Angle-of-arrival Fluctuations of Electromagnetic Wave Propagation through the Solar Corona

Guanjun Xu[1], Zhaohui Song[1,2]
[1] School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin, China
[2] School of Information Science and Technology, East China Normal University, Shanghai, China

***Abstract* - This preliminary work focus on the effect of the solar wind on the angle-of-arrival (AOA) fluctuations of the radio wave propagation through the solar corona. Based on the formula of phase fluctuations, the variance of AOA fluctuations is derived by applying the solar wind irregularity spectrum. The simulated values show that the characteristics of the solar wind play an important role in the AOA fluctuations. Apart from this, enhancing the wave frequency and antenna radius can eliminate the AOA fluctuations extremely. Furthermore, the antenna gain reduction is quantitatively calculated with the special antenna model. Therefore, this study can be used for the future deep space exploration.**

***Index Terms* — Wave propagation, Angle-of-arrival fluctuations, solar wind, spectral index.**

1. Introduction

Solar wind scintillation is fluctuations in the amplitude, phase and AOA of the EM wave caused by the irregularities in solar corona that degrade the performance of deep space communication [1, 2]. Since the signal inevitably transverse through the solar corona, the AOA fluctuations has attracted the interest of many researchers [3, 4]. It has been well known the solar corona has higher plasma density, the plasma ceaselessly fluctuates over an extensive range both in spatial and temporal, and the spectral index fluctuates between 3 and 4. All these characteristics of the complex media give an obstacle to achieve the AOA fluctuations of the EM wave passing through the solar corona [2, 3].

The purpose of this work is to understand how these characteristics of the solar wind affect the fluctuations. Considering the mathematical relationship between the AOA fluctuations and phase fluctuations, the fluctuations formula is derived on the basis of the extensively used phase fluctuations variance and the solar wind density spectrum. Therefore, the effect of the characteristics is discussed.

2. Formulation of the problem

Since the effect of atmosphere and ionosphere of the Earth on the AOA fluctuations is very small [2], we only consider the effect of the solar corona plasma. Figure 1 depicts the geometry model of the communication link. Using the Rytov's iteration theory, the expression of the covariance of the phase fluctuations [5] has the form of:

$$\langle \varphi(t)\varphi(t+\tau)\rangle = 4\pi^4 r_e^2 \lambda^2 \int_0^\infty dz \int_0^\infty \kappa d\kappa \Phi(\kappa) \cdot J_0(\kappa\tau V)\left[2J_1(\kappa a_r)/(\kappa a_r)\right]^2 \quad (1)$$

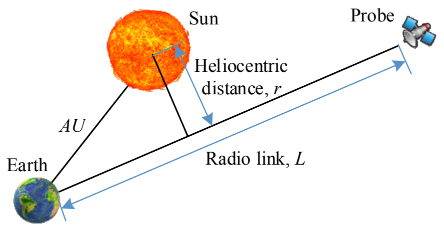

Fig. 1. Geometry model of EM wave commute between the Earth and the probe through the solar corona.

where, r_e is the classical electron radius, λ is the wavelength, V is the solar wind speed, a_r is the antenna radius, J is the Bessel function. $\Phi(\kappa)$ is the spatial spectrum of the electron density in inhomogeneities of solar corona.

Considering the characteristic of the solar corona, the generalized solar wind spectrum, which has a general spectral index in the range of 3 to 4, can be given as [6]:

$$\Phi(\kappa) = \frac{2}{3}\frac{\Gamma(11/6)(2\pi/l_0)^{2/3}}{(2\pi)^{3/2}\Gamma(4/3)}\varepsilon^2 N_e^{\,2}\kappa^{-11/3} \quad (2)$$

where, l_o is the outer scale of the solar wind turbulence, $\Gamma(\,)$ is the gamma function. ε is the solar wind density fluctuations coefficient. Therefore, the phase fluctuations spectrum can be obtained by the Fournier transform.

Assuming frozen flow turbulence, the relationship between the phase spectrum and AOA spectrum has been derived as [7]: $W_\theta(\omega) = [\lambda\omega/(2\pi V)]^2 W_\varphi(\omega)$. Therefore, the AOA fluctuations spectrum can be achieved by (1) and (2). Besides, the variance of the AOA fluctuations can be obtained:

$$\langle \theta^2 \rangle = 2\pi^2 r_e^2 \lambda^4 \int_0^\infty d\kappa \int_0^L dz \kappa^3 \Phi(\kappa) \cdot \left[1+\sin(\kappa^2 z/k)/(\kappa^2 z/k)\right]\left[2J_1(\kappa a_r)/(\kappa a_r)\right]^2 \quad (3)$$

3. Numerical simulation

In the following, calculations are conducted to understand the dependence of the AOA fluctuations on the key parameters. The corresponding simulation setting is similar to that of [2].

As shown in Figure 2, the AOA fluctuations decrease along the increase of heliocentric distance. It is reasonable since there is less solar wind density when the heliocentric distance get larger. Besides, the turbulence of the solar wind induce less impact on wave propagation with the increase of the wave frequency and antenna radius. Therefore, operating at high radio frequency and increasing the antenna radius

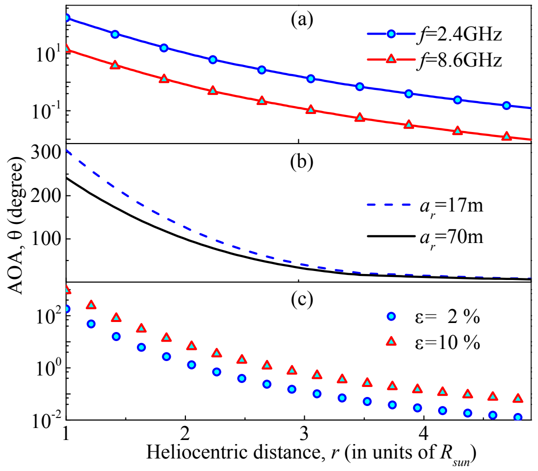

Fig. 2. AOA as a function of heliocentric distance with different wave frequencies, antenna radii, and solar wind density fluctuations coefficients in (a), (b) and (c).

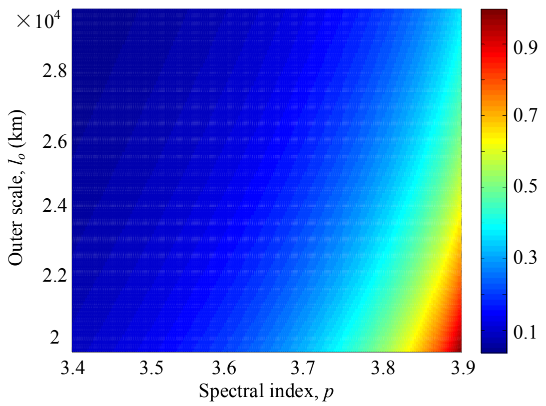

Fig. 3. The dependence of AOA fluctuations on both spectral index and outer scale.

can be used to eliminate the effect of AOA fluctuations and further enhance communication performance. Apart from this, the EM wave passing through the solar corona with ε=2% experiences 90% less AOA fluctuations than that with ε=10% at the same heliocentric distance.

Figure 3 illustrates the effect of spectral index and outer scale on the AOA fluctuations. The color bar denotes the normalized fluctuations. Obviously, the high spectral index induces larger AOA fluctuations. Intuitively, the AOA fluctuations decrease along with the increase of the outer scale. This can be interpreted that the turbulent scale falls into the interial subrange when the outer scale gets larger and finally induces less AOA fluctuations.

Figure 4 plots the gain reduction caused by AOA fluctuation under the F.699 antenna model with the antenna radii are 35m and 70m in (a) and (b), respectively [8]. The results suggest that operating at higher radio frequency can extensively deduce the effect of AOA fluctuations, which has been concluded by Figure 1(a). Besides, the gain reduction can also be decreased with the larger antenna radius when we compared (a) with (b). Moreover, the attenuation due to AOA fluctuations will get larger when the communication link gets close to the solar corona.

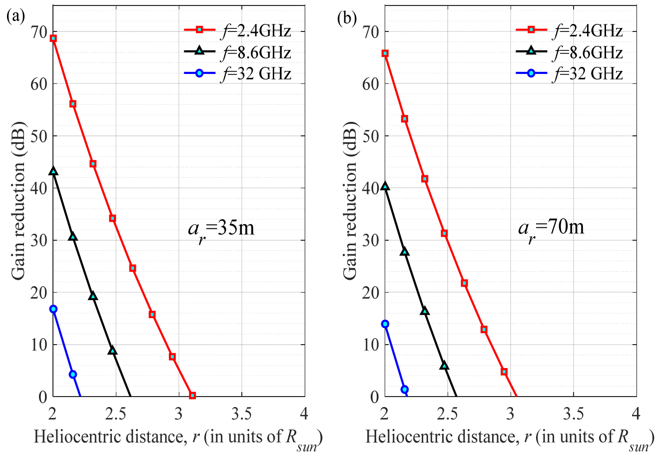

Fig. 4. Antenna gain reduction as a function of heliocentric distance under the F.699 antenna model.

4. Conclusion

In this paper, the variances of the AOA fluctuations of the EM wave passing through the solar corona is derived. The derived formula is used to analyze the influence of characteristic of the solar wind on the AOA fluctuations. It can be concluded that the AOA fluctuations decreases monotonically with the increase of the heliocentric distance, outer scale, wave frequency and decreases along the decrease of the spectral index. Besides, the antenna gain reductions due to AOA fluctuation is obtained with the special antenna model. Finally, it is noteworthy that the above conclusions give a way to minimize the AOA fluctuations due to the solar wind irregularities for the future deep space exploration.

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