STUDY ON THE EFFECTS OF PRECIPITATION ON EARTH-to-SATELLITE LINKS IN THE Ka BAND

Alexandru Luigi RICOBON[1] Ramona Maria TRESTIAN[2]
([1]) *Technical University of Cluj-Napoca, Romania;* ([2]) *Dublin City University, Ireland*
([1]) alex.ricobon@com.utcluj.ro ([2]) ramona@eeng.dcu.ie

Abstract: The use of higher frequency bands, above 10 GHz, for satellite communication provides a number of important benefits. It relieves congestion in the lower frequencies which are sheared with terrestrial links, in the same time providing larger bandwidths and cheaper implementation of terrestrial equipment. However, the severity of atmospheric influence on the radiowave propagation (especially due to rain) increases markedly with frequency. It is therefore necessary to identify and predict the effects of hydrometeors on wireless links.

Key words: *Satellite links, Ka Band, Precipitation effects, Radar maps.*

I. INTRODUCTION

Weather radars have been routinely used for investigating propagation phenomena which affect satellite communication links. Weather radar returns can be used to estimate both attenuation and depolarization produced by hydrometeors.

Some of the early radar measurements resulted in the discovery of high altitude ice particles as a potential source for depolarization and the development of models for the melting layer or the radar bright band

The data used in our study is taken from weather radar measurements done by the I.E.I.I.T radar situated at Spino d'Adda (CR) in northern Italy from 6th of July 1988 to 10th of February 1992. During this time there were 57 recorded rain events, cumulating 16,278 scenes, each one recording the rain intensity in mm/h according to the distance from radar at a given time. The time between two succeeding scenes of the same rain event is 77 seconds.

The rain intensity data is stored in 80km x 80km square maps with a resolution of 0.5km, thus, a 160x160 matrix. One element of the matrix, called pixel, stores the rain intensity on a 0.25 square kilometer area. Each event is stored in a file called NPCxxx, where xxx is the number which codes that event. The file contains also data about its name, date and time of the event and number of scenes.

The distribution function D(x), also called cumulative (or complementary) distribution function (CDF) describes the probability that a variable X takes on a value greater than or equal to a number x.

$$D(x) = P(X > x) = \sum_{X>x} P(x) \quad (1)$$

II. WEATHER RADARS

Weather radar (RADAR is the acronym derived from **Ra**dio **D**etection **a**nd **R**anging) is a type of radar used to locate precipitation, calculate its motion, estimate its type (rain, snow, hail, etc.) and forecast its future position and intensity. Modern weather radars are mostly Doppler radars, capable of detecting the motion of rain droplets in addition to the intensity of the precipitation. Both types of data can be analyzed to determine the structure of storms and their potential to cause severe weather.

Weather radars work by sending directional pulses and listening to their echoes. A pulse is a microwave radiation, on the order of a microsecond long, generated using a magnetron or a klystron tube.

Electromagnetic waves reflect (scatter) from any large change in the dielectric or diamagnetic constants. This means that any significant change in atomic density between an object and what is surrounding it will scatter radar waves. Electromagnetic waves scatter in a variety of ways depending on the wavelength and the size and shape of the target.

After each pulse is sent, the radar station acts as a receiver and listens for return signals from targets in the air. The duration of the "listen" cycle is generally a thousand times longer than the pulse duration. This duration is determined by the travel time from the radar to the target and back, a distance that could be of several hundreds of kilometers. If pulses are emitted too frequently, the return from one pulse will be confused with returns from previous pulses, resulting incorrect distance measurements.

The radar return from precipitation particles is proportional to the number density of particles in the radar pulse volume. The reflectivity can be converted to equivalent rain rate or signal attenuation through appropriate assumptions on the particle size distribution. If the radar is capable of measuring reflectivity in two orthogonal polarizations, the difference between the two reflectivity measurements is a direct estimate of the anisotropy of the particulate medium. Differential reflectivity can be used to detect regions containing highly non-spherical particles such as the melting layer and high altitude ice particles.

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The radar equation presented below helps to calculate the amount of power returning to the antenna.

$$P_r = \frac{P_t G_t \sigma F^4}{(4\pi)^2 R^4} \quad (2)$$

where:

- P_r – received power;
- P_t – transmitter power;
- G_t – gain of the transmitting antenna;
- A_r – effective aperture (area) of the receiving antenna;
- σ – radar cross section;
- F – pattern propagation factor;
- R – range ;

III. MAP PROCESSING

In order to calculate the attenuation caused by rain, the radar maps had to be processed in order to eliminate the corrupt ones and improve the accuracy of measurements.

The first step was to eliminate the corrupt scenes. This was done by observing anomalies such as rain in the zones not covered by the radar. Based on [1] we eliminated some scenes in which the clutter zones were very different from the rest, thus abnormal.

In [1] NPC390, NPC404 and NPC466 rain events were marked as erroneous because in the header the number of scenes was different from the actual scenes in the file. We have corrected this error, obtaining another 154 valid scenes.

The next step was to view all the scenes, to eliminate the incorrect ones. In this step we searched for anomalies in successive scenes. If the rain in several scenes is in an area of the map and in the next one is in a different area, it can be caused by a plane flying in that area or signal processing errors. After all these steps we obtained 16,238 rain scenes.

After all scenes were validated, we improved the maps by scanning the clutter areas and removing isolated clutter pixels. The remove this pixels, we implemented three interpolation methods. All methods use the information from the adjacent pixels.

The first method gives more importance to the adjacent pixels and less to the diagonal pixels. In order to change a clutter pixel, all four adjacent or 3 adjacent pixels and two diagonal pixels should be rain pixels.

The second method does not differentiate adjacent pixels from diagonal ones, changing a clutter pixel if five surrounding pixels are valid rain pixels. The third method is similar with the second, but the threshold for changing a clutter pixel is set to four.

In the first scene, the first method cured 35 clutter pixels, the second method cured 53 and the third one cured 84 pixels. Considering this, for all scenes we used the third method to cure isolated clutter pixels. Figure 1 shows a radar map (only clutter is displayed) before and after isolated clutter is removed.

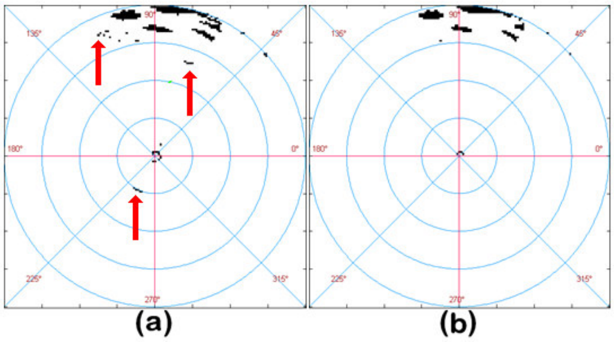

Figure 1. Clutter on a radar map (a) and clutter after the curing procedure (b).

IV. ATTENUATION CAUSED BY RAIN

Rain attenuation is the most important atmospheric effect in terms of its impact on satellite communications systems above 10 GHz. Since long time, studies both theoretical as well as extensive measurements have been carried out on this topic, resulting in several prediction models and algorithms.

Rain varies considerable in space and time, which complicates the modeling of rain attenuation, along a slant path. The specific attenuation of rain depends on the micro structural proprieties of rain, which are temperature, drop size distribution, terminal velocity and shape of the raindrops.

In practice, it is not possible to use all the micro and macro structural parameters as input parameters for a rain attenuation prediction. Usually, available methods of attenuation prediction attempt to relate cumulative statistics of attenuation on slant path to cumulative statistics of ground rainfall intensity, substantially differing one another for the different hypotheses and assumptions.

Both the space-time structural and micro structural proprieties of the rain depend on its type, if the rain is stratiform (widespread) or convective (shower) type.

Attenuation caused by rain along the slant path is calculated using equation 3. In our case, because of the discrete domain of rainfall values, the attenuation equation becomes (4).

$$A = \int_0^L k R^{\alpha} dl \; [dB] \quad (3)$$

$$A = \sum_{i,j} k R_{i,j}^{\alpha} dl_{i,j} \; [dB] \quad (4)$$

The k and α parameters are described in [7] and are calculated from the radio frequency, polarization angle and elevation. L is not the distance from the earth station to the satellite, but the length of the link that can be affected by hydrometeors. Based on the geographical position of the earth station, in [8] is described how to calculate the annual average of the 0°C isotherm height (Y) in kilometers. Knowing Y and the elevation angle Φ, L is calculated according to (5).

$$L = \frac{Y}{\sin(\Phi)} \; [km] \quad (5)$$

Figure 2 gives a better perspective on how the link length is calculated.

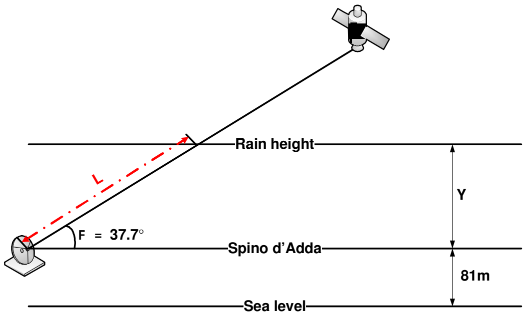

Figure 2. The way L is calculated.

Table 1 contains known and calculated parameters needed in order to calculate rain attenuation. Note that in our study azimuth is intended as the plane angle starting from East, calculated towards North (anticlockwise).

Table 1. Known and calculated parameters.

Known parameters		Calculated parameters	
Frequency	18.7 GHz	α	1.0846
Polarization	π/2 rad.	k	0.0601
Elevation	37.7° = 0.6579 rad.	Y	2,9807
Latitude	45.4°	L	4.8742
Longitude	9.5°		
Azimuth	275.81°		

V. SOFTWARE IMPLEMENTATION

In order to process the radar maps and calculate the attenuation, we used Matlab 7.0. The most important functions that we implemented are:

- correctNPC() – reads all NPC files, cures isolated clutter pixels and removes marker pixels as described before;
- attenuation() – calculates the rain attenuation in each point of the map according to the parameters described in table 1;
- attAllNPC() – scans all scenes, calculates the attenuation on each map and calculates the attenuation CDF.

The second function scans the matrix and in each point calculates the rain attenuation along the slant path. Since the rain is considered to be uniform in our database, we just have to move in the matrix in the direction given by the azimuth (θ).

Let's suppose that the function has to calculate attenuation in the pixel with coordinates (i,j), as shown in figure 3. In order to see which pixels are crossed by the link and to calculate dl, we considered the intersection points of the link with the grids of the matrix (knowing that a pixel represents a 0.25 square kilometer). We presumed that the link starts exactly in the center of the (i,j) pixel, and calculated the intersection pints with the grid by using basic geometry (sine, cosine and tangent functions).

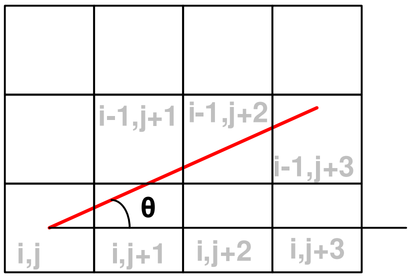

Figure 3. Matrix scanning along the slant path.

VI. RESULTS

Figure 4 shows is the result of applying the attenuation function on a radar map. The first picture represents the rain intensity in millimeters per hour. After calculating the attenuation, in the second picture one can easily see the direction of the link (275.81°).

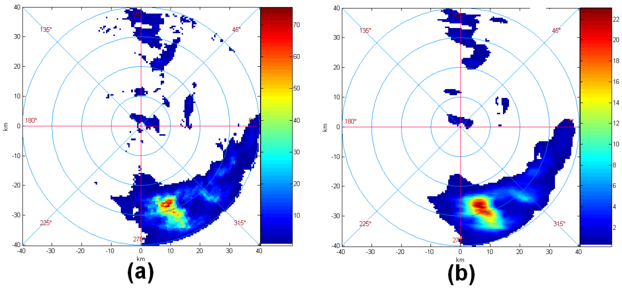

Figure 4. Rainfall [mm/h] (a) and rain attenuation [dB] (b).

By applying the attenuation function to all 16,238 scenes, we calculated the rain attenuation CDF, shown in figure 5.

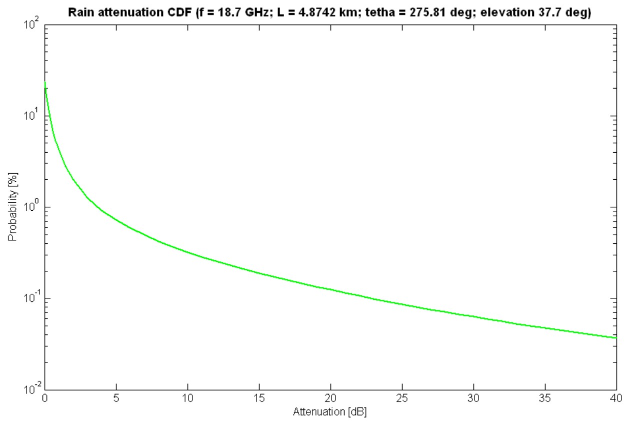

Figure 5. Rain attenuation CDF at 18.7 GHz

In order to evaluate the effects of rain on wireless links, we calculated the attenuation CDF for three different frequencies: 18.7, 20 and 25 GHz, keeping the polarization, elevation and azimuth constant. Changing the link's frequency is reflected in both α and k parameters. Table 2 shows the values of these parameters for the tested frequencies.

Table 2. α and k depending on frequency.

Frequency [GHz]	α	k
18.7	1.0846	0.0601
20	1.0730	0.0701
25	1.0368	1.1145

The attenuation CDF curves are shown in figure 6. As expected, for a given rain intensity, RF attenuation is an increasing function of frequency.

The probability of having 5dB attenuation caused by rain is 0.82% at 20 GHz and 1.3% at 25 GHz. 35 dB attenuation has a probability of 0.1% at 25Ghz and only 0.05% at 20 GHz. We can loosely say that the attenuation probability doubles by increasing the frequency with 5 GHz.

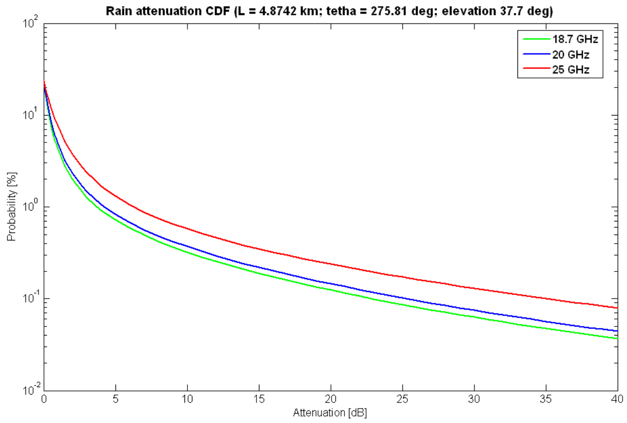

Figure 6. Rain attenuation CDF depending on frequency.

VII. CONCLUSIONS AND FUTURE WORK

In this paper we tried to evaluate the effects of precipitation on satellite links based on radar measurements. There are many mathematical models (like ITU-R, EXCELL, etc.) useful to simulate the attenuation, but as shown in technical literature they are not always precise. We believe that by studying real meteorological data the prediction of attenuation is more precise.

Such a study is a time-consuming process, calculating the rain attenuation CDF with a set of parameters taking about 120 hours (5 days) on a Intel Celeron M 1.5GHz computer with 1 GB of RAM.

In the near future we intend to analyze the influence of elevation and orography (rain orientation under the influence of mountains) on rain attenuation. Combining all the results, we can elaborate a prediction model useful for calculating the link budget .

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