Paper

The Influence of Meteorological Phenomena on Modern Satellite Systems

Jan Bogucki, Jacek Jarkowski, and Ewa Wielowieyska

Abstract— The areas of attention, described in this paper, extend throughout the modern satellite systems. Future satellite systems are to be planned for the millimeter band, which has greater weather attenuation effects than until now used bands. This paper provides a brief overview of propagation factors on millimeter-band earth-satellite paths and requirements in relation to the need for specific types of propagation data.

Keywords*— *millimeter waves, propagation, satellite link.

1. Introduction

A variety of commercial organizations have recently expressed an intent to provide commercial earth-space service via millimeter-band satellite systems. Both mobile and fixed services have been proposed using geostationary orbit or non-geostationary orbit satellite systems, and non-commercial systems are also planned.

Satellite telecommunication has grown to be the most important commercial space application. In terms of business volume, industrial activity and employment generated, satellite communication is so far the most important segment of the industry.

The modern satellite technology has shown the world new ways to use orbital space and radio spectrum resources. It offers alternatives in voice, video and data communications networking to distant places where there is a little or no ground infrastructure. Satellite systems will play an important complementary role in providing the global coverage for both fixed and mobile communication. There are four important satellite industry segments:

- satellite service (mobile, fixed and broadcasting);
- satellite manufacturing and their components (for commercial and government customers);
- launch industry (launch services, production of vehicle and their components);
- ground equipment (networks and consumer equipment).

Satellites are a key component of the world's communication infrastructure, including technically advanced and developing countries alike. For example, the UK space industry sector growing by nearly 8% in 2006/2007 and overall turnover of 5.8 GBP billion with almost 19,000 people employed in high-tech, high value jobs [1].

Overall worldwide industry revenue growth was 16% from 2006 to 2007. Satellite television and direct broadcast satellite (DBS), representing three-quarters of total satellite services revenues in 2007, increased 18% overall to 55.4 billion dollars. The present crisis can slow down this growth [2].

These economic factors make a last decade saw a big increase in the number of satellites and satellite operators and also make innovation in development of satellite systems. Nowadays, multibeam satellites are introduced as an attractive means to reduce the size and cost of the earth stations. Regenerative satellites and onboard processing are also covered as they fulfill the same objective. Actually, these techniques bring more complexity to the routing of information compared to the "bent pipe" routing associated with single beam satellites.

2. Performance Parameters of Modern Satellite Systems

There is a trend in the satellite telecommunication towards larger effective apertures, a significantly higher number of smaller beams, a higher effective isotropic radiated power, a higher gain-to-temperature ratio, more complex switching functions, and onboard processing functions. Satisfying those demands will require an antenna technology significantly more advanced than that employed by current wide area coverage transponder systems [3].

There are very important parameters of antennas:

- *antenna gain*: high gain antennas minimize the terminal size and maximize the capacity;
- *number of beams*: determines the percentage of the desired coverage area available;
- *coverage flexibility*: defines the ability of the antenna to provide high performance coverage across a wide field of view.

Most of the new systems propose to employ new technologies such as multiple narrow spot-beam antennas, on-board demodulation and routing of traffic between beams, intersatellite links, and in some cases scanning beams to continuously illuminate the service area as the satellite flies by. It gives the satellite communication systems a huge potential to offer, promising high-capacity transmission capabilities over wide areas.

Modern satellite systems have to operate at the higher frequencies, i.e., in the millimeter range. Communication between the RF terminal and the satellite is governed by the basic principles of electromagnetic wave propagation. This spectrum of radiation covers everything from AM radio to light, but satellite systems operate in microwave frequency between about 1 GHz and 80 GHz (the segment above 30 GHz is more aptly called millimeter waves). These frequencies are not so crowded, and channels are wider there. All frequency bands are allocated by the International Telecommunication Union (ITU) and its committees and conferences.

Contemporary communication satellite systems have entered a period of transition from point-to-point high-capacity trunk communications between large, costly ground terminals to multipoint-to-multipoint communications between small, low-cost stations. A technique called frequency reuse allows satellites to communicate with a number of ground stations using the same frequency by transmitting in narrow beams pointed toward each of the stations. Beam widths can be adjusted to cover areas as large as the entire Europe or as small as Mazovia Province. Two stations far enough apart can receive different messages transmitted on the same frequency. Satellite antennas have been designed to transmit several beams in different directions, using the same reflector [4].

3. Propagation on Satellite Paths

Propagation impairments produced by the troposphere are limiting factors for the effective use of the millimeter range. Use of smaller earth terminals, while very attractive for consumer and transportable applications, make it difficult to provide sufficient link margin for propagation related to outages.

Future satellite systems are planned for the millimeter range, which has greater troposphere and weather attenuation effects than C- (6/4 GHz) and Ku- (14/12 GHz) bands [5]. In the emergence of new satellite communication systems operating in the millimeter range, the role of atmospheric effects on propagation paths has gained increased significance. The impairing factors of rain have always been considered when designing links at up to centimeter range.

Meteorological statistics are abundantly available for locations around the world. But often, the parameters maintained in weather records do not reflect the information require by propagation analysis (Table 1).

Table 1
Standard meteorological parameters of interest
to meteorologists and propagation analysis

Typical weather records		Propagation interest	
Max/min temperature	[°C]	Mean temperature	[°C]
Relative humidity	[%]	Water vapour density	[g/m^3]
Cloud cover	[%]	Cloud liquid water	[kg/m^2]
Rain accumulation	[mm]	Rain rate	[mm/hr]

The ITU-R has worked out the tables of needed parameters and they are accessible on the Internet pages of ITU-R.

The optimal performance of satellite path is when it works with 99.99% availability. Accurate estimates of the propagation impairments that the effect link quality and availability and determine signal interference fields are essential for the reliable design of telecommunication systems and the efficient use of the electromagnetic spectrum.

At the National Institute of Telecommunications (NIT), Warsaw, a computer program for the system power budget analysis of satellite radio links was developed. As known, such analysis is very important in the radio link network planning and the optimization of the existing transmission networks.

This paper addresses the issues related to predicting different types of propagation impairments as well as combining them together to determine the overall impact on satellite links over a wide range of outage probabilities.

4. Equations for Satellite Paths

Every communication link through satellite includes a transmission from an earth station to the satellite and a transmission from the satellite to the earth station. Therefore to calculate the system performance two sets equations are used; one for the uplink and one for the downlink.

The carrier power to noise power spectral density ratio at the satellite receiver input (uplink) can be calculated as follows:

$$\frac{C_u}{N_{ou}} = \frac{w P_T G_T G_{ru} \lambda^2}{(4\pi R_u)^2 \mathrm{k} T_d L_d} \tag{1}$$

or expressing in dB:

$$\left(\frac{C_u}{N_{ou}}\right)_{[\mathrm{dB}]} = P_{T[\mathrm{dBW}]} + G_{T[\mathrm{dBi}]} + G_{ru[\mathrm{dBi}]} + 20\lg\frac{\lambda}{4\pi R_u} + 10\lg\frac{w}{\mathrm{k}T_d} + 10\lg\frac{1}{L_d}, \tag{2}$$

where: C_u – power of the received carrier at the input to the satellite transponder, N_{ou} – noise power spectral density, P_T – power fed to the transmitting antenna, G_T – earth station transmit antenna gain in pertinent direction, R_u – distance, earth station to satellite, λ – wave length emitted at earth station to satellite path, G_{ru} – the satellite receive antenna gain in pertinent direction, T_d – the uplink system noise temperature, k – the Boltzman constant, $\mathrm{k} = 1.38 \cdot 10^{-23}$ [JK^{-1}], w – antenna efficiency, L_d – additional losses – attenuation due to propagation conditions in troposphere.

A set of six elements is used to fully describe the carrier power to noise power spectral density ratio. The first element is often called *effective isotropical radiated power* (EIRP) and the second *free space loss*. The last element shows additional losses which are attenuations due to propagation conditions in troposphere – due to rain, atmospheric gases, clouds and fog. They can be described only statistically.

The downlink is similar to the uplink. The equations are the same, but there are differences in the numbers and the emphasis.

5. Propagation Effects for Satellite Paths

The atmospheric loss is the result of the combined effects of attenuation due to atmospheric gases and attenuation due to water (rain, clouds, snow and ice) [6], [7]. The results of calculation of free space loss and additional losses for several of elevation angles (path distance) and frequencies from 10 GHz to 50 GHz are presented below. It is assumed that the ground station is situated at NIT and receives signal from several GEO satellites which position changes from 7° up to 30°.

5.1. Free Space Loss Versus Elevation Angle

The free space loss L_{FS} depends on the frequency and on the distance d between the earth station (ES) and the satellite station (SS). The distance of satellite path depends on elevation angle:

$$d = \sqrt{(\mathrm{R}+h)^2 - (\mathrm{R}\cos\theta)^2} - \mathrm{R}\sin\theta\,, \qquad (3)$$

where: R – the radius of Earth, 6371 km, h – the satellite orbit height, θ – the elevation angle.

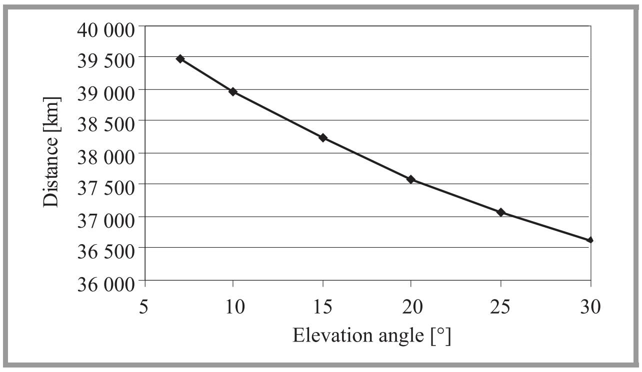

Fig. 1. Distance of GEO – Earth satellite path.

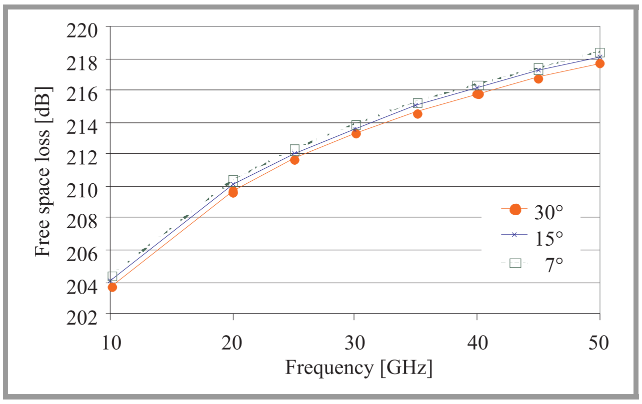

Fig. 2. Free space loss for satellite paths.

The maximum distance from a satellite to an earth station as seen on the edge-of-earth is 41 679 km. The minimum distance, when ES is located on equator "under" the SS is 35 786 km equal $d = h$, when $\theta = 90°$. The length of GEO-Earth satellite path depends on elevation angle is shown in Fig. 1.

The free space loss depends on elevation angle and frequency. When the elevation angle decreases by 5°, free space loss increases only by 0.1 dB for each frequency points at the x axis. It is connected with path lengthen (Fig. 2).

5.2. Attenuation Due to Gas Versus Elevation Angle

Oxygen and water vapour are the main atmospheric gases affecting the signal at millimeter waves. Oxygen concentration is almost constant during the day and during the year and slightly varies over the globe. The oxygen specific attenuation depends on frequency, ground temperature and atmospheric pressure. The amount of water vapour is highly variable being the function of temperature and of atmospheric conditions. ITU-R Rec. P.676-6 [8] indicates how to calculate yearly average gaseous attenuation.

Pressure, temperature and water vapour are functions of the height and consequently these parameters depend on elevation angle.

When the elevation angle θ includes from 5° up to 90°, attenuation due to gas can then be written as follows:

$$A = \frac{h_o\gamma_o + h_w\gamma_w}{\sin\theta}, \qquad (4)$$

where: γ_o – specific attenuations due to dry air [dB/km], γ_w – specific attenuations due to water vapour [dB/km], h_o – equivalent height for dry air, h_w – equivalent height for water vapour.

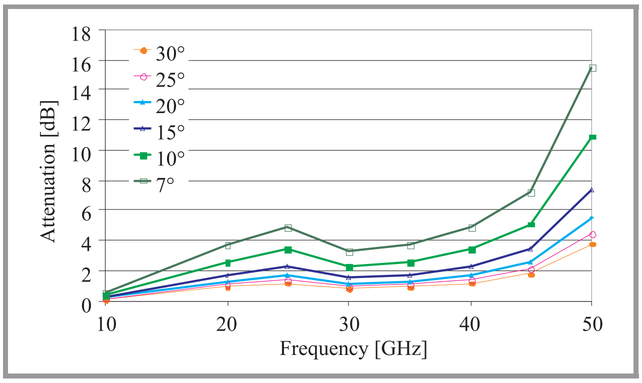

Fig. 3. Attenuation due to dry air and water vapour for satellite paths.

Attenuation due to dry air and water vapour depends on elevation angle and frequency (see Fig. 3).

5.3. Rain Attenuation Versus Elevation Angle

The specific attenuation of rain depends on temperature, terminal velocity and shape (mainly radius) of the raindrops. One of the popular performing models of rain attenuation at frequencies up to 50 GHz is ITU-R Rec. P.618-8 [9]. When measured distributions of rain intensity are not available, the global map of the parameters of the rain intensity recommended by ITU-R P.837-4 [10] can be used, without substantial degradation of the performance of rain attenuation models.

At first the mean rain height above the mean sea level h_R may be obtained from the 0°C isotherm as [11]

$$h_R = h_o + 0.36\,, \tag{5}$$

where: h_o – the height the 0°C isotherm above mean sea level [km].

For $\theta \geq 5°$ compute the slant-path length L_S below the rain height from:

$$L_S = \frac{h_R - h_s}{\sin\theta}\,, \tag{6}$$

where: h_s – the height above mean sea level of the ground station [km].

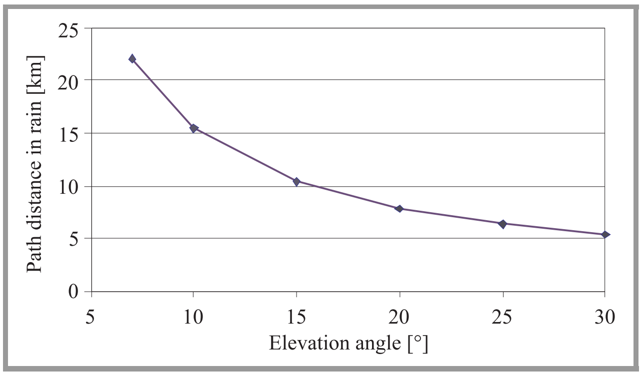

Fig. 4. Effective path length in the rain.

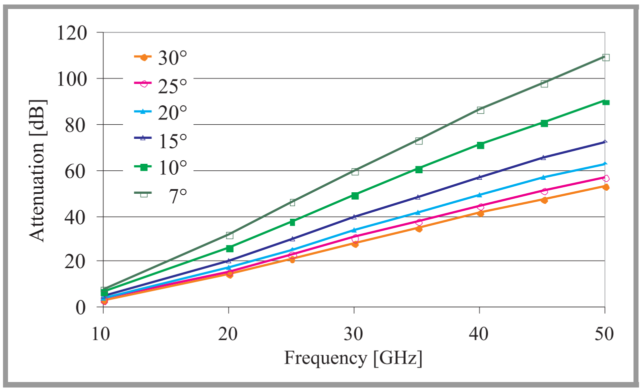

Fig. 5. Attenuation due to rain for satellite paths.

The predicted attenuation $A_{0.01}$ [dB] exceeded for 0.01% of an average year is obtained from:

$$A_{0.01} = \gamma_R L_E\,, \tag{7}$$

where: L_E – the effective path length, γ_R – the specific attenuation,

$$\gamma_R = \mathrm{k}(R_{0.01})^{\alpha}\,, \tag{8}$$

where: $R_{0.01}$ – the rainfall rate, exceeded for 0.01% of an average year (with an integration time of 1 min), γ, α – the frequency-dependent coefficients.

Figure 4 shows the effective path length in rain and Fig. 5 presents how the attenuation due to rain depends on the elevation angle and frequency.

5.4. Attenuation Due to Clouds and Fog Versus Elevation Angle

Clouds and fog consist of suspended water droplets of size smaller than the wavelength for frequencies up to V band. Clouds attenuation is highly variable, depending on the presence or not of clouds along the link and on their liquid water content. One of the commonly used models to compute attenuation is ITU-R Rec. P.676-6 [8] and Rec. P.840-3 [12], which indicates how to calculate clouds attenuation as function of the integrated reduced liquid water content, the frequency, the elevation angle and the dielectric constant of the water.

For clouds or fog consisting entirely of small droplets, generally less than 0.01 cm, the Rayleigh approximation is valid for frequencies below 200 GHz and it is possible to express the attenuation in terms of the total water content per unit volume. Thus the specific attenuation within a cloud or fog can be written as

$$\gamma_c = K_l\, M\,, \tag{9}$$

where: γ_c – specific attenuation within the cloud [dB/km], K_l – specific attenuation coefficient [(dB/km)/(g/m^3)], M – liquid water density in the cloud or fog [g/m^3].

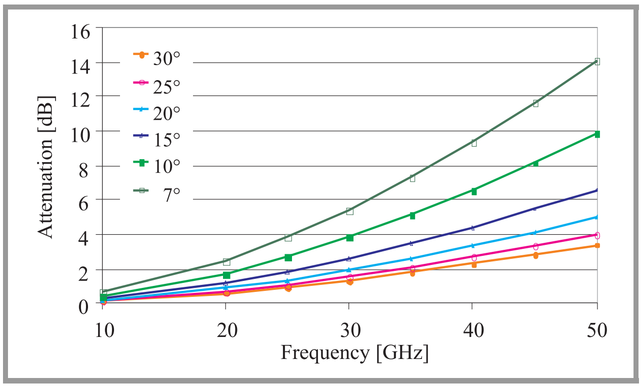

Fig. 6. Attenuation due to clouds or fog for satellite paths.

Attenuation due to clouds and fog depends on elevation angle and frequency (see Fig. 6).

5.5. Total Attenuation

Figures 7 and 8 restore our sense of proportion each part of attenuation takes in total loss and show how total attenuation depends on frequency and elevation angle of GEO path.

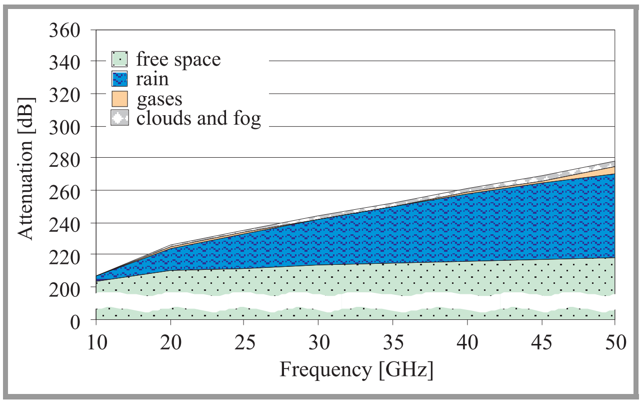

Fig. 7. Total attenuation of GEO path (30° elevation angle).

The ground station is located at NIT with antenna directed on the 30° elevation angle. It is "easy" path because elevation angle is fairly high although propagation conditions are difficult. Total attenuation is 279 dB at 50 GHz within 0.01% time. To achieve availability of 99.99% of time for this path on the frequency of 50 GHz the system requires an excess margin of approximately 60 dB.

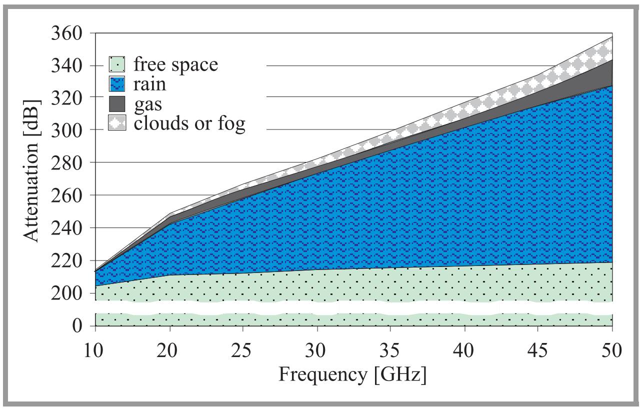

Fig. 8. Total attenuation of GEO path (7° elevation angle).

The reduction of the elevation angle form 30° to 7° causes the increase of the total attenuation about 80 dB at 50 GHz.

Tropospheric scintillations due to small-scale refractive index inhomogenities induced by atmospheric turbulence along the propagation path which causes rapid fluctuations of the received signal amplitude are not taken into consideration in this paper.

6. Example of Prediction and Empirical Data at Satellite Link

The measurements of the 12.5 GHz beacon signal from Lucz 1 were conducted and simultaneously of 1-minute average rain rate under the Earth-Lucz path. Antenna elevation angle was 22° and azimuth 224.3°, location NIT-Warsaw.

Figure 9 shows the rain attenuation statistics, the percentages of the year in 4 consecutive years that attenuation level has been exceeded in case of rain on this path and the average of 4 years. During a storm with very intense rainfall the signal exceeded 20 dB level during 10 min.

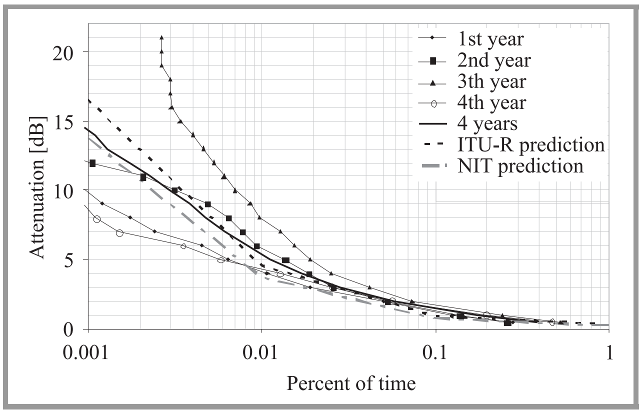

Fig. 9. Measured and calculated distributions of rain attenuation at satellite path.

Empirical annual attenuation distributions were compared with the predicted distribution, based on ITU-R model [9].

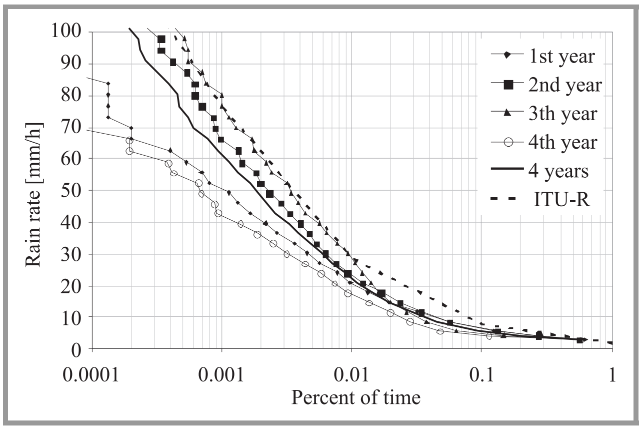

Fig. 10. Measured and calculated distributions of rain rate on the path under satellite link.

The dashed line ITU-R prediction shows calculated rain attenuation exceeded with chosen probability using formula recommended by ITU for average year and the parameter $R_{0.01}$ obtained from the ITU tables. The dashed line NIT prediction shows calculated rain attenuation for chosen time percent using formula recommended by ITU for average year but the parameter $R_{0.01}$ was obtained from NIT measurements [13].

Empirical annual distributions of rain and prediction annual distributions of rain for Warsaw – H region, are presented in Fig. 10.

In our measurement system typing bucket gauges were applied. Their parameters were:

- 1 tip/min corresponded to rain rate of 2.8 mm/h;
- rain rates from this value down to 0.28 mm/h were processed by dedicated software, which averaged single tips in the gaps shorter than 10 min, longer gaps were considered as the breaks between the rain events;
- rain intensity was measured in millimeters per hour with an integration time of 1 min.

Figure 11 shows three distributions of rain rates:

- ITU-R (H): defined by ITU for H region which was recommended by ITU-R Rec. P.837-1 [14] which was in force up to 1994;
- ITU-R: calculated from the tables recommended by ITU-R Rec. P.837-5 [15] which is now in force;
- NIT 4 years: calculated from the empirical data obtained in NIT, averaged for the period of four years.

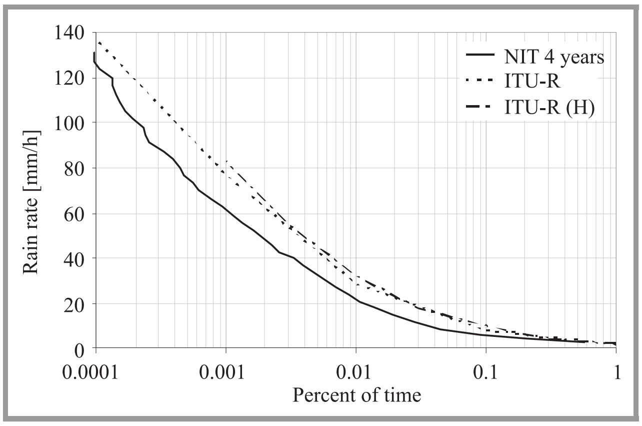

Fig. 11. The comparison of empirical and predicted annual rain distribution.

It is indicated that in recent years theoretical predicted satellite attenuations changed in accordance with real conditions. Difference observed between measured and predicted attenuation is smaller nowadays (ITU-R Rec. P.837.5 [15]) than a dozen years ago (ITU-R Rec. P.837.1 [14]).

7. Conclusions

Considerable variation of attenuation across the satellite coverage area is fairly common and the system design can be optimized by analyzing such variations. In this context the reliable prediction of propagation impairments for millimeter-wave systems becomes important. Modern satellite links can be properly and precisely engineered to overcome potentially detrimental propagation effects. Knowledge of fading estimation is extremely important for the design of millimeter-wave satellite systems. If reception frequently cuts in and out during light rainstorm or other atmospheric events, this is a good indication that the system has not been peaked to maximum performance.

The role of atmospheric effects on propagation paths gained increased significance with increase of frequency new satellite systems operate on.

Until now only the impairing factor of rain has been considered when designing satellite links. Gases, clouds and fog were previously considered “secondary affects” and now they are appearing to play a significant part in total losses; particularly at higher frequencies and lower elevation angles (Fig. 8).

One of consequences of operating the satellite path millimeter region close to the molecular absorption line is that there can be a significant difference in the atmospheric attenuation between the two edges of the band.

The change of elevation angle by 23° has caused the increase of attenuation due to rain by 56 dB at frequency of 50 GHz and for 0.01% of time (Fig. 5), while the effective path length in rain increase only 16.65 km.

Modern satellite systems ought to operate with high exceedance probability levels up to 1% and then link margins are economically practical.

Signal-to-noise of modern satellite systems required to achieve BER of 10^{-10} (bit error ratio of ten to the power minus ten) can be only 5 dB to comply with suitable coding.

Measured distributions of attenuation at satellite path even at 12 GHz indicated that atmospheric events influence is significant at quality of slant links. For accurate prediction of attenuation on slant paths it is necessary to perform long-term data measurements of the above factors different regions.

Our studies indicate that ITU-R model with ITU rain parameters corresponds to experimental few years average data of attenuation caused by rain; maximum difference is 2 dB and the ITU-R model with local rain parameters is even better. The maximum difference is less then 1 dB.

Empirical annual attenuation distributions differ from each other a lot.

In this work, computer program *TraSat* has been used to make calculations for all propagation parameters of satellite links. The program uses algorithms which are recommended by ITU-R and can apply parameters recommended by ITU-R as well as parameters from others resources, e.g., kown local values for chosen parameters.

Benefit of modern satellite systems is their ability to operate with broader bandwidths in the millimeter and the spacecraft is thus able to accommodate smaller antennas. The role of the space industry is very important in meeting our connectivity access telecommunication targets and to contribute to the well-being of the world's population.

It may be that new mobile voice, data and video applications capture consumer interest to growth rates similar to that of satellite television and radio.

Overall satellite industry growth of 16% indicates a fundamental robustness and flexibility to weather business cycles. The prospects of a credit crunch and low stock values will raise the interest of new investors or those returning to the satellite industry sector, with attention focusing on business fundamentals and quality of operations.

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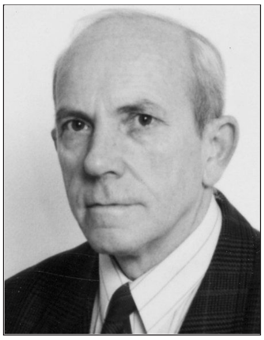

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