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Authors: Wu, Tong, Yan, Yi, Li, Yongcheng, Wang, Chunmei, Yao, Xiujuan, Li, Xue

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Abstract

Electromagnetic waves used for deep space communications are mainly affected by the charged particles ejected by the sun. These effects may result in degradation of communication quality or communication interruption. This paper discusses the effects of solar scintillation on electro-magnetic waves, including the scintillation index which is a measure of the intensity scintillation, the coherence bandwidth and the coherence time of deep space communication channel. The deep space communication channel under solar scintillation is modeled by using Rician fading channel according to the scintillation index. The coherence bandwidth will determine whether the channel is flat fading or frequency selective fading and the coherence time will determine whether the channel is slow fading or fast fading. The approach of choosing signal band width is determined by the coherence bandwidth and the coherence time with the change of the solar elongation angle. The simulation results show the bit error rate of the signal bandwidth chosen by the proposed approach is lower than a random choice.

Full Text

Deep Space Communication Channel Characteristics Under Solar Scintillation

Tong Wu[1,2,3], Yi Yan[1], Yongcheng Li[1], Chunmei Wang[2], Xiujuan Yao[2], Xue Li[2]

[1]The State Key Lab. of Complex Electromagnetic Environment Effects on Electronics and Information System, Luoyang, China
[2]Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing, China
[3]University of Chinese Academy of Sciences, Beijing, China

wutong963852@163.com, yanyi@nssc.ac.cn, lyncan@163.com, wangchm@nssc.ac.cn, yaoxj@nssc.ac.cn, lixue@nssc.ac.cn

Abstract

Electromagnetic waves used for deep space communications are primarily affected by charged particles ejected by the sun. These effects may result in degradation of communication quality or even complete communication interruption. This paper discusses the effects of solar scintillation on electromagnetic waves, including the scintillation index as a measure of intensity scintillation, as well as the coherence bandwidth and coherence time of the deep space communication channel.

The deep space communication channel under solar scintillation is modeled using a Rician fading channel based on the scintillation index. The coherence bandwidth determines whether the channel exhibits flat fading or frequency-selective fading, while the coherence time determines whether the channel exhibits slow fading or fast fading. The approach for selecting signal bandwidth is determined by the coherence bandwidth and coherence time as functions of the solar elongation angle. Simulation results show that the bit error rate of signals using bandwidth chosen by the proposed approach is lower than that of randomly chosen bandwidths.

Keywords– coherence bandwidth; coherence time; fading channel; solar scintillation

I. Introduction

The effects of solar scintillation on radio waves may result in degradation of communication quality or even communication interruption, such as telemetry or telecommand failures, when deep space probes experience solar conjunction. To avoid damage to deep space probes caused by the solar corona, solar wind, and cosmic rays, data must be transmitted to Earth in a timely manner. Therefore, ensuring the reliability of the communication link under solar scintillation is of significant importance.

In terms of physical mechanism, the solar corona and solar wind are considered random media [?]. Brown [?] studied the moment equations in random media. Lee et al. [?] studied the fourth-moment equation and obtained the scintillation index. Woo et al. [?] analyzed the spectral broadening of monochromatic radio signals when solar scintillation and solar events occurred; the reciprocal of spectral broadening is the coherence time. Xu et al. [?] studied the mutual coherence function and coherence parameters of random media and applied these parameters to analyze ionospheric irregularities.

To study the reliability of communication links under solar scintillation, Feria et al. [?] modeled amplitude scintillation effects on telemetry signals using the statistical characteristics of telemetry data, but did not consider coherence time and coherence bandwidth in the model.

The purpose of this paper is to model the deep space communication channel under solar scintillation using a Rician fading channel based on the scintillation index, and to propose an approach for selecting signal bandwidth using coherence bandwidth and coherence time. Therefore, in Section II, we provide definitions of scintillation index, coherence bandwidth, and coherence time, respectively, and then simulate these three channel characteristics versus solar elongation angle. The results can be explained by Kolmogorov' s turbulence theory [?]. In Section III, we present the deep space communication channel model and briefly review fading channel characteristics by comparing coherence bandwidth and coherence time with signal bandwidth. Then in Section IV, we simulate the fading channel obtained in Section III using the characteristics from Section II and propose an approach for selecting signal bandwidth. Section V concludes the paper.

II. Influence by the Solar Wind

Electromagnetic waves emitted by deep-space satellites are affected by the sun. The continuous solar wind and occasional coronal mass ejections are the main solar events that may affect electromagnetic waves. Charged particles in interplanetary space behave as plasma and cause intensity scintillation, spectral broadening, and phase scintillation [?, ?]. The inverse of spectral broadening is the coherence time [?]. The signal is assumed to be a monochromatic radio wave to elicit intensity scintillation and coherence time, and a two-frequency radio wave to elicit coherence bandwidth.

A. Intensity Scintillation

Intensity scintillation is the intensity fluctuation of the received electromagnetic wave, typically quantified by the scintillation index to indicate the degree of intensity scintillation. The scintillation index reflects the strength of small-scale turbulent density fluctuations [?] and is defined as [?]:

$$m^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$$

It is proven by [?] that for weak scintillation, $B_I(x,\rho) = 4B_\chi(x,\rho)$, where $B_\chi(x,\rho)$ is the correlation function of the magnitude. Therefore, the scintillation index can be expressed as [?, ?]:

$$m^2 = 4B_\chi(x, 0)$$

Using Rytov' s approximation, the amplitude fluctuation variance can be calculated and given by [?]:

$$\sigma_\chi^2 = 0.563 a_1 k^{7/6} \int_0^R c_{n0}^2(z) z^{5/6}\, dz$$

where $a_1 = 0.85$ [?], $k = 2\pi/\lambda$ is the wavenumber, λ is the electromagnetic wavelength in the random medium, and R, L, L_1, L_2 are shown in Fig. 1 [Figure 1: see original paper]. c_{n0} is the structure constant at the closest approach point of the propagation path and is given by [?]:

$$c_{n0} = \frac{55.59\sigma_{ne}^2}{f^2 L_0^{1/3}}$$

where σ_{ne} is the RMS electron density at the closest approach point of the propagation path and is directly proportional to the electron density of the solar wind, f is the carrier signal frequency, and L_0 is the outer scale of solar wind turbulence. c_{n0} is related to the solar elongation angle, i.e., as the solar elongation angle decreases, c_{n0} increases.

Fig. 2a [Figure 2: see original paper] shows that when the propagation path approaches the sun, the scintillation index increases until saturation due to the increase of c_{n0} at the closest approach point. Moreover, the higher the wave frequency, the smaller the scintillation index before saturation. Fig. 2b shows that the scintillation index decreases with increasing outer scale, which can be explained by Kolmogorov spectrum theory [?]. With increasing outer scale, the probability of turbulent scales falling into the inertial subrange increases, meaning the turbulence property changes from anisotropy to isotropy, so the impact on electromagnetic waves and the scintillation index decreases.

B. Coherence Bandwidth

The coherence bandwidth in random media is derived from the two-frequency mutual coherence function, which satisfies the second-moment parabolic equation [?, ?]. The coherence bandwidth represents the maximum frequency difference for which the frequency responses at two frequencies remain strongly correlated. Two sine waves with different frequencies whose frequency difference exceeds the coherence bandwidth are affected differently by the channel.

The definition of coherence bandwidth is given by [?] for ionospheric irregularities:

$$f_{coh} = \frac{\omega_{coh}}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{2}{\lambda^2\sigma_\phi^2 L}}\left(\frac{2\pi}{L}\right)^{1/2}$$

where ω is the center angular frequency of the electromagnetic wave, L is the thickness of the irregularity, and σ_ϕ^2 is the phase fluctuation variance. The electron plasma angular frequency and wavenumber are:

$$\omega_p = \sqrt{\frac{N_e e^2}{m\varepsilon_0}}, \quad k_p = \frac{\omega_p}{c}$$

where N_e is the electron density (1/m³), e and m are the charge and mass of the electron, respectively, and ε_0 is the dielectric constant in vacuum. When the angular frequency of the electromagnetic wave is greater than ω_p, electromagnetic waves can propagate in the plasma; otherwise, they suffer total reflection or strong attenuation.

The coefficient A is also defined by [?]:

$$A = \begin{cases} \frac{K_0(\xi)}{K_1(\xi)} & \text{for } \xi \leq 1 \\ \frac{K_1(\xi)}{K_0(\xi)} & \text{for } \xi > 1 \end{cases}$$

where K is a modified Bessel function of imaginary argument, l_0 is the inner scale of solar wind turbulence (50–200 km [?]), $\kappa_0 = 1/L_0$, and $\xi = \Delta N_e/\langle N_e \rangle$. When the spectral index $p = 11/3$, the Shkarofsky spectrum degenerates to the Kolmogorov spectrum.

The coherence bandwidth of ionospheric irregularities is analyzed by [?], and we extend it to interplanetary space by making a slight modification to (5) for both weak and strong scintillation:

$$f_{coh} = \frac{1}{2\pi}\sqrt{\frac{2}{\lambda^2\sigma_\phi^2 L}}\left(\frac{2\pi}{L}\right)^{1/2} A^{-1/2}$$

Fig. 3a [Figure 3: see original paper] shows that the coherence bandwidth decreases with decreasing solar elongation angle, especially within 1° of the sun. Increasing the center frequency helps increase the coherence bandwidth of the channel. Fig. 3b shows that the coherent bandwidth increases with the outer scale of turbulence, which can also be explained by Kolmogorov turbulent energy spectrum theory [?] similar to the explanation for the scintillation index. Fig. 3c shows that the coherence bandwidth increases with the inner scale of turbulence because the probability of turbulent scales falling into the dissipation range increases.

C. Coherence Time

The coherence time in random media is derived from the temporal mutual coherence function, which satisfies the temporal second-moment parabolic equation [?]. The coherence time represents the maximum time difference for which the impulse responses at two temporal channels remain strongly correlated. When the time difference is less than the coherence time, the channel characteristics remain substantially the same.

The spectral broadening is given by [?]:

$$\Delta f = 0.542 \left(\frac{c}{v}\right)^{6/5} k^{11/5} a^{6/5} R^{1/5}$$

where v is the average velocity of the solar wind at the closest approach point and perpendicular to the propagation path. Therefore, the coherence time of the channel is:

$$T_{coh} = \frac{1}{\Delta f} = 1.845 \left(\frac{v}{c}\right)^{6/5} k^{-11/5} a^{-6/5} R^{-1/5}$$

Fig. 4a [Figure 4: see original paper] shows that the coherence time decreases with decreasing solar elongation angle, similar to the coherence bandwidth. Increasing the center frequency helps increase the coherence time of the channel. Fig. 4b shows that the coherence time increases with the outer scale of turbulence, resembling the behavior of coherence bandwidth.

III. Channel Model

The deep space communication channel model is presented in this section based on the factors obtained above. The propagation factor caused by solar scintillation is treated as multiplicative noise, while noise and interference are treated as additive noise. Assume that the multiplicative noise factor is $a_{sc}(t)$, and the noise and interference are $n(t)$ and $J(t)$, respectively. The deep space communication channel model is shown in Fig. 5 [Figure 5: see original paper].

The relationship between the scintillation index m and the Rician factor γ of the Rician distribution is derived by Shaft [?]:

$$\gamma = \frac{1 - m^2}{m^2}$$

Therefore, the probability density function (PDF) of the envelope $R = |a_{sc}(t)|$ can be considered as Rician distribution:

$$p(R) = \frac{R}{\sigma^2} \exp\left(-\frac{R^2 + R_0^2}{2\sigma^2}\right) I_0\left(\frac{RR_0}{\sigma^2}\right)$$

where R_0 is the amplitude of the specular component, σ^2 is the variance of the Gaussian noise component, and I_0 is the zero-order modified Bessel function of the first kind. The Rician factor is $\gamma = R_0^2/(2\sigma^2)$. The PDF of the envelope of the additive noise factor $n(t)$ and $J(t)$ can be simplified by a Gaussian distribution, representing an AWGN (Additive White Gaussian Noise) channel.

The coherence bandwidth and coherence time limit the bandwidth of the transmitted signal to some extent. Assume that the bandwidth of the transmitted signal is W, and the duration of each symbol is $T \approx 1/W$. If the deep space communication channel exhibits flat and slow fading, the bandwidth and symbol duration should satisfy:

$$W \ll f_{coh}, \quad T \ll T_{coh}$$

Equation (13) can be rewritten using $T \approx 1/W$ as:

$$\frac{1}{T_{coh}} \ll W \ll f_{coh}$$

Thus, the scintillation index determines the amplitude of the signal, while the coherence bandwidth and coherence time, as limiting factors, determine the signal bandwidth.

IV. Simulation Results

We calculate theoretical Bit Error Rate (BER) performance with different scintillation indices in Fig. 6 [Figure 6: see original paper]. It shows that as the scintillation index decreases, BER performance improves and approaches that of a non-scintillating channel (AWGN) under weak scintillation. The modulation is DBPSK and there is no channel coding.

Assume that the signal bandwidth is W and the duration of each symbol is $T \approx 1/W$. The coherent bandwidth and the inverse of coherent time can divide the two dimensions of solar elongation angle and signal bandwidth into four regions, as illustrated in Fig. 7 [Figure 7: see original paper]. The flat and slow fading channel is the easiest to handle. Therefore, to determine the signal bandwidth, we should ensure the channel is mostly flat and slow at different solar elongation angles. The proposed approach is to choose the intersection of the two curves, which is optimal.

Fig. 7 shows that the intersection of the two curves is about 40 Hz at 8.43 GHz and 25-60 Hz at 32 GHz. Therefore, we choose this signal bandwidth and simulate BER performance versus solar elongation angle in Fig. 8 [Figure 8: see original paper] and Fig. 9 [Figure 9: see original paper]. We also use 10 Hz and 400 Hz for comparison. The modulation is DBPSK and the SNR of the AWGN channel is 12 dB.

Fig. 8 shows that for strong scintillation, the BER performance of 40 Hz bandwidth is much better than 400 Hz but slightly worse than 400 Hz when $\alpha \approx 0.4^{\circ}$. This is because with increasing solar elongation angle, the channel for 400 Hz signal bandwidth enters the slow fading region slightly earlier than for 40 Hz. The channel for 40 Hz signal bandwidth is better than for 10 Hz. For the region between strong and weak scintillation, the BER performance of 40 Hz is also better than 10 Hz. For weak scintillation, the three curves are close together. In Fig. 9, with a carrier frequency of 32 GHz, the BER performance of 40 Hz is the best among the three curves as solar elongation angle increases.

V. Conclusion

This paper studies the effects of the sun on electromagnetic waves in deep space communications, including the dissemination of factors, noise, and interference. The deep space communication channel model is derived using a Rician fading channel model with an additive white Gaussian noise channel model. The coherence time and coherence bandwidth are calculated to determine the characteristics of the deep space channel and the signal bandwidth, which lays the foundation for future exploration activities.

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Note: Figure translations are in progress. See original paper for figures.