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Improving the reliability of data transmission on the communication line spacecraft-ground tracking station: intermittent emission mode

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A method for increasing the reliability of data transmission under conditions of lognormal amplitude fluctuations of millimeter radio waves on the spacecraft–ground tracking station line using intermittent radiation modes with coherent signal reception is considered. It is shown that the radio link utilization factor is fixed at a constant ratio of the threshold level and the average signal-to-noise ratio.

Keywords: tropospheric channel, millimeter waves, dispersion, Fraunhofer diffraction, lognormal amplitude fluctuations, intermittent communication, radio line usage coefficient.

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It is known that the use of millimeter (mm) band significantly increases the spectral efficiency of wireless transmission of ground-space radio interferometry data along the line spacecraft (SC) – ground tracking station [1,2] to speeds commensurate with the speed of recording digital broadband data in the onboard memory of the spacecraft, which ensures uninterrupted operation of the ground-space interferometer.

However, when propagating in a turbulent atmosphere, mm-band electromagnetic waves experience lognormal fluctuations in amplitude [3], and the signal-to-noise ratio (SNR) probability density γ, as well as the amplitudes of mm-band signals, are described by a lognormal law [4].

In turn, the dispersion of the lognormal process in data transmission, for example, from a Lagrangian point $L2$, when the radius of the first Fresnel zone is significantly larger than the external scale of turbulence [2], will be determined by the Fraunhofer diffraction and linearly increase with the path length of the electromagnetic wave through the tropospheric channel. The dispersion of the tropospheric channel of the millimeter wavelength range, taking into account the average profile coefficient [5] will be as follows

$$\langle\chi^2\rangle = \sigma_\chi^2 \approx \left(\sqrt{2\pi}/16\right)(0.714C_{\varepsilon 0})^2 L_0^{5/3} k^2 z = \left(\sqrt{2\pi}/16\right) 0.51 C_{\varepsilon 0}^2 L_0^{5/3} k^2 z. \tag{1}$$

Here, $C_{\varepsilon 0}$ — the structural constant of the dielectric permittivity in the surface layer, which is approximately $0.5 \cdot 10^{-6}\,\mathrm{m}^{-1/3}$; L_0 — the outer scale of turbulence (corresponding to about 10 m); k — the wave number $(2\pi/\lambda)$, where λ — the wavelength; z — the path length of an electromagnetic wave through a channel with lognormal fluctuations (through the tropospheric channel).

It is advisable to transmit data at times when there are no signal fades. The use of the above algorithm is due to the fact that the envelopes of duplex signals on the communication line from the SC to the ground tracking station and back are correlated, wherein $T \ll \tau$, where T — time of signal propagation along the communication line, τ — interval of signal envelope correlation in time.

The signal level meter at the receiver input allows to make a decision to switch on/off the transmitter if this level becomes higher/lower than a certain threshold value.

Since data in the channel are transmitted only at certain points in time, it is reasonable to introduce a radio link utilization factor equal to the ratio of the duration of a particular data transmission interval to the total length of the communication session. Then, $\eta(\gamma_t)$ will be defined by the expression

$$\eta(\gamma_t) = \left(0.5/\sqrt{2\pi\sigma_\chi^2}\right)\int_{\gamma_t}^{\infty} \gamma^{-1} \times \exp\left[-\left(\ln\sqrt{\gamma/\gamma_0} + \sigma_\chi^2\right)^2 / 2\sigma_\chi^2\right] d\gamma = 0.5\operatorname{erfc}\left(\ln\sqrt{\gamma_t/\gamma_0} + \sigma_\chi^2/\sqrt{2}\sigma_\chi^2\right). \tag{2}$$

In (2), γ corresponds to the instantaneous value of the SNR. It follows from the equation that the radio line usage coefficient is independent of the mean value of the SNR only when the SNR threshold γ_t is normalized to the mean value γ_0.

The normalization parameter k is correspondingly equal to $k = \gamma_t/\gamma_0$. Dependence of the radio line usage coefficient on the normalization parameter k at fixed σ_χ^2 in E-band (71–76, 81–86 GHz) is described by expression (3) (Fig. 1).

$$\eta(k) = 0.5\operatorname{erfc}\left(\ln\sqrt{k} + \sigma_\chi^2/\sqrt{2}\sigma_\chi^2\right). \tag{3}$$

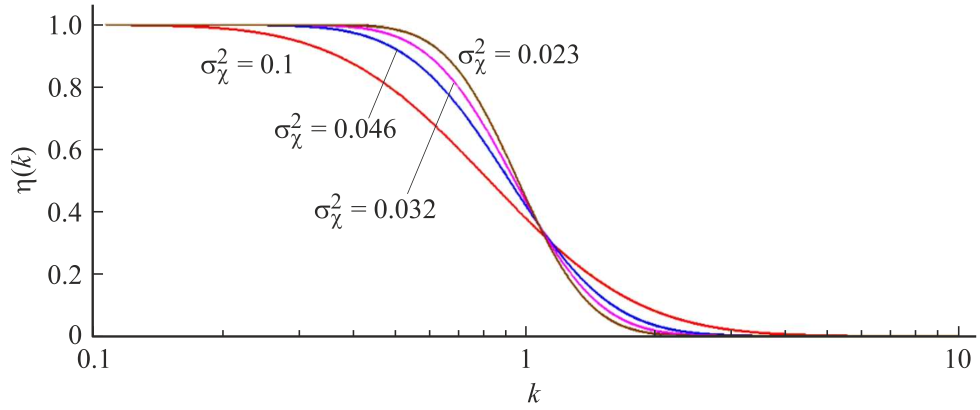

Figure 1. Dependences of radio line usage coefficient on the normalization parameter k at different fixed values of dispersion σ_χ^2.

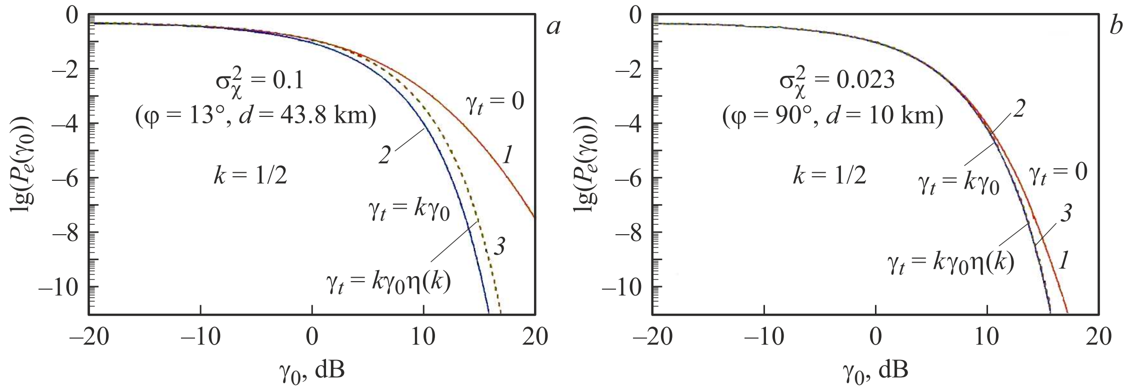

Figure 2. Error probabilities of receiving signals in intermittent emission mode compared to the error probability in the absence of intermittent emission (*1*) for the cases of fixed bit energy (*2*) and fixed transmitter power (*3*). Parameter of normalizing $k = 1/2$ and $\sigma_\chi^2 = 0.1$ (*a*) and 0.023 (*b*).

At inclined ranges of 43.8 km ($\sigma_\chi^2 = 0.1$) and 10 km ($\sigma_\chi^2 = 0.023$), the antenna site angle φ is 13 and 90°, respectively.

By averaging the error probabilities of BPSK/QPSK signals in Gaussian noise using the statistics of lognormal fading in the tropospheric channel at SNR values above the threshold level, we can obtain the dependence of the coherent reception error probability on γ_0

$$P_{c\perp}(\gamma_0) = \left(1/4\eta(k)\sqrt{(2\pi\sigma_\chi^2)}\right)\int\limits_{\gamma_t}^{\infty}\gamma^{-1}$$

$$\times\ \exp\left[-\left(\ln\sqrt{\gamma/\gamma_0 z} + \sigma_\chi^2\right)^2/2\sigma_\chi^2\right]\operatorname{erfc}\sqrt{\alpha\gamma}d\gamma. \qquad (4)$$

We define a threshold normalized to the mean SNR γ_0 threshold $\gamma_t = k\gamma_0$. Note that in order to transmit a complete data set, the transmission rate must increase inversely with the radio line usage coefficient $\eta(k)$. Two cases are of interest in this case:

1) $\gamma_t = k\gamma_0$, $z = 1$, when the bit energy (SNR) at the receiver input is independent of the radio line usage coefficient $\eta(k)$ and accordingly the transmitter power should increase inversely proportional to $\eta(k)$;

2) $\gamma_t = \eta(k)k\gamma_0$, $z = \eta(k)$, when the transmitter power is fixed and the SNR (bit energy) at the receiver input depends on $\eta(k)$.

The error probability curves (4) for the variances $\sigma_\chi^2 = 0.1$ and 0.023 are presented graphically in Fig. 2, *a* and it b, respectively.

In Fig. 2 φ and d — the antenna site angle and slant range, respectively. At $k = 1/2$, dispersions 0.1 and 0.023, the radio line usage coefficient (3) will be 0.782 and 0.983, respectively (Fig. 1).

It can be seen from Fig. 2 that the gain in the intermittent mode increases with increasing dispersion and average SNR when the lognormal fluctuations of the signal amplitude in the troposphere are significant. In addition, the differences in error probabilities in intermittent emission modes at fixed signal bit energy and transmitter power are negligible, especially when the dispersion value is small (Fig. 2, *b*). Therefore, the mode of intermittent emission at unchanged transmitter power is more preferable, because fixing its parameters provides more reliable long-term autonomous operation of the transmitting device.

It should be noted that in the intermittent emission mode (with QPSK signal modulation), the E-band (71–76, 81–86 GHz) data rate can be up to 20 Gb/s.

Conflict of interest

The author declares that he has no conflict of interest.

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