# SIMULATION OF RAIN FADING AND SCINTILLATION ON Ka-BAND EARTH-LEO SATELLITE LINKS

David G. Michelson and Weiwen Liu

University of British Columbia, Department of Electrical and Computer Engineering Radio Science Lab 2332 Main Mall, Vancouver, BC, Canada V6T 1Z4

Email : <u>davem@ece.ubc.ca</u> | <u>weiwenl@ece.ubc.ca</u>

### ABSTRACT

In the near future, many of the research, communications relay and Earth observation satellites that will be placed into low Earth orbit (LEO) will use high speed Ka-band links to communicate with Earth stations during the short time they pass over a given location. The motion of a LEO satellite across the sky will cause the Earth-space path to pass through any rain cells and turbulence cells in the vicinity very quickly leading to steeper fade slopes and more rapid scintillation than in the well-studied geostationary case. Until extensive measurement programs are undertaken, simulation based upon reasonable models of the atmosphere is the likely best option for assessing the severity of fading on such links. If the spatial statistics and/or distributions of the rain and turbulence cells are known, one can predict the rate at which rain fading and scintillation will occur. We have used this insight to construct a channel simulator that can provide plausible predictions of the instantaneous path loss on Earth-LEO links during a given pass.

*Index Terms* — fade slope, Ka-band, rain fading, satellite communications, scintillation

# **1. INTRODUCTION**

Although both rain fading and scintillation on Earth-space links are more pronounced at Ka-band than at lower frequencies, moving to higher frequencies offers many potential advantages including less congested spectrum, the possibility of supporting higher system bandwidths (and higher data rates), reduced interference potential, and smaller equipment size (especially smaller antennas) compared to lower frequencies [1]. At present, most Kaband Earth-space links are used to increase the capacity of conventional communications satellites located in geostationary Earth orbit (GEO) [2]. In recent years, however, system designers have begun to express serious interest in using Ka-band links to provide high speed data communications with satellites in low Earth orbit (LEO) during the relatively short time that a satellite passes within range of an Earth station.

Past interest in establishing Ka-band Earth-LEO links was driven by ambitious but, in many cases, short-lived plans to deploy large multi-satellite constellations capable of providing commercial users with access to voice and data networks from anywhere on Earth [3]. Current interest in Ka-band Earth-LEO links has been mostly driven by the possibility of: (1) retrieving gigabytes of data from Earth observation and scientific satellites during a single pass over an earth station [4] and (2) transferring terabytes of data between any two locations on Earth within twenty-four hours using a store-and-forward data transfer scheme based upon specialized LEO-based communications satellites [5]. In both cases, the objective is to accomplish such transfers of large amounts of data more efficiently and less expensively than by relaying the data through a satellite in GEO.

To date, very little channel measurement data has been collected on Ka-band Earth-LEO links [6]. For designers of future satellite communications systems, the resulting lack of insight concerning propagation on Earth-LEO links at Ka-band is problematic because it impairs their ability to set link budgets and to evaluate the performance of alternative fade mitigation techniques, *e.g.*, [7]-[8]. Until more extensive measurement programs are undertaken, simulation based upon reasonable models of the atmosphere is the likely best option for assessing the severity of fading due to rain fading and scintillation on Ka-band Earth-LEO links.

Earth-LEO links are distinguished from Earth-GEO links by the limited time that the satellite is visible to a given earth station and the rapid rate at which the satellite passes across the sky. It is a relatively simple matter to predict the rapid changes in the range from the satellite to the earth station and the length of the slant path through the atmosphere that play a key role in determining the free

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space path loss and attenuation due to atmospheric gases, clouds and fog. Accounting for the effects of rain and atmospheric turbulence requires a little more effort. In the GEO case, rain fading and scintillation occur as wind advects rain cells and turbulence cells through the fixed Earth-space path. In the LEO case, rain fading and scintillation occur as the motion of the satellite causes the Earth-space path to sweep through rain cells and turbulence cells. If the spatial distributions and/or spatial statistics of the rain and turbulence cells are known, one can predict the rate at which rain fading and scintillation will occur. We have used this insight to construct a channel simulator that can provide plausible predictions of the instantaneous path loss on Earth-LEO links during a given pass. If the spatial models of rain and turbulence are based upon long-term statistics, it seems reasonable to assume that the statistical properties of the simulated channel are also valid in the long term.

The remainder of this paper is organized as follows: In Sections 2 and 3, we describe the models upon which we base our simulations of rain fading and scintillation, respectively, on Earth-to-LEO links. In Section 4, we describe the implementation of these models within the channel simulator and details of the simulation process. In Section 5, we present typical results and our first attempts to validate the results. In Section 6, we summarize the insights gained and the principal contributions of this work.

#### 2. PREDICTION OF RAIN FADING ON EARTH-LEO LINKS

Our approach to predicting rain fading on Earth-LEO links begins with construction of a set of synthetic rain fields that are consistent with the global rain statistics obtained from the ECMWF (European Centre for Medium-Range Weather Forecast) ERA-40 re-analysis database, as described in the current version of ITU-R Rec. P.837-5. Given the typical height of the rain layer and our focus on the portion of a pass with an elevation angle of greater than 10 degrees, it can be easily determined that the track of a typical LEO satellite pass across the top of the rain layer will fit comfortably within a rain field of medium scale (~150 x 150 km<sup>2</sup>). Each of the synthetic rain fields used in this study consists of hundreds of rain cells, each of which is based upon the EXCELL model which describes each rain cell by a circular exponential profile given by

$$R(r) = R_M \exp\left(-\frac{r}{\rho_0}\right),\tag{1}$$

where  $R_M$  is the peak rain rate, r is the horizontal distance from the centre of the cell and  $\rho_0$  is the distance scale factor [10].

We determine the number, intensity and distribution of the rain cells in our rain field using Goldhirsh's method [11] with slight modifications. The major steps include: (1) determining the absolute CCDF (Complementary Cumulative Distribution Function) of rain rate as specified by ITU-R Rec. P.837, (2) setting a rain rate threshold, (3) determining the conditional CCDF by dividing the absolute CCDF by the absolute probability of the rain rate equaling the specified threshold, (4) estimating the parameters  $P_{0}$ ,  $R^*$ and  $\kappa$  by fitting the resulting conditional CCDF to

$$P(R_q) = P_0 \left[ \ln \left( \frac{R^*}{R_q} \right) \right]^{\kappa}, \qquad (2)$$

where  $R_q$  is an arbitrary threshold level of rain rate,  $P(R_q)$  is the probability that the rain rate is greater than  $R_q$  and  $R_M$  is the peak rain rate at the center of the rain cell, (5) determining the peak rain rate values, (6) calculating the number of rain cells that belong to various peak rain rate intervals, and (7) randomly distributing the cells throughout the rain field. A typical result is shown in Fig. 1.

We determine the attenuation due to rain along a given slant path according to the model geometry shown in Fig. 2. At each point along the path, the rain rate is determined and the total attenuation is determined in accordance with the procedure given in ITU-R Rec. P.838-3 where

$$\gamma_R = k R^{\alpha} , \qquad (3)$$

*R* is the rain rate (mm/h) and the coefficients *k* and  $\alpha$  are dependent on frequency. In our channel simulator, we sample the path gain once per second. Given the rate at which the Earth-space path typically sweeps through a rain field, successive values of rain attenuation are determined by differences in rain intensity at points within the field that are typically less than one hundred metres apart. The manner in which path gain evolves during a typical pass is shown in Fig. 3. Full details of our method are given in [6].

## 3. PREDICTION OF SCINTILLATION ON EARTH-LEO LINKS

Scintillation on Earth-space paths is the result of signal propagation through a relatively thin layer of turbulence located at altitudes of a few kilometers [12]-[14]. Although generally much less severe than rain fading, scintillation can impair the performance of fade mitigation techniques and interfere with fade slope estimation. Two parameters, the intensity and the corner frequency, define the scintillation process. For Earth-LEO links, the intensity varies with the elevation angle of the Earth-space path and can be determined using standard models that describe the distribution of the intensity, *e.g.*, [15], and same long-term prediction models that apply to satellites in GEO, *e.g.*, ITU-R P.618, as shown in

$$\sigma_{\chi} = \frac{\sigma_{ref} f^{7/12} g(x)}{(\sin \theta)^{1/2}}, \qquad (4)$$



Fig. 1 – A 150x150 km synthetic rain field generated using a modified version of Goldhirsh's method for estimating the parameters of the EXCELL rain cell model from long-term rain statistics. Also shown is the track of a simulated LEO satellite pass over Tampa, FL at an altitude of 800 km across the top of the rain layer. The scale at right shows the rain rate in mm/hr.

where  $\sigma_{ref}$  is the reference (or normalized) standard deviation, g(x) is the antenna aperture averaging factor, f is the transmission frequency,  $\theta$  is the elevation angle. As the satellite passes from horizon to horizon, the length of the slant path to the turbulence layer changes rapidly. This affects the standard deviation of the scintillation process, which reaches its maximum value at low elevation angles, as shown in Fig. 4, and/or during periods of rain.

We used a geometric model of propagation through the turbulence layer during a LEO satellite pass, as shown in Fig. 5, in conjunction with Tatarskii's theory of propagation through turbulent media, to predict the corner frequency of the scintillation process, using

$$f_c = \frac{1.43v_t}{\sqrt{2\pi\lambda z}},\tag{5}$$

where  $v_t$  is the transverse velocity and *z* is the length of the slant path from the earth station to the turbulence layer. Because both the length of the slant path and the velocity at which the slant path passes across the turbulence layer evolves during a pass, the corner frequency also evolves and reaches its maximum value at high elevation angles, as suggested by Fig. 4. We have also shown that the effect becomes more pronounced as the orbital altitude decreases and as the height of the turbulence layer increases. Full details of our method and additional results are given in [16].

# 4. SIMULATION OF THE EARTH-LEO CHANNEL

Our Earth-LEO channel simulator generates time series of instantaneous path gain based upon the models of rain



Fig. 2 – The model geometry used to predict rain fading on Earth-space links.



Fig. 3 – Path gain due to free space path loss, atmospheric gases, cloud and fog attenuation, and rain attenuation as observed during the pass depicted in Fig. 1 where the carrier frequency is 20 GHz.

fading and scintillation that we briefly described in Sections 2 and 3. The simulator output may be used for two purposes. In the first, the time-series of instantaneous path gain are used directly in simulations of the Ka-band communications system including realistic simulation models of the transmitter and receiver in order to assess the performance of signaling schemes, system hardware, fade mitigation techniques and interference suppression schemes in both typical and extreme propagation environments. In the second, time-series from hundreds or thousands of passes are analyzed directly to yield estimates of the outage probability, fade slope distribution and power spectrum.

Our Earth-LEO channel simulator requires two classes of inputs. The satellite's altitude and orbital inclination, the location of the earth station and the height of the turbulence layer determine the *path dynamics*, *i.e.*, the manner in which the path evolves during a pass. The rain rate, wind speed and direction, temperature, humidity and atmospheric turbulence (often characterized in terms of the structure constant  $C_n^2$ ) along the path determine the degree of *atmospheric impairment*.



Fig. 4 – Evolution of the corner frequency  $f_c$  and standard deviation  $\sigma$  during an overhead pass by a satellite in an 800-km polar orbit with a turbulence layer that is 1-km in height.

In a typical application, simulation of the Earth-LEO channel proceeds as follows:

1. After selecting the longitude and latitude of the earth station, and the orbital altitude and inclination of the satellite of interest, one generates a series of satellite passes over the earth station. These consist of predictions of the look angles (elevation and elevation) and range to the satellite at successive instants.



Fig. 5 - The model geometry used to predict both the total and transverse velocities of I, the intersection of the Earth-space path with the top of the turbulence layer

2. Based upon long-term rain statistics for the region in which the earth station is located, we use Goldhirsh's method to generate a rain field based upon the EXCELL rain cell model for each pass.

3. At each instant during a pass, the simulator determines the intersection of the Earth-space path with the atmospheric and then predicts the attenuation due to: (1)

range, (2) atmospheric gases, clouds and fog, (3) rain and (4) scintillation. We note that:

- a. Free space attenuation depends only upon the satellite range and the carrier frequency.
- b. Attenuation due to atmospheric gases, clouds and fog are calculated in accordance with ITU-R Rec. P.676-6 and ITU-R Rec. P. 840-3, and depends upon the length of the slant path through the atmosphere and the local temperature, atmospheric pressure and water vapour density.
- c. The depth of rain fading at a given instant is determined by the intersection of the Earth-space path with the rain field at that instant and is calculated using the procedure described in Section 2.
- d. Scintillation at a given instant is described by two parameters: the corner frequency of the scintillation power spectrum and the standard deviation (or amplitude) of the scintillation process, and is calculated using the procedure described in Section 3. We can then generate scintillation time-series by (1) passing the Gaussian noise through a low-pass filter with time-varying corner frequency and (2) scaling the amplitude of output signal as required to achieve the desired standard deviation.

Fade slope and corner frequency describe the rate of rain fading and scintillation, respectively. They are determined by the spatial statistics of the cells that comprise the rain field or turbulence layer and: (1) the rate at which the Earth-space path passes through the rain field or turbulence layer and (2) the rate at which the rain field and turbulence are advected past the Earth-space path by the wind. For satellites in geostationary orbit, the Earth-space path is fixed, and fade slope/corner frequency is determined mainly by wind speed. For satellites in high LEO, both factors play a significant role in determining the fade slope or corner frequency, while for satellites in low LEO, the velocity of the Earth-space path through the rain/turbulence environment plays the dominant role.

#### 5. TYPICAL RESULTS AND MODEL VALIDATION

The manner in which total path gain evolves during a typical simulated pass is shown in Fig. 6 where the minimum elevation angle is 10 degrees. The simulation assumes that the satellite is in a 1500-km polar orbit and is making a low elevation pass (maximum elevation angle = 22 degrees) over an earth station located near Tampa, FL (Latitude:  $28.0^{\circ}$  N Longitude:  $82.5^{\circ}$ W Altitude of earth station: 3 m). The carrier frequency is 27.5 GHz. The result shows the combined effect of attenuation due to: (1) range, (2) atmospheric gases, clouds and fog, (3) rain and (4) scintillation. The increase in attenuation due to increased range and a longer slant path through the atmosphere at the



Fig. 6 – Evolution of path gain during a typical pass by a LEO satellite in a 1500-km polar orbit over Tampa, FL. The downlink frequency is 27.5 GHz.

start (t = 0 sec) and end of the pass (t = 730 sec.) is apparent. The increase in the amplitude of scintillation at the start and end of the pass, when the elevation angle is lowest, is also apparent. The steep increase in attenuation at t = 500sec. is due to the Earth-space path passing through an intense rain cell. The increase in scintillation as the depth of the rain fade increases and as the elevation angle drops for t > 600 sec. is also apparent. Thus, the simulated pass appears to account for the essential nature of fading on Ka-band links from Earth-to-LEO.

Conditional CCDFs of both the rising and falling fade slopes observed on simulated 20 and 27.5 GHz links from satellites in 200, 800 and 1500-km polar orbits to an earth station located near Tampa, FL are presented in Fig. 7. The results suggest that links to LEO will encounter fade slopes that will be twice to ten times greater than those reported previously for links to GEO. In particular, we note that fade slopes become much steeper: (1) as the altitude of the satellite decreases (and the angular velocity of the satellite across the sky increases), (2) as the carrier frequency increases (the path geometry in our simulation implies that the frequency scaling factor for attenuation will also be the frequency scaling factor for fade slope; this may not be strictly true in practice). Further, our results suggest that rising and falling fade slopes of a given value are equally likely.

Ideally, we would validate our simulation model by comparing its predictions with results obtained from hundreds of hours of measurement data from actual LEO Earth-space links at Ka-band. Because such data is not yet available, we took a different route and compared our simulator's predictions of the long-term fade slope distributions likely to be observed over geostationary links to earth stations located at Tampa, FL to those actually observed at these sites during the ACTS (Advanced Communications Technology Satellite) program [17]. Because the Earth-space path is fixed, we assume that fade



Fig. 7 – CCDFs of the fade slope observed on simulated Earth-space links at f = 27.5 GHz from LEO satellites in 200, 800 and 1500-km polar orbits and ACTS in GEO to a site near Tampa, FL. Fade slopes based upon data collected and reduced during the ACTS program are superimposed upon the simulated ACTS data.

slope is due solely to advection of the rain field past the earth station by the wind. We assumed a lognormally distributed wind speed with a median value of 30 km/h and a standard deviation of  $\log_c 2$ . In a manner similar to our LEO simulations, we ran 3000 simulations each of 20-minutes in length, yielding 1000 hours (or 3.6 million seconds) of time-series data. In processing our data, we used the same ACA (Attenuation with respect to Clear Air) threshold as the ACTS team used in processing theirs. The results, which are shown in Fig. 7 are a close match to the measurement data presented in [17]. In the absence of more complete validation data, this gives us confidence that our simulations yield useful results.

## 6. CONCLUSIONS

We have developed what we believe is the first channel simulator that can predict the manner in which received signal strength evolves during a typical LEO satellite pass. Given long-term statistics of rain rate, rain height, temperature, humidity, wind speed, wind direction and estimates of the parameters that describe atmospheric turbulence from ITU-R Recommendations and other sources, the simulator produces plausible snapshots of the atmosphere during a given pass. Given the satellite's orbital altitude and inclination, the earth station's latitude and the height of the atmospheric turbulence layer, the simulator predicts the manner in which the path geometry evolves during the pass. At each instant during a pass, the simulator determines the intersection of the Earth-space path with the atmospheric and then predicts the attenuation due to: (1) range, (2) atmospheric gases, clouds and fog, (3) rain and (4) scintillation. Although the simulator cannot capture of the actual channel, the close correspondence between fade slope distributions observed on Earth-to-GEO links during the ACTS program to our simulator's predictions give us confidence that the results of our simulations are likely useful representations of reality.

Taken over many passes, the output of the simulator can be processed to yield estimates of outage probability, fade slope distribution and/or power spectrum. Until Earthto-LEO channel measurement data become more generally available and statistically reliable measurement-based channel models are formulated, channel simulation based upon plausible models of the atmosphere is likely the best option for assessing the performance of Ka-band Earth-to-LEO links and the fade mitigation and interference suppression techniques that will be used to ensure the reliability of such links. When measurement data becomes more generally available, simulation models such as ours will likely provide an effective basis against which such data can be interpreted and assessed.

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