Multi-aperture coherent reception in the turbulent atmosphere

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The signal-to-noise ratio for the multi-aperture coherent reception of lidar return signals from a turbulent atmosphere is analyzed. The efficiency factor of the multi-aperture reception has been calculated for different intensities of turbulence. It is shown that with a large number of subapertures the coherent reception is the most effective from short paths of sounding under weak turbulence and at extended paths under strong turbulence.

Introduction

A possibility of increasing the signal-to-noise ratio by use of a coherent detection of light with multi-aperture systems has been investigated in Refs. 1–3. Several methods of such reception are known. It is shown in Ref. 1 that the most effective among these methods is the method of maximum ratio (MR). The main idea of the method is as follows. The radiation propagated along an atmospheric path is received by a set of receiving apertures separated in space and after mixing with a reference radiation it arrives at photodetectors that are in the focal planes of the subapertures. As a result, in the detectors the photocurrent components arise with the frequency equal to the difference of frequencies of received and reference beams. Because the received radiation is not completely coherent spatially the photocurrent components at the difference frequency have different phases. After phasing and multiplication of the photocurrents by the gains that are proportional to photocurrent amplitudes at every detector they are added. At a poor spatial coherence of received radiation when the coherence radius of incident wave ρ_c is found to be essentially smaller then the dimension of a receiving aperture the change of the single-aperture reception for the reception with several subapertures, each being of a smaller size, while making up the equivalent total area allows one to improve the efficiency heterodyning and increase the signal-to-noise ratio with this method.[1,3]

In Ref. 3 for the coherent reception of a lidar signal the dependences of the gain $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ are found, where $\langle CNR_\Sigma\rangle_{\rm MR}$ is the average value of the signal-to-noise ratio for the multi-aperture reception by the method of maximum ratio and $\langle CNR_0\rangle$ is the average value of the signal-to-noise ratio for the reception by a single aperture from the number of subapertures N for different ratios of the total area of a receiver $A_{R,O}$ to the coherence area $A_c = \pi\rho_c^2$.

Results obtained in Ref. 3 neglect the effect of the atmospheric turbulence. In the atmosphere the turbulent inhomogeneities of the air refractive index cause an essential worsening of the spatial coherence of received wave field and, as a result, a decrease of the efficiency of heterodyning and a fall of the signal-to-noise ratio. In the case of monostatic optical arrangement of the detection and ranging the use of results from Ref. 3 to calculate the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ allowing for the turbulence in calculations of the coherence area A_c is incorrect because the correlation of waves propagating forward and backward is neglected.[4] In this paper the efficiency of multi-aperture coherent reception of a lidar return signal from the turbulent atmosphere is investigated. Using numerical simulation, the average values of the signal-to-noise ratio are calculated for the case of reception by the method of maximum ratio.

1. Formulae for the mean signal-to-noise ratio and the reception geometry

In case of a coherent reception of return signals with a single telescope the mean signal-to-noise ratio $\langle CNR_0\rangle$ is described by the following expression[5]:

$$\langle CNR_0\rangle = \frac{\eta}{h\nu B}\frac{1}{P_0}\langle\Big|\int\limits_{A_0} d^2\rho\, E_s(\rho, t)\, E^*_{LO,0}(\rho)\Big|^2\rangle, \quad (1)$$

where η is the quantum efficiency of the detector; $h\nu$ is the photon energy; B is the receiver's transmission band; P_0 is the reference beam power; $E_s(\rho, t)$ is the complex amplitude of the scattered wave at a time t; $E_{LO,0}(\rho)$ is the complex amplitude of the reference beam field. In expression (1) the integration is performed over the surface of a receiving aperture of the telescope A_0, the field $E_{LO,0}(\rho)$ is given in the form

$$E_{LO,0}(\rho) = \sqrt{\frac{P_0}{\pi a_0^2}}\exp\left\{-\frac{\rho^2}{2a_0^2}\right\}, \quad (2)$$

where a_0 is the reference beam radius.

For the reception of a return signal with N apertures using the method of maximum ratio the following formula for average value of the signal-to-noise ratio $\langle CNR_\Sigma\rangle_{\rm MR}$ has been obtained in Ref. 3:

$$\langle CNR_\Sigma\rangle_{\rm MR} = \frac{\eta}{h\nu B}\frac{1}{P_{LO,N}}\times$$
$$\times\sum_{i=1}^{N}\langle\,|\int_{A_i} d^2\rho\; E_s(\rho,t)\; E^*_{LO,i}(\rho)\,|^2\,\rangle, \qquad (3)$$

where it is proposed that the subapertures A_i have equal areas and all the reference beams have equal powers: $P_{LO,N} = P_0/N$. Let us present the amplitude of a field of the ith reference beam as

$$E_{LO,i}(\rho) = \sqrt{\frac{P_0}{\pi a_0^2}}\exp\left\{-\frac{(\rho-\rho_i)^2}{2a_0^2/N}\right\}, \qquad (4)$$

where the vector of position of the center of ith beam with the radius $a_0/N^{1/2}$ is determined as

$$\rho_i = \{2(n+1-2k)a_0/n,\; 2(n+1-2l)a_0/n\}, \qquad (5)$$

$i = k + n(l-1)$; $k, l = 1, 2, \ldots, n$; $N = n^2$. In the given geometry of receivers the sum $\sum_{i=1}^{N}$ in formula (3) corresponds to the double sum $\sum_{k=1}^{n}\sum_{l=1}^{n}$.

In future we will consider that $A_i \gg \pi a_0^2/N$ (for example, the radius of subaperture a_t is larger two times of a_0 and a_t/n exceeds so many times a_0/n). Then in the expressions (1) and (3) the integrals $\int_{A_0} d^2\rho$ and $\int_{A_i} d^2\rho$ can be replaced by $\int_{-\infty}^{+\infty} d^2\rho$ without any essential loss in accuracy.

As a result from Eqs. (1)–(5) for the efficiency factor of multi-aperture reception, which is determined as the relation $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$, we have

$$\frac{\langle CNR_\Sigma\rangle_{\rm MR}}{\langle CNR_0\rangle} =$$
$$= N\frac{\sum_{i=1}^{N}\left\langle\left|\int_{-\infty}^{+\infty} d^2\rho E_s(\rho,t)\exp\left\{-\frac{N}{2a_0^2}(\rho-\rho_i)^2\right\}\right|^2\right\rangle}{\left\langle\left|\int_{-\infty}^{+\infty} d^2\rho\, E_s(\rho,t)\exp\left\{-\frac{1}{2a_0^2}\rho^2\right\}\right|^2\right\rangle}. \qquad (6)$$

Let us consider two limit cases when the coherence radius ρ_c of the wave, which is incident at the receiving aperture of a telescope, satisfies the following conditions: 1) $\rho_c \gg a_0$ and 2) $\rho_c \ll a_0/n$. In the first case for $E_s(\rho, t)$ in Eq. (6) we can neglect the dependence on ρ and then $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle = 1$. When the condition $\rho_c \ll a_0/n$ is satisfied we can use in Eq. (6) for the coherence function $\langle E_s(\rho_1,t)\,E_s^*(\rho_2,t)\rangle$ the approximation $\langle E_s(\rho_1,t)\,E_s^*(\rho_2,t)\rangle \sim \delta(\rho_1-\rho_2)$. As a result we have $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle = N$. Thus, the value of the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ is form 1 to N and the relative efficiency of a multi-aperture reception increases with the deteriorating coherence of a scattered wave.

In the case of pulsed sounding radiation scattered on aerosol particles the complex amplitude $E_s(\rho, t)$ of the field entering into Eq. (6) is determined by the expression[5,7]

$$E_s(\rho,t) = \lambda\sum_{m=1}^{M_p} A_m\, e^{j\psi_m} E_T(z_m,\rho_m,t)\, G(z_m,\rho_m;0,\rho), \qquad (7)$$

where λ is the wavelength; A_m is the amplitude of backscattered wave; $\{z_m, \rho_m\}$ is the coordinate of the mth particle; M_p is the number of particles; ψ_m is the initial phase of wave scattered by the mth particle; G is the Green's function;

$$E_T(z_m,\rho_m,t) = \int d^2\rho' E_T(0,\rho',t-2z_m/c)\, G(0,\rho';z_m,\rho_m) \qquad (8)$$

is the complex amplitude of a field of sounding pulse. We will consider that the initial radius of sounding beam coincides with the radius of the reference beam for the single-aperture reception. Then

$$E_T(0,\rho',t') = \sqrt{\frac{P_T(t')}{\pi a_0^2}}\exp\left\{-\frac{\rho'^2}{2a_0^2}\right\}, \qquad (9)$$

where $P_T(t)$ is the instantaneous power; $\int_{-\infty}^{+\infty} dt' P_T(t') = U_p$ is the energy of a sounding pulse.

We present the average value $\langle CNR\rangle$ in the formula (6) as $\langle\,\overline{CNR}\,\rangle_{\rm turb}$, where the bar means the averaging over turbulent fluctuations of the air refractive index, which cause the stochastic form of Green's functions in the formulae (7) and (8). As a result, from expressions (6)–(9) we can obtain the expression for the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ as

$$\frac{\langle CNR_\Sigma\rangle_{\rm MR}}{\langle CNR_0\rangle} = N\frac{\sum_{i=1}^{N}\int_{-\infty}^{+\infty} d^2\rho''\langle I_T(R,\rho'')\; I_{N,i}(R,\rho'')\rangle_{\rm turb}}{\int_{-\infty}^{+\infty} d^2\rho''\langle I_T(R,\rho'')\; I_{1,1}(R,\rho'')\rangle_{\rm turb}}, \qquad (10)$$

where

$$I_T(R,\rho'') = \left|\int_{-\infty}^{+\infty} d^2\rho'\exp\left\{-\frac{\rho'^2}{2a_0^2}\right\} G(0,\rho';R,\rho'')\right|^2 \qquad (11)$$

is the normalized intensity of a sounding beam; $R = ct/2$ is the distance from a lidar to the center of a volume sounded, c is the speed of light;

$$I_{N,i}(R,\rho'') = \left|\int_{-\infty}^{+\infty} d^2\rho\exp\left\{-\frac{N}{2a_0^2}(\rho-\rho_i)^2\right\} G(0,\rho;R,\rho'')\right|^2 \qquad (12)$$

is the normalized intensity for the ith reference beam when it propagates from the ith subaperture to the plane of scattering. It is obvious that in the case of monostatic optical arrangement of the detection and ranging which is considered here the reference beam intensity for the single-aperture reception $I_{1,1}(R, \rho'')$ completely coincides with the intensity of sounding beam $I_T(R, \rho'')$.

2. Calculated results

For analysis of the efficiency of multi-aperture sounding we restrict ourselves to consideration of the vertical and slant sounding paths when we can use the approximation of phase screens supposing in Eqs. (11) and (12) that

$$G(0, \rho'; R, \rho'') = G_0(0, \rho'; R, \rho'')\, e^{j\psi_t(\rho')}$$

and $G(R, \rho''; 0, \rho) = G_0(0, \rho; R, \rho'')\, e^{j\psi_t(\rho)}$,

where $G_0(0, \rho'; R, \rho'') = \dfrac{k}{2\pi jR} \exp\left\{j \dfrac{k}{2R} (\rho' - \rho'')^2\right\}$ is the Green's function in a homogeneous medium; $k = 2\pi/\lambda$; ψ_t is the phase shift caused by the turbulent inhomogeneities of the refractive index.

First we find the ratio $\langle CNR_\Sigma\rangle_{MR} / \langle CNR_0\rangle$ neglecting the correlation between the intensity of a sounding beam $I_T(R, \rho'')$ and the reference beam $I_{N,i}(R, \rho'')$ supposing in Eq. (10) that $\langle I_T\, I_{N,i}\rangle = \langle I_T\rangle \langle I_{N,i}\rangle$ and $\langle I_T\, I_{1,1}\rangle = \langle I_T\rangle \langle I_{1,1}\rangle$. As a result, we have

$$\frac{\langle CNR_\Sigma\rangle_{MR}}{\langle CNR_0\rangle} = \frac{N[1 + \Omega(1 + 4a_0^2/\rho_c^2)]}{1 + N\Omega(N + 4a_0^2/\rho_c^2)} \times \left[\sum_{i=1}^{n} \exp\left\{- \frac{4(n + 1 - 2i)^2}{1 + N\Omega(1 + N + 4a_0^2/\rho_c^2)}\right\}\right]^2, \quad (13)$$

where $N = n^2$ is the number of subapertures; $\Omega = (R/ka_0^2)^2$; ρ_c is the coherence radius of scattered wave in the plane of reception; $\rho_c^{-2} = \rho_{cv}^{-2} + 2\rho_{ct}^{-2}$,

$$\rho_{cv} = 2a_0/(1 + \Omega^{-1})^{1/2} \quad (14)$$

is the coherence radius in a homogeneous medium,

$$\rho_{ct} = (1.46k^2C_n^2(0)z_{eff})^{-3/5} \quad (15)$$

is the coherence radius of a plane wave in the turbulent atmosphere; C_n^2 is the structure characteristics of turbulent fluctuations of the air refractive index; $z_{eff} = \int\limits_0^\infty dz\, C_n^2(z)/C_n^2(0)$ is the effective depth of the turbulent layer of the atmosphere.

It follows from Eq. (13) that if the conditions $(N + 8a_0^2/\rho_{ct}^2)\Omega \ll 1$ and $N \gtrsim 4$ hold, in the case of short sounding paths, we have

$$\langle CNR_\Sigma\rangle_{MR} / \langle CNR_0\rangle = c_1 N, \quad (16)$$

where $c_1 = (\pi/8)\, [\mathrm{erf}(2)]^2 \approx 0.389$. Note that in this case the coherence radius $\rho_c \approx \rho_{cv} \approx 2R/(ka_0)$ is significantly smaller than the radius of a single reference beam $a_0/N^{1/2}$. Nonetheless, the coefficient c_1 in Eq. (16) is smaller than 1 that is related to the effect of sphericity of the average phase front of scattered wave within the reference beams which have the plane phase fronts.

The case of long paths when $\Omega \gg 1$ (the far diffraction zone of a sounding beam) is of primary practical interest. In this case, according to Eq. (14), the coherence radius in homogeneous medium ρ_{cv} in the limit equals to the initial diameter of a sounding beam $2a_0$, and the average phase front of the scattered wave can be considered as a plane one. For the case $\Omega \gg 1$ we obtain from Eq. (13) that

$$\frac{\langle CNR_\Sigma\rangle_{MR}}{\langle CNR_0\rangle} = \frac{N(1 + 4a_0^2/\rho_c^2)}{N + 4a_0^2/\rho_c^2}, \quad (17)$$

where $\rho_c^{-2} = (2a_0)^{-2} + 2\rho_{ct}^{-2}$.

Let us consider the case when the spatial coherence radius ρ_c is much larger than the diameter of a single reference beam $2a_0/N^{1/2}$, i.e., the condition $N \gg 4a_0^2/\rho_c^2$ is satisfied. In this case from Eq. (17) we obtain $\langle CNR_\Sigma\rangle_{MR} / \langle CNR_0\rangle = 2(1 + 4a_0^2/\rho_{ct}^2)$. Under weak turbulence, ($a_0 \ll \rho_{ct}$) the use of a multi-aperture system provides for an increase in the signal-to-noise ratio as compared with the case of a lidar with a single receiving aperture by 2 times only. With the growth of the turbulence intensity the coherence of scattered wave and the efficiency of heterodyning of the reception on a single aperture worsen and, as calculations neglecting the correlation of the counter propagated waves show, the value $\langle CNR_0\rangle$ monotonically decreases. In this case, if the condition $\rho_c \gg 2a_0/N^{1/2}$ holds, the signal-to-noise ratio for the multi-aperture reception remains unchanged. Thus, the stronger the turbulence the larger the ratio $\langle CNR_\Sigma\rangle_{MR} / \langle CNR_0\rangle$ is, which equals to $8a_0^2/\rho_{ct}^2$ at $\Omega \gg 1$ and $8a_0/N^{1/2} \ll \rho_{ct}^2 \ll 8a_0^2$, as it follows from Eq. (17).

If the coherence radius is much smaller than the radius of a reference beam ($\rho_c \ll a_0/N^{1/2}$), then from Eq. (17) we have $\langle CNR_\Sigma\rangle_{MR} / \langle CNR_0\rangle = N$. It conforms to the conclusion drawn above from analysis of the relationship (6) in the case of the smallest coherence radius ρ_c and directly follows from equation (13) for $\rho_{ct} \to 0$.

The approximation of independent intensities in the numerator of formula (10) $\langle CNR_\Sigma\rangle_{MR}$ used to obtain Eq. (13) does not lead to any essential loss of accuracy in the general case too, especially at $N \gg 1$. Therefore we can use this approximation to estimate $\langle CNR_\Sigma\rangle_{MR} / \langle CNR_0\rangle_{|\mu_T = 0}$, where $\mu_T = (2a_0/\rho_{ct})^2$, $\langle CNR_0\rangle_{|\mu_T = 0}$ is the signal-to-noise ratio for the reception with a single aperture in the case of $\mu_T = 0$ ($\rho_{ct} = \infty$). Let us find the number of subapertures N when at $\Omega \gg 1$ the signal-to-noise ratio will be the same as for the reception with a single aperture but in the absence of turbulence. By setting the relation $\dfrac{\langle CNR_\Sigma\rangle_{\rm MR}}{\langle CNR_0\rangle_{\,|\mu_T=0}} = \dfrac{2N}{1+N+2\mu_T}$ to unity we find that

$$N = 1 + 2\mu_T. \qquad (18)$$

For a lidar with $\lambda = 2$ μm and $a_0 = 7.5$ cm for $C_n^2(0) = 10^{-13}$ m$^{-2/3}$ and $z_{\rm eff} = 500$ m when the effect of turbulence on the signal-to-noise ratio is eliminated the number of subapertures equals, in accordance with the equation (16), to about 100.

The denominator in formula (10) can be presented as

$$\int d^2\rho'' \,\langle I_T(R,\rho'')\rangle^2\, [1 + \sigma_I^2(R,\rho'')] ,$$

where σ_I^2 is the relative variance of the intensity fluctuations of a sounding beam. It is well known that under very strong turbulence ($\mu_T \gg 1$) the variance is $\sigma_I^2 \approx 1$. Hence, under conditions $\mu_T \gg 1$ and $N \gg 1$ the calculations by formula (13) will overestimate the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ by at least 2 times.

In order to take into account the correlation between the intensities I_T and $I_{N,i}$ in the expression (10) the numerical simulation of propagation of the beam passed through the turbulent phase screen was carried out. After obtaining 100 independent realizations of instantaneous distributions $I_T(R,\rho'')$ and $I_{N,i}(R,\rho'')$ by the formula (10) the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ was calculated.

Figure 1 presents the dependences of the $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ ratio on the number of subapertures N for a lidar with $\lambda = 2$ μm and $a_0 = 7.5$ cm for $z_{\rm eff} = 500$ m, and various $C_n^2(0)$. The points on the dashed lines are the calculation by the formula (13), and points on the solid lines are the result of the numerical simulation. The dependences of the efficiency factor of multi-aperture receiving system on the number of subapertures N when the turbulence is absent ($C_n^2 = 0$) presented in Fig. 1*a* qualitatively conform to the results obtained in Ref. 3 where different geometry of reception was considered. Comparison of the calculated results on $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ when correlation between the intensities I_T and $I_{N,i}$ is neglected (by the formula (13)) and when this correlation is taken into account (by the numerical simulation) presented in Figs. 1*b–d* shows that in several cases the correlation between the counter waves reduces the efficiency of multi-aperture reception by nearly 3 times (compare the dashed and solid curves).

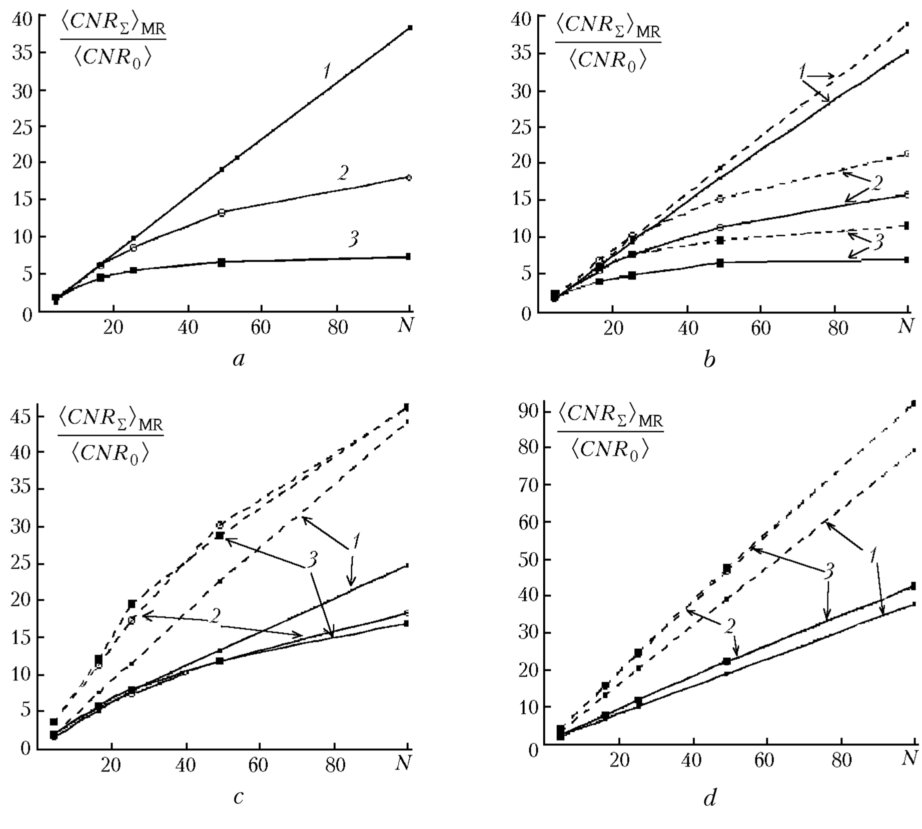

Fig. 1. Dependence of the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ on the number of apertures N for $C_n^2 = 0$ (*a*), $C_n^2 = 10^{-14}$ m$^{-2/3}$ (*b*), $C_n^2 = 10^{-13}$ m$^{-2/3}$ (*c*), and $C_n^2 = 10^{-12}$ m$^{-2/3}$ (*d*); $R = 1$ (*1*); 5 (*2*); 10 km (*3*).

Calculations by the formula (13) give the increase of the ratio $\langle CNR_\Sigma\rangle_{\rm MR} / \langle CNR_0\rangle$ with the growth of C_n^2 only. However, the results of numerical simulation where the correlation between waves propagating in the forward and backward directions is taken into account shows that in several cases the dependence of the factor $\langle CNR_\Sigma\rangle_{\rm MR} / \langle CNR_0\rangle$ on C_n^2 is non-monotonic. Figure 2 clearly illustrates this.

In particular, for the length of a sounding path of R = 1 km and N = 100 (curve *2* in Fig. 2) the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ first decreases with the growing C_n^2 and then it increases. We can explain such a behavior of $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ if we take into account that, on the one hand, the increase of C_n^2 causes a deterioration of the spatial coherence of received signal while, on the other hand, it causes more noticeable effect of the backscatter amplification at the reception with a single aperture.[6,7] For the parameters R = 1 km for λ = 2 μm, a_0 = 7.5 cm, and $z_{\rm eff}$ = 500 m the change of C_n^2 up to the values ($C_n^2 > 10^{-13}$ m$^{-2/3}$) will inessentially affect the coherence of received wave and, correspondingly, the quantity $\langle CNR_\Sigma\rangle_{\rm MR}$ changes weakly, whereas $\langle CNR_0\rangle$ increases owing to the effect of the backscatter amplification. Therefore, the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ in this case decreases with the increasing C_n^2. Further increase of C_n^2 ($C_n^2 > 10^{-13}$ m$^{-2/3}$) will finally cause an essential deterioration of the spatial coherence of scattered wave. The efficiency of the multi-aperture reception increases in this case.

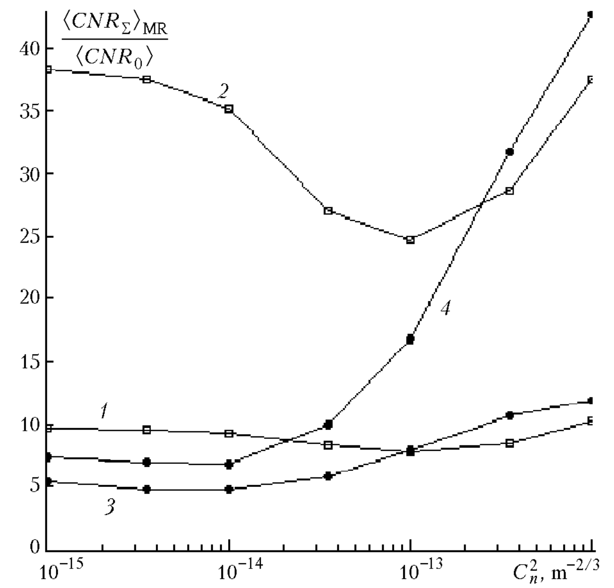

Fig. 2. Dependence of the ratio $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ on C_n^2; R = 1 (*1*, *2*); R = 10 km (*3*, *4*); N = 25 (*1*, *3*); N = 100 (*2*, *4*).

As follows from the data shown in Fig. 2 the use of a large number of receiving subapertures provides for the strongest effect in the case of short sounding paths under weak turbulence, and in the case of long paths it occurs under strong turbulence.

Conclusion

In this paper analysis of the signal-to-noise ratio for the multi-aperture coherent reception of a lidar return from the turbulent atmosphere is presented. Calculations of the efficiency factor for the multi-aperture reception in the turbulent atmosphere neglecting the correlation between sounding radiation and scattered radiation showed that $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ for a large number of subapertures N increases with the increasing intensity of turbulence. Owing to that in the turbulent atmosphere for a monostatic optical arrangement of sounding the effect of the backscatter amplification (due to correlation of the sounding and scattered radiation) is strongest in the case of reception with a single aperture, and for the multi-aperture reception it is practically absent the value $\langle CNR_\Sigma\rangle_{\rm MR}/\langle CNR_0\rangle$ has a nonmonotonic dependence on C_n^2 and in the case of short sounding paths the efficiency of the multi-aperture reception can be noticeably lower (up to 1.5 times) than in a homogeneous medium.

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