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Propagation Characterization of LEO/MEO Satellite Systems at 900-2100 MHz

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Abstract - This paper focuses on the propagation characterization of satellite communication systems in non-geostationary orbits at 900-2100MHz. An overview of available statistical propagation models for the mobile satellite communications channel is provided. Path loss equations for satellite communication systems in the range of 900—2100MHz for different environments and different probabilities of link closure are addressed. We also introduce a series of experiments being conducted to deepen understanding of these issues.

I. INTRODUCTION:

With the launch of the Iridium spacecraft in 1997 and 1998, a significant new architecture has been introduced into the field of satellite communications. These LEO and MEO systems have several advantages over geosynchronous systems. The most significant advantages are, (1) the reduction in range provides a large decrease in path loss resulting in much smaller receiving antennas; (2) the reduction in range provides a significant reduction in propagation delay making voice conversation more pleasing to user and increasing the throughput of most data communication protocols.

These systems can and will serve mobile and portable users with small near-omni antennas. However, the use of small antennas, as well as, the motion of the transmitter and the receiver, introduces the possibility of multipath and blockage in the propagation conditions found in these satellite systems. This paper is concerned with our research into the propagation characterizations for LEO satellite mobile communications. The two most significant questions are: (1) How to develop the path loss equations of nonstationary mobile satellite systems to predict the received signal level? (2) How to characterize the 1st and 2nd order fade distributions of the signal received by the ground terminal in mobile nonstationary systems?

The first question addressed the basic path loss equation for LEO/MEO systems. The path loss equations for these systems must include an allowance for such natural factors as the rain, snow, clouds, and fog. Even the effects of the ionosphere may have a contribution to the power loss in a space to ground link, in addition to the free space path loss and blockage due to buildings, trees, etc. The second question addresses the random fluctuation in the received signals due to different fading phenomena. These phenomena affect signal quality and system availability and are ultimately a major cause of system outages. In section II, we present our version of the basic path loss equations which are shown to provide a very good fit to the experimental data presented in [2,7]; our equations incorporate some terms which can be adjusted according to the environments. Based on these equations, we plot the ground terminal received power level versus the elevation angle for various environments and frequency bands, respectively. These figures may be used to determine required signal margins in link budget analysis.

A primary reason to address the 1st and 2nd order fading statistics is to provide estimates of the nature and the level of the signal impairments, so the bit error rate (BER), level cross rate (LCR) and average duration of fades(ADF) can be estimated on the basis of this distribution. A good model for such phenomena can help design good counter-measures such as better modulation, equalization, diversity, and channel coding to combat such fading impairments and to maintain communication between the satellite and the ground terminal receiver. Statistical models have been used to characterize various fading environments.

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There has been intensive research in the area of terrestrial mobile/cellular systems, and a large number of papers have been published based upon research in this area (see [2, 6-14, 23] and references therein). J.F.Ossanna ([3]) was the first to attempt to give an explanation of the statistical characteristics of the received mobile-radio signal in terms of a set of interfering waves. R.H.Clarke ([4]) derived the Rayleigh distribution of the received signal envelope in the urban area based on the assumption that the received signal phase is uniformly distributed through $-\pi$ to π and the received multipath signal amplitudes are equally distributed. Furthermore, after introducing the concept of large-scale fading and small-scale fading, Suzuki ([5]) gave the now classical Rayleigh-lognormal model which has been well-tested as a model for propagation in terrestrial mobile communications systems.

The propagation characteristics in satellite communication channels vary from pure line of sight situations between high gain antennas in point-to-point systems to paths with significant multipath fading and blockage found in LEO/MEO systems. In this paper, we will focus on the situation found in LEO/MEO systems and particularly those in the 900 to 2100 MHz frequency bands. The first attempts to model the propagation characteristics of these systems were based upon extending the now classic Suzuki model of terrestrial mobile radio systems. However, satellite systems generally have a much stronger direct component in the signal than is found in the terrestrial systems, hence the Suzuki model needs to be adjusted to account for this difference.

The first of these modified models was a nonselective multipath fading and shadowing model for the land-mobile satellite communication systems proposed by Loo ([6]) for rural environments, which assumes that the received signal is affected by nonselective Rice fading with lognormal shadowing on the direct component only, while the diffuse scattered component has constant average power level. G.E.Corazza and F.Vatalaro presented Rice-lognormal distribution, with shadowing affecting both direct and diffuse components in [7]. Both the Loo and Corazza models assume the small-scale fading contains a strong component, so they use the Rice distribution to describe the fading conditioned on constant shadowing loss. Furthermore, M. Patzold et al [8] proposed an extended Suzuki model, in which the orthogonal components of the Rician process used to model the scattering are allowed to be mutually correlated. This is equivalent to considering asymmetrical doppler power spectral densities, and the line-of-sight component is frequency shifted due to the doppler effect. William P. Osborne et al [34] derived a general statistical model for mobile systems on the basis of propagation scattering theory. This model can be used as a fading model in all types of environments. The probability density function (p.d.f.) of received signal envelope and the p.d.f. of the received signal power were given, and all of the models discussed above are special cases of this general model.

One of the most modern attempts to model LEO/MEO paths attempts to exploit the fact that the path may change very quickly as a user moves from a clear state (one with a line of sight component) to a blocked state (one in which the path to the satellite is totally blocked by a building or a mountain). The models discussed above are so-called *single state models and are* suitable for use in quasi-stationary channels, i.e. channels characterized by uniform environmental conditions under the assumption of time and frequency flatness. The *multi-state models* provide an approach for characterizing the channel under wider and more abrupt variations of the environmental conditions, such as those encountered in urban based vehicular communication. We will discuss different models developed in the literature next.

All the models discussed above are suitable for use as single state models when the received terminal travels in a uniform environment. When the terminal travels in a large non-uniform area, the received signal envelope can change abruptly between quite different levels and should be described by multi-state models. Lutz et al [9] introduced a two-state model, which is Rician-lognormal under *good state* and Rayleigh-lognormal under *bad state*. Markov Transition Model based on Rician fading was proposed by H. Wakana [10]. R.Akturan and W.J.Vogel [11] introduced a three-state model, which is Rice under *clear state* and Loo's model (running parameters) under *shadowing state* and *block state*. F. P. Fontan et al [12] used the Loo's model as the basis of their three-state Markov model. W.Osborne et al [34] introduced their model as the basis of multi-state model.

In addition to these channel models of land-mobile satellite communication systems, propagation in maritime and aeronautical satellite communication system have also been studied [14~19]. Sandrin and others [15] proposed a generalized model, similar to the ones used in land mobile studies, for the maritime multipath fading on the basis of Rician fading.

Although there exist a large number of papers and experimental results in the field of modeling mobile satellite communications systems, the previously published experimental results are not sufficient to determine the fade distributions of the ground terminal's received signals in different fading environments, different elevation angles and different frequencies for systems using nonstationary orbits. One of the principal reasons for this state, is the change the world has made in the architecture of mobile satcom systems. Originally these systems were conceived to be very large geostationary satellites communicating with ground based mobile users and because of this much of the development and experimental work has employed geosynchronus spacecraft. A second reason for the lack of experimental data that relates directly to the case of a moving spacecraft and a moving user is, the only programs addressing this case are commercial programs who have little interest in sharing propagation data with potential competitors. The only known experimental data available for the case of a moving spacecraft were provided by Vogle [2] and Butterworth [6] using a helicopter in a tree shaded rural environment only and Davidson [36] using the GPS satellite.

In order to extend the work of Vogel and Butterworth, and to obtain fade distributions in suburban and urban environments for a moving spacecraft, we plan to do a series of simulation experiments. The intent of these experiments is ultimately to give a correct estimation of BER based on a link budget and the second order statistics such as LCR and ADF in LEO for LEO/MEO mobile satellite communication systems. Section III introduces our preliminary work on these experiments.

II. PATH LOSS EQUATIONS OF LEO SATELLITE MOBILE COMMUNICATION CHANNEL:

To address the issue of the signal margin estimation in the LEO satellite mobile communication systems, the path loss equations in LEO satellite mobile communication systems must be determined. This is similar to the work done by Okumura, Hata and other researchers in the area of terrestrial cellular communication systems [26-33] and Hess in satellite communications [25]. The difference between terrestrial cellular communication and satellite communications is that propagation impairments caused by the natural medium (rain, fog, scintillation etc.) between the satellite and ground terminal must be included and the satellite case must allow for a direct path component.

In this section after the propagation concerns are introduced, the path loss equations in the rural shadowed areas are presented for different elevation angles, different probabilities, and different frequencies in the 900—2100MHz range including weather effects. These equations are used to calculate the ground terminal received signal level and the results are summarized in Fig.1~6. These figures are illustrations of variation in the received signal level and will be helpful in preparing link budgets.

(2.1) Propagation considerations of LEO satellite mobile communication channel:

In order to give a concise introduction, a summary of relevant propagation impairments is listed below:

(1) Absorption of the atmosphere (*Lair*)

It is very low in the range 0.3 - 10 GHz (lower than 1 dB) and decreases as the elevation angle increases.

(2) Attenuation caused by rain (absorption and scattering) (L_{rain})

It is proportional to the strength of rain.

$L_R = \gamma_R l_R$ (dB) (always less than 0.5 dB) (1)

where, γ_R (dB/km) is the attenuation coefficient, varies in the range of 0~0.02 in the frequency band 900MHz~2100MHz.

l_R (km) is the equivalent path distance, the range is 0~25 and decrease rapidly with the elevation increase.

(3) Attenuation caused by cloud or fog (L_{fog})

$L_F = 0.148 f^2 / \upsilon_m^{1.43}$ (dB/km) (always less than 0.03dB) (2)

where, f = frequency GHz
υ_m (m) is visibility,
heavy fog: $\upsilon_m < 50m$
median fog: $50 \le \upsilon_m < 200m$
light fog: $200 \le \upsilon_m < 500$

(4) Attenuation cause by snow

$$L_S = 7.47 \cdot 10^{-5} f \cdot I\left(1 + 5.77 \cdot 10^{-5} f^3 I^{0.6}\right) \quad \text{(dB/km)}$$

(less than 0.01dB) (3)

where, f = frequency GHz
I (mm/H) is the strength of snow

(5) Refraction by atmosphere (L_{ref})

When elevation angle is higher than 5°, attenuation is less than 0.2dB.

(6) Scintillation of troposphere and ionosphere (L_{scin})

The random variations of atmosphere refractive index result in EM waves focus or defocus. According to experiments, attenuation caused by the scintillation of atmosphere is less than 0.6 dB.

The EM waves propagating in ionosphere can be scattered by the variation of physical structure in ionosphere. This effect may result in about 2.2 dB of additional loss in the 900-2100MHz range.

(6) Polarization effects (L_{fraday})

Linear polarized system are subject to the effects of polarization rotation when waves propagate through the earth's ionosphere in the presence of the earth's magnetic field. The rotation angles vary approximately with $1/f^2$. The signal loss can be around 9 dB at 900MHz and almost 0.3 dB at 2100 MHz. This effect can be avoided by using circular-polarized signal.

But it should be pointed out that some effects, especially diffraction by roof edges and corners of building structures as well as reflections from various planar surfaces, are, however, polarization sensitive and the orthogonal polarization components of circular polarization will be affected differently.

(2.2) Path Loss Equations in Rural Shadowed Area (900MHz~2100MHz)

In the rural shadowed area, the propagating electromagnetic waves are shadowed and scattered by trees, causing the excess path loss. Experimental and emperical data are given in [2] and [7,23]. $Ltree50(\alpha)$ or $Ltree90(\alpha)$ were derived from the experimental results in [2] by Osborne et al [34] to describe the excess path loss term that caused by the rural environment for different elevation angles and probability of closure path loss equations. The results match the received signal envelope records in [7,23] that can be described by statistical model.

In many experiments of [2], helicopters were used as the transmitter platform and ESA measurement results using geosynchronous spacecraft were given in [7]. On the basis of the data of these experiments, the path loss equations in the 900MHz~2100MHz range for different environmental conditions are presented below.

(i) for 50% probability

The path loss in the nonstationary satellite system can be expressed as a sum of free space path loss and excess path loss that caused by natural factors such as rain, ionosphere, troposphere etc. and multipath effects. The values of natural factors in the following equations are synthesized from a vast amount of materials including NASA reports. The excess path loss caused by tree in the following equations are deduced from [2].

$$L_{50}(\alpha) = 32.44 + 20\log(d(\alpha)\text{km}) + 20\log(f\text{MHz}) + Lair(\alpha) + Lrainl(\alpha) + Ltree50(\alpha) + Lfog + Liono + Lfrad \quad (4)$$

where

$$d(\alpha) = \sqrt{r_e^2 + \left(r_e^2 + h\right)^2 - 2r_e\left(r_e + h\right)\cos\left(\arccos\left[\frac{r_e}{r_e + h}\cos\alpha\right] - \alpha\right)}$$

the satellite-to-terminal distance d as a function of elevation angle α. (5)

$r_e = 6378.14$ km radii of the globe

h: 700km~1280km satellite orbit height

$Lair(\alpha) = 0.1(1 + \cos(\alpha))$ dB

$Lrainl(\alpha) < 0.1$ dB (for rain day)

$Lfog = 0$ dB

$Liono + Lfrad = 0$ dB

$$Ltree50(\alpha) = \left(7.5e^{-2.8\alpha\frac{1.57}{90}} + 0.35\cos\left(\alpha\frac{1.57}{90}\right)\right)\sqrt{\frac{f\text{MHz}}{900}}$$

dB (6)

(ii) for 90% probability

$$L_{90}(\alpha) = 32.44 + 20\log(d(\alpha)\text{km}) + 20\log(f\text{MHz}) + Lair(\alpha) + Lrainl(\alpha) + Ltree90(\alpha) + Lfog + Liono + Lfrad \quad (7)$$

where $Ltree90(\alpha) = \left(22.5e^{-2.1\alpha\frac{1.57}{90}} + 0.1\cos\left(\alpha\frac{1.57}{90}\right)\right)\sqrt{\frac{f\text{MHz}}{900}}$ (8)

(iii) for 99% probability

$$L_{99}(\alpha) = 32.44 + 20\log(d(\alpha)\text{km}) + 20\log(f\text{MHz}) + Lair(\alpha) + Lrainl(\alpha) + Ltree99(\alpha) + Lfog + Liono99 + Lfrad99 \quad (9)$$

where

$$Ltree99(\alpha) = \left(25.8e^{-1.1\alpha\frac{1.57}{90}} + 1.5\cos\left(\alpha\frac{(1.57 - 0.3)3.1}{90}\right)\right)\sqrt{\frac{f\text{MHz}}{900}}$$

(10)

$Liono99 + Lfrad99 = 3$ dB

(2.3) Calculations of Ground Received Signal Level

Based on the discussions above, the excess path loss in the ground terminal received signal relative to free space path loss in rural shadowed area at 900MHz, 1500MHz, 1900MHz, on clear days and rainy days, is showed in Fig. 1~6 (In these graphs, the notation R50, R90 and R99 indicate the received signal level for 50%, 90% and 99% probability, respectively).

From these figures we can conclude the following:

(i) The excess path loss increases with the frequency (as shown in equation (4)-(10)). For example, for clear days, 99% probability and 20 degree elevation angle, the level at 900MHz transmitting frequency is almost 16 dB lower than that at 1900MHz, but the difference between LOS signal level is around 6 dB .

(ii) The excess path loss increases with the elevation angle decreasing (as shown in Equations (4)-(10)). The signal lever difference between those of 20 degrees and 90 degrees is 21 dB for 900MHz and for 99% probability when the difference for LOS signal is only 7 dB.

(iii) The impact of rain is not serious in the 900MHz to 2100MHz ranges. The raindrops scattering cause attenuation. The decrease in the wavelength of propagation waves results in an increase in attenuation.

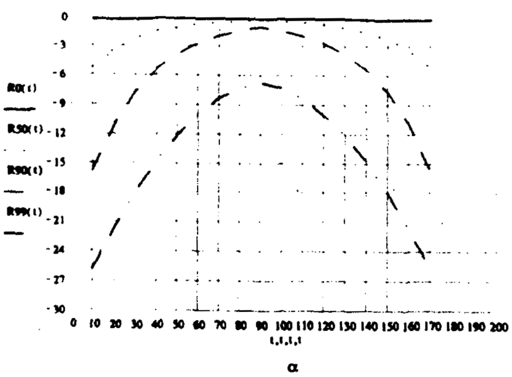


Fig. 1 Excess path loss to elevation angle (900MHz, clear days, rural shadowed area; From the top: The level of LOS, R50, R90, R99)

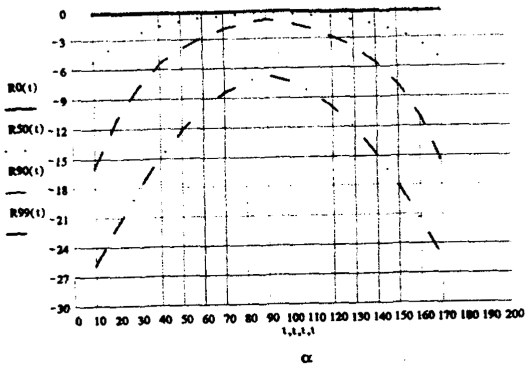


Fig. 2 Excess path loss to elevation angle (900MHz, rainy days, rural shadowed area; From the top: The level of LOS, R50, R90, R99)

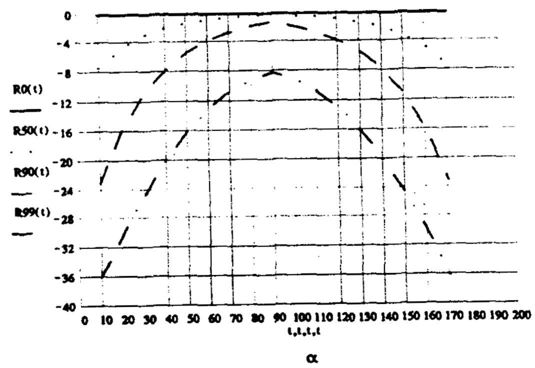


Fig. 3 Excess path loss to elevation angle (1900MHz, clear days, rural shadowed area; From the top: The level of LOS, R50, R90, R99)

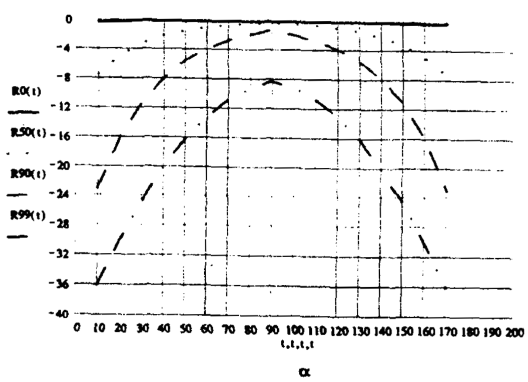


Fig. 4 Excess path loss to elevation angle (1900MHz, rainy days, rural shadowed area; From the top: The level of LOS, R50, R90, R99)

III. Experiments:

(3.1) Objectives of experiments:

In order to contribute to a future non-geostationary mobile communication system design, we plan to set up a series of experiments to investigate the basic channel parameters and transmission performance.

One of our objectives is to investigate the 1st order statistics as fading distributions and 2nd order statistics as LCR, ADF of ground terminal's received signal for 0-90° elevation angles when the terminal is located in a kind of environment such as an urban area, a suburban area etc. A good statistical model of the received signal's fading distribution is very important to predict the BER and the second order statistics as LCR, ADF are also important to predict the performance of the nonstationary satellite mobile communication system. Thus it is important to derive the received signal fading distributions, LCR and ADF from a great deal of experimental data when the ground receiver is located in various environments.

But the published experimental data is not sufficient to provide these statistics, especially when the receiver is located in a dense area. Although some materials [23] dealt with these statistics, they used a GEO satellite system as the transmitter. In this case, the scenario is that of a moving receiver and a stationary satellite. This is different from the scenario in the LEO satellite system with a moving or stationary ground terminal receiving a signal from a moving spacecraft. And the received signal fading distribution that derived from different places for different elevation angles with a GEO satellite (for example for urban areas, they chose different big cities in Europe) should be different from the fading distribution derived from a fixed ground terminal receiving from moving spacecraft.

Another issue that needs to be improved in previous experiments is the antenna. Some researchers used omni-directional antenna [35] to calculate the unfaded signal, but it is more appropriate to use the high-gain antenna to get the line-of-sight signals. Furthermore the type of antenna also significantly influences the received signal's fading distributions as well as LCR and ADF. So to compare the measurement results of fading distributions, LCR using different received antenna is also valuable.

To analyze the adequate propagation measurement results of the time domain signal level of continuous waves (CW) at 900—2100 MHz in simulated nonstationary satellite system can obtains fading distributions, normalized LCR and ADF (normalized to vehicle velocity). Furthermore, the power spectrum estimate at different elevation angles as a function of vehicle velocity can also be derived by fast Fourier transform (FFT).

Moreover, the coherence bandwidth caused by multipath effect is also an important parameter to determine the channel bandwidth in the nonstationary satellite system design. It appears no published experimental results address this issue regarding this parameter in a nonstationary satellite system. Estimation of this parameter can be derived by measuring the time delay of pulse signal propagating in a simulating nonstationary satellite system.

Consequently we have decided to conduct a series of simulation experiments in this year. In the first phase, we plan to engage the experiments in a narrow band to simulate the received signal fading distributions, normalized LCR and ADF, as well as the power spectrum as a function to vehicle velocity in nonstationary satellite mobile communications. In the second phase, we plan to do experimental research on the coherence bandwidth in nonstationary satellite communications.

(3.2) Design of the experiment to accomplish the objectives above

In order to fulfill these objectives, we have designed the appropriate test plan to perform our experiments. The first phase measurement plan (CW measurement) that we are doing is introduced below:

(3.2.1) Test Set-up:

We plan to use a helicopter as the transmitter platform. The advantages of this choice are:

(i) The multipath effect resulting in the satellite communication signals fading is caused by buildings, trees, hills and other obstructs on the ground. Using a helicopter as a transmitter platform is suitable to simulate the signals fading caused by multipath effects for a given elevation angle.

(ii) We can use signal sources that transmit signals at different frequency in a wide frequency band (900-2500MHz), in order to obtain adequate experimental data for different frequencies and elevation angles.

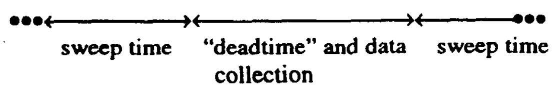
(iii) We can control the distance between transmitter and receiver, and adjust transmitted signal power to obtain the suitable dynamic range for measurement.

(iv) We can determine the normalized LCR and ADF from the different measurements results that obtained when the helicopter fly at different velocities.

High-gain antenna and omni-directional antenna will be used when we measure line of sight (LOS) signals and normal signal levels. The HP 8596E-spectrum analyzer is chosen to be the receiver to receive the signal level transmitted from the helicopter as it is used in zero-span mode

(3.2.2) Data Acquisition System (DAS):

The receiver is connected to computer by GPIB interface. The LabVIEW software is used to perform the instrument control and data acquisition. The sweep trace is digitized and stored in the computer. The time domain output is a sweep period alternated with a non-work period as:



The sweep time can be adjusted in the range of 20ms-100s and the 401 points can be collected for every trace. Thus the sampling rate will be 4Hz to 20KHz. The aliasing error should be avoided. However the fading rate in this case should be around 100Hz. In order to count the LCR and deduce the power spectrum, the compromise sweep time should be 260-360ms.

(3.2.3) Data Analyses:

Appropriate analyses of measurement data results in various conclusions that may be helpful in nonstationary satellite system design. Based on the data in our DAS, we plan to investigate such parameters as fading distributions, LCR, ADF and power spectrum.

(i) Fading distributions: After performing these experiments in an urban area, a suburban area, an open area etc., we will normalize the received signal level to LOS signal level. The excess path loss caused by the multipath effects in nonstationary system can be derived as a probability density function (PDF) and cumulative probability distribution (CPD) at different elevation angles and different frequencies.

(ii) LCR and ADF: After counting the LCR at different vehicle velocities, the normalized LCR at different elevation angles can be derived that can be used to predict the LCR in nonstationary satellite system. The ADF can be deduced on the basis of the LCR and CPD.

(iii) Power spectrum: After performing FFT to the data at different elevation angles, the power spectrum as a function of vehicle velocity can be derived which can be used to predict the power spectrum in nonstationary satellite system.

IV. Conclusion:

The propagation characterization in LEO/MEO mobile satellite communication system is discussed in this paper. The existing research on statistical models of the received signal fading distribution were outlined. The path loss equations in LEO mobile satellite communication system were described. Finally, the experiments we are conducting were introduced.

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