DOPPLER LIDAR WITH CO_2-LASER INTRACAVITY RECEPTION

A.P. Godlevskiĭ, E.P. Gordov, A.I. Zhiliba, and P.P. Sharin

Institute of Atmospheric Optics,
Siberian Branch of the Academy of Sciences of the USSR, Tomsk
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The possibilities of lidar with CO_2-laser intracavity reception in both laboratory measurements and the open atmosphere were studied. Retroreflections with amplitude up to 50 μт *from distances up to 500 m were recorded.*

Doppler-1ldar studies of the parameters of moving objects are usually performed using a heterodyne reception scheme.[1] In addition to this, a different version of supersensitive reception of the Doppler-lidar echo signal based on coherent laser reception Is under development.[2] Laboratory implementation of a Doppler lidar with reception on YAC:Nd^{3+} laser is reported in Ref. 3. In this paper we present the results of an investigation of Doppler lidar with reception on a CO_2 laser both in laboratory measurements and in the real atmosphere at distances of up to 500 m.

1. The basic idea of laser reception in the Doppler lidar system is that the echo signal to be analyzed is directed back into the laser cavity, where it mixes with the field inside the cavity. This makes it possible, under certain conditions, to rise quite significantly above the noise of the photoelectronic circuit. The main features of the dynamics of lasing In such a receiver-transmitter are described by the model of laser with an external mirror,[2] for which in our case we employ a reflecting surface,

$$I = -\left(C - \frac{\kappa}{1+\beta I} - \alpha\cos\Omega t\right) I, \qquad (1)$$

where I Is the dimensionless intensity of the field in the laser cavity, C is the cavity width, k and β are linear gain and saturation of the active laser medium, and a characterizes the propagation losses owing to incomplete reflection by the surface, scattering, and absorption on the section “output mirror of CO_2-laser – reflecting surface”. The value of α also depends on which part of the wave returning into the laser is matched with the cavity mode. Of course, for a CO_2-laser, in addition to Eq. (1). which describes the laser dynamics based on Lamb's model,[4] it would also be necessary to introduce an equation for the populations of the working levels. However this would not change the interpretation of the experimental data obtained. The dependence of the Doppler frequency shift Ω on the velocity v of the reflecting surface along the optical axis of the receiver-transmitter has the form

$$\Omega = \frac{4\pi v}{\lambda}. \qquad (2)$$

The velocity v varies periodically from zero to v_{max} as the reflecting surface oscillates. The intensity in the cavity changes correspondingly, namely, there appears a modulation having the form of repeating structures. At the turning point of the oscillatory motion of the surface, when $v = 0$, the direction of motion changes. According to Eq. (1) there are no beats at this moment. The interval between the vanishing of the beats corresponds to the half-period $T/2$ of the oscillations of the surface. The amplitude of the oscillations can be expressed in the form $x(t) = \int_0^{T/2} v(t)dt$ or $x(t) \approx \bar{v}\frac{T}{2}$, where $\bar{v}$ is the average velocity over a half-period. Bearing this in mind as well as the relation (2), we represent x In the form

$$x = \frac{T}{T_D}\frac{\lambda}{2} \qquad (3)$$

where T_D Is the period of the Doppler modulation of the intensity. Using Eqs. (2) and (3) we find x and v from the obtained oscillograms. We note that Eqs. (1) and (3) are inapplicable when the period of the Doppler modulation is equal to or less than the relaxation time of the field in the cavity $\sim C^{-3}$, because in that case the laser cannot follow the rapidly varying perturbation. The maximum recordable velocity is determined from the relation $v_{max} = \frac{\lambda}{2}v^{max}$. For a CO_2 laser $v^{max} \sim 10^8$ Hz, so that $v_{max} = 530$ m/s. The measurable amplitudes and velocities are also limited by the fluctuations of the index of refraction of the atmosphere, which result in fluctuations of the optical path length. If the characteristic period of these fluctuations is comparable to the period of the Doppler signal, then intensity beats will be present even if the reflecting target is stationary. It is well known that In the absence of precipitation the time scale of atmospheric turbulence T_0 is the order of 10^{-3} s, while

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in the presence of precipitation $T_0 = 10^{-4}$–10^{-5} s.[5] To record the minimum oscillations the effect of turbulence must be reduced by increasing the velocity of the target. For velocities $v > 5.3 \cdot 10^{-3}$ m/s under atmospheric conditions with no precipitation and $v > 5.3 \cdot 10^{-2}$ m/s with precipitation the effect of atmospheric turbulence can be neglected. The question of the accuracy and sensitivity of a Doppler lidar with laser reception will be discussed in detail in this paper.

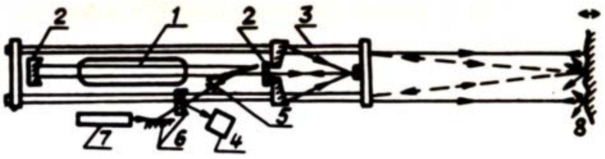

FIG. 1. The optical arrangement of the Doppler lidar setup: 1) gas-discharge tube of the CO_2 laser; 2) mirrors of the laser cavity; 3) Cassegrainian telescope; 4) photodetector (FSG-22-3A); 5) optical attenuators; 6) rotating mirrors; 7) He-Ne alignment laser; 8) target.

2. A diagram of the experimental setup is shown in Fig. 1. The setup consists of a CO_2 laser, the receiving-transmitting optical system, and the signal recording apparatus. A gas-discharge tube with a discharge gap length $l \sim 120$ cm was employed in the cw CO_2 laser; the output power of the CO_2 laser was equal to 18 W (P(20), $\lambda = 10.6$ μm). The laser cavity is of the Fabry-Perot type and 130 cm long. The cavity is formed by copper spherical mirrors (with a radius of curvature of 3 m) and a flat half-transmitting germanium mirror. An iris diaphragm was inserted into the cavity in order to select the transverse modes. The laser intensity was stabilized by reducing external mechanical perturbations of the cavity by placing the gas-discharge tube and all optical elements, including the receiving-transmitting system, on the same framework consisting of invar rods 2 cm in diameter, by reducing the instability of heat removal from the active medium, and by stabilizing the current supplied to the gas-discharge tube. The stabilizer made it possible to maintain a fixed current from 4 to 35 mA with an accuracy of up to 1% and to reduce the pulsation level to 0.2%. The optical system for transmitting and receiving radiation consisted of a Cassegrainian telescope with the principal mirror aperture of 15 cm and a focal length of 70 cm. Precise aiming and focusing on the object was performed, correspondingly, by fine adjustment of the principal mirror and by changing the position of the secondary mirror along the optical axis of the telescope. The part of the laser beam that is reflected from the window of the gas-discharge tube was focused with a spherical mirror having a focal length of 5 cm on a photodetector (FSG-22-3A). The signal from the photodetector was studied with the help of an oscillograph and ROBOTRON-01012 and SK-4-56 spectrum analyzers. In addition, the output signal of the photodetector was fed through am acoustic frequency amplifier to a headphone. Measuring the output radiation of the laser in this manner is convenient for adjusting "by ear" the optical elements of the system, for setting the optical level of excitation of the laser, and for detecting the object of interest.

3. The measurements were performed both in the laboratory at a distance of 3 m and in the open atmosphere at distances of 20, 110, and 500 m. The targets consisted of objects with different reflectances. They were subjected to vibrations with the help of a powerful dynamic head, amplifier, and acoustic-frequency generator. Continuous regulation of the frequency and amplitude of vibrations made it possible to obtain a Doppler signal in the frequency band from 1 to 20 kHz. A simulator of a rectilinearly moving object was used to observe slow vibrations with high amplitude.[6] It consists of an Archimedes spiral, made of a sheet of duralumin. As the spiral executed uniform reversible rotation around the axis it simulated the reciprocal motion of the surface. When a light wave is incident normally on such a surface the reflected wave acquires a Doppler frequency shift equal to $\frac{\lambda}{2}(r_{max} - r_{min})f$, where r_{max} and r_{min} are, respectively, the maximum and minimum radii of spiral and f is the rotational frequency of the shaft of the spiral. Figure 2a shows a typical oscillogram of the beats of the laser intensity, obtained with reflection from an aluminum foil oscillating harmonically with a frequency of 100 Hz. The distance from the laser system to the reflector was equal to 20 m. The bottom beam shows the voltage proportional to the law of motion of the reflector. It is obvious that the beats represent a frequency-modulated signal without the carrying frequency, which is proportional to the velocity of the target. Indeed, at the peaks of the sinusoid, when the velocity is equal to zero and the direction of motion of the surface is reversed, the beats vanish. The interval between the vanishing of the beats corresponds to one-half the period of the oscillations of the target. The total number of fringes in this interval indicates the amplitude of the oscillations In units of one-half the wavelength of the laser. Thus the oscillogram presented indicates oscillation of the object with a frequency of 100 Hz and a maximum amplitude of 26.5 μm. A Doppler frequency of the order of –2.5 kHz corresponds to a maximum velocity of the reflector equal to ~ 1.32 cm/s. As an example of the recording of slow oscillations with high amplitude. Fig. 2b shows an oscillogram illustrating a 5-ms fragment of the Doppler signal from the simulator. The total number of fringes, equal to 45 over the observation time, indicates a displacement amplitude of ~ 0.25 mm. The velocity is of the order of ~ 4.8 cm/s.

In the next series of laboratory experiments, consisting of numerous measurements of the amplitude of the Doppler signal from the reflector oscillating with a constant frequency and an amplitude of the order 10λ, we studied the dependence of the amplitude of the beats on the power of the radiation returning into the laser. In these experiments the telescope was removed and the radiation was attenuated with the help of targets with known reflectances. Figure 3 shows the dependence of the normalized signal amplitude on the effective reflectance of the target. As one can see from the graph, the amplitude of the beats is proportional to the square root of the power of the reflected radiation. The minimum observable power was equal to $4.0 \cdot 10^{-13}$ W/Hz$^{1/2}$.

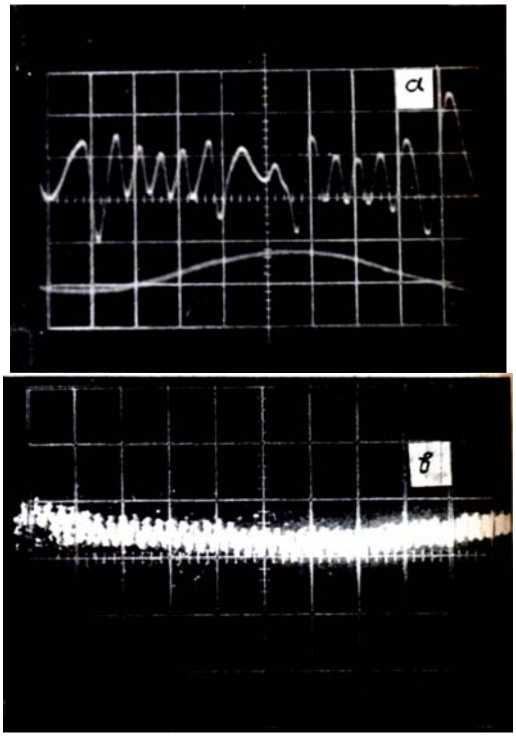

FIG. 2. Oscillograms of the beats of the laser intensity: a) from, aluminum foil oscillating with a frequency of 100 Hz (top beam) and the voltage proportional to the law of motion of the foil (bottom beam). The sweep is 1 ms/division and the horizontal scale is 100 mV/division, b) from the simulator of a rectihnearly moving object (5-ms fragment of the Doppler signal). The sweep is 0,5 ms/division and the horizontal scale is 20 mV/division. The distance from the laser system to the object is equal to 20 m.

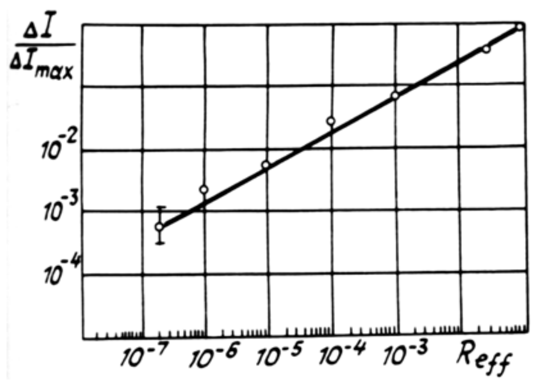

FIG. 3. The normalized amplitude of the Doppler signal versus the effective reflectance, characterizing the power returning to the laser.

TABLE I

The dependence of the SNR on the target distance

Target	SNR, dB		
	Distance, m		
	1	110	500
Aluminum mirror	93-96	63-65	32
Duralumin plate with rough surface	63	42	20
Uneven aluminum foil	67	29-32	15
Wood surface	40	22	9
Cardboard	43	20	-
Emery paper (d > 1 mm)	32	19	-
Emery paper (d < 1 mm)	30	15-16	-

The atmospheric studies included measurements of the attenuation of the signal and fluctuations of the signal. The results of the measurements of the SNR for seven objects with different reflectances and roughness are presented in Table I. The objects were located at distances of 3, 110, and 500 m from the laser system. The noise level was set by covering the laser beam after the telescope. The diameter of the collimated beam at the target at distances of 110 and 500 m was equal to about 18 and 28 m, respectively. The angle of Incidence of the laser beam on the target relative to the normal to the target surface was not monitored, but in all measurements it did not exceed 30° (in both planes). It is evident from Table I that at a distance of 30 m the SNR is correlated with the reflectance of the target, and it reaches its maximum value for reflection from metallic surfaces with specular and specularly diffuse reflection. The decrease in the SNR as the distance from the aluminum reflector increased amounted to ~ 0.044 dB/m, while for the two other metallic targets with rough surfaces it amounted to, on the average, ~ 0.07 dB/m. The attenuation of the signal from the other targets with diffuse reflection reached values of the order of ~ 0.14 dB/m. When the beam was focused on a duralumin sheet, placed at distances of 110 and 500 m, the SRN increased by factors of 15 and 9, respectively, compared with the values measured with a collimated beam. On the whole the significantly stronger attenuation of the signal than In the case of quadratic attenuation could be connected with the increase in the beam size and a change in the effect of the roughness as the distance increases.

Figure 4a shows an oscillogram of the Doppler signal from a duralumin target with a rough surface.

The target oscillated with a frequency of 45 Hz and was placed 110 m from the laser system.

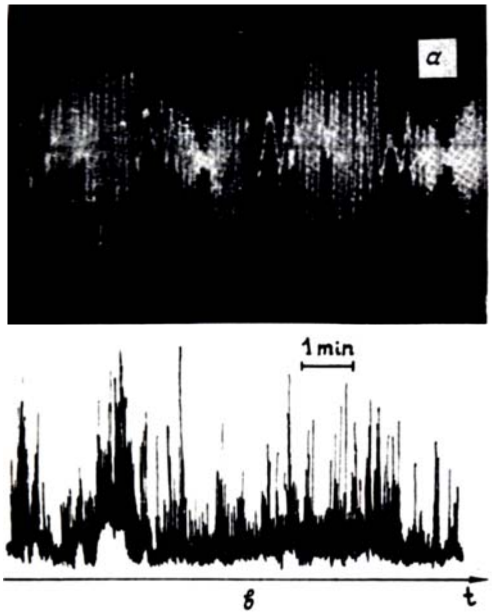

FIG. 4. Oscillogram of the echo signal: a) from a duralumin target placed 100 m from the laser system. The sweep is 5 ms/division and the horizontal scale is 10 mV/'division; b) from a duralymin target rocking under the action of air mot ion.

The observed strong temporal variations of the amplitude of the Doppler signal are caused by two effects: variation of the speckle structure on the target and atmospheric turbulence. One can see from Fig. 4a that the frequency of the variations caused by these effects is significantly lower than the Doppler frequency, which In this case is of the order of 1.3 kHz. The degree of modulation reached 80%. Weaker low-frequency variations of the signal amplitude with degrees of modulation of up to 20% were observed on reflection from the specular target. They are apparently caused by atmospheric turbulence. In addition to measuring the amplitude and velocity of the reflecting surface moving under the action of regular perturbations we also recorded the Doppler signal from wind-rocked objects. Figure 4b shows a tracing of the envelope of the Doppler signal from a duralumin sheet suspected at a distance of 110 m from the laser system. The bandwidth of the electric channel was equal to 0.5–1 kHz. The observed strong fluctuations of the signal are caused mostly by the disorientation of the reflecting surface of the object relative to the optical axis of the laser beam owing to the significant relative magnitude of the specular component of the reflection rather than drift of the signal frequency outside the band of the electric channel. Under the same conditions, the fluctuations of the signal from the wood target, having a wide reflection pattern, were significantly smaller.

Thus the main result of our investigation of a Doppler lidar with laser reception is that we recorded the oscillations of topographic objects with an amplitude of 50 μm at distances of up to 50 m in the atmosphere. This was made possible by the fact that the intensity of the CO_2 laser was stabilized and the Doppler lidar with laser reception had a high dynamic sensitivity and low noise sensitivity.

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