COMPARISON OF MULTI-YEAR KA-BAND PROPAGATION CHARACTERISTICS AT FOUR SITES IN NORTH AMERICA AND EUROPE

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Abstract

Tropospheric phenomena such as clouds and mainly rain cause higher attenuation at Ka-band than at lower frequencies. In this collaborative paper, the main results of four long-term Ka-band propagation campaigns are presented. The experiments are carried out in Ottawa, Canada (satellite Anik F2); Aveiro, Portugal; Madrid, Spain; and Toulouse, France (satellite HotBird 6 in the last three cases) and have been running since 2004 in Aveiro, 2006 in Ottawa and Madrid, and 2008 in Toulouse. After a brief introduction of the experiments, rain rate and excess attenuation results are discussed, first for a common two-year measurement period and later for the whole database available. Seasonal attenuation statistics for Madrid, Ottawa and Aveiro are compared. Finally, fade duration and fade slope statistics derived at three locations are presented and discussed.

1. INTRODUCTION

Satellite communication systems operating in the Ka-band and above are expected to experience significant growth in the next few years, with the launch of new satellites such as the KA-SAT satellite in Europe, ViaSat-1 in the USA and Yahsat in the Middle East [1]. In this band, propagation effects such as rain attenuation and the influence of clouds cause deeper fades than at lower frequencies. Communication systems may provide means to mitigate such propagation impairments, and a better experimental characterization of propagation effects can lead to better design and operation of Fade Mitigation Techniques (FMT) [2].

Several propagation experiments in the Ka-band were carried out in the past with the Olympus and Italsat satellites in Europe [3], [4] and with COMSTAR [5] and ACTS [6] in the USA and Canada. Currently, long-term propagation campaigns are being carried out in Ottawa, Canada [7] (satellite Telesat Anik F2); Aveiro, Portugal [8]; Madrid, Spain [9]; and Toulouse, France [10] (satellite Eutelsat HotBird 6 in the last three cases). Measurements started in 2004 in Aveiro, in 2006 in Ottawa and Madrid, and in 2008 in Toulouse, and have been running since then with only short service interruptions. A large database is thus available for each site.

In this collaborative paper, each experiment is briefly presented. Then, the main results on rainfall rate and attenuation statistics at each site are discussed. First, data from a common period of measurements are presented and compared. Then, results for the whole database are analyzed. The complete period analyzed so far is 6 years for Aveiro and Ottawa, 5 years for Madrid and 2 years in Toulouse. Cumulative distributions of rain attenuation at each site are presented for several years, showing the yearly and seasonal variability, and illustrating differences arising from link and climate characteristics. Fade duration and fade slope statistics calculated at Ottawa, Madrid and Toulouse are also discussed. Finally, the paper addresses the need for carrying out multiple-year experiments and results that can be achieved from these campaigns.

2. EXPERIMENTAL SETUPS

The main characteristics of the four setups are presented in Table 1, showing the different locations, climatic conditions and link features. More complete descriptions can be found in references [7]-[10]. The three European sites measure the same beacon signal and have similar latitude, elevation angle and antenna size. The main differences among the four experimental sites are to be found in their climate and geographic situation, Madrid being the driest of the four and also the one with the highest altitude above mean sea level.

The Canadian site presents the most extreme climate regarding temperature variations, the highest annual precipitation amount and the lowest elevation angle, factors that could make it susceptible to higher attenuation levels. Periods with snowfall are not considered during the extraction of attenuation time series. Preliminary analysis shows that the impact of snow on attenuation levels is below about 2 dB. Fortunately, this experiment has also the largest receiver margin, as the EIRP and antenna diameter are both significantly higher than in the other three experiments. The two beacon frequencies are quite close to one another, making differences related to this variable quite unlikely.

Table 1. Main characteristics of the four experiments

	CRC, Ottawa Canada	**UPM, Madrid Spain**	**U. of Aveiro Portugal**	**ONERA, Toulouse France**
Site coordinates: Altitude amsl:	45.35° N 75.89° W 80 m	40.38° N 3.72° W 630 m	40.63° N 8.66° W 10 m	43.57° N 1.47° E 141 m
Satellite: Orbital position: EIRP:	Anik F2 111.1° W 29 dBW	HotBird 6 13° E 17 dBW (estimated)	HotBird 6 13° E 17 dBW (estimated)	HotBird 6 13° E 17 dBW (estimated)
Period of measurements reported	January 2006 – December 2011	July 2006 – June 2011	September 2004 – August 2010	July 2009 – June2011
Beacon frequency	20.199 GHz	19.701 GHz	19.701 GHz	19.701 GHz
Path elevation angle	27.3°	40.2°	38°	38.6°
Receiver antenna	Cassegrain 2.4 m diameter	Cassegrain 1.2 m diameter	Offset 1.5 m diameter	Cassegrain 1.2 m diameter
Rx dynamic range	45 dB	30 dB	25 dB	30 dB
Climate: Annual precipitation:	Continental, mid-latitude rainy (-15 ºC Jan. to 26 ºC July). 910 mm (rain+snow) 222 cm snowfall	Continental, dry. 430 mm; rain mainly in spring and autumn	Oceanic, sea level. 786 mm; high variability, rain mainly Sept.-April	Subject to oceanic and Mediterranean influences. 668.5 mm, small seasonal variations

3. COMMON PERIOD OF MEASUREMENTS

Figs. 1 and 2 present results for the common period of measurements covering July 2009 to June 2011. Comparison plots of the results at the four sites bring about some interesting observations. Fig. 1 presents the cumulative distributions of rain rate. Madrid and Toulouse show similar characteristics, Madrid presenting higher rain rates for the lower time percentages (below about 0.01%). On the other hand, Aveiro and Ottawa also share some similarities, with rain rates being slightly higher in Aveiro for the higher time percentages and higher in Ottawa for the medium and lower ones.

Cumulative distributions of rain attenuation are shown in Fig. 2. It is interesting to note that conversion from point rainfall rate to rain attenuation is different at the four sites. The lower elevation angle in Ottawa partially explains the large attenuation values reached for time percentages below 0.1%. Also, most of the rain at this site falls during the summer months when the maximum values of rain rate and rain height occur. In Madrid, the higher altitude of the site can play a role, as the path length through the rain is shorter than in other sites with similar latitude and link elevation angle. Beside these considerations, it seems reasonable to assume that other climatic factors, such as those affecting rain cell size for instance, may also play a role in these results.

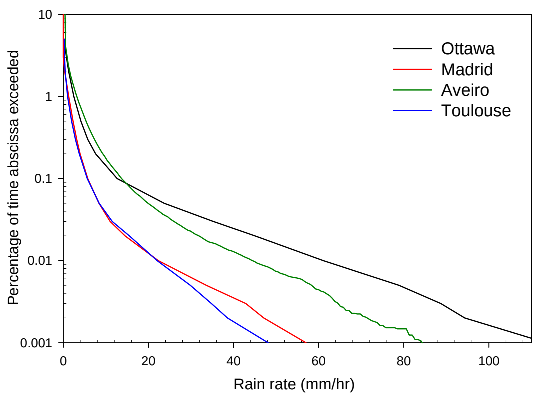

Fig. 1. Cumulative distributions of rain rate for common two-year period July 2009-June 2011.

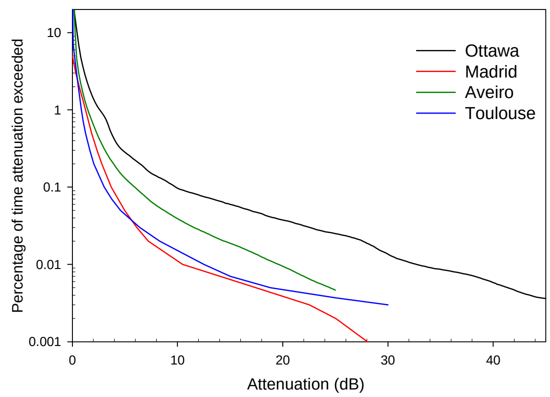

Fig. 2. Cumulative distributions of rain attenuation for common two-year period July 2009-June 2011.

4. RAIN RATE AND ATTENUATION

Cumulative distributions of rain rate for the four sites are plotted in Figs. 3 to 6. In each figure, the distributions for each- and for the average-year are represented and compared with predictions by the model in ITU-R Rec. P.837-5 [11]. In general, predictions from the ITU-R model are good at Aveiro and Madrid, although it somewhat overestimates average rain rates observed at both sites. Underestimation of measurements in Ottawa may be due to significantly higher precipitation levels experienced by this location during the last several years. However, the largest differences between predictions and measurements occur in Toulouse, and can perhaps be attributed to local climatic characteristics. In Ottawa and Toulouse, the years measured at each location present a very similar statistical distribution. It should be noted that, as the statistics presented for these two sites were derived from data collected over a rather short period of time, any conclusion on their behavior must be considered provisional. A larger interannual variability of rain rate is observed in Madrid and especially in Aveiro, which experienced minimum and maximum annual rainfall amounts of about 300 and 1100 mm in the periods 09/2004-08/2005 and 09/2006-08/2007, respectively.

Attenuation statistics have been measured for several years at the four sites, in order to obtain a more reliable characterization of the average year distributions as well as a description of the yearly variability at the different locations. The results are plotted in Figs. 7 to 10 and are compared to predictions by the model in ITU-R Rec. P.618-10 [12].

Attenuation results for Aveiro (Fig. 7) show, as expected from yearly rain rate cumulative distributions, also a pronounced yearly variability, with more than one order of magnitude of difference between probability levels for attenuation greater than about 17 dB. Predictions from Rec. ITU-R P.618-10 for the average of the six-year database are, however, remarkably accurate, mainly above about 13 dB, when the locally-measured rain rate is used instead of predictions with Rec. ITU-R. P.837-5. Below 13 dB the model overpredicts rain attenuation. It is interesting to note that this overprediction also occurs in Ottawa below about the same attenuation threshold.

Because of its drier climate, rain attenuation is lower in Madrid (Fig. 8), and also presents a large interannual variability, larger than its rain rate (shown in Fig. 4). This result is maybe due to the local characteristics of precipitation. Except for the highest attenuation levels (above about 10 dB), Rec. ITU-R P.618-10 represents well the mean annual behavior, but not the individual years. The model agrees well with measurements for smaller fades (less than 10 dB), but the higher attenuation values are generally underpredicted.

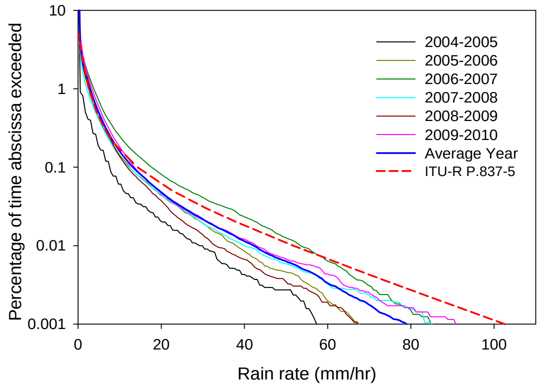

Fig. 3. Cumulative distributions of rain rate in Aveiro.

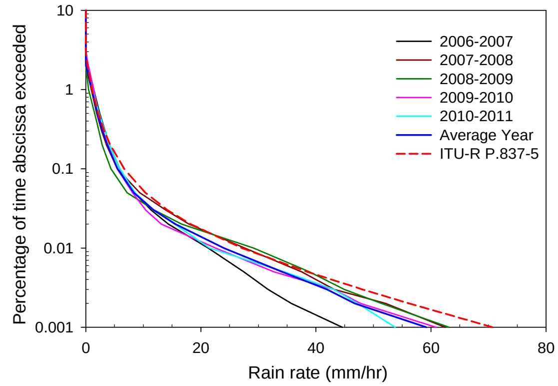

Fig. 4. Cumulative distributions of rain rate in Madrid.

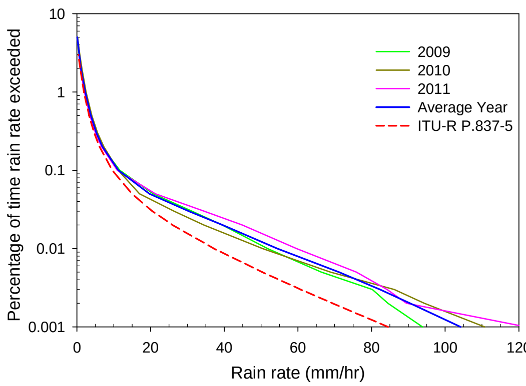

Fig. 5. Cumulative distributions of rain rate in Ottawa.

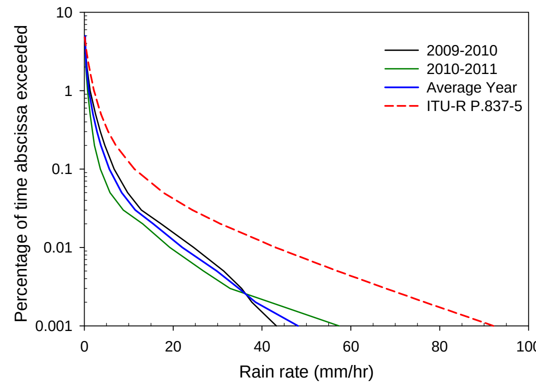

Fig. 6. Cumulative distributions of rain rate in Toulouse.

Rain-induced attenuation statistics for Ottawa (see Fig. 9) show a moderate interannual variability during the measurement period. Attenuation levels in 2007, 2008 and 2010 are close to one another and higher than those in 2006. Below 0.01% time percentage, attenuation is higher in 2009 due to the larger number of convective events occurring that year. Levels in 2011 were in general above the average. Predictions from Rec. ITU-R P.618-10 generally match the measured distributions. However, the model overestimates the annual average in the region below about 12-14 dB, and underestimates above these levels. Overestimation of lower attenuation values, and underestimation of higher ones, is also apparent in the results for Toulouse (Fig. 10). At the four sites, the attenuation predictions from the ITU-R model make use of locally measured rain rate. In particular, the rain rate exceeded for 0.01% of the average year is 42 mm/h in Aveiro, 24 mm/h in Madrid, 54 mm/h in Ottawa and 22 mm/h in Toulouse. These values were used in the calculations, instead of those calculated by Rec. P.837-5 (52 mm/h for Aveiro, 28 mm/h for Madrid, 37 mm/h for Ottawa and 43 mm/h for Toulouse). As a consequence of the use of local rain data, predictions of rain attenuation match the measurements much better than predictions of rain rate shown in Figs. 3 to 6. It is interesting to note also, that in general, the year-to-year variability is higher in the rain attenuation results than in the rain rate results.

When the four sites are compared to one another, similar conclusions as those drawn from Fig. 2 can be derived for the long measurements periods. The highest attenuation levels occur in Ottawa, where 30 dB is exceeded 0.01% of the time. This is partly due to the lower elevation angle, but the main factor is the local rain regime. Attenuation exceeded 17 dB for 0.01% of the time for Aveiro and reached similar levels for Madrid and Toulouse (11 and 12.5 dB, respectively).

Seasonal statistics were calculated for Madrid, Aveiro and Ottawa with the aim of analyzing differences in the expected attenuation throughout the year. Results for Aveiro (Fig. 11) show a clear seasonal behavior. The highest fade levels at every time percentage occur in the autumn, followed by the spring. In fact, December, January and February are usually not the rainiest months, but a lot of events occur in later March and April. The local perception of winter as the rainiest season is not verified in practice in terms of attenuation. June, July and August are the driest months and attenuation is much less. The seasonal statistics of rain rate (not shown) do not mimic those of attenuation, so probably other factors such as rain height and rain cell sizes also play an important role in addition to point rain intensity.

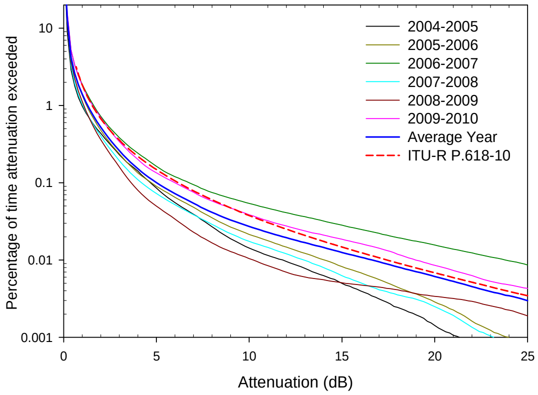

Fig. 7. Statistics of rain attenuation in Aveiro.

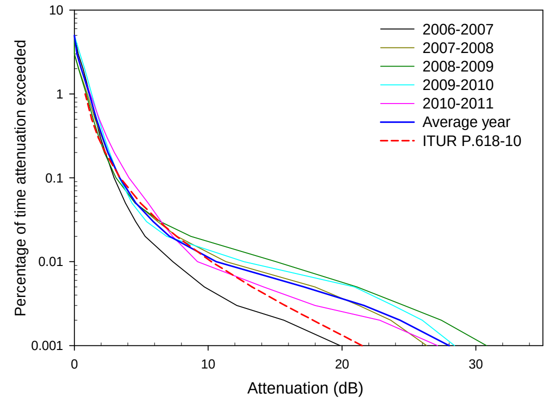

Fig. 8. Statistics of rain attenuation in Madrid.

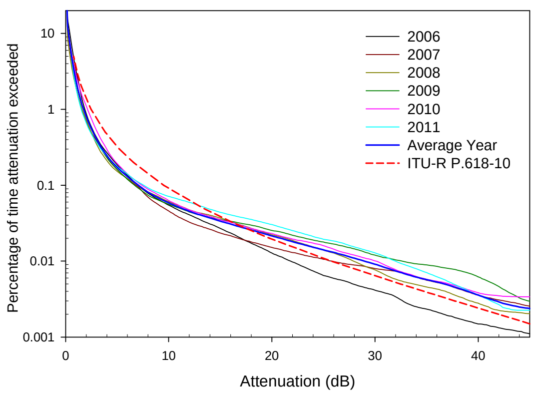

Fig. 9. Statistics of rain attenuation in Ottawa.

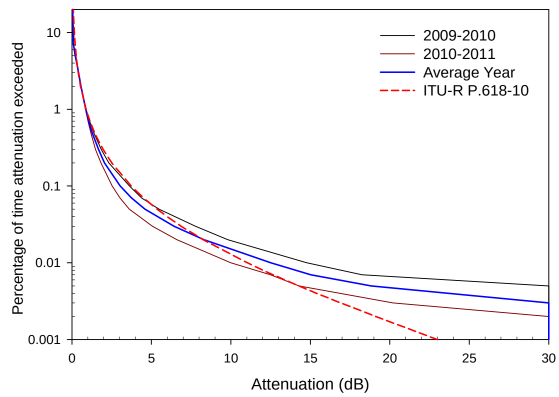

Fig. 10. Statistics of rain attenuation in Toulouse.

As may be expected for a location experiencing a continental mid-latitude rainy climate with cold winters, seasonal attenuation statistics for Ottawa are clearly dominated by the summer, as can be seen in Fig. 12. The monthly average statistics (not shown) confirm that June, July and August are the months that exhibit the largest attenuation levels, which closely reflects the significant rain accumulation and the occurrence of most of the convective events during this period of the year. Fig. 12 also shows that attenuation levels are similar in autumn and in spring and that the smallest fades are recorded during the cold winter months. This behavior may be explained by the fact that many precipitation events in the winter are dry-snowfall events, inducing less attenuation than rain. Seasonal attenuation statistics for Madrid are dominated by the rainy seasons, autumn (October to December) and spring (April to June), with 14 and 16 dB of attenuation, respectively, at 0.01% of the time. The summer season is important only for very low percentages of time (25 dB at 0.001%), due to a few but strong convective events. The winter season is the driest of the year, with about 6 dB at 0.01% of the time.

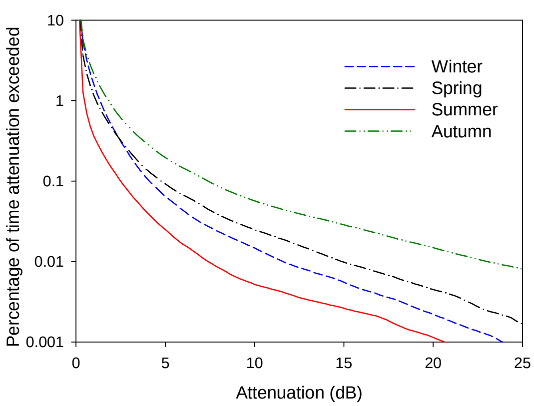

Fig. 11. Seasonal statistics of rain attenuation for Aveiro.

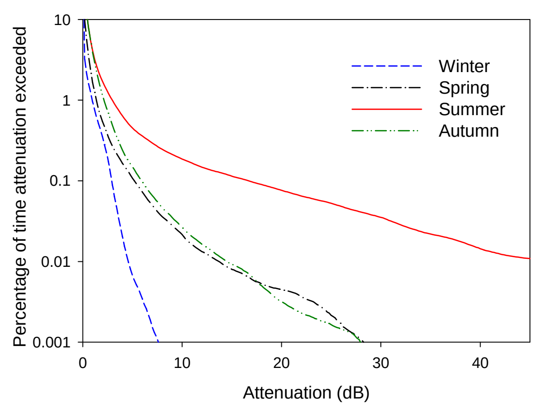

Fig. 12. Seasonal statistics of rain attenuation for Ottawa.

5. FADE DYNAMICS

The design of FMTs (Fade Mitigation Techniques) requires detailed knowledge of the dynamic behavior of fading represented by the duration of fades and fade slope or rate of change. The probability of occurrence of fades of duration *d* longer than *D*, given that a specified attenuation threshold has been exceeded, is referred to as the *relative number of fades*. This parameter is plotted in Figs. 13 to 15 for the Madrid, Ottawa and Toulouse experiments, respectively. The results are compared to the Rec. ITU-R P.1623-1 [13] and CRC [14] models.

Both models use a combination of two functions to represent duration distributions, one accounting for the region of short durations and the other for the region of long durations. Recommendation ITU-R P.1623-1 combines a power law with a lognormal function, whereas the CRC model uses a double lognormal fit.

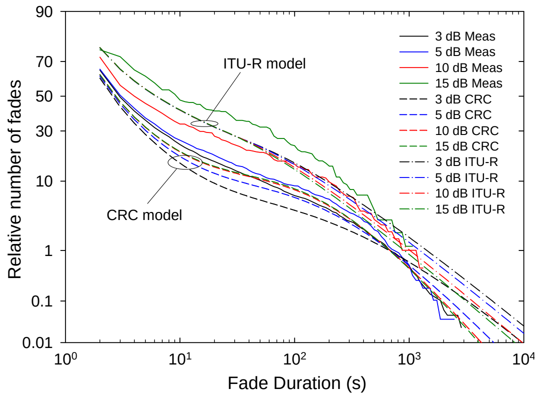

Fig. 13. Fade duration statistics for Madrid.

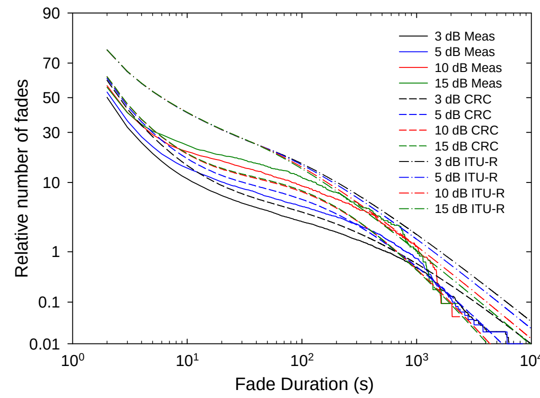

Fig. 14. Fade duration statistics for Ottawa.

Fig. 13 shows comparisons of distributions of the relative number of fades measured in Madrid for four thresholds between 3 and 15 dB with predictions by both models. The CRC model shows a better behavior for the 3- and 5-dB thresholds, whereas the ITU-R model is closer to the experimental results for the highest thresholds. The same comparison for Ottawa is presented in Fig. 14. The CRC model matches the measured statistics better than the ITU-R model, except for durations between about 100-1000 seconds for the 10 and 15 dB thresholds. In the case of Toulouse (Fig. 15), the CRC model performs better than the ITU-R model, except again for the higher thresholds above about 100 seconds. The somewhat different behavior of Madrid can be explained by the local climate. It is the site with the lowest accumulated rainfall in an average year. Moreover, the distributions for the 15-dB fade threshold may not be very stable because of the small number of events of this type per year.

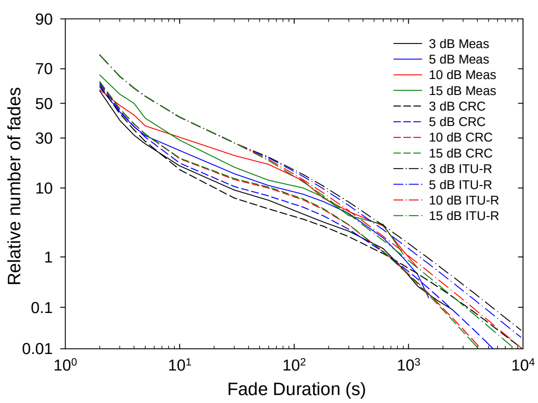

Fig. 15. Fade duration statistics for Toulouse.

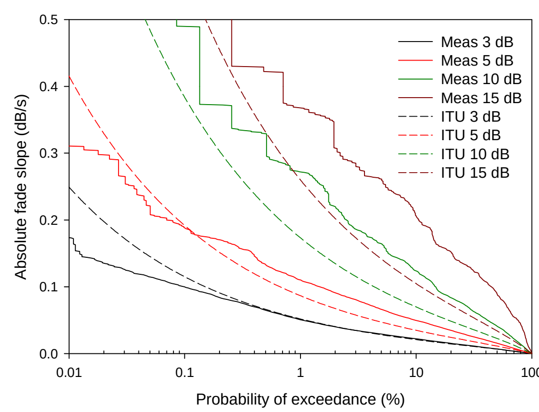

Fig. 16. Fade slope statistics for Madrid.

Fade slope statistics were also calculated for Madrid, Ottawa and Toulouse. Following standard practices, the attenuation time series are low-pass filtered before computing fade slopes, in order to eliminate scintillation. Different filters have been used in the different experiments (raised-cosine, Butterworth), but in all cases the cut-off frequency is very close to the recommended value of 0.025 Hz, so results are to a large degree comparable.

Cumulative distributions of fade slope, calculated over a time interval of 30 seconds, are plotted in Figs. 16 to 18 for the three sites. ITU-R model predictions [13] are also shown for comparison. Results for Madrid, presented in Fig. 16, compare cumulative distributions of absolute fade slope (positive and negative slopes together) for attenuation levels of 3, 5, 10 and 15 dB, measured at the center of the time interval of 30 s. Statistics are remarkably close to predictions from the ITU-R model, though differences are higher for the lower probabilities and for the highest attenuation thresholds. Both cases present smaller amounts of experimental data. It is not clear if differences can be attributed to this fact.

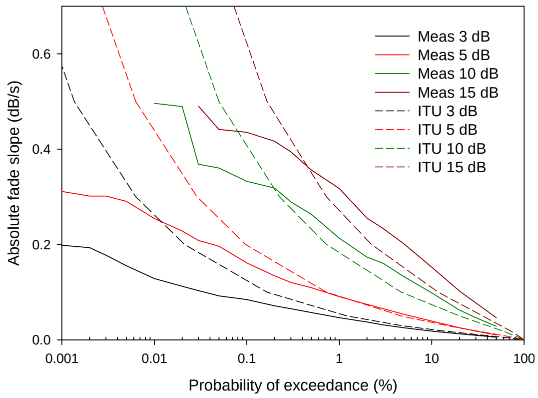

Fig. 17. Fade slope statistics for Ottawa.

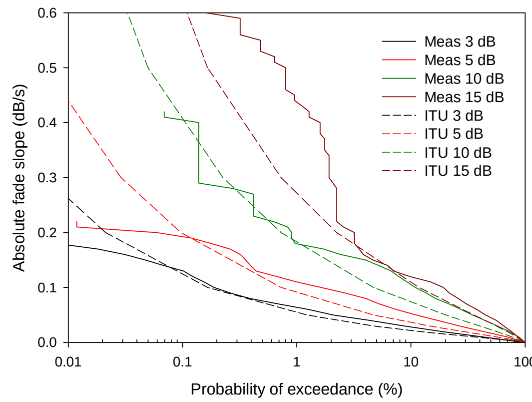

Fig. 18. Fade slope statistics for Toulouse.

Results for Ottawa (Fig. 17) and Toulouse (Fig. 18) also show general good agreement between measurements and predictions, including the cases with larger amounts of data: lower thresholds and higher probabilities. The agreement deteriorates somewhat for the other cases.

6. CONCLUSIONS

Four ongoing propagation experiments, all with ancillary measurements, have been described. New data now totaling more than 19 years and encompassing four different climates. Several interesting issues have arisen from this collaborative work. The comparison of experimental results from the three European sites – Aveiro, Madrid, Toulouse – with similar latitude, small longitude separation (about 5-10º), same beacon frequency and similar elevation angles, shows significant differences that can be attributed to orographic and climatic factors.

Ottawa has a very cold winter, with little liquid precipitation (precipitation being mainly dry snow), while most of the rain occurs during the summer. The other three sites have temperate climates, with rain more evenly spread throughout the year. Aveiro is markedly influenced by its proximity to the sea, whereas Madrid and Toulouse are not and have somewhat similar climates.

The availability of a large number of years of data in some of the sites results in more stable statistics. As all the experiments are still ongoing, new data are added to each database continuously, further increasing its value. As a general conclusion, the availability of multiyear propagation results permits insight into the variability of rain intensity and rain-induced attenuation. Year-to-year variability of path rain attenuation is not completely explained by the differences in point rain rate statistics, though this phenomenon is more apparent for Madrid than for the rest of the sites.

Predictions by the model of rain rate proposed in ITU-R Rec. P.837-5 produced generally good results for Madrid. Some overestimation was observed for Aveiro, underestimation at Ottawa and a larger disagreement for Toulouse that has been attributed to local factors not accounted for in Rec. P.837-5. Rain attenuation measurements are in general good agreement with the predictions of ITU-R Rec. P.618-10, provided that local rain data are used in the calculations. In the four cases, the predictions slightly overestimate the measurements for the lower percentages. They underestimate the measurements for the higher percentages in Madrid, Ottawa and Toulouse, with larger differences in the case of Madrid. Fade duration probabilities measured in Ottawa, Madrid and Toulouse were compared with two models, Recommendation ITU-R P.1623-1 and a second model developed at CRC. The performance of both models is somewhat equivalent for Madrid. In the cases of Ottawa and Toulouse, the CRC prediction method generally matches the measured distributions better. Finally, the ITU-R fade slope model shows good performance when compared with statistics measured in Ottawa, Madrid and Toulouse.

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