Comparison of heterogeneous network rain fade simulation tools: global integrated network SIMulator and MultiEXCELL

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1 Introduction

Terrestrial and Earth-space microwave links experience large dynamic fade variations because of scattering and/or absorption by liquid and mixed-phase hydrometeors, for example, rain, sleet, fog, wet snow and cloud. For links operating above 5 GHz, this is the dominant fade mechanism limiting availability. Hydrometeor fade exhibits complex spatial and temporal correlations, because of its dependence upon the atmospheric circulations [1]. The Radio Sector of the International Telecommunication Union (ITU-R) maintains a large set of propagation models in the Propagation recommendations (http://www.itu.int/rec/R-REC-P/en). Models exist to predict average annual, one-minute, fade distributions for individual Earth-space and terrestrial links. Models are also provided for some second-order statistics such as diversity gain, fade duration and fade slope distributions. The ITU-R models are adequate for the regulation and coordination of radio networks and for assigning fixed fade margins. However, they are of limited use in the planning of fade mitigation techniques (FMTs) and almost no use for the design and optimisation of dynamic network management (DNM) systems. For these tasks, it is necessary to resort to models capable of predicting joint channel time-series of fade or, at least, joint fade distributions, often at a time resolution considerably shorter than one-minute.

Joint channel simulators can be utilised for the design, evaluation and optimisation of arbitrarily complex radio networks that may incorporate various types of radio links, both fixed and mobile, for example, terrestrial, Earth-space, to high altitude platforms (HAPs) and unmanned airborne vehicles (UAVs), at C to W bands. SATNEx II (IST 027393) European Network of Excellence and the recently completed COST Action IC0802, specifically address channel models for such global integrated networks (GINs). One specific example is the land mobile satellites operating at Ka/Ku bands and higher EHF frequencies. Two French space agency (CNES) projects, SWIMAX and SDMB, have recognised the potential of such systems to be the future for broadband and broadcast systems to mobile receivers in cars trains and planes, see [2]. The main obstacles to this system are the atmospheric fade mechanisms, that is, extinction by rain, sleet, cloud, that will severely attenuate radio signals connecting content providers, ground stations and satellites. Communications signal outages will severely reduce the quality of service provided by such systems.

To some extent, FMTs can reduce the impact of these fades by increasing power or reducing capacity to maintain connection during fades around outage levels, see COST 280 www.cost280.rl. ac.uk. The design and optimisation of FMTs requires channel time-series models with one-second temporal resolution and correct first- and second-order statistics. Also, FMTs based on power control often need to be managed across a network. Increasing power to maintain capacity in one part of a network can lead to interference that reduces capacity in another part. DNM tools aim to balance capacity and demand throughout the network. Predictive DNM systems may pre-load nodes with streamed data before outage or reschedule data movements to reduce required nodal capacity during high fade periods.

Joint channel simulation tools could provide standard statistics currently obtained with ITU-R models, including fade, fade duration and fade slope distributions, but at a range of temporal resolutions much finer than that currently available. Unlike ITU-R models, they could also provide any joint statistics for arbitrary pairs of links, or larger networks. For many users, the principle output will be the joint fade time-series. This will be used to simulate and optimise the performance of the user's particular network and DNM tool. An intermediate-term application of these models is the generation of semi-analytic fade data for the production or refinement of ITU-R recommendations, where the experimental collection of such data would be prohibitively difficult or expensive. This is commonly the case where a large number of parameters exist, such as for multi-hop or route diverse link systems.

This paper compares the performance of the GINSIM tool (from global integrated network SIMulator) with the relatively well established MultiEXCELL model. Predictions are compared against measured microwave link data acquired in southern England and Scotland. We focus on the joint fade statistics of pairs of terrestrial and Earth-space links. Currently there is no

ITU-R model able to estimate such distributions. Section 2 provides an introduction to the GINSIM tool and the MultiEXCELL model. Section 3 describes the data used for verification while Section 4 compares simulated with measured results. Section 5 discusses the performance of the two simulators and identifies features effecting accuracy of fade predictions, while Section 6 draws some more general conclusions.

2 Network fade simulation tools

The only known method of producing joint hydrometeor fade samples with correct cross-covariance is to simulate the fade on link networks superimposed on specific attenuation fields derived from realistic hydrometeor fields. The Rec. ITU-R P.838–3 model is generally used to transform rain rate to specific attenuation. This method has been used in many systems: [1, 3–7].

This document compares the performance of two network fade simulators: MultiEXCELL and GINSIM. These are described in more detail in the sections below. It should be noted that GINSIM is designed to produce joint fade time-series with the correct first and second order statistics, while MultiEXCELL has the less ambitious goal of producing joint fade vectors consistent with the rain rate distribution provided as input. A review of network fade simulation tools is provided in Chapter 4 of the Working Group 2 Final Report of COST IC0802, and in [8].

2.1 Global integrated network SIMulator

The Hull rain fade network simulator (HRFNS) [6], was a heterogeneous network simulation tool capable of producing joint rain fades time-series for arbitrary networks of terrestrial SHF and EHF links. Since 2009, GINSIM has been developed from the HRFNS. Its application link type has been extended to include slant paths including links to space platforms, UAVs, HAPs. Furthermore, the regional span has been extended to cover most of Europe. The input data used in this paper is composite rain field time-series produced by the UK Meteorological Office NIMROD rain radar network. NIMROD is a fully automated system for weather analysis and nowcasting, based around a network of C-band rain radars. It produces composite data sets of rain rate maps spanning the UK and the edge of countries bordering the North Sea. However, the use of equivalent data produced by the OPERA project (http://www.eumetnet.eu/opera) extends the region of application to most of Europe. NIMROD (from 2004) and OPERA composite rain field images have a 1 km spatial resolution and 5-minute sample time. The numerical downscaling processes employed by both GINSIM and HRFNS, necessary to produce short integration time fade samples, are described in detail in Paulson and Zhang [6] and Zhang [9]. These include spatial disaggregation using the log-Poisson multiplicative cascade algorithm of Deidda, [10, 11] and interpolation using an asymmetric variant of the Local Area Subdivision algorithm of Fenton and Vanmarcke [12]. To simulate slant paths, a model of the vertical variation of specific attenuation is required. GINSIM assumes a stratified atmosphere with the Bacon-Tjelta sleet model, as used in Rec. ITU-R P.530-13, to provide the vertical variation. This includes a sleet amplification factor, $\Gamma(\Delta h)$ (see (1)) where Δh is the altitude of a point on the link path relative to the rain height.

Rain heights are derived from NOAA NCEP/NCAR Reanalysis I data, [13]. The GINSIM tool has been verified against ITU-R models of fade distribution, fade duration and fade slope for both terrestrial and Earth-space links in the southern UK [14]. For the results in Section 4, NIMROD rain fields are numerically downscaled to a spatial resolution of 125 m and a sample time of 18.75 s. GINSIM is extremely numerically intensive: one year of NIMROD data yields a time-series of 1.68 million rain fields.

2.2 MultiEXCELL

The best known of the rain cell models proposed in the literature are the EXCELL model [15], its recent enhancement, MultiEXCELL [16] and the HYCELL model [17]. Such models allow the generation of synthetic rain fields consistent with a climate described by the rain rate exceedance distribution, also known as the complementary cumulative probability function (CCPF). Rain fields are composed of individual rain cells characterised by distributions of properties such a peak rain rate and parameters describing the geometry. The EXCELL model uses individual cells while the newer MultiEXCELL combines multiple rain cells consistent with an assumed rain rate spatial autocovariance. EXCELL and HYCELL assume a constant specific attenuation up to the Rec. ITU-R P.839–3 average annual rain height [18].

The EXCELL and MultiEXCELL models have been tested against the ITU-R Study Group 3 database of global propagation measurements (DBSG3) for both Earth-space [19] and terrestrial links [20, 21]. They have been used for performance assessment of time [22] and site [23] diversity schemes, prediction of the radio interference because of hydrometeor scattering, [24]; conversion of rainfall statistics from long to 1-minute integration time [25]; fade slope analysis of Ka-Band Earth-LEO satellite links [26] and performance evaluation of an adaptive coding and modulation system for the provision of advanced services via satellite [19].

For this investigation, MultiEXCELL was conditioned to reproduce the rain rate CCPF for the two UK regions, derived from NIMROD 1 × 1 km resolution data. MultiEXCELL generated 504 square rain fields, with lateral dimension of 200 km and with 1 × 1 km spatial resolution, which, together with 2300 notional rain fields with no rain, are sufficient to properly reproduce the NIMROD CCPF provided as input to the model. The rain rate exceeded for 0.01% of the year is approximately 30 and 24 mm/h, respectively, for the English and Scottish sites, compared with 28 and 25 mm/h predicted by Rec. ITU-R P.837-6.

3 Measured fade data

Microwave link receive power data was acquired by Rutherford Appleton Laboratory and archived by the British Atmospheric Data Centre (BADC). Three Earth-space links operated between a 20.7 GHz beacon on a global broadcast system satellite, which is left hand circularly polarised, and ground stations in the UK. The receivers had a measurement dynamic range of approximately 13 dB. Two receivers are separated by about 9 km in southern England; at Sparsholt (51°04′N, 01°26’W) with data spanning October 2003 to March 2005 and Chilbolton (51°08’N, 01°26’W) with data from August 2003 to March 2005. A Scottish receiver in Dundee (56.45811°N, 2.98053°W) provided data spanning February 2004 to August 2006. The collection and analyses of these data are described in [27]. The Earth-space data will be examined to determine the accuracy of simulated individual and joint fade distributions. Also, diversity gain from

$$\Gamma(\Delta h) = \begin{cases} 0 & 0 < \Delta h \\ \dfrac{4\left(1 - \mathrm{e}^{\Delta h/70}\right)^2}{\left(1 + \left(1 - \mathrm{e}^{-(\Delta h/600)^2}\right)^2 \left(4\left(1 - \mathrm{e}^{\Delta h/70}\right)^2 - 1\right)\right)} & -1200 \le \Delta h \le 0 \\ 1 & \Delta h < -1200 \end{cases} \quad (1)$$

simultaneous use of the two ground stations will be simulated and compared with measured distributions.

Fade data is also available from a terrestrial link, Sparsholt to South Wonston (51.0838°N, 1.3908°W), of length 5 km, operating at 38 GHz with data spanning October 2002 to March 2005. These data allow the joint distributions of fade on convergent Earth-space and terrestrial links to be compared with distributions predicted by both GINSIM and MultiEXCELL.

4 Comparison of simulated and measured fade data

4.1 Fade distribution

In this section, measured and simulated joint fade distributions are compared. The network considered consists of the terrestrial 38 GHz link and the Earth-space 20.7 GHz link that converge at Sparsholt. GINSIM simulated fade time-series have been generated for the one-year overlap between NIMROD 1 km resolution data and fade measurements: April 2004 until the end of March 2005. The satellite link fade data archived on the BADC is relative to a notional clear-sky level and exhibits 1 dB Gaussian noise and some drift around the 0 dB reference level. The 13 dB dynamic range of the Earth-space receiver and variation in measured the clear-sky receive power level leads to a tapered capping of measured fades from approximately 12 dB.

Fig. 1 illustrates the measured annual fade distributions of the two Earth-space links situated in Chilboton and Sparsholt. These are compared with the distributions predicted by GINSIM and MultiEXCELL and the prediction of the Rec. ITU-R P.618-10 using the NIMROD rain rate exceeded for 0.01% of the time. The limited dynamic range of the measurement equipment has caused the measured distributions to under-estimate the incidence of fades above about 12 dB. Both GINSIM and MultiEXCELL begin to deviate from the measured data at fades of around 8 dB while the Rec. 618 rain fade model under-estimates the incidence of fades at all reliably measured fade levels.

Fig. 2 illustrates the same distributions for the satellite link in the north of the UK; in this case, Rec. 618 under-estimates the incidence of fades below 10 dB, while GINSIM and MultiEXCELL perform much better. The Rec. 618 performs worst as the only fitting parameter is the rain rate exceeded 0.01% of the time, and in this case, the incidence of light rain is under-estimated. Although the measured data is restricted by equipment limitations at times below 0.01%, the GINSIM prediction agrees to measured data better than the curve obtained with MultiEXCELL.

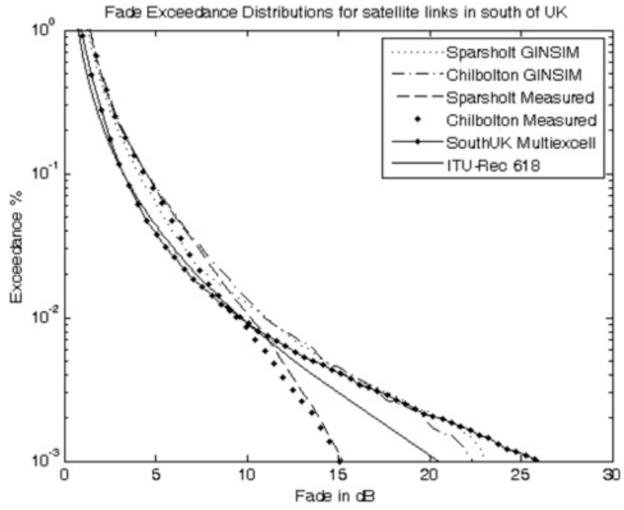

Fig. 1 *Annual fade exceedance distributions for earth-space (satellite) links*

Single and joint statistics for south UK (Chilbolton and Sparsholt) using the GINSIM, MultiEXCELL and the measured NIMROD measurements from April 2004–March 2005

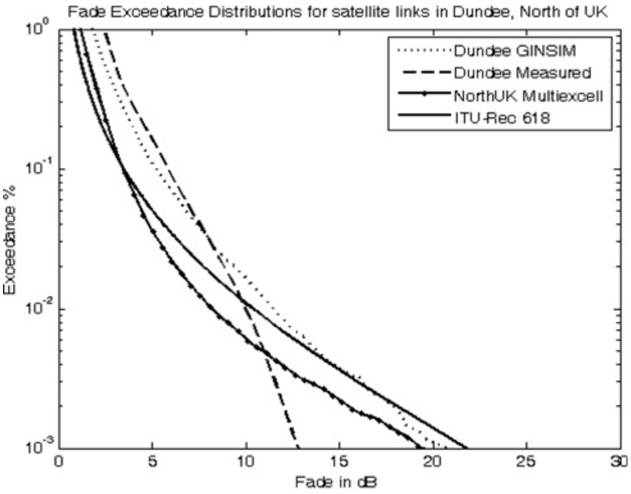

Fig. 2 *Annual fade exceedance distributions for earth-space links (satellite)*

single and joint statistics for North UK (Dundee) from April 2004–March 2005

Fig. 3 presents the measured fade distribution for the 5 km, 38 GHz, terrestrial link in the southern UK. Also plotted are the predicted distributions using GINSIM, MultiEXCELL and Rec. ITU-R Rec. 530-13, including the sleet model. The measured, GINSIM and ITU-R Rec. 530-13 distributions are indistinguishable below the Rec. 530 fitting point at 0.01%. Both MultiEXCELL and GINSIM over-estimate fade at exceedances below 0.01%. Measured exceedances at these low probability levels are determined by only a few events. The higher fade predicted by GINSIM is because of random variation introduced by the downscaling process. For MultiEXCELL, part of this bias is likely to be because of the assumed spatial autocovariance.

A more detailed discussion on the differences in the prediction performance of the two models is offered in Section 5.

4.2 Goodness of fit

The ITU-R P.311-13 provides procedures for the acquisition, presentation and analysis of data in studies of tropospheric propagation. The goodness-of-fit (GoF) metric measures the distance between pairs of fade exceedance distributions. It is derived from the logarithm of the ratio of fades or rain rates exceeded at the same time percentage, and results in a statistic approximately normally distributed where a value close to zero indicates a good fit. A correction is applied to reduce the influence

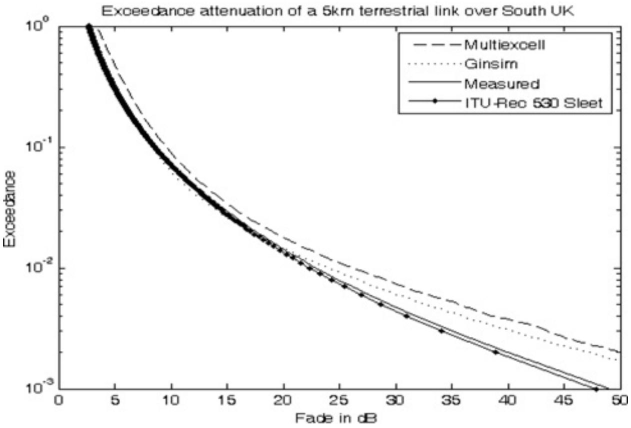

Fig. 3 *Annual fade exceedance distributions for a 5 km terrestrial link*

Single and joint statistics for South UK from April 2004–March 2005

Table 1 Rec. 311 GoF values comparing GINSIM and MultiEXCELL predictions to measured annual fade distributions for 0.01, 0.02, 0.03, 0.05 and 0.1% exceedance time percentages

Links	Earth-space links			Terrestrial
	Sparsholt	Chilbolton	Dundee	Sparsholt
GINSIM	0.18903	0.13993	0.14386	0.03561
MultiEXCELL	0.25336	0.25382	0.34531	0.24089

of low fades. Table 1 provides the Rec. 311 GoF values comparing GINSIM and MultiEXCELL predictions to measured annual fade distributions for 0.01, 0.02, 0.03, 0.05 and 0.1 exceedance time percentages.

In all comparisons, GINSIM provides significantly better fit than MultiEXCELL.

4.3 Joint fade exceedance distribution

Currently there exists no ITU-R model for the calculation of joint fade exceedance distributions for any combination of links. However, from the joint fade exceedance, a range of useful parameters can be derived such as diversity gain and the performance of multi-hop or route diverse link systems. There is also no ITU-R method to quantify the GoF of joint distributions.

Fig. 4 illustrates the two dimensional joint fade exceedance distribution for a network comprised of the Ka-band Earth-space link and 38 GHz terrestrial link, convergent at Sparsholt. Predictions produced by GINSIM and MultiEXCELL are also presented. To allow direct comparison of simulated and measured results at exceedances of 0.01% and below, the GINSIM and MultiEXCELL simulated Earth-space fades have been filtered to mimic the measurement equipment. Simulated fade measurements have a random low frequency drift with an amplitude of 1 dB added and are then contaminated by independent additive Gaussian noise with a standard deviation of 1 dB. The limited dynamic range of the measurement equipment has been introduced by truncation at 13 dB, though relative fades of ±2 dB could be obtained by simulations because of the changing dynamics of fade in the environment.

The measured joint distribution and that predicted by GINSIM are very close down to 0.01% of time. Below this exceedance probability, the Earth-space fade is strongly influenced by the measurement system and sampling statistics are poor. Although there is no recognised metric for the distance between joint fade distributions, the GINSIM predictions are much closer to the measured results than the MultiEXCELL results, for all exceedance probabilities.

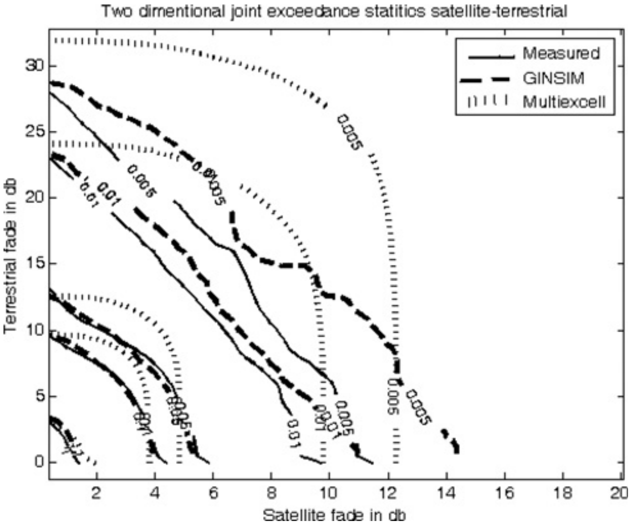

Fig. 4 *Two-dimentional joint fade exceedance for both the satellite and terrestrial links in the south of the UK*

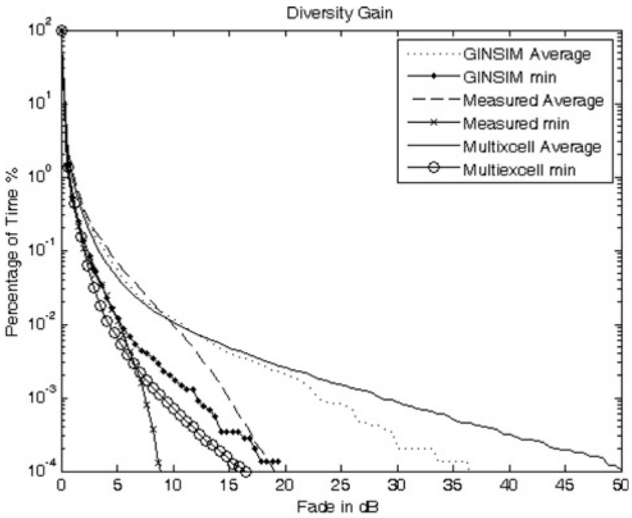

Fig. 5 *Diversity gain for two earth-space links in sparsholt and chilbolton, using the GINSIM, and MultiEXCELL April 2004–March 2005*

4.4 Site diversity

Site diversity prediction is tested using the two Earth stations at Sparsholt and Chilbolton, approximately 9 km apart. These links experience near identical average annual fade distributions. However, when both ground stations are used, a diversity gain exists as, at any time, the link experiencing the lower fade may be used. Rec. ITU-R P.530-14 defines diversity gain as the difference in dB between the fade exceeded at a given time percentage by an individual link and fade experienced by the diversity system, generally the minimum fade.

Fig. 5 illustrates the diversity gain performance, both simulated and measured, for the Sparsholt and Chilbolton Earth-space links. The diversity gain predicted by GINSIM is almost indistinguishable from the measured results, down to 0.01% of time. The measured fades below this time percentage are dominated by equipment constraints. The MultiEXCELL predictions only slightly under-estimate diversity gains around the important 0.01% level (by 1 to 2 dB). This implies that the MultiEXCELL spatial autocovariance of specific attenuation, which is directly related to rain field autocovariance, is not as accurate as the GINSIM autocovariance, for this one-year period, with a lag of 9 km.

5 Explaination for differences in performance

The GINSIM and MultiEXCELL simulation tools aim to be able to simulate joint hydrometeor fade on arbitrary, heterogeneous networks of microwave links. Additionally, GINSIM can produce time-series of joint fades. In this paper we have tested the ability of these two simulators, to predict distributions of fade, joint fade and diversity gain, for Earth-space and terrestrial links, for a specific one-year period.

The two tools differ enormously in their complexity. GINSIM requires an input time-series of rain rate maps produced by national weather radar networks. A large amount of computation is also required to downscale measurements to the temporal and spatial scales necessary to predict link performance. In contrast, MultiEXCELL only requires as input the rain rate CCPF over the period of interest. Large numbers of simulated rain maps can be computed with relatively little computation.

Three major features are expected to dominate the differences in the performance of the two systems, and these will be discussed in the following paragraphs.

The mathematical relationships and the statistical assumptions underpinning MultiEXCELL (e.g. the equivalent radius of rain cells being lognormally distributed) have been derived from a large set of radar derived rain fields [16]. As a result, the predictions achieved using MultiEXCELL are statistically stable long-term results. It is likely that MultiEXCELL would perform better at estimating long-term averages than the specific one-year comparison presented in this paper. This needs to be considered when evaluating the performance of MultiEXCELL in predicting joint fade distributions. In fact, MultiEXCELL assumes a particular spatial autocorrelation function for the rain rate that results from imposing a fixed distribution of the distance between rain cells [16]. Over a particular interval, the autocorrelation of events affecting a network will be strongly determined by the mix of stratiform and convective events. Particularly at low time percentages, the fades experienced can be determined by a very small number of events experienced over a year. This will give GINSIM an advantage when relatively short periods, such as a year or two, are examined. The 1 km resolution of NIMROD/OPERA data is sufficient to define these intense convective events. Similarly, at much higher exceedance probabilities, the spatial extent of light stratiform events is likely to be only partially described by an autocorrelation function. This effect is likely to contribute to the relatively poor MultiEXCELL fit to Scottish fade data. Figs. 6 and 7 compare the spatial second moment of rain rate

$$M_2(\Delta x, \Delta y) = E[R(x, y)R(x + \Delta x, y + \Delta y)] \qquad (2)$$

derived from the 504 MultiEXCELL rain maps and the 105120 NIMROD rain maps covering Chilbolton. Fig. 6 displays the two-dimensional distribution for lags (Δx and Δy) east and north while Fig. 7 is the one-dimensional distribution assuming rotational symmetry, as suggested by Fig. 6. These plots show that the MultiEXCELL distribution decays faster than the GINSIM distribution over these distances typical of most telecommunications links. The higher MultiEXCELL correlation at a lag of 7 km is consistent with the lower predicted diversity gain in Fig. 5. These plots assume stationarity and average over a large number of events. Over a year, autocorrelation is likely to be different for stratiform and convective events and so GINSIM events will be more diverse than the MultiEXCELL events; which are all derived from the same underlying autocovariance distribution.

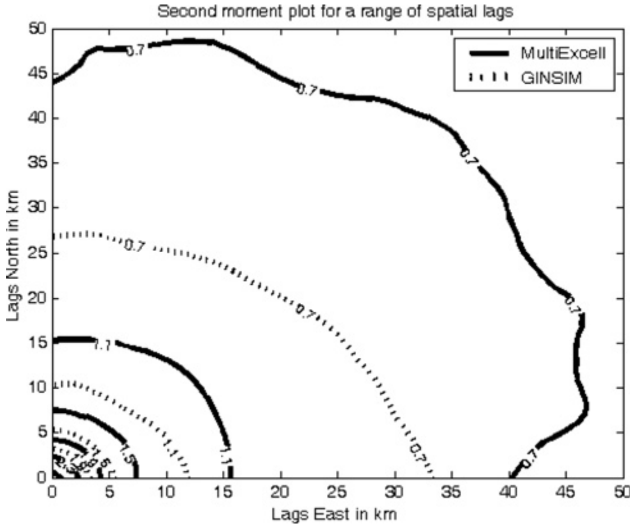

Fig. 6 *Two-dimentional comparison of the second moment of rain rate derived from MultiEXCELL and NIMROD rain maps*

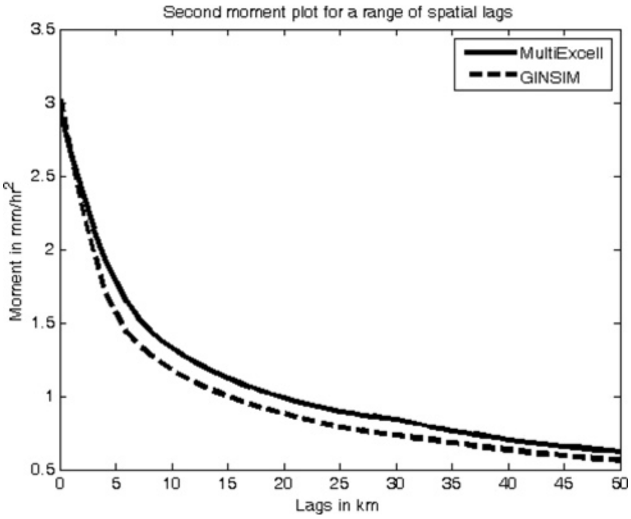

Fig. 7 *Comparison of the second moment of rain rate derived from MultiEXCELL and NIMROD rain maps*

The second major feature is the model of specific attenuation variation with height. MultiEXCELL assumes that the specific attenuation is constant up to the average annual rain height. By contrast, GINSIM uses time series of rain height values derived from the zero-degree isotherm height calculated from NOAA Reanalysis data. Such rain height values cannot be straight-forwardly paired to the synthetic maps generated by MultiEXCELL which are not linked to any particular time. Furthermore, in GINSIM, atmospheric layering is assumed, leading to a melting layer and specific attenuation variation with height as used in Rec. ITU-R P.530-13. The GINSIM method is considerably more complex, but necessary when time-series are to be produced. It is also necessary when simulating terrestrial links that spend a significant proportion of the year in the melting layer; either at latitudes above approximately 40° or high altitude links nearer the equator. For Earth-space links, the length of path experiencing hydrometeor fade is directly proportional to rain height. Seasonal variation in rain height will lead to more attenuation extremes because of the rain height being above the annual average in summer and below in winter.

The third feature is the spatial integration used for the rain rate measurements. MultiEXCELL produces 1 × 1 km rain maps with a rain rate distribution matching the NIMROD distribution of rain rate over notional 1 km squares. The actual spatial resolution depends upon the distance from each grid point to the nearest radar. GINSIM downscales the rain rate measurements to squares of side 125 m. The downscaling process increases the incidence of extreme rain rates and tends to increase the incidence of high fading on links of length up to approximately 5 km [28]. In these tests GINSIM has not consistently predicted higher incidence of high fades and this could be because of the differences in autocorrelation in the rain maps.

6 Conclusions

The lack of an internationally recognised goodness of fit metric to measure the distance between joint fade distributions means that comparisons of simulator performance is largely subjective. In the tests presented in this document it appears that GINSIM performs significantly better than MultiEXCELL, though at the expense of a much higher complexity, both in terms of inputs and of computation time. The current Rec. ITU-R P.311 metric cannot be extended directly to joint distributions as it compares fades experienced at the same exceedance probability. For joint distributions, this fade is a contour within a higher dimensional space. Different applications focus on different areas within the fade-space and so may require different metrics. Also, the uncertainty because of point-to-point or year-to-year variability needs to be incorporated into a metric.

Both simulators have demonstrated that they can produce useful annual distributions of fade and joint fade, for a variety of links and pairs of links in the UK. MultiEXCELL achieves this with considerably less computational effort than GINSIM. However, GINSIM is also capable of producing high resolution time-series with seasonal variation. It is likely that GINSIM could produce average annual results using a small selection of the input rain maps, and this will be explored in the future. To some extent, the choice of current simulators comes down to the application and resources available.

Simulation systems, such as GINSIM and MultiEXCELL, are quickly maturing. It is very likely that a validated simulator with characteristics drawing from the strengths of these and applicable across Europe will be available within a few years. A simulator with global application waits for the availability of global meteorological data of sufficiently fine resolution, or for development of rain field downscaling algorithms applicable over much wider ranges of spatial and temporal scales. However, it is likely to be achievable within a decade. Such simulators greatly augment the functionality of ITU-R recommendations and it appears inevitable that, ultimately, one or more will be adopted by the ITU-R and globally recognised as valid propagation models.

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