of the lidar method in ionosphere investigations is discussed. The physical basis of this method may be the resonance scattering on the exited atoms and ions of the upper atmosphere.

Keywords: lidar sounding, ionosphere, atmosphere, scattering

1. INTRODUCTION

According to the data of lidar and ionospheric observations on March 28, 2008, it was shown in the paper[1] that on that day the difference of a composite signal from the height region of 200-300 km, after the reduction of separately measured background signal, correlates with plasma content in the region of maximum of the nighttime ionospheric F2 layer. The papers[2-4] illustrate other experimental data confirming such correlations. Investigation of the geophysical conditions accompanying the phenomenon showed that correlation of the lidar signal from the upper layers of the atmosphere with ionosphere foF2 may occur both during geomagnetic disturbances and during magnetically calm conditions. It was shown that correlation of the lidar signals with ionosphere foF2 is always accompanied by the appearance of corpuscular Es layers. A possible mechanism explaining these correlations, resonance scattering at excited ions of nitrogen atoms appearing during electron precipitation into the ionosphere, is validated.

2. HARDWARE COMPLEX

Experimental data obtained at lidar and ionospheric stations, located in Paratunka (52.9N, 158E), Kamchatka, are applied. The hardware complex was described in the paper[2]. YG982E laser with the frequency of 10 Hz and the pulse energy of about 1 J for the wavelength of 532 was used in the observations of 2014. The receiving system was equipped with a telescope with a mirror diameter of 60 cm, Hamamatsu H8259-01 PMT and Hamamatsu M8784 photon counter. Optical filter with passband width at half maximum of 1 nm, transition of %T>65%, interlock in the region of 300-1100 nm E-5 was used. Background signal was measured from the 20th to the 24th ms with the step of 10 μs after each laser pulse. During the measurement of the background signal, the sounding pulse is in the region of the heights of 6000-6600 km, background signal does not contain aftereffect pulses and ensured by good data accumulation. The beginning of background measurement is set by software and, as our experience showed, may be set by any from the range of 10-95 ms after sending a pulse. Application of this method for noise measurement allowed us to detect weak signals from the upper atmosphere region at a well-averaged background.

3. OBSERVATIONS RESULTS

The most convincing case of increased scattering of laser light at a wavelength of 532 nm from the heights of the ionosphere and its correlation with foF2 was detected in 2008. Figure 1a,b shows the results obtained on 28 March 2008[1]. At night from 13:00 until 14:30 UT, an increase in critical frequency was observed in the F2 layer. A rise of the same shape was simultaneously observed for the lidar signal. The geomagnetic disturbance observed after the storm with a maximum on 26 March was recorded on the same night. The ionosonde registered sporadic E (Es) layers of corpuscular type at altitudes of 130 to 150 km with critical frequencies (foEs) of 1.5 to 1.6 MHz.

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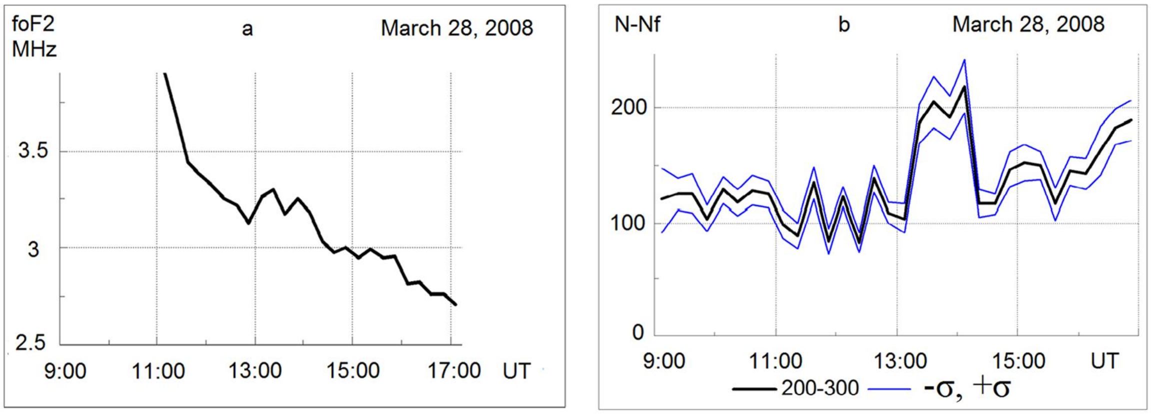

Fig. 1 Critical frequency of the ionospheric F2 layer and lidar signal. (a) Critical frequency of the ionospheric F2 layer (foF2) and (b) lidar signal S = N − Nf summed for altitudes of 200 to 300 km, where N is the total number of detected impulses and Nf is the noise level. The middle curve shows the average signal, and the upper and lower curves illustrate the total standard deviations.

An analogous cases was observed on September 5 and 6, on 10 November 2008[1-4] and on some others days.

During the geomagnetic disturbance on August 28-30, 2014, lidar sounding of the atmosphere at the wavelength of 532 nm was carried out on August 30 due to weather conditions. According to the data of IKIR ionospheric station, nighttime Es of corpuscular type were registered on August 29 and 30. Figures 2a, 2b show the observation results of ionosonde on August 30. Dots in Fig. 2a show foEs values. To be plotted on one graph with foF2, all foEs values are increased by 3 MHz. Lidar signal (N) was accumulated for 15 min and then averaged over 9 000 laser pulses. Fig. 2b presents lidar signal summed over the layers 150-200 and 200-300 km. The background signal (Nf) was averaged over 400 measurements from 20th to 24th ms after every laser pulse.

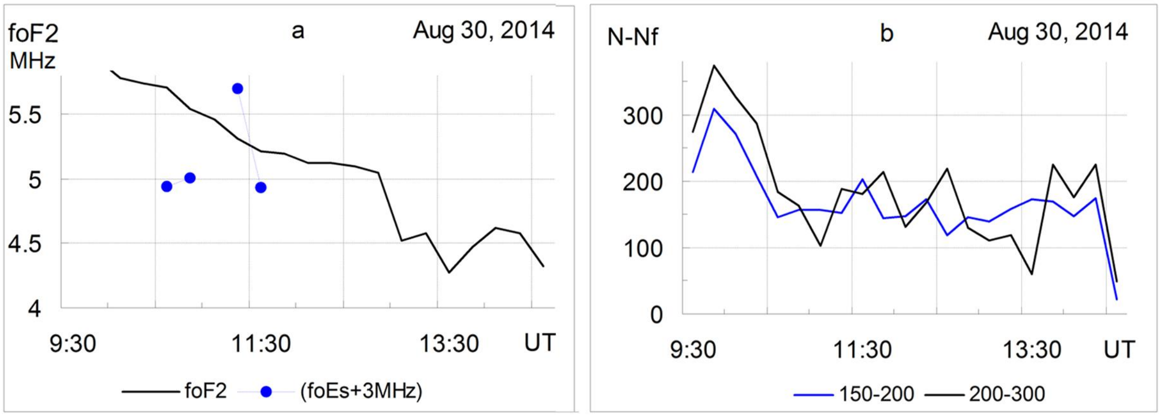

Fig. 2 Critical frequency of the ionospheric F2 layer and lidar signal. (a) Critical frequency of the ionospheric F2 layer (foF2) and (b) lidar signal S = N − Nf summed for altitudes of 200 to 300 km and of 150 to 200 km, where N is the total number of detected impulses and Nf is the noise level.

Correlation between the lidar signals from the layers of the upper atmosphere and ionosphere foF2 are observed within 12:00-13:30 and 13:30-15:30 UT. Corpuscular Es appeared at the heights of 100-114 km. Signals from the layers of 150-200 and 200-300 km have the correlation coefficient between each other equal to 0.78. High correlation with the coefficient of 0.81 was observed on that day between the composite signals from the layers of 200-300 and 300-400 km. The correlated behavior of lidar signals from different layers is not characteristic for the heights more than 100 km. In practical sense, correlated behavior of lidar signals from different layers is the most useful to apply this property of the lidar signals to detect cases of lidar signal correlations with ionosphere foF2. Also it may be used for qualitative evaluation of a precipitated particle spectrum.

Correlations of the lidar signal with foF2 values within 5 hours of observations were also observed on November 18, 2014. According to the data of geomagnetic observatory, all geomagnetic K-indexes were equal to zero. Lidar signal correlations with ionosphere foF2 during magnetically clam conditions on May 14, 2014 are described in the paper[4].

Analysis of the geophysical conditions accompanying the phenomenon showed that correlation of the lidar signal from the ionospheric heights with ionosphere foF2 may occur both during geomagnetic disturbances and during magnetically calm conditions. The phenomenon is always accompanied by the appearance of the night Es of corpuscular type. It may be caused by the appearance of the precipitations of soft electrons in the ionosphere at hundreds of electron-volts (eV) to kiloelectron-volts (keV).

Detection of this effect required good weather and an absence of the moon. We were able to perform observations in precipitations two to five times annually during 2008 to 2014.

4. DISCUSSION OF THE RESULTS

In the papers[3,4], correlations of lidar signals from large heights with plasma content in F2 are explained by resonance scattering at excited states of nitrogen atom ion with the principal quantum number of n=3. In Fig. 3, on the emission spectrum of solid Nd:YAG laser, emission lines of excited ion of nitrogen atom taken from the work[4] are shown.

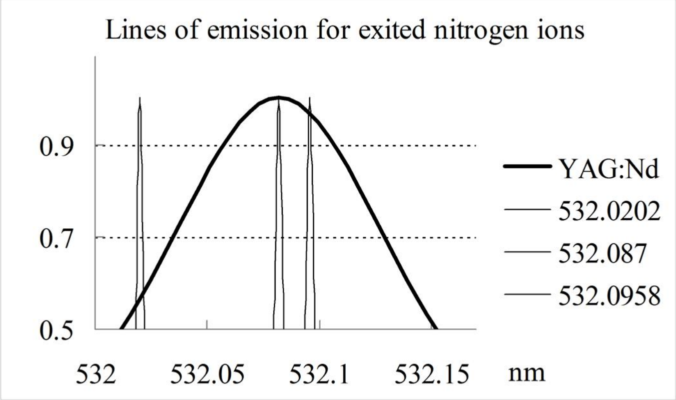

Fig. 3. Scheme of lines of emission for exited nitrogen ions relatively Nd:YAG laser spectrum

The laser emission spectrum width at the half height is 0.14 nm. The corresponding state terms are illustrated in the Table of the paper[4]. Line emission of nitrogen ions are calculated taking into account the Doppler broadening to a temperature of 800 K.

Contributions of each of these states into the lidar signal have not been determined yet. Experiments with the best frequency resolution of the received signals are required.

Lidar observations of the upper atmosphere may give new information on charged component distribution in the ionosphere with significantly better space resolution and improve the understanding of ionosphere structure. The main disadvantage of this method is a very weak lidar signal and poor signal/noise relation even at moonless nights. Mainly it is due to the low content of nitrogen atom ions falling within the emission band of solid lasers at the wavelength of 532 nm. The content of nitrogen atom ions in the region of 150-300 km is estimated as units of percent of total content by day and it is negligibly small at night. We succeeded to detect this scattering only on the nights when additional sources of ionosation appeared.

It is perspective to make lidar observations by a dye laser. For example, TDL-90 laser with YG-982E pumping laser (Quantel, France) may give emission with the energy of the order of 0.2 J in a pulse. Nevertheless, from the energy point of view there may be an advantage. According to Fig. 3, less than 10% of photons of a laser pulse of YG-982E laser may participate in the scattering on nitrogen atom ions at the wavelength close to 532 nm. At the same time, emission spectrum with of TDL-90 laser at the wavelength of 560 nm is equal to 0.025 nm, i.e. almost an order narrower.

Accordingly, the proportion of photons involved in the excitation will be higher. More considerable is the possibility to work at the frequencies corresponding to the transitions between the states of atoms or ions of atomic oxygen, the main ion in the region of F2 of the ionosphere. Table 1 shows two lines of atomic oxygen ion falling within the energy band of a laser operating on Rhodamine 590 dye.

Table 1. Dipole transitions of excited atoms and ions of oxygen in the laser emission band with Rhodamine 590 dye. OII – atomic oxygen ion O^+, J – full angular momentum number.

	Compo-nent	Wavelength Air (nm)	A_{ki} (s^{-1})	Lower Level	Term	J	Upper Level	Term	J
4	O II	558.3217	2,17e+06	$2s^22p^2(^1S)3s$	^2S	$^1/_2$	$2s^22p^2(^3P)4p$	$^2P°$	$^3/_2$
5	O II	561.1072	2,14e+06	$2s^22p^2(^1S)3s$	^2S	$^1/_2$	$2s^22p^2(^3P)4p$	$^2P°$	$^1/_2$

The maximum energy of a laser pulse for this dye is achieved when the laser is set to the wavelength of ~562 nm. When working on the lines shown, the pulse energy is more than 95% from the maximum.

6. CONCLUSIONS

The correlations of the lidar signal with ionosphere foF2 during soft electron precipitations into the ionosphere observed since 2008 have been validated during quite a long period of observations. The hypothesis on resonance scattering on atomic nitrogen ions is well-grounded and still do not have a decent alternative. The possibility of lidar investigations of the ionosphere in the frequency range of atomic oxygen seems real and requires experimental proof.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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