PROCEEDINGS OF ISAP '92, SAPPORO, JAPAN

NEAR-EARTH TURBULENT ATMOSPHERE EFFECT ON BEAM COHERENCY AND ANTENNA PARAMETERS OF MILLIMETER WAVES

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The two-frequncy spatially-temporal mutual coherence function of millimeter radiowaves in the turbulent boundary layer is studied. The analysis of the coherent property dependences on beam parameters, path characteristics and propagation conditions has been carried out. A comparison of obtained results with the experimental data has been conducted, and the near-earth atmosphere irregularities influence on antenna characteristics has also been investigated.

The performance of communication, radar and remote sensing systems is highly dependent on propagation conditions. The study of statistical characteristics of a wave beam in the turbulent boundary layer is of the great practical interest.

The most complete information about the medium influence on radiation parameters can be obtained on the base of two-frequency spatially-temporal mutual coherence function (MCF) [1,2]. The numerous experimental investigations showed [3] that the smooth perturbation method (SPM) can be used for theoretical study of millimeter (mm) wave propagation at the practical interesting near-earths paths (a distance up to 30 km). In the frame of considering model MCF can be written as

$$\Gamma_2(\vec{r}_1,\vec{r}_2,k_1,k_2,t_1,t_2)=\Gamma_2^0(\vec{r}_1,\vec{r}_2,k_1,k_2)\cdot\tilde{\Gamma}_2(\vec{r}_1,\vec{r}_2,k_1,k_2,t_1,t_2) \qquad (1)$$

where

Γ_2^0 -characterize the coherence properties in a homogeneous atmosphere,
$\tilde{\Gamma}_2=\langle \exp[\Phi(\vec{r}_1,k_1,t_1)+\Phi^*(\vec{r}_2,k_2,t_2)]\rangle$ -discribe the turbulence effect,
$\Phi(\vec{r},k,t)$ -is the complex phase.

As we showed in [4], the specific peculiarity of mm-band is different from zero mutual correlation of level and phase fluctuations under wave propagating in the near-earth turbulent layer, therefore the complex phase Φ is to be considered as the single random value.

Let the index of refraction is statistically homogeneous and isotropic, and its fluctuations is δ-correlated along the propagation direction. Using the Taylor's "frozen" turbulence hypothesis, after averaging we obtain the following expression for MCF in the first approximation of SPM for the Gaussian beam with the initial effective radius ρ_e

$$\tilde{\Gamma}_2(L,\vec{\rho}_1,\vec{\rho}_2,k_1,k_2,\tau)=\exp\Big\{2\pi^2\int_0^L dx\int_0^\infty \varkappa\, G_n(\varkappa)\big[(k_1H(P_{1*}))^2+ (k_2H^*(P_{2*}))^2+2k_1k_2H(P_{1*})H^*(P_{2*})J_0(\varkappa\mathcal{D})\big]d\varkappa\Big\} \qquad (2)$$

where vectors $\vec{\rho}_1$ and $\vec{\rho}_2$ determine the observation points in the reception plane $x=L$, G_n is the spectral density of the index of refraction fluctuations, $\vec{V}$ is the transverse velocity of irregularity transfer, $P(x)=x/(k\rho_e^2)$ is the beam wave parameter, J_0 is the Bessel function, $\tau=t_2-t_1$,
$H(P_*)=i\exp[-iP_*(L-x)\varkappa^2/(2k)]$, $P_*=(1+iP(x))/(1+iP(L))$,
$\mathcal{D}=\sqrt{(\rho_1^2P_{1*}-(\vec{\rho}_2\cdot\vec{\rho}_1)P_{2*}^*+(\vec{V}\cdot\vec{\rho}_1)\tau)^2+(|[\vec{\rho}_2\times\vec{\rho}_1]|P_{2*}^*-|[\vec{V}\times\vec{\rho}_1]|\tau)^2}/\rho_1$.

Expression (2) permit to study simultaneously the turbulence atmosphere effect on the radiation coherence in the time, space and frequency domain for different beam parameters, path characteristics and propagation conditions (in the sphere of validity of using model).

Note that in the first approximation of SPM the wave attenuation because of energy loss due to absorption and scattering is not taken into account. In this case it is convenient to discribe the radiation properties by means of complex coherence degree $\widetilde{\gamma}_2$ determined by the next expression

$$\widetilde{\gamma}_2(L,\vec{\rho}_1,\vec{\rho}_2,k_1,k_2,\tau)=\frac{\widetilde{\Gamma}_2(L,\vec{\rho}_1,\vec{\rho}_2,k_1,k_2,\tau)}{\sqrt{\widetilde{\Gamma}_2(L,\vec{\rho}_1,\vec{\rho}_1,k_1,k_1,0)\,\widetilde{\Gamma}_2(L,\vec{\rho}_2,\vec{\rho}_2,k_2,k_2,0)}}=$$
$$=\exp\Big\{2\pi^2\int_0^L dx\int_0^\infty \varkappa\, G_n(\varkappa)\big[2ik_1^2\,\mathrm{Re}(H(P_{1*}))\,\mathrm{Im}(H(P_{1*}))- \tag{3}$$
$$-2ik_2^2\,\mathrm{Re}(H(P_{2*}))\,\mathrm{Im}(H(P_{2*}))+2k_1k_2\,H(P_{1*})\,H^*(P_{2*})\,J_0(\varkappa\mathcal{D})-$$
$$-k_1^2|H(P_{1*})|^2 J_0(2i\varkappa\rho_1\,\mathrm{Im}\,P_{1*})-k_2^2|H(P_{2*})|^2 J_0(2i\varkappa\rho_2\,\mathrm{Im}\,P_{2*})\big]\,d\varkappa\Big\}$$

A von Karman two-parametric spectrum [1] modelling the saturation of the index of refraction fluctuations has been applied in calculations.

Fig.1 shows the numerical results of temporal complex coherence degree on the beam axis for the different path characteristics and turbulence conditions. The analisis of the dependencies has shown that coherence time $\tau_{c.*}$ increases as the parameter $\varkappa_{0*}=\sqrt{2\pi\lambda L}/L_0$ determined by the ratio of the first Fresnel zone to the outer scale of turbulence L_0 grows. This effect can take place under the decrease of the averege path height. The similar behaviour of $\tau_{c.*}$ is observed under weakening of radiation fluctuations the magnitude of which is discribed by parameter $\beta_0=1.3028C_n^2k^{7/6}L^{11/6}$ where C_n is the index of refraction structure constant. It has been established that at the long near-earth paths under the worst conditions the coherence time is shortened to tenths of second. It must be noted that the maximum values of $\tau_{c.*}$ are observed for a collimated beam. Therefore, the use of highly directive antenna in radiosystems permits to diminish the near-earth turbulent atmosphere influence.

The results of experimental investigations [5] carryed out in the short-wave part of the band ($\lambda\approx2$ mm) at 1 km and 2 km near-earth paths satisfactory agree with numerical culculations of the coherence time.

Fig.2 shows the absolute values of the spatial coherence function when one of the observation points is placed at the beam axis. Note, that when the space diversity does not exceed the normalized effective beam radius $\rho_{ef.*}=\rho_{ef.}/\sqrt{L/k}$, the magnitude of $|\widetilde{\gamma}_2(L,0,\rho_*)|$ for a collimated beam is greater then the one for the divergent beam with $P=100$ (curves 1 and 2 under $\rho_*\leq1.7$). Since in the reception plane the effective radius $\rho_{ef.*}$ equals $\sqrt{2}$ for $P=1$ then the further increase of ρ_* results in a considerable growth of level and phase fluctuations and, also, a faster decrease of $|\widetilde{\gamma}_2(L,0,\rho_*)|$ than for the beam with $P=100$, for which $\rho_{ef.*}\approx10$. Parameters β_0 and $\varkappa_{0*}$ substantially influence on the spatial coherence function as well as on $\widetilde{\gamma}_2(L,\tau_*)$. The value of ρ_{c*} is reduced as the fluctuation intensity and the average heigth of path are increased.

The numerical calculation analysis has revealed that the phase of the spatial coherence function is significant for a collimated beam especially under great diversity. The maximum values of $\arg \widetilde{\Gamma}_2 (L, 0, \rho_*)$ are observed when the size of the first Fresnel zone coincides with the outer scale size of turbulence. Just then the strongest correlation of level and phase fluctuation of wave takes place [4].

Spatial coherence disturbance can restrict the potential possibilities of receiving antenna systems. The calculation results of the spatial frequency characteristics $A(\nu_*)$ [6] obtained for two circle antennas under incident wave with ρ =100 and $C_n=10^{-6}$ m$^{-1/3}$, L =30 km, λ =2 mm are represented on Fig.3. The analysis of the dependencies showed that the near-earth turbulent atmosphere genarally decreases the spectral amplitude in the middle spatial frequency region, and besides, this effect is mostly significant for large apertures. Moreover, the near-earth layer irregularities may reduce the antenna gain. It has been found that the gain losses can reach to - 3dB and - 2,6 dB for aperture radii $R_* = R/\sqrt{L/k}$ =4 and R_*=2 under above-mentioned conditions and respectively - 0.8 dB and - 0.7 dB under λ =8 mm.

The results of calculation absolute value of the frequency coherence function are shown on Fig.4. In computing the parameters $\bar{\beta}_c$, $\bar{\varkappa}_{ck}$, $\bar{\rho}$ were determined for wave number $\bar{k} = \sqrt{k_1 \cdot k_2}$. The analysis of obtained dependencies has revealed that turbulence strengthening, the path distance increase, the wave length decrease result in narrowing of the coherence bandwidth. The similar effect takes place under the average path height growth. The maximum values of the coherence bandwidth are observed for a collimated beam. It has been found that $\arg \widetilde{\Gamma}_2 (L, \bar{k}, \vartheta)$ reaches the maximum magnitudes as well as spatial coherence when the size of the first Fresnel zone coincides with the outer scale size of turbulence.

The analysis of the carried out study has permited to determine the frequency band when the near-earth atmosphere does not restrict the signal bandwidth of radiosystems. When the mm-radiation is propagating in the turbulent boundary layer (not interacting with the surface) the coherence bandwidth exceeds 10 GHz. The short pulse ($\tau \approx 3$ ns) propagation experiments obtained at 4 km line-of-sight in the long-wave part of the band (λ_1=9 mm and λ_2=7.4 mm) have shown [7] that the near-earth turbulent atmosphere does not distort the signal shape. This confirms the theoretical calculations carried out in this work.

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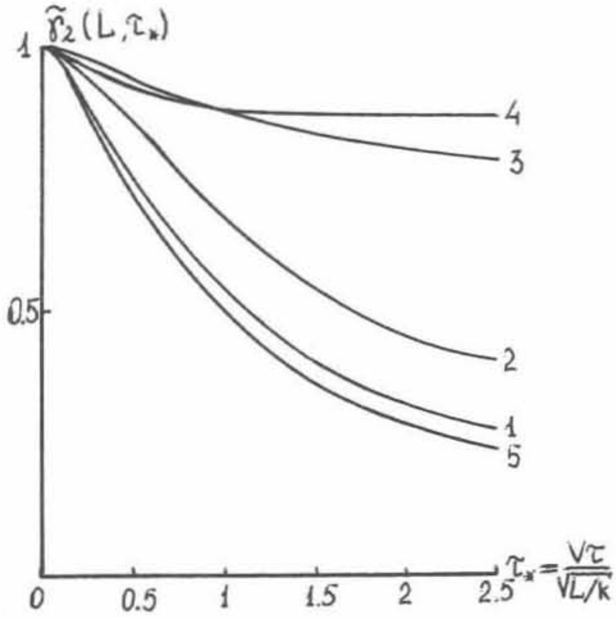

Fig. 1. The temporal complex coherence degree.
1, 2, 4, 5- β_0=2, 5; 3- β_0=0, 5;
1, 2, 3, 5- $\varkappa_{0*}$=1; 4- $\varkappa_{0*}$=4;
1, 3, 4- P=100; 2- P=1; 5- P=10^{-6}.

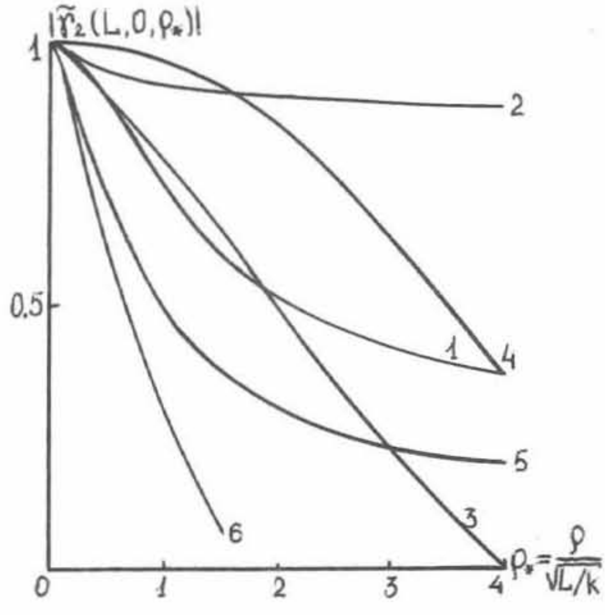

Fig. 2. The absolute values of the spatial coherence function.
1, 2, 3, 5, 6- β_0=2, 5; 4- β_0=0, 5;
1, 3, 4, 5- $\varkappa_{0*}$=1; 2- $\varkappa_{0*}$=4; 6- $\varkappa_{0*}$=10^{-4};
1, 2- $\bar{P}$=100; 3, 4, 6- $\bar{P}$=1; 5- $\bar{P}$=10^{-6}.

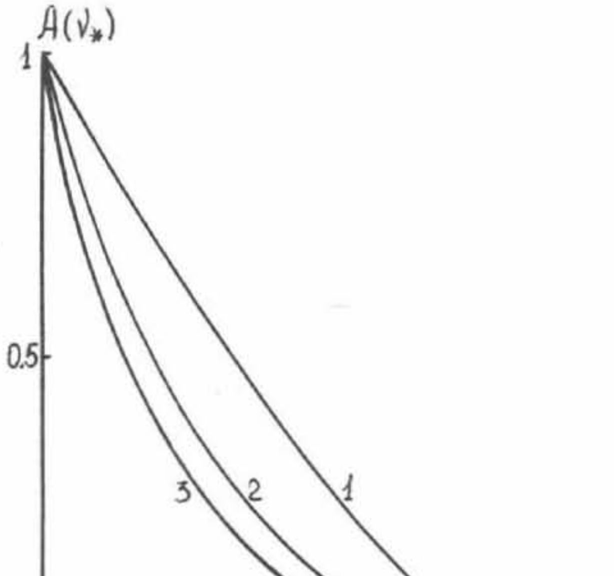

Fig. 3. Effect of the near-earth turbulent atmosphere on the spatial frequncy characteristics.
1- C_n=0; 2- R_*=2; 3- R_*=4.

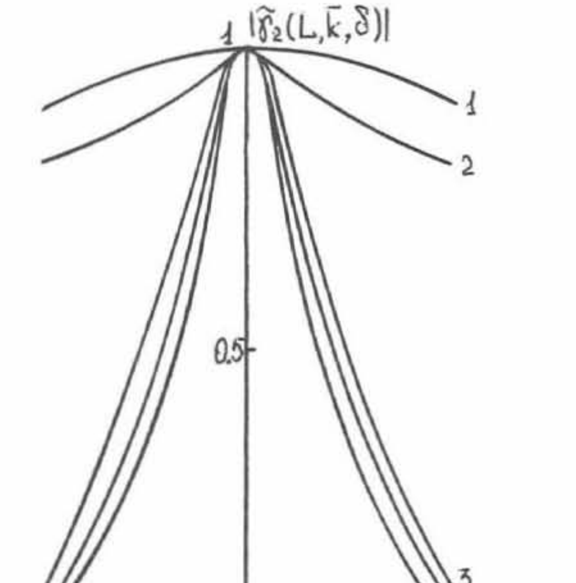

Fig. 4. The absolute values of the frequency coherence function.
$\bar{\beta}_0$=2, 5; 1, 2- $\bar{\varkappa}_{0*}$=4; 3, 4, 5- $\bar{\varkappa}_{0*}$=1;
1, 3- $\bar{P}$=1; 2, 4- $\bar{P}$=100; 5- $\bar{P}$=10^{-4}.