Estimating One-Minute Rain Rate Distributions in the Tropics From TRMM Satellite Data (October 2017)

Geraldine Rangmoen Rimven, Kevin S. Paulson, and Timothy Bellerby

***Abstract*—Internationally recognized prognostic models of rain fade on terrestrial and Earth-space extremely high frequency (EHF) links rely fundamentally on distributions of 1-min rain rates. In Rec. ITU-R P.837-6, these distributions are estimated from the data provided by Numerical Weather Products (NWPs). NWP yields rain accumulations over regions typically larger than 100 km across and over intervals of 6 h. Over the tropics, the Tropical Rain Measuring Mission (TRMM) satellite data yield instantaneous rain rates over regions 5 km across. This paper uses TRMM data to estimate rain rate distributions for telecommunications regulation over the tropics. Rain rate distributions are calculated for each 1° square between 35° south to 35° north. These distributions of instantaneous rain rates over 5 km squares are transformed to distributions over 1 km squares using a correction calculated from U.K. Nimrod radar data. Results are compared to rain distributions in DBSG3, the database of ITU-R Study Group 3. A comparison with the new Rec. ITU-R P.837-7 is also presented. A table of 0.01% exceeded rain rates over the tropics is provided as associated data.**

***Index Terms*—Link budget, microwave, propagation, rain, rain fade, satellite data, spectrum planning.**

I. Introduction

RAIN-INDUCED attenuation is a major impairment for wireless line of sight communications operating above 10 GHz, such as terrestrial and Earth-space links and links to high-altitude platforms (HAPs) and unmanned airborne vehicles (UAVs). A fundamental input parameter to the International Telecommunications Union - Radio Section (ITU-R) models of rain fade on terrestrial and Earth-space links, Rec. ITU-R P.530-16 [1] and Rec. ITU-R P.618-12 [2], respectively, is the 1-min rain rate exceeded for 0.01% of an average year, R0.01%. Many parts of the world do not have measured data of 1-min rain rates and so rely upon distributions provided by Rec. ITU-R P.837-6 [3]. This recommendation is based on work by Salonen and Poiares-Baptista (SPB), [4], [5], and The ITU-R Study Group 3 [6]. It assumes that the average annual 1-min rain rate complementary cumulative probability function (CCPF or exceedance), globally, is well approximated by a double exponential distribution. Furthermore, the SPB method links the four distribution parameters to three output parameters from Numerical Weather Products (NWP). These NWP output parameters are 6-h precipitation accumulations over regions typically 100 to 200 km square. The SPB method has serious deficiencies, described in [7]. A fundamental problem is that the NWP outputs are precipitation accumulations over regions much larger than convective rain events, and over intervals that are much longer than their life-time. These convective events typically produce the moderate or heavier rain than leads to outage on telecommunications links. A second major problem is that the annual accumulations used by the SPB method are very poorly correlated to any parameter of 1-min rain rate distributions. Due to these and other problems, the 0.01% exceeded rain rates derived from the SPB method deviate from measured results in the ITU-R Study Group 3 database by an average of 30% [8], [9]. There are particular concerns about the accuracy of the SPB method in the tropics, where 0.01% exceeded rain rates are high and there is little data in the database of ITU-R Study Group 3, DBSG3.

The Tropical Rain Measuring Mission (TRMM) was a joint USA–Japanese satellite-based Earth observation mission, which carried, alongside other instruments, a spaceborne precipitation radar (PR) with a nominal spatial resolution ∼5 km and a spatial coverage spanning 35º north and south of the equator [10]. Compared to NWP, the 5-km PR pixels are closer to the typical convective rain cell, which is reported to have an average diameter of about 2.6 km in [11] and between 1.2 and 1.5 km in [12]. However, these diameters were for regions experiencing rain rates well above the 0.01% exceeded rain rate of principal interest for radio system regulation. The 5 km pixels are much closer than NWP data to the point 1-min data required for telecommunications regulation. Paulson [7] has shown that the instantaneous rain rates averaged over 1 km squares, as produced by the U.K. Nimrod radar network, provide an unbiased estimate of point 1-min rain rates exceeded 0.01% of the time.

TRMM data have been validated through a ground validation programme by the National Aeronautical Space Agency (NASA) using several sources of rain data collected from four primary sites [13], including Kwajalein in the Pacific. TRMM data have been used to estimate 1-min rainfall rates in some studies [14], [15]. However, these are not direct estimations of point 1-min rain rate distributions. TRMM data were used to

Manuscript received October 26, 2017; revised May 11, 2018 and August 11, 2018; accepted August 25, 2018. Date of publication September 26, 2018; date of current version October 15, 2018. The work of G. R. Rimven was supported by the Faculty for the Future Programme by the Schlumberger Foundation funds. *(Corresponding author: Geraldine Rangmoen Rimven.)*

G. R. Rimven is with the School of Engineering and Computer Science, University of Hull, Hull, HU6 7RX, U.K., and also with the Electrical/Electronic Department, Faculty of Engineering, University of Jos, Jos 930001, Nigeria (e-mail: g.r.rimven@2016.hull.ac.uk).

K. S. Paulson is with the School of Engineering and Computer Science, University of Hull, Hull, HU6 7RX, U.K. (e-mail: k.paulson@hull.ac.uk).

T. Bellerby is with the School of Environmental Sciences, University of Hull, Hull, HU6 7RX, U.K. (e-mail: T.J.Bellerby@hull.ac.uk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSTARS.2018.2869322

estimate thunderstorm ratio and the average annual total rainfall, and these parameters have been correlated with parameters of point 1-min rain rate distributions such as the 0.01% exceeded rain rate.

This paper develops estimates of average annual point 1-min rain rate distributions for the tropics using TRMM data. Section II introduces the TRMM and Nimrod data, and the DBSG3 database. Section III describes the calculation of distributions of 5 km instantaneous rain rates, and presents some data. In Section IV, Nimrod data are used to calculate the correction required to estimate point 1-min rain rates from the 5 km instantaneous rain rates. Section V compares the predicted rain rate distributions with those in the DBSG3 database. Conclusions are drawn in Section VI.

II. Data Used

A. *TRMM 2A25*

The TRMM data product 2A25 [16] is the primary input data for this study. This dataset provides instantaneous attenuation-corrected near-surface rainfall from the TRMM PR. The spatial resolution changed due to an orbit boost on August 2001. The satellite had pre- and post-boost orbital periods of 91.5 and 92.5 min, yielding about 16 orbits per day, with spatial resolutions ~4.3 and ~5.0 km, respectively. The data span the interval from December 1997 to April 2015. The retrieval algorithm [17] has continuously evolved and been enhanced [18]. The current algorithm is 2A25 version 7 (V7) [19]. As with terrestrial radar, PR rainfall estimates are sensitive to the local variation in the reflectivity/rainfall (Z/R) relationship, ground clutter, and other factors such as calibration errors [20], path attenuation, and bright-band effects [21]. Retrieval errors are sensitive to both rainfall rate and meteorological regimes [22].The changes in TRMM 2A25 V7 have not only improved the Z/R relationship over preceding versions but also contains corrections for attenuation, as well as nonuniform beam-filling effects [23]. TRMM PR estimates have been compared to other types of precipitation data in numerous studies.

B. *Nimrod*

The U.K. Meteorological Office Nimrod system combines data from a network of 15 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 U.K. and parts of Western Europe. These are available from the British Atmospheric Data Centre from April 2004 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 is described in [24]. Distributions of Nimrod rain rates have been shown to be good estimates of distributions of 1-min rain rates derived from networks of rapid-response rain gauges [7]. Furthermore, Nimrod data can be spatially integrated to compare rain rate distributions over 1 and 5 km squares, for the same rain fields. Rain

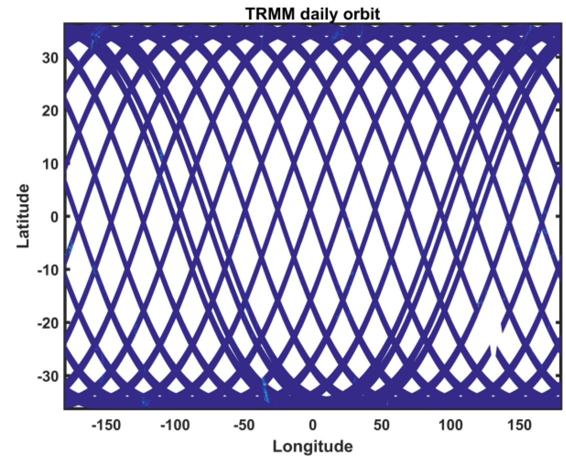

Fig. 1. Typical coverage captured in one day from the 16 orbits of TRMM satellite.

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

C. *DBSG3*

The database of the ITU-R Study Group 3, DBSG3, contains 1127 records of annual rain rate distributions collected since 1959. A selection of rain rates exceeded at time percentages from 1% to 0.001% are presented for each site and for each measurement interval. Often, individual years are reported as well as results derived by accumulating data from several consecutive years. The data have been provided by the national spectrum regulators of many countries. However, the database contains no data from Africa, and much of the data is from developed countries in temperate regions of Europe, Asia and the Americas. Furthermore, there is no information in the database of measurement reliability. Rain gauges are difficult to site, particularly in urban areas and can provide biased measurements when in the wind shadow of buildings, trees, etc. Measurements of low-probability rain rates are also very sensitive to temporary blockage, due to insects or plant matter in the funnel. Finally, several authors have published evidence of temporal trends in R0.01% [7], [25], [26] starting in the 1980s. The non-stationarity of R0.01% needs to be taken into account when comparing estimates measured in different decades.

III. Calculation of 5-km Rain Rate Distributions

Each orbit of the TRMM satellite yields a 247-km-wide swath of ~5 km rain rate measurements under an orbit that extends 35° north and south of the equator (see Fig. 1). The satellite orbits just less than 16 times a day, and the orbit path shifts around the world, giving near universal coverage over the tropics, but with irregular return times.

TRMM 2A25 data from 9 years, 2004 to 2012, were downloaded and analyzed. Each rain rate measurement was allocated to a single 1° by 1° square by its latitude and longitude. Histograms of measurements were calculated for each 1° square,

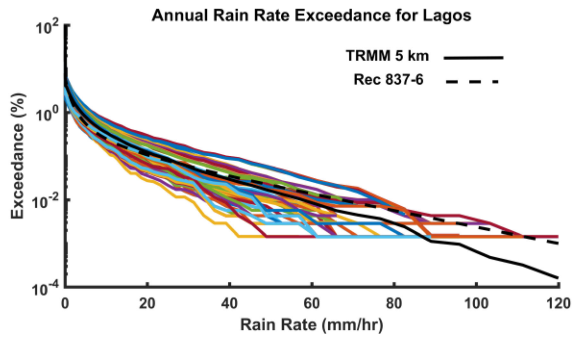

Fig. 2. Exceedance distributions of 5 km rain rates from TRMM, with Rec. ITU-R P. 837-6 prediction for Lagos, Nigeria. Colored lines are for individual years, while the black solid line is derived from all the nine years of data.

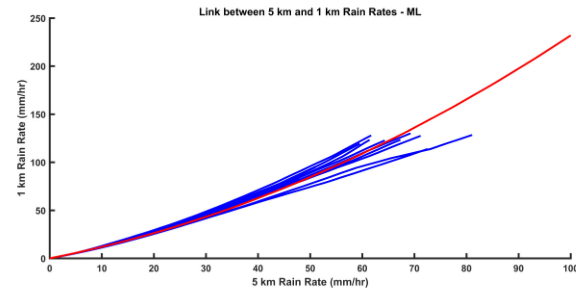

Fig. 3. Equiprobable 1 and 5 km rain rate relationships for the ten years in the Midlands region (blue) and the best-fit quadratic (red).

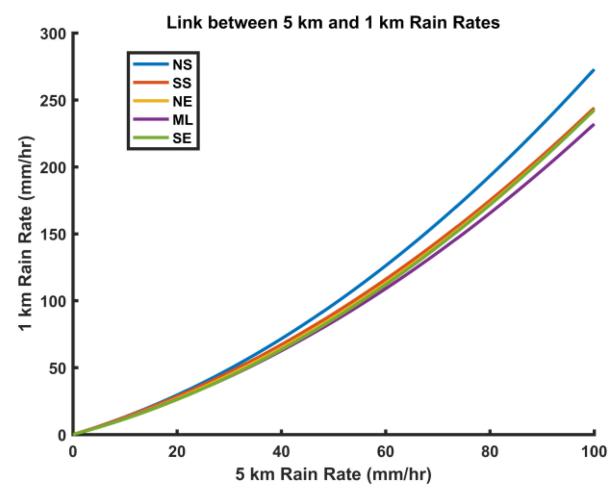

Fig. 4. Equiprobable 5 and 1 km rain rate relationships for the five U.K. regions.

and these were transformed into exceedance distributions. Fig. 2 shows the exceedance distribution of 5 km rain rates for Lagos, Nigeria (6.52 °N, 3.38 °E). This is compared with the Rec. ITU-R P.837-6 prediction. The 5-km rain rates are smaller than point 1-min rain rates as averaging reduces the incidence of extremes. A correction needs to be applied to TRMM derived distributions to approximate distributions with less spatial averaging. It is known that spatial averages over 1 km squares yield unbiased estimates of the point 1-min rain rate exceeded 0.01% of the time in the U.K. Therefore, in the next section, a transformation will be developed between distributions of 5 and 1 km instantaneous rain rates.

IV. Transformation From 5 to 1 km Rain Rate Distributions Units

In this section, we compare distributions of 1 and 5 km rain rates derived from the same Nimrod rain rate fields. Each Nimrod composite rain rate map yields 200 × 200 rain samples at approximately 1 km resolution, each 5 min, for each of the five regions. When the rain rate samples in 5 × 5 arrays are averaged, they yield an estimate of the rain rate averaged over a 5-km square. Each region, for each composite rain field, yields 196 × 196 not-independent 5 km rain rates. Over a year, there are 365 × 24 × 12 maps yielding 4.2 × 10^9 1 km rain rates and 4.0 × 10^9 5 km rain rates. These data allow annual distributions of 1 and 5 km rain rates to be compared down to very low exceedance probabilities.

Ten years of Nimrod data have been analyzed, from 2005 to 2014 inclusive. Fig. 3 shows the relationship between 1 and 5 km exceeded rain rates, for the same exceedance probabilities, for the Midlands region. The blue lines are for each of the ten individual calendar years, and the red line is the best-fit quadratic to these relationships.

Figure 4 shows the best-fit quadratic equiprobable 5 and 1 km rain rate relationships, derived from ten years of data, for the five regions considered. An average has been taken of the relationships for the four southern regions (SS, NE, ML, and SE) and this may be expressed as

$$R_{0.01\%}^{1\ \mathrm{km}} = \left(0.0126\, R_{0.01\%}^{5\ \mathrm{km}} + 1.0619\right) \times R_{0.01\%}^{5\ \mathrm{km}}. \qquad (1)$$

The climate across the five U.K. regions varies from Northern Scotland dominated by stratiform rain off the Atlantic to Southern England with a large proportion of heavy convective events origination in continental Europe. Despite this, there is little variation in the equi-probably 1 km–5 km exceeded rain rate relationships and no discernible trend in the four southernmost regions. This suggests that the average relationship may be applicable to tropical regions. This is clearly speculative, and we would have more confidence in a transformation based on data from the tropics. Ideally, the estimation of TRMM to 1-min transformation requires 1-min rain data, which are not available even from the validation sites. The radar data from the TRMM ground validation site at Kwajalein, could be used to calculate a 5- to 1-km transformation, but the link between Kwajalein 1 km data and 1-min data has not been demonstrated.

V. Predictions of Point 1-Min Rain Rate Distributions

A. Comparison to Rec. ITU-R P.837-6

Applying the transformation (1) presented in Section IV to the 5-km rain rate distributions calculated in Section III yields estimates of the 1 km distributions, and hence, the point 1-min distribution, for each 1° square in the tropics. The 0.01% exceeded rain rates can be estimated directly from these

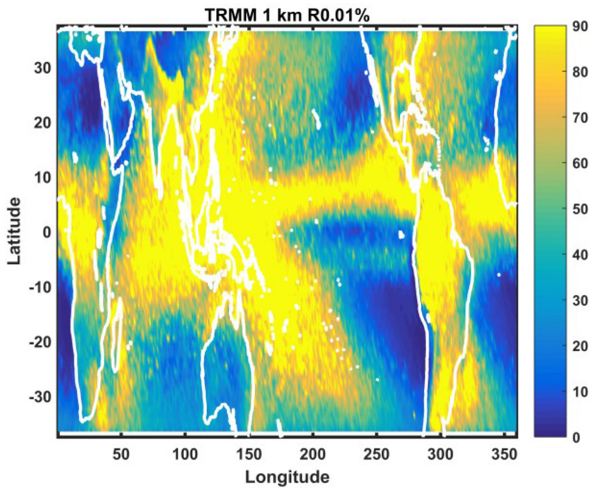

Fig. 5. 0.01% exceeded rain rates derived from distributions of TRMM 5 km rain rates transformed using (1).

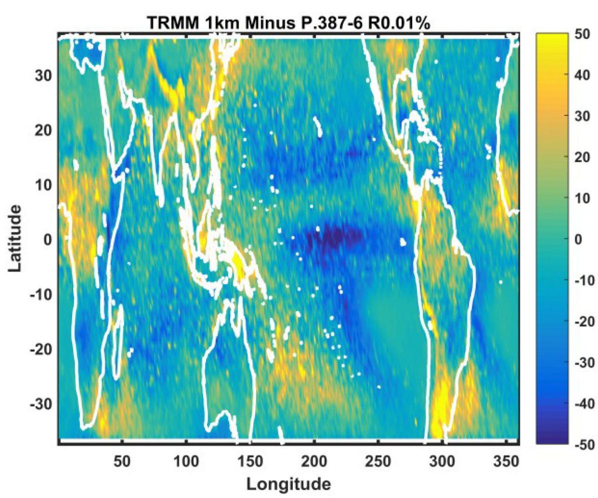

Fig. 6. Difference between 0.01% exceeded rain rates derived from transformed TRMM 5 km rain rates and Rec. ITU-R P.837-6 prediction.

distributions. Fig. 5 shows the 0.01% exceeded rain rates derived from the transformed distributions of TRMM 5 km rain rates. The spatial variation of R0.01% is similar to that provided by Rec. ITU-R P.837-6, but with significant regional differences. For example, regions along the lower coastal regions of West Africa extending to locations in central Africa, coastal areas of Southern Africa, as well the island of Madagascar have been shown by TRMM distributions to have rain rates between 80 and 90 mm/h. This is much higher than the Rec 837-6 values around 20–30 mm/h along the coast of Southern Africa and 60–70 mm/h for the West and central African regions. The TRMM distributions also show high rain rates over the areas around Argentina in South America. Coordinates of locations over the Pacific and the North Atlantic also show rain rates higher than the Rec. ITU-R P.837-6 predictions. These and other differences are shown in Fig. 6, which is a plot of the difference

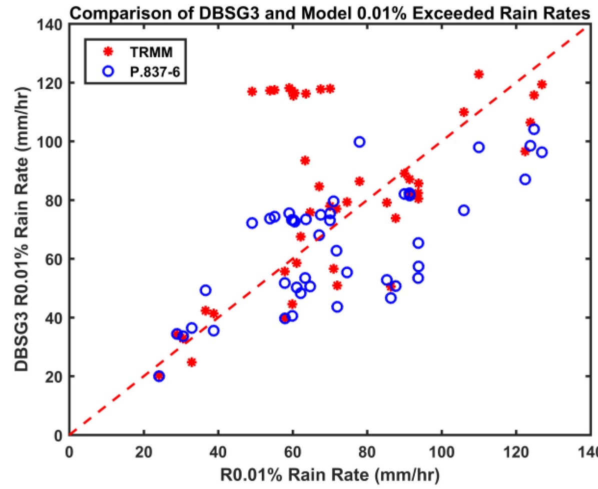

Fig. 7. Comparison of 0.01% exceedance from 1 km TRMM distribution and Rec. ITU-R P.837-6 prediction, with DBSG3 data from the tropics.

between the TRMM rain rates and Rec. ITU-R P.837-6 predictions.

The 0.01% exceeded rain rates derived by this process can also be compared with those in the DBSG3 database. Sites with at least four individual years of measurements have been selected, yielding 50 sites out of 64 that fall within the TRMM boundary. Selection has been performed as the year-to-year variability provided by the four or more years of results allows the standard error in the R0.01% to be estimated.

Figure 7 compares the R0.01% predicted using the TRMM data and Rec. ITU-R P.837-6, with the average DBSG3 value for each site. Table I lists the Rec. ITU-R P.837-6 prediction and that derived from TRMM and the average over at least four years of DBSG3 site data.

Using the *t*-test, Table II shows the probability that the TRMM estimates differ from the DBSG3 values only by chance. *N* gives the number of years over which the data are collected, and *the* standard errors in the values were estimated from year-to-year variation. This probability is just an indication as it assumes that 0.01% exceeded rain rates are normally distributed and independent from year to year. However, the high probabilities of observing the difference between DBSG3 and the TRMM estimates provide some confidence in the method. The low values are for a group of sites in Colombia that are quite close together.

Figure 7 shows that the TRMM method yields generally better estimates of DBSG3 values than Rec. 837-6. The Rec. 837-6 values show a bias at high rain rates that the TRMM values do not have. The notable outliers are the group of sites where TRMM estimates R0.01% to be 120 mm/h compared to the DBSG3 values around 60 mm/h. All these sites are close together in Colombia, within the Ayura valley and in the wind shadow of the Central Range mountains. Within the valley, the terrain may also lead to biased TRMM rain rate estimates due to clutter returns. It is likely that the TRMM values are more representative of the region over the 100-km resolution of the method. Furthermore, it is likely that ITU-R Recommendations are artificially biased by taking the fit to these sites as a measure of improved quality of a method.

TABLE I
REC. ITU-R P.837 PREDICTION, TRMM 1 KM DISTRIBUTION, AND AVERAGE DBSG3 MEASUREMENT FOR POPULATION CENTERS IN TROPICS

LOCATION	LAT	LON	DBSG3	TRMM	Rec837-6	Rec837-7
ALMERIA	36.85	-2.38	16.18	20.6	31.1	22.0
CADIZ	36.5	-6.26	36.6	44.1	49.2	31.7
MALAGA	36.67	-4.48	35.33	33.7	35.9	27.9
MELILLA	35.28	-2.92	28.9	36.6	34.4	26.7
TENERIFE NORTE	28.47	-16.32	32.89	25.8	36.4	32.2
DAEJON	36.37	127.36	87.66	71.1	50.7	59.2
TAEGU	35.88	128.62	57.89	62.8	51.7	54.1
PUSAN	35.1	129.03	93.70	83.9	53.4	61.5
CHONGQING	29.58	106.47	71.96	50.7	43.6	60.5
DONGXING	21.53	107.97	141.80	144.2	82.4	103.8
FUZHOU	26.08	119.28	85.28	77.5	52.8	65.7
GUANGZHOU	23.05	113.32	105.98	114.4	76.5	83.6
GUILIN	25.33	110.3	93.79	85.4	57.4	72.9
HAIKOU	20.03	110.47	122.42	105.1	87.0	86.7
HANGZHOU	30.32	120.2	61.09	49.9	50.2	63.7
JINAN	36.68	116.98	61.58	48.5	44.1	51.1
KUNMING	25.02	102.68	59.91	45.5	40.5	46.4
LANZHOU	36.05	103.88	24.12	15.3	20.0	24.4
NANCHANG	28.67	115.97	74.59	84.2	55.3	69.5
NANGJING	32.32	118.8	62.15	70.7	48.3	57.6
WUHAN	30.63	114.07	86.37	43.6	46.6	62.3
XIAN	34.3	108.93	30.55	22.6	33.6	36.7
YICHUN	27.8	114.38	63.36	98.5	53.4	67.6
ZHENGZHOU	34.72	113.65	57.94	38.7	39.7	46.5
PUSAN	35.1	129.03	93.70	83.9	53.4	61.5
BUKIT TIMA	1.3	103.9	124.79	100.8	104.1	99.7
HOUSTON	29.77	-95.73	93.75	83.0	65.3	58.8
JACKSONVILLE	28.34	-80.93	91.40	89.7	81.5	69.5
FLORIDA	28.34	-80.602	91.38	89.7	82.3	69.3
NORMAN	35.21	-97.44	64.68	78.3	50.6	50.4
WHITE	32.54	-106.61	38.79	41.7	35.5	28.4
TAMPA	28.06	-82.42	90.01	84.2	82.0	69.3
AYURA	6.1689	-75.5681	60.21	120.1	73.1	63.3
CHORRILLOS	6.2991	-75.5061	60.55	120.1	72.6	64.4
CONVENTO	6.3378	-75.5163	59.76	120.1	73.2	64.1
CUCARACHO	6.2869	-75.6119	67.52	120.1	75.0	61.6
GERONA	6.2342	-75.5583	63.57	120.1	73.4	63.2
GIRARDOTA	6.3855	-75.4575	49.12	120.1	72.2	66.1
MANANTIALES	6.3209	-75.5436	53.90	120.1	73.7	63.3

TABLE I
CONTINUED.

PEDREGAL	6.3074	-75.5777	55.15	120.1	74.4	62.4
SAN ANTONIO DE PRADO	6.1877	-75.6649	70.03	120.1	75.4	62.0
SAN CRISTOBAL	6.2837	-75.639	59.07	120.1	75.5	61.2
BELEM	-1.45	-48.48	126.9	120.7	96.2	103.9
BRASILIA	-15.48	-47.83	71	57.5	79.5	67.7
MANAUS	-3.15	-60.02	110	133.1	97.9	98.3
RIO DE JANEIRO	-22.92	-43.95	71.78	78.9	62.7	71.9
STA RITA DO SAPUCAI	-22.25	-45.72	70	82.9	73.1	60.3
SAO PAULO	-23.55	-46.63	67.11	88.0	68.1	63.3
PALAU PIG (SAINS)	5.3546	100.3012	123.8	108.3	98.5	104.1
KWAJALEIN	8.79	167.62	77.93	88.4	99.7	108.9

TABLE II
COMPARISON OF POINT 1-MIN RAIN RATES FOR MULTIYEAR 1 KM TRMM AND DBSG3

	DBSG3			TRMM			PROBABILITY OF DIFFERENCE
LOCATION	N	STDEV(σ)	MEAN	N	STDEV(σ)	MEAN	
ALMERIA	20	7.40	15.01	9	8.38	20.38	0.24
CADIZ	5	4.85	36.81	9	22.16	44.04	0.44
MALAGA	10	14.93	32.58	9	10.15	31.67	0.91
MELILLA	18	7.09	25.40	9	8.29	35.61	0.03
TENERIFE NORTE	14	6.38	31.00	9	14.41	26.59	0.50
DAEJON	10	18.07	83.79	9	51.18	78.07	0.81
TAEGU	10	11.15	57.31	9	15.80	59.28	0.82
PUSAN	10	27.94	85.81	9	29.93	80.26	0.77
HOUSTON	8	20.65	92.19	9	25.77	76.76	0.33
JACKSONVILLE	8	18.35	88.80	9	28.35	81.82	0.66
NORMAN	4	4.57	68.64	9	15.63	79.33	0.15
WHITE	5	7.69	39.91	9	11.72	40.03	0.99
TAMPA	4	8.21	95.46	9	26.64	81.05	0.27
AYURA	4	0.45	60.26	9	38.66	130.38	0.00
CHORRILLOS	4	3.83	60.08	9	38.66	130.38	0.00
CONVENTO	4	12.14	57.97	9	38.66	130.38	0.00
CUCARACHO	4	8.72	65.95	9	38.66	130.38	0.00
GERONA	4	9.82	61.48	9	38.66	130.38	0.00
GIRARDOTA	4	8.18	49.86	9	38.66	130.38	0.00
MANANTIALES	4	7.86	54.49	9	38.66	130.38	0.00
PEDREGAL	4	17.69	61.93	9	38.66	130.38	0.00
SAN ANTONIO DE PRADO	4	9.60	69.69	9	38.66	130.38	0.00
SAN CRISTOBAL	4	7.29	60.87	9	38.66	130.38	0.00
BELEM	7	12.31	126.86	9	31.61	121.74	0.74
BRASILIA	4	26.58	71.03	9	20.20	61.86	0.65
MANAUS	7	2.71	109.78	9	39.01	132.94	0.10
RIO DE JANEIRO	11	11.19	58.80	9	27.30	84.10	0.04
KWAJALEIN	7	16.70	63.95	9	24.64	83.16	0.19

Rec. ITU-R P.311 provides the procedure for the acquisition, presentation, and analysis of data in studies of radiowave propagation [27]. Of importance is the goodness of fit (GoF) metric, which measures the distance between pairs of fade exceedance distributions. It is calculated using the logarithm of the ratio of rain rates exceeded at the same time percentage, which results in a statistic that is approximately normally distributed where a value close to zero indicates a good fit.

The GoF for the 0.01% exceeded rain rate for TRMM compared to DBSG3 data was 0.1304, while for Rec. ITU-R P.837-6 was 0.0931. Excluding the outliers, the GoF for TRMM improves remarkably to a value of 0.0374 while the GoF for Rec. ITU-R P.837-6 is 0.1030. A validation was done using all 120 tropical sites regardless of the number of years of data, and the GoF for TRMM and Rec. ITU-R P.837-6 were 0.0881 and 0.0776, respectively. Without the outliers, the values were 0.0471 and 0.0789 for TRMM and Rec. ITU-R P.837-6, respectively.

B. Comparison to Rec. ITU-R P.837-7

Shortly before the submission of this paper, the ITU-R published Rec. ITU-R P.837-7. The recommendation uses inputs derived from a global rain gauge network and reanalysis data, i.e., the Global Precipitation Climatology Centre (GPCC) gridded rain gauge dataset and the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA Interim database, over land and water, respectively. The new recommendation is therefore not affected by the problems observed with the SPB method used in the Rec. ITU-R P.837-6 model. However, the issues associated with rain gauges still apply. Moreover, it has been reported that developing countries, which constitute a large part of the tropics, have a sparse distribution of rain gauges [28]. It is expected that this lack of data will limit the resolution and accuracy of Rec.ITU-R837-7 in the tropics.

VI. Conclusion

Rec. ITU-R P.837-6 is based on input data with severe and fundamental limitations and is known to perform poorly in the tropics. Similarly, its recent replacement, Rec. ITU-R P.837-7, relies upon rain gauge data that are very sparse in the tropics. Data from the TRMM satellite mission yield a large amount of data derived from integration regions smaller that the convective cells that are fundamentally important for radio system design and regulation. This paper has developed a method to estimate point 1-min rain rate distributions over the tropics from TRMM data. Radar data, either terrestrial or satellite based, yield rain rate estimates with systematic errors due to fine-scale rain variation, partial beam filling, and drop size distribution variations. TRMM dataset 2A25 V7 tries to mitigate many of these errors but still yields estimates with some error and uncertainty [34]. Despite these errors, the proposed method still performs better than ITU-R Recommendations on the DBSG3 validation data.

A transformation from 5 km rain rate distributions to 1 km distributions has been derived from U.K. data and applied in the tropics. No north–south variation was found in the transformation, and so it has speculatively been applied to tropical data. The validity of this has been tested against the DBSG3 database of rain rate distributions. Future work will explore the use of data from the TRMM ground validation sites to refine this transformation. Future research can also address the limitations associated with the validation dataset.

This paper has highlighted the importance of regional representation of data in DBSG3. The Colombian sites are not representative of their region due to orographic effects. If the evolution of ITU-R Recommendations is driven by their fit to the database, then such sites will introduce bias into the recommendations. When these sites are excluded from consideration, the TRMM method performs significantly better than P.837-6 and P.837-7. Furthermore, the TRMM method relies on more recent data than methods based on ERA40 and other reanalysis data and so is more likely to match the present-day climate.

The method developed will be applicable to other satellite precipitation datasets as they become available in the future. It is expected that higher resolution data covering more of the globe will be available in the near future and that these data will be the best starting point for the estimation of distributions of point 1-min rain rate distributions for radio regulation.

Acknowledgment

The authors used Nimrod composite rain maps produced by the U.K. Meteorological Office and supplied by the British Atmospheric Data Centre. The DBSG3 database is maintained by ITU-R Study Group 3 and is accessible to SG3 members through the TIES system: https://www.itu.int/TIES/.

References

[1] *Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems*, Recommendation ITU-R p. 530–16, 2016.

[2] *Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems*, Recommendation ITU-R p. 618–12, 2016.

[3] *Characteristics of Precipitation for Propagation Modelling*, Recommendation ITU-R p. 837–6, 2015.

[4] E. T. Salonen and J. P. V. Poiares Baptista, "A new global rainfall rate model," presented at ICAP'97, Edinburgh, U.K., Jan. 1997, doi: 10.1049/cp:19970359.

[5] J. P. V. Poaires Baptista and E. T. Salonen, "Review of rainfall rate modelling and mapping," presented at CLIMPARA'98, Ottawa, ON, Canada, 1998.

[6] *ITU-R Propagation Prediction Methods for Interference and Sharing Studies*, ITU-R Study Group 3, 2012.

[7] K. S. Paulson, "Evidence of trends in rain event size effecting trends in rain fade: Trends in rain event size effecting fade," *Radio Sci.*, vol. 51, no. 3, pp. 142–149, 2016.

[8] K. S. Paulson, C. Ranatunga, and T. Bellerby, "Estimation of trends in distributions of one-minute rain rates over the UK," presented at EuCAP 2014, The Hague, The Netherlands, doi: 10.1109/EuCAP.2014.6901749.

[9] G. Blarzino, L. Castanet, L. Luini, C. Capsoni, and A. Martelucci, "Development of a new global rainfall rate model based on ERA40, TRMM, GPCC and GPCP Products," presented at EUCAP 2009, Berlin, Germany.

[10] README Document for the Tropical Rainfall Measurement Mission. [Online]. Available: https://disc2.gesdisc.eosdis.nasa.gov/data/TRMM_L2/TRMM_2A23.7/doc/TRMM_Readme_v3.pdf. Accessed on: Feb. 7, 2017.

[11] H. Sauvageot, F. Mesnard, and R. S. Tenório, "The relation between the area-average rain rate and the rain cell size distribution parameters," *J. Atmos. Sci.*, vol. 56, no. 1, pp. 57–70, 1999.

[12] N. H. H. Khamis, J. Din, and T. A. Rahman, "Determination of rain cell size distribution for microwave link design in Malaysia," presented at Radio and Microwave 2004, Selangor, Malaysia, doi: 10.1109/RFM.2004.1411069.

[13] D. B. Wolff *et al.*, "Ground validation for the tropical rainfall measuring mission (TRMM)," *J. Atmos. Ocean. Technol.*, vol. 22, no. 4, pp. 365–380, 2005, doi: 10.1175/JTECH1700.1.

[14] T. V. Omotosho and C. O. Oluwafemi, "One-minute rain rate distribution in Nigeria derived from TRMM satellite data," *J. Atmos. Sol. Terr. Phys.*, vol. 71, no. 5, pp. 625–633, 2009.

[15] T. V. Omotosho *et al.*, "Distribution of one-minute rain rate in Malaysia derived from TRMM satellite data," *Ann. Geophys.*, vol. 31, pp. 2013–2022, 2013.

[16] TRMM 2A25. [Online]. Available: https://search.earthdata.nasa.gov/?q = TRMM+2A25&ok = TRMM+2A25. Accessed on: Mar. 17, 2017.

[17] T. Iguchi, T. Kozu, R. Meneghini, J. Awaka, and K. I. Okamoto, "Rain-profiling algorithm for the TRMM precipitation radar," *J. Appl. Meteorol.*, vol. 39, no. 12, pp. 2038–2052, 2000.

[18] D. B. Wolff and B. L. Fisher, "Comparisons of instantaneous TRMM ground validation and satellite rain rate estimates at different spatial scales," *J. Appl. Meteorol. Climatol.*, vol. 47, no. 8, pp. 2215–2237, 2008.

[19] Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar Algorithm. Instruction Manual for Version7. [Online]. Available: http://www.eorc.jaxa.jp/TRMM/documents/PR_algorithm_product_information/pr_manual/PR_Instruction_Manual_V7_L1.pdf. Accessed on: Sep. 23, 2017.
[20] P. Kirstetter *et al.*, "Toward a framework for systematic error modeling of spaceborne precipitation radar with NOAA/NSSL ground Radarâ Based National Mosaic QPE," *J. Hydrometeorol.*, vol. 13, no. 4, pp. 1285–1300, 2012.
[21] D. B. Wolff and B. L. Fisher, "Comparisons of instantaneous TRMM ground validation and satellite rain-rate estimates at different spatial scales," *J. Appl. Meteorol. Climatol.*, vol. 47, no. 8, pp. 2215–2237, 2008.
[22] Y. Duan, A. M. Wilson, and A. P. Barros, "Scoping a field experiment: Error diagnostics of TRMM precipitation radar estimates in complex terrain as a basis for IPHEx2014," *Hydrol. Earth Syst. Sci.*, vol. 19, no. 3, pp. 1501–1520, 2015.
[23] P. Kirstetter *et al.*, "Comparison of TRMM 2A25 products, version 6 and version 7, with NOAA/NSSL ground Radarâ based national mosaic QPE," *J. Hydrometeorol.*, vol. 14, no. 2, pp. 661–669, 2013.
[24] S. H. Chan, R. R. Halterman, and D. G. Long, "Cross-validation of Jason-1 and QuikSCAT wind speeds," presented at IGARSS 2004, Anchorage, AK, USA, doi: 10.1109/IGARSS.2004.1369866.
[25] L. S. Chiu *et al.*, "Comparison of TRMM and water district rain rates over New Mexico," *Adv. Atmos. Sci.*, vol. 23, no. 1, pp. 1–13, 2006.
[26] M. N. Islam and H. Uyeda, "Use of TRMM in determining the climatic characteristics of rainfall over Bangladesh," *Remote Sens. Environ.*, vol. 108, no. 3, pp. 264–276, 2007.
[27] Y. Fu *et al.*, "Recent trends of summer convective and stratiform precipitation in Mid-Eastern China," *Sci. Rep.*, vol. 6, p. 33044, 2016.
[28] Q. Cao *et al.*, "Statistical and physical analysis of the vertical structure of precipitation in the mountainous west region of the United States using 11+ years of spaceborne observations from TRMM precipitation radar," *J. Appl. Meteorol. Climatol.*, vol. 52, no. 2, pp. 408–424, 2013.
[29] D. L. Harrison, S. J. Driscoll, and M. Kitchen, "Improving precipitation estimates from weather radar using quality control and correction techniques," *Meteorol. Appl.*, vol. 7, no. 2, pp. 135–144, 2000.
[30] K. S. Paulson, C. Ranatunga, and T. Bellerby, "Estimation of trends in distributions of one-minute rain rates over the UK," presented at EuCAP 2014, The Hague, The Netherlands, doi: 10.1109/EuCAP.2014.6901749.
[31] T. Tjelta and J. Mamen, "Climate trends and variability of rain rate derived from long-term measurements in Norway," *Radio Sci.*, vol. 49, no. 9, pp. 788–797, 2014.
[32] *Acquisition, Presentation and Analysis of Data in Studies of Radiowave Propagation*, Recommendation ITU-R P. 311-16, 2016.
[33] T. Islam, M. A. Rico-Ramirez, D. Han, K. P. Srivastava, and M. A. Ishak, "Performance evaluation of the TRMM precipitation estimation using ground-based radars from the GPM validation network," *J. Atmos. Solar Terr. Phys.*, vol. 77, pp. 194–208, 2012, doi: 10.1016/j.jastp.2012.01.001.
[34] P. Kirstetter *et al.*, "Impact of sub-pixel rainfall variability on spaceborne precipitation estimation: Evaluating the TRMM 2A25 product: Impact of Sub-Pixel Rainfall Variability on TRMM 2A25," *Q. J. R. Meteorol. Soc.*, vol. 141, no. 688, pp. 953–966, 2015.

Geraldine Rangmoen Rimven received the B.Eng. degree in electrical/electronic engineering from Abubakar Tafawa Balewa University, Bauchi, Nigeria, in 2000, and the M.Sc. degree in personal, mobile, and satellite communication from the University of Bradford, Bradford, U.K., in 2011. She is currently working toward the Ph.D. degree from the School of Engineering and Computer Science, University of Hull, Hull, U.K.

She worked in various computing and electrical support roles before joining the University of Jos, Nigeria, as a Systems Engineer for its Network and Internet Services. Since 2014, she has been a Lecturer in the Electrical/Electronic Department, Faculty of Engineering, University of Jos.

Kevin S. Paulson received the B.Sc. and M.Sc. degrees in atmospheric physics from the University of Auckland, Auckland, New Zealand, in 1983, and 1985, respectively, and the Ph.D. degree in mathematics from the Oxford Brookes University, Oxford, U.K., in 1991.

He was Leader of the Terrestrial Systems in the Radio Communications Research Unit of Rutherford Appleton Laboratory until 2004 when he joined the University of Hull, Hull, U.K., as a Senior Lecturer in telecommunications.

Timothy Bellerby received the B.Sc. degree in applied mathematics from the University of Warwick, Warwick, U.K., in 1986, and the Ph.D. degree in geophysics from the University of Sheffield, Sheffield, U.K., in 1991.

He is a Senior Lecturer in Geography in the School of Environmental Sciences, University of Hull, Hull, U.K. He has formerly been a Research Associate at the University of Bristol Centre for Remote Sensing, U.K., and a Contactor to the United States National Weather Service. He was a Consultant to the United Nations Food and Agricultural Organization. His current research interests include the application of artificial intelligence and machine vision approaches to satellite cloud monitoring, precipitation estimation, and the development of ensemble and probabilistic representations of uncertainty in precipitation estimates. He has an interest in monitoring and forecasting the River Nile.