AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE
10.1002/2015RS005832

Key Points:
- The size of rain events in the UK has changed over a 10 year period
- In most cases, this change reduces rain fade on links
- This effect counters the increasing incidence of heavy rain

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Citation:
Paulson, K. S. (2016), Evidence of trends in rain event size effecting trends in rain fade, *Radio Sci.*, *51*, doi:10.1002/2015RS005832.

Received 13 OCT 2015
Accepted 13 FEB 2016
Accepted article online 18 FEB 2016

Evidence of trends in rain event size effecting trends in rain fade

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Abstract Rain gauge studies have shown that the incidence of rain at rates associated with outage on terrestrial links has shown an increasing trend in several countries over the last 30 years. However, no evidence is available from microwave links to show whether outage rates, or the incidence of fade, is similarly increasing. This paper presents evidence of fade trends, derived from a decade of rain radar data. Although a decade is too short a period to observe rain rate trends, evidence is presented that trends in the size of rain events is leading to changes in the relationship between point rain rates and rain fade. Furthermore, these trends are shown to vary significantly across the UK. Temporal trends in both rain rates and their link to rain fade, make it more difficult to adapt International Telecommunication Union Radiocommunication Reccomendations to a changing climate.

1. Introduction

There is a growing body of evidence that the incidence of rain rates at intensities associated with outage on terrestrial links has exhibited growing tends over the last 30 years. In the UK this was first observed by *Paulson* [2010, 2011], where the incidence of 1 min rain rates between 20 and 30 mm/h were shown to have doubled in each of the past two decades. These studies speculated that outage rates had almost certainly shown similar trends and spurred a much larger study by the UK spectrum regulator Ofcom. The *Bacon Report* [2012] examined 1350 Environment Agency tipping bucket rain gauges, sited across the UK, and came to broadly similar conclusions as [*Paulson*, 2010, 2011]. It reported increasing trends in the 0.01% exceeded rain rate between 0.4 mm/h/yr in the northern UK, rising to 0.8 mm/h/yr in the southern UK. It concluded that the current Ofcom map of 0.01% exceeded rain rates had been pessimistic, and so the increasing trends would not present problems for several years but would need to be addressed in the near future. A recent study in Norway [*Tjelta and Mamen*, 2014] has reached similar conclusions. Furthermore, a recent paper [*Paulson et al.*, 2015] has estimated the trend in 0.01% exceeded rain rates, globally, using Numerical Weather Prediction data. This paper predicts trends in the UK similar to those measured and much steeper trends in tropical regions.

Although increasing rain rate trends have been observed, associated increases in fade and outage have not been reported. There are several likely reasons for this to be the case, even if the increases are happening. To observe fade trends, it is necessary to monitor a sizable number of stable links, operating at a frequency above 5 GHz, for a period of a decade or preferably longer. Most commercial links are not stable for this length of time, either due to equipment changes or changes in the interference. Also, receive power data from commercial links tends not to be archived for long periods. Furthermore, these data are considered commercially sensitive and not shared. A number of links are required to average out location dependent variation, principally due to convective events a few kilometers in diameter and to yield a result that is plausibly applicable to a climate region. For these reasons, even quite significant trends in outage are unlikely to be reported. Despite this, the ability to predict the performance of future radio systems is important when developing their business case.

There is a fundamental difficulty when using point rain rate statistics to predict the rain fade distributions experienced by links. Rain fade is a distributed effect due to the rain experienced along the path of the link. If rain events were simultaneously getting heavier while the area spanned by rain events was getting smaller, then the fade experienced by links could stay the same or decrease even as the incidence of heavy point rain rates increased. The previously UK Climate Impacts Programme 2009 report [*Jenkins et al.*, 2008] suggested that total annual rain accumulation in the UK was not changing. Combined with evidence of more heavy rain, this would be consistent with events becoming heavier but smaller in spatial extent. Other effects could change the relationship between point rain statistics and fade statistics, including changes in the specific attenuation-rain rate relationship associated with changes in rain drop-size distributions. Changes in the mixture of ice and snow in hydrometeors, associated with changes in temperature and convection, can also dramatically change the specific attenuation caused.

Rain distribution trends present problems for International Telecommunication Union Radiocommunication (ITU-R) models, whether or not rain fade is changing in a way consistent with changes in rain rate distributions. The current Recommendation ITU-R P.837-6 provides distributions of 1 min rain rates globally. The model assumes a stationary climate in that the distributions are assumed to be time invariant and in the way historical data is used to derive and test the model. Trends in these distributions could be introduced by updating the model regularly. Even then, the model would not allow users to predict the performance of proposed radio systems over their typical 20 to 30 year life cycle. Including information on distribution trends in the model would address this. The rain rate exceeded 0.01% of the time, often derived from Recommendation ITU-R P.837-6 [*International Telecommunication Union (ITU-R)*, 2012], is an important input parameter to models of rain fade in Recommendation ITU-R P.530-16 [*ITU-R*, 2015a] for terrestrial links and Recommendation ITU-R P.618-12 [*ITU-R*, 2015b] for Earth-space links. If rain and rain fade are not changing in a way consistent with these models, then further modifications are required. In particular, if the incidence of heavy rain is increasing but the incidence of rain fade is not, then the horizontal distance factors in these models will need to be adjusted. Increasing convection associated with warming is likely to lead to changes in the proportions of convective and stratiform rain, which would need to be reflected in smaller distance factors (see section 6).

Distance factors (sometimes known as path reduction factors) have typically been derived from studies performed using rain radars, [*Goddard and Thurai*, 1997]. These provide spatial maps of rain rate that can be used to derive the statistical link between point rain rates and path-integrated rain rates. Radar studies have the advantage that the parameter measured, radar reflectivity, is likely to be more closely linked to microwave specific attenuation than the derived rain rates. However, radar-derived rain maps are often based on calibration by gauges sited on the ground. This paper describes a study based on the UK Meteorological office Nimrod rain radar network.

Section 2 describes the Nimrod data while section 3 compares Nimrod rain rates with gauge measurements. Section 4 presents time series of path averaged rain rates derived from Nimrod data. Section 5 interprets path averaged rain rate in terms of link fade and analyses the time series using distance factors. Section 6 uses statistical tests to identify trends in fade and distance factors while section 7 provides some analysis and conclusions.

2. Nimrod Data

This document reports on a numerical experiment where path averaged rain rates are estimated for paths between 1 km and 16 km and provides direct evidence of temporal changes in the sizes of rain events. The rain field information comes from the UK Nimrod system. This section introduces the Nimrod rain data while section 3 verifies these data by comparison with gauge data. Ten years of Nimrod data is examined to estimate trends in both point rain rates and path integrated rain rates (a surrogate for link rain fade). Time series of rain rate and simulated link rain fade distributions are examined to answer the following questions: (1) Is the temporal variation of Nimrod rain rate distributions consistent with large rain gauge studies? (2) Is the variation of rain rate and rain fade consistent with ITU-R models?

The Nimrod system combines data from a network of fifteen C-band radars with satellite data, together with surface reports and Numerical Weather Prediction (NWP) fields. Composite rain field images are produced, with a 5 min sample interval and presented on a 1 km spatial Cartesian grid, spanning the UK and parts of Western Europe. These are available from the British Atmospheric Data Centre from 2005 to the present. Although presented on a uniform grid, the actual spatial averaging is limited by the distance from a point to the nearest radar. The Nimrod system, radar calibration, and the formation of composite rain field data are described in [*Harrison et al.,* 2000].

Rain data from five regions have been extracted from the Nimrod data set. These regions are 200 km squares and cover southern England (SE), the Midlands (ML), northern England (NE), Southern Scotland (SS), and Northern

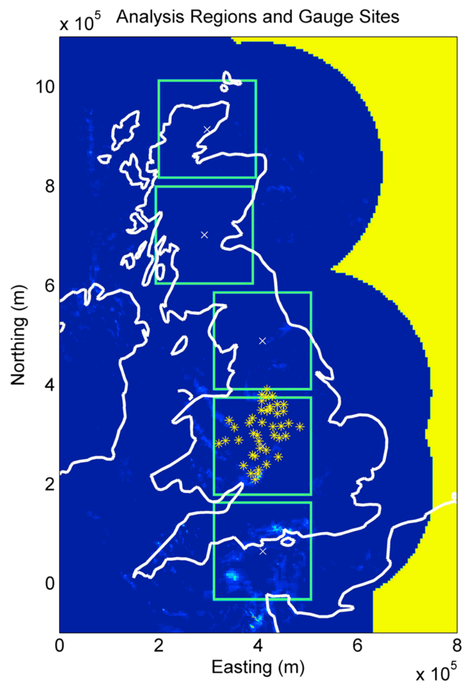

Figure 1. Annual 0.01% exceeded rain rates for the ML region, derived from gauge (circle) and Nimrod (asterisk). Periods starting before August 2006 are indicated by larger symbols and solid lines.

Scotland (NS). These regions were chosen to correspond to grid cells in the NOAA Reanalysis I data set, used in a different project.

Typically, each day yields 288 composite images. From these images, distributions are calculated of rain rates and average rain rates along lines of length 2, 4, 8, 12, and 16 km; orientated north-south or east-west. For each day, each region yields $288 \times 200 \times 200 = 11.5$ million rain rate samples and more path averaged samples. In a second stage of processing, annual distributions of rain rate and path averaged rain rate are formed from the daily distributions.

3. A Comparison of Nimrod and Gauge Data

Figure 1 shows the time series of annual rain rates exceeded for 0.01% of the time, for the ML region, calculated both from Nimrod data and from the rain gauge network. Figure 2 shows the same data in a scatter plot. Each value is derived from all the data for the one-year period starting on the abscissa date. For the gauge data, the value is the average of 0.01% exceeded rates from a network of Environment Agency rain gauges in the region, as described in [*Paulson*, 2010, 2011; *Bacon,* 2012]. Although 48 gauge sites of data were analyzed, only 5 were available at the beginning of 2005, and an average of 30 sites were used from 2006 onwards. To be included in the calculation of an annual 0.01% exceeded rain rate at least 360 days of data needed to be available from a site. The position of all 48 gauge sites is plotted in Figure 3. These data were available until mid-2011.

Some disparity between gauge and Nimrod data is expected due spatial averaging: gauges yield point values while Nimrod provides averages over areas at least 1 km square. Furthermore, the gauges are sparsely and unevenly spaced over the ML region. Most rain rates at outage intensities are associated with convective cells typically 5 to 10 km in diameter. With a small number of gauge sites, the gauge network is likely to either over or underestimate the incidence of heavy rain, depending on whether intense events encounter a gauge or not. Also, it should be noted that as annual averages are plotted, a single intense event can have a strong influence on the time series for start dates spanning a year. The difference between the gauge and Nimrod estimates over the period January 2005 to August 2006 is probably due to the very low number of gauges fully operational in 2005. After this there is fair agreement between the two estimates, with a Pearson correlation of 0.91. There is no evidence that the Nimrod estimate is biased.

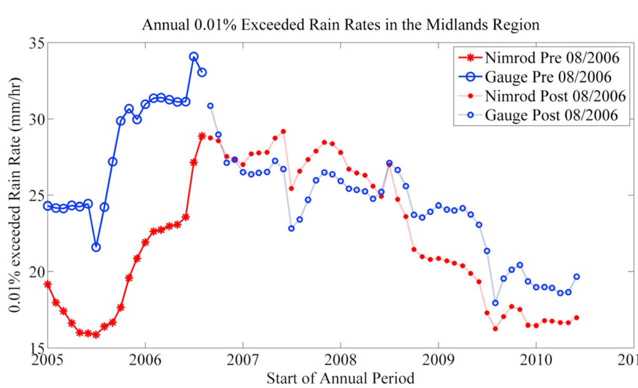

Figure 2. Scatter plot of annual 0.01% exceeded rain rates for the ML region, derived from gauge and Nimrod. Periods starting before August 2006 are indicated by circles and after by asterisks. The black line indicates equality.

4. An Analysis of Path Averaged Rain Rate

For each 1 year period within the data set, path averages of rain rates $\overline{R}$ were

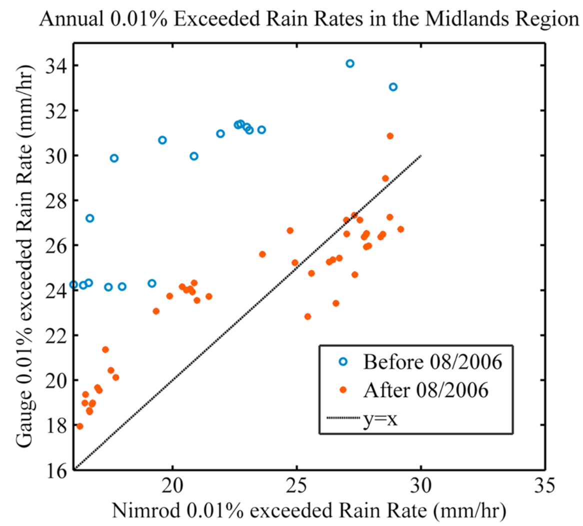

Figure 3. Map showing Nimrod composite rain field, the five square regions considered in this paper (with crosses at the center), and the rain gauge sites in the Midlands (asterisks). The white outline indicates the coast of the UK and nearby countries.

calculated, where $\overline{R} \approx \frac{1}{N}\sum_{i=1}^{N} R_i$ is the average of N Nimrod rain rates forming a line. As the pixels are averages over 1 km squares, the average of N values in a line is approximately a path average of N km. For each annual distribution, the 0.01% exceeded path average rain rate is calculated, i.e., $\overline{R}_{0.01\%}$ is the $\overline{R}$ exceeded with probability 0.0001. Figures 4 and 5 show the time series of $\overline{R}_{0.01\%}$, for the regions ML and NS, respectively. For all regions there is a trend toward lower values for averages over longer paths, as increasing spatial or temporal averaging reduces the incidence of extreme values. Temporal variation can also be observed, e.g., the intense rain years of 2007–2008 and 2011–2012. Increasing or decreasing trends can also be observed, but these trends are not consistent between regions. There is also a trend for the fades experienced by different path lengths to become more separated. This implies a change in the distance factor, discussed in the next section.

5. Analysis of Simulated Fade Data

For a link of length d, the rain fade can be estimated using

$$A(t) = \int_0^d \gamma(\mathbf{x}, t)d\mathbf{x} \approx \frac{d}{N}\sum_{i=1}^{N} \gamma(\mathbf{x}_i, t). \quad (1)$$

where the integral is along the link path and $\gamma(\mathbf{x}, t)$ is the specific attenuation at position $\mathbf{x}$ at time t. For the discretized approximation $\gamma(\mathbf{x}_i, t)$ is the average specific attenuation along a line of length d/N centered on $\mathbf{x}_i$. Recommendation ITU-R P.838-3 [*ITU-R*, 2005] provides a power law relationship between rain rate, R, and specific attenuation:

$$\gamma = kR^{\alpha}. \quad (2)$$

The parameters k and α are frequency, polarization, and elevation angle dependent. For a frequency near 20 GHz, $\alpha = 1$ and specific attenuation is proportional to rain rate. At this frequency the link rain fade is approximately proportional to the path averaged rain rate $\overline{R}$:

$$A(t) \cong \frac{kd}{N}\sum_{i=1}^{N} R(\mathbf{x}_i, t) \cong kd\overline{R}(t). \quad (3)$$

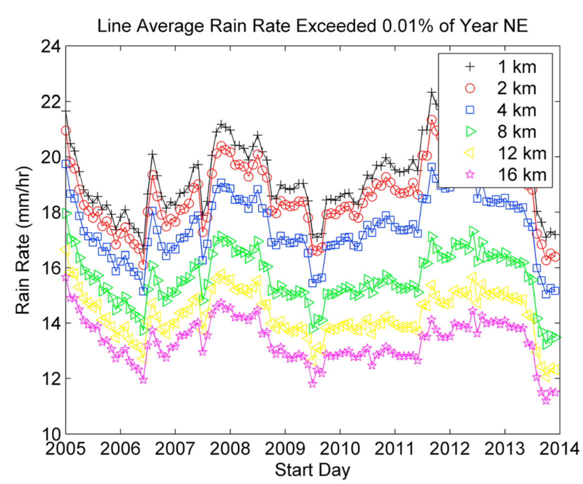

Figure 4. Annual 0.01% exceeded rain rate averages over a range of path lengths for the NE region.

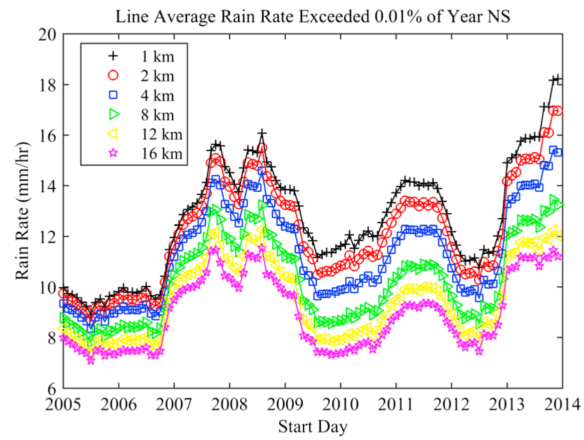

Figure 5. Annual 0.01% exceeded rain rate averages over a range of path lengths for the NS region.

The parameter α is between 0.8 and 1.2 for frequencies in the approximate range 10 GHz to 50 GHz. The investigation of path averaged rain rates is a fair indication of fade for the majority of commercial links whose availability is limited by rain. In this paper we assume $k = 1$. This is not correct but, as we will only look at ratios of fade, will not affect the results. With this assumption, $A/d \cong \overline{R}$.

Recommendation ITU-R P.530-16 [*ITU-R*, 2015a] provides a prediction method for the rain fades experienced at annual time percentages between 1% and 0.001%. The fade exceeded for 0.01% of time, $A_{0.01\,\%}$, is expressed:

$$A_{0.01\%} = \gamma_R d r. \tag{4}$$

where $\gamma_R = kR^{\alpha}_{0.01\%}$ is the specific attenuation and $R_{0.01\,\%}$ is the 1 min rain rate, exceeded for 0.01% of the time. The distance factor is

$$r \equiv \frac{1}{0.477 d^{0.633} R_{0.01\%}^{0.073\alpha} f^{0.123} - 10.579(1 - \exp(-0.024d))}, \tag{5}$$

where f is the frequency in GHz and α is the Recommendation ITU-R P.838-3 specific attenuation power law exponent.

The values plotted in Figures 4 and 5 are $(A/d)_{0.01\,\%}$, i.e., the path averaged rain rate exceeded for 0.01% of an annual period, for the regions NE and NS, calculated from the Nimrod data. As $R_{0.01\,\%}$ is a constant for each annual interval, the spread of values indicate the distance factor r as a function of link length d. As expected from (5), higher $R_{0.01\,\%}$ values are associated with more widely spread attenuations, and this is visible in Figures 4 and 5. The plots for the other three regions share this characteristic.

Figures 6 and 7 are plots derived from the same data as in Figure 4 and for the SS region, normalized by the predicted attenuation, and assuming $k = 1$ and $\alpha = 1$, i.e.,

$$F \equiv \frac{A_{0.01\%}}{\gamma_R d r} = (A/d)_{0.01\%} \times \frac{1}{\gamma_R r}. \tag{6}$$

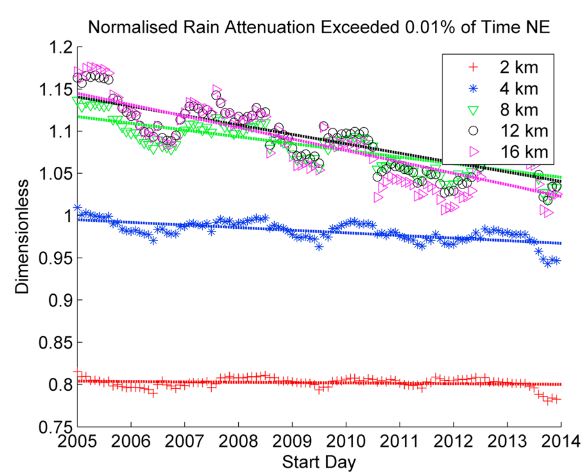

Figure 6. Annual F factors over a range of path lengths, for the NE region, with linear regression lines.

The factor F is close to unity when the prediction model (4 and 5) is accurate. The ITU-R models are designed to be applied to average annual values and so are not expected to be exact for single years. However, they can be expected to yield an unbiased estimate, and trends in the parameter F would indicate the presence of mechanisms leading to divergence between actual and predicted attenuations.

The second term in (6) requires the point rain rate exceeded for 0.01% of an annual period for both γ_R and the distance factor r. We have used the Nimrod rain rates with the notional 1 km square spatial resolution for this

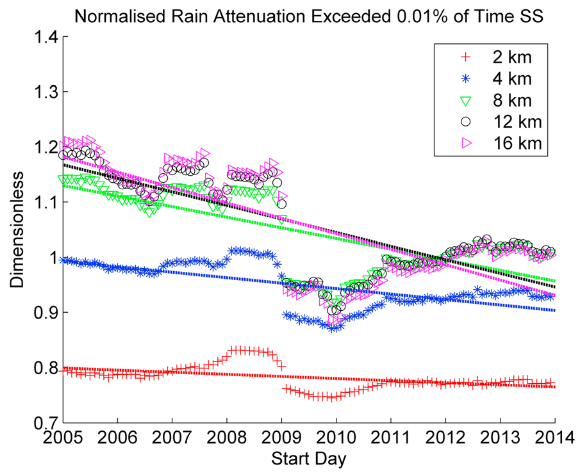

Figure 7. Annual *F* factors over a range of path lengths, for the SS region, with linear regression lines.

value. Figures 1 and 2 lead us to think that the Nimrod values are accurate estimates of these values.

The factors *F* in Figures 6 and 7 show systematic deviation from unity with link length and an apparent trend in factor values. The systematic deviations with link length are present and consistent across all five regions and suggest that the Recommendation ITU-R P.530-16 distance factor could be improved upon when applied in the UK. The current distance factor leads to large underestimation of the fade for links shorter than 4 km and over estimation for longer links. For links longer than 4 km, the distance factor appears to be reducing toward unity over time. For these links, the apparent trends suggest a temporal change in the mix of rain events experienced in the region leading the distance factor being too small in 2005 and closer to correct in 2014, i.e., consistent with heavy rain events getting smaller.

6. Analysis of Trends

The Pearson Correlation test has been used to determine if the observed trends are statistically significant. The correlation coefficient is calculated between the time parameter and the time series, e.g., between time t_i and $F(t_i)$. A value equal to zero indicates that no linear relationship exists between t_i and $F(t_i)$ while values close to ± 1 are evidence of a linear trend. The probability of measuring a given value of correlation coefficient, or larger, is calculated from the Student's *t* distribution using the Mantel-Haenszel statistic.

This test assumes that the deviations of the measured variable from the linear trend are independent. The annual 0.01% exceeded rain rates exhibit a correlation period of several years, suggesting that only a few of the points marked in Figures 4 and 5 could be used in the trend test. None of the regions yield statistically significant slopes in the path averaged rain rates, over the 10 year period. However, published analysis of longer rain gauge records show statistically significant increasing trends in point rain rates, so there is virtually no doubt that trends exist. The *F* deviations have a correlation period of between 9 and 13 months, and so 10 equispaced points are used in the hypothesis test for trends i.e. the annual results starting from January 1st each year 2005 to 2014. The correlation period has been extracted from the autocorrelation function, estimated assuming stationarity i.e. no trend. The correlation period is plausible given excursion periods above and below the fitted trend, and the analysis is relatively insensitive to its value. The trends and their two-tail test probabilities of occurring by chance are presented in Table 1, for the three regions NS, SS and NE. For links in NE and SS of length 4 km and longer, the probability of the observed variation in *F*, if there were no trend, is typically less than 3%; and so this is evidence that trends do indeed exist. No significant trends were observed in the other regions. The test is sensitive to variation in the data around trend lines, as this increases the likelihood of the observed trend being due to random variation. The data in Table 1 show consistent variation of the *F*-trend, even when these trends are not statistically significant in the NS region.

Table 1. Trend Slope of *F* Factor (×100 Per Year), With the Probability of Occurrence by Chance in Brackets (×100) for Three UK Regions

	NE	SS	NS
2 km	-0.04 (58)	-0.40 (14)	-0.03 (98)
4 km	-0.21 (3.8)	-1.0 (3.0)	-0.31 (31)
8 km	-0.84 (1.0)	-1.9 (1.3)	-0.92 (19)
12 km	-1.1 (0.8)	-2.5 (1.1)	-1.1 (19)
16 km	-1.4 (0.7)	-2.7 (1.0)	-1.1 (23)

Table 2. Calculation of Fade Margin for Two Notional Links Allowing for Changes in 0.01% Exceeded Rain Rate and Distance Factor

			Southern Scotland		Northern England	
16 km 20 GHz	$R_{0.01\ \%}$(mm/h)	dr (km)	F	$A_{0.01\ \%}$ (dB)	F	$A_{0.01\ \%}$ (dB)
2005	23	9.75	1.2	24.7	1.15	23.2
2015	27	9.42	1.0	23.2	1.05	23.7

A typical value of F factor trend slope in these regions is -0.01 per year. This would mean that that over a 20 year period, the actual and predicted $A_{0.01\ \%}$ for a given $R_{0.01\ \%}$, would diverge by 20%. For the most extreme case, a 16 km 20 GHz link in Southern Scotland, the divergence could be over 50%.

For example, consider two theoretical 16 km links in SS and NE; both operating in vertical polarization at 20 GHz. In this example the specific attenuation is calculated using Recommendation ITU-R P.838-3. The 0.01% exceeded rain rate, derived from the UK regulator Ofcom map for central Southern Scotland around 56° North, is approximately $R_{0.01\ \%} = 25$mm/h. This rain rate yields a specific attenuation exceeded 0.01% of time of 2.29 dB/km. If this is used to calculate the fade margin $A_{0.01\ \%}$ using (4) and (5), then for 16 km links this yields 21.9 dB. The Bacon report identified long term trends on the 0.01% exceeded rain rate of 0.4 mm/h/yr in the northern UK, and so we shall also consider $R_{0.01\ \%}$ increasing from 23 to 27 mm/h over this decade. The 0.01% exceeded rain attenuations may be estimated using

$$A_{0.01\%} = F\gamma_R dr. \tag{7}$$

For the initial and final rain rates, 23 and 27 mm/h, the specific attenuations exceeded 0.01% of time are 2.11 and 2.47 dB/km from (2). In a climate where the incidence of rain at outage levels was increasing, but event size remained consistent with the distance factor method in (4) and (5), the mean attenuation exceeded 0.01% of the time would increase from 20.5 dB to 23.2 dB for a 16 km link. This is the current most likely scenario given the Bacon report.

However, over the decade considered, the F value for a 16 km link in SS decreases from 1.2 to 1.0, and in NE it decreases from 1.15 to 1.05. To some degree, this effect counters the increasing incidence of higher rain rates. Using (7) the attenuations exceeded 0.01% of time may be calculated at 2005 and 2015 for the two notional links; see Table 2.

The effect of changes in the size of rain events has moderated the expected increase in fading associated with increasing incidence of rain rates at outage levels and in some cases leads to a decrease in fading.

7. Conclusions

This paper has looked at line averaged rain rates derived from Nimrod rain radar composite images to see if rain event size has changed over this period. Ten years of data has been examined over five 200 km square regions spanning the UK.

Ten years of data is not adequate for the identification of trends in 0.01% exceeded rain rates due to the substantial year-to-year variation and multiyear correlations in the numbers of extreme events. However, these trends have been established beyond doubt by the papers referenced in section 1. It has been shown that Nimrod rain data may be used to estimate annual 0.01% exceeded rain rates. It is likely that 20 years or more of Nimrod 1 km resolution data will be required before these data can replace gauge data when estimating trends in $R_{0.01\ \%}$.

The F parameter measures how well the Recommendation ITU-R P.530-16 method, including the distance factor, transforms point rain rates into line averages. This parameter exhibits shorter correlation intervals than $R_{0.01\ \%}$, and so statistically significant trends can be identified. For three of the five UK regions, the F parameter has exhibited a significant decreasing trend over the decade 2005 to 2015. This reflects a change in the size of rain events to be more intense but with a smaller foot print. Changing event size mitigates the expected increases in fading associated with increasing incidence of rain at outage levels. However, in the southern UK, no significant trend was observed and this region has experienced the fastest growth in 0.01% exceeded rain rate in the UK of 0.8 mm/h/yr. It is clear that the UK situation is complicated and further data and study are required to predict changes in propagation over coming decades. The UK spectrum regulator Ofcom has planned for the future based on the assumption that rain fade is increasing. This work shows that the likely increase in fade is less than that expected from the increasing incidence of heavy rain.

Methods to predict fading on communications links are required to produce a convincing business model for developing systems. These models need to predict fade distributions several decades into the future to cover the lifetime of new systems. Current ITU-R models assume a stationary climate whereas the UK climate has been shown to be experiencing trends in rain rates and now rain event sizes that have significant effects on fade distributions. Current ITU-R models need to be augmented with local data of trends in climate parameters linked to propagation to predict future fade distributions. This is certainly true for regions in the UK and almost certainly for many other places globally.

Acknowledgments
This work was not funded and made use of Nimrod composite rain maps produced by the UK Meteorological Office and supplied by the British Atmospheric Data Centre: Met Office (2003): Met Office Rain Radar Data from the NIMROD System. NCAS British Atmospheric Data Centre, March 2015: http://catalogue.ceda.ac.uk/uuid/82adec1f896af6169112d09cc1174499.

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