

1-MIN RAIN RATE STATISTICS PREDICTIONS FROM 1-HOUR RAIN RATE STATISTICS MEASUREMENTS

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1. Abstract: In this paper a new method is presented, which allows the recovery of the cumulative distribution function (CDF) of point rain rate with 1-min integration time ($P(R)_1$) from rain rate CDFs with longer integration time (in this case, 1-hour time average rain rate statistics $P(R)_{60}$). The method generates the scaling factors between $P(R)_{60}$ and $P(R)_1$ as a function of the probability level and of the site geographical coordinates. From the scaling factors, a scaling law of the form proposed by Chebil and Raman is devised. The method is applicable worldwide and produces predictions far more accurate than the ones provided by general $P(R)$ estimation techniques.

2. Introduction: The design of telecommunication systems implies the fulfillment of stringent availability requirements that depend on the type of service to be provided. In particular, the new telecommunication systems which are asked to support wide bandwidth multimedia services operate at millimeter wave that are heavily influenced by rain and other atmospheric constituents such as oxygen, water vapor and clouds. Among them, rain plays the most significant role. In Europe, special attention has been devoted to these issues as demonstrated by the theoretical studies carried out within the COST actions 210, 255 and 280 [1], [2] and the experimental activity with Olympus and ITALSAT satellites [3], [4]. The accurate knowledge of rain rate statistics for the location of interest used as input to prediction methods allows the evaluation of the statistical behavior of the attenuation caused by rain.

Toward this aim, the International Telecommunication Union (ITU) recommends the use of rain rate CDFs with 1-min integration time in order to

derive attenuation CDFs. In fact, such integration interval guarantees a good level of accuracy in reproducing the time variability of attenuation as it is confirmed by various authors [5], [6]. On the other side, 1-min integration time is not the standard time interval used in meteorological applications, for which there is no interest in rapid changes of rain intensity, but rather in reliable average quantities (half-hourly, hourly, daily, monthly or yearly cumulated rain). Therefore, rain gauge data routinely collected for meteorological purposes and covering long observation periods are easily available worldwide, whilst specialized measurements for propagation applications are carried out on spot basis at specific sites (usually associated to other experimental activities on electromagnetic propagation).

This fact has driven research efforts towards the development of procedures aimed at deriving rain rate CDFs with 1-min time resolution from the knowledge of rain rate CDFs with much longer integration time or from the knowledge of general meteorological conditions. In this context, the existing prediction methods can be grouped into three different categories:

- meteorology based methods which use as input general climatic information, like the annual or monthly average rain rate, the number of rainy days per year, the peak annual rain rate and so on. The most acknowledged ones are the Rice-Holmberg [7], Dutton-Dougherty [8], Crane [9] and ITU-R [10] methods;
- analytical methods based on the assumption that the analytical form of the rain rate CDF is maintained while changing the integration time; in other words, the 1-min and 1-hour CDFs are different because the parameters of the CDF equation are different. These methods predict how the parameters of the distribution change according to the integration time. In this group of models, the ones proposed by Moupfouma [11] and Karasawa [12] must be cited;
- empirical methods like the ones proposed by Segal, Burgueño and Watson et al., which provide conversion factors between the known CDF and the one to be estimated as a function of the probability level. In particular, Segal in [5] and [13] analyzed long-term data of 45 locations in Canada and thus derived a fitting power-law (on probability) for the $P(R)_{60}$

to $P(R)_1$ conversion factors. This relationship has been modified (through the introduction of an exponential term) and fitted to Malaysian data by Chebil and Rahman in [6]. In [14], Burgueño observed long-term data in Barcelona, Spain, and proposed another fitting power-law (on rain rate). In [15], Lee et al. reanalyzed the works in [6] and [14] and provided regional coefficients for the law proposed by Burgueño, for different integration times. Finally, Watson et al. in [16] analyzed rainfall data in various European locations and calculated average conversion factors for some probability levels. All the aforementioned methods provide only regional coefficients since they were developed as initiating from local data.

Actually, not one of the proposals grouped in the last two categories can be applied worldwide because of the lack of proper conversion coefficients. Only recently some ITU-R proposals [15], [17], still under investigation, are going to provide coefficients of the law proposed by Burgueño on a global basis to convert τ -min into 1-min, with τ ranging from 5 to 30 minutes.

With respect to the techniques of the $P(R)_1$ prediction, which use general meteorological information as input, those methods exploiting the measured $P(R)$ s with long integration time have the inherent advantage of retaining as much of the local peculiarities of precipitation (topographic effects as well as yearly variability) as possible.

3. A new prediction method: The method presented in this paper cannot be included in any of the aforementioned categories: in fact, as an intermediate step, it takes advantage of a physical model of synthetic rain cells in order to simulate the actual counting process of a rain gauge operating at a given integration time.

The rationale of the method can be summarized as follows: let us assume that we can describe the meteorological environment of the location of interest by means of an ensemble of synthetic rain structures; the rain field-rain gauge interaction can be simulated by properly moving the rain field with respect to the rain gauge, which is assumed to operate at the specified integration time τ . It follows that we can derive both $P(R)_{60}$ and $P(R)_1$ and evaluate the corresponding scaling factors at different probability levels. Specifically:

1. the meteorological environment is described through the EXCELL (Exponential CELL) model [18],[19], a method that makes use of an ensemble of synthetic cells (the probability density of which is analytically derived from the local $P(R)_1$) in order to accurately represent the precipitation statistics of a site;
2. the interaction of the rain field with a rain gauge operating at a given integration time τ , is simulated by taking into account the space-time evolution of the rain field through an equivalent cell velocity v ;
3. it follows that the $P(R)_{60}$ is obtainable using the $P(R)_1$;
4. $P(R)_1$ being unknown, a “first guess” estimate of which, specific for the zone of interest, must be used;

from the knowledge of the two CDFs, it is possible to derive the scaling factors at different probability levels and afterwards to apply them to the measured $P(R)_{60}$ to derive the corresponding $P(R)_1$.

3.1 The physical rain model: Developed in 1987 at the Politecnico di Milano as a tool for propagation studies and rain impairment predictions, the EXCELL model assumes that the precipitation peculiarities of any location can be statistically represented using an ensemble of synthetic cells with rotational symmetry and exponential spatial distribution of rain, with different radii and peak rain rates. Rain cells have the same structure in any location (exponential distribution of rain intensity, relation between the peak value and the cell dimension) and the difference in the rain field estimation from one location to another is the cells' probability of occurrence.

In this study, a slightly modified version of the EXCELL model, referred to as “Lowered EXCELL”, has been employed. The novelty feature implemented is the introduction of a lowering factor R_{low} which modifies the rain profile $R(\rho)$ as:

$$R(\rho) = (R_M + R_{low}) e^{-\frac{\rho}{\rho_0}} - R_{low} \quad (1)$$

where ρ is the distance from the cell center in which the peak R_M is located, and the lowering factor R_{low} allows the rain profile $R(\rho)$ to reach zero for $\rho_l = \rho_0 \ln(1 + R_M / R_{low})$. Finally, ρ_0 is the radius of the cell such that:

$$R(\rho_0) = \frac{(R_M + R_{low})}{e} - R_{low} \approx \frac{R_M}{e} \quad (2)$$

if R_{low} is small enough with respect to R_M , more precisely $R_{low} \leq 2$ mm/h. More details on the characteristics of the Lowered EXCELL model can be found in [20].

3.2 Types of precipitation: The proposed method is based upon the space-time evolution of precipitation fields which are very complex atmospheric phenomena.

In general, cloud formation is caused by the encounter of cold and warm air flow and the result is different, depending on the way in which the air masses interact. For our application, it is enough to distinguish between two different types of clouds:

cumulus: warm air tends to move towards higher layers and to get cold very quickly. This process gives rise to fast warm updrafts and cold downdrafts, generated by the sudden temperature decrease (due to condensation) of the highest air levels. In turn, it causes a convective air motion and can produce cumulonimbus clouds whose associated rain is often characterized by extremely intense values (even up to 250 mm/h), short duration and high vertical, but horizontally limited, extent (convective precipitation);

stratus: warm air masses just move horizontally below cold air masses and this mechanism leads to very extended cloud layers (some hundreds of kilometers) at low altitude. The result can be nimbostratus clouds that lead to a precipitation characterized by low intensity and long duration (stratiform precipitation).

Occasionally, the two types of precipitations coexist, giving rise to very extended stratiform rain with embedded small convective areas.

Stratiform and convective precipitations have a definite different space-time evolution: this feature has been taken into account in the development of the present model which, in fact, is based on the translation of rain cells. As a

consequence, a subdivision of the yearly $P(R)_{year}$ into stratiform $P(R)_{strat}$ and $P(R)_{conv}$ has been applied, according to Capsoni et al. [20]. Obviously:

$$P(R)_{year} = P(R)_{strat} + P(R)_{conv} \quad (3)$$

where the sum is in probability for any given value of rain rate R .

The procedure adopted in [20] to subdivide $P(R)_{year}$ uses again the Lowered EXCELL model and is based on the assumption that, when considering stratiform rain, rainfall peaks hardly exceed 10 mm/h, as already suggested by other authors [21]. The method identifies a threshold $R_{M,mean}$ on the peak value of rain cells to discriminate between cells that contribute either to stratiform or to convective rain.

Additional details regarding the stratiform/convective discrimination method can be found in [20].

3.3 Cell movement: During their lifetime, rain structures are subject both to translation and to deformation so that the apparent velocity of movement as “seen” by a rain gauge or derived from a sequence of radar images is a complex function of the air mass movement.

Depending on the type of precipitation, rain structures appear to move mostly because of wind speed (convective rain), or, rather, because of time evolution (stratiform rain).

A good indicator of the average cell speed is the wind velocity v_{600} measured at the altitude corresponding to the 600 mb air pressure (approximately 4000-4200 m above the ground). The wind flow at that altitude is not influenced by the attrition caused by soil. In particular, the wind intensity provided worldwide by the ECMWF (European Centre for Medium-Range Weather Forecast) on a $1.5^\circ \times 1.5^\circ$ geographical grid and retrievable from the ERA-15 (ECMWF Re-Analysis) database, has been employed.

In practice, cells contributing to convective rain are subject to movement at velocity v_{conv} :

$$v_{conv} = v_{600} / k_1(\tau) \quad (4)$$

where $k_1(\tau)$ is a reduction factor that is dependent on the time integration τ of the rain gauge. Instead, cells contributing to stratiform rain are translated at velocity v_{strat} :

$$v_{strat} = k_2(\tau) v_{conv} \quad (5)$$

which is a fraction $k_2(\tau)$ of v_{conv} . Whilst considering cell translation, two hypotheses are made: the cell shape does not vary during the translation process and cells move along a straight line, with constant velocity v_{strat} or v_{conv} .

$k_1(60)$ and $k_2(60)$ have been evaluated through a best fit procedure by considering six locations belonging to different climatic zones (refer to Table 1). The optimized values are:

$$k_1(60) = 2.2 \quad \text{and} \quad k_2(60) = 0.3 \quad (6)$$

The definite reduction of v_{600} also for convective rain is justified not only by the complex space-time evolution of the precipitation structures but also by the peculiarity of the EXCELL model which assumes that only one single cell is acting at a time. Consequently, the interaction of multiple cells with the rain gauge, a situation that is more and more frequent as the integration time increases, is here taken into account through an equivalent decrease of the translation speed of rain cells.

As an example, Figure 1 shows the estimation of the $P(R)_{60}$ from the measured $P(R)_1$ in Rome. The agreement between the estimated and the measured $P(R)_{60}$ is quite satisfactory, thus giving a clear indication of the appropriate representation of the rain field characteristics and of its space-time modifications.

3.4 Generation of the parameters of the $P(R)$ conversion law: The complete procedure to obtain the scaling law between $P(R)_{60}$ and $P(R)_1$ consists of the following steps:

- choose a first guess $P(R)_1$ appropriate for the site of interest;
- use the Lowered EXCELL model with the $P(R)_1$ above as input and obtain the probability of occurrence of all the rain cells representing the local rain field;
- discriminate between stratiform and convective cells;
- extract wind velocity information, v_{600} , appropriate for the site of interest from the ERA-15 database;

- translate stratiform cells over the virtual rain gauge at $v = v_{strat}$ and convective cells at $v = v_{conv}$ (see equations 4 and 5);
- build up $P(R)_{60}$;
- calculate the conversion factors from 1-hour to 1-min integration time as:

$$\rho_{60}(P) = \frac{R_1(P)}{R_{60}(P)} \quad (7)$$

where P is the probability level for which the scaling factor is calculated, $R_1(P)$ and $R_{60}(P)$ are the rain rate values of $P(R)_1$ and $P(R)_{60}$ respectively, at the probability level P ;

- fit the conversion factors using the law proposed by Chebil and Rahman in [6]:

$$\rho_{60}(P) = a P^b + c e^{dP} \quad (8)$$

Different types of analytical curves have been taken into account (quadratic, cubic, double exponential, double power-law, to name a few) but the one proposed by Chebil and Rahman revealed to be the most accurate and suitable for fitting the conversion factors on a wide time percentage range (10^{-4} % to 10 %).

4. $P(R)_{60}$ to $P(R)_1$ conversion law. The choice of a first guess $P(R)_1$ (step 1) is not very critical. It is, in fact, necessary to retain the basic information about the characteristics of the local precipitation. Two different solutions have been considered and tested in this study. The first one makes reference to the ITU-R Rec. P.837-4 that is currently suggested as the best performing model to predict worldwide the 1-min rain rate CDF from general meteorological information. In this case, $P(R)_1$ is obtained by entering the appropriate software code with the geographical coordinates of the location. The second solution makes reference to the old ITU-R Rec. P.837-1, which divided the world in 15 zones, each one characterized by a different $P(R)$, and has proved to work satisfactorily although with some limitations clearly visible at the boundary between rain zones.

4.1 First guess $P(R)_1$ extracted from the ITU-R Rec. P.837-4: In this case, the ITU-R Rec. P.837-4 model has been embedded in a software tool which

derives from it the first guess $P(R)_{1,i,j}$ for the location (i,j) , being i the latitude and j the longitude. Accordingly, the wind velocity at the 600 mb altitude $v_{600}(i,j)$ is extracted from the ERA-15 database by applying a bilinear interpolation to the original ERA data ($1.5^\circ \times 1.5^\circ$ grid) as in the ITU-R Rec. P.837-4.

Running the developed software tool, the conversion factors can be generated worldwide. The coefficients a , b , c and d of equation 8 are calculated and the corresponding conversion law is derived.

Figure 2 shows some examples of $P(R)_1$ estimation from $P(R)_{60}$, for Manantiales in Columbia and Prague in the Czech Republic. The rain rate statistics predicted by the current ITU-R recommendation are also plotted for comparison.

The results clearly point out the advantage of using, when possible, local data, although with non appropriate integration time, coupled with a conversion law, rather than the general $P(R)_1$ prediction model. The large overestimation of the ITU-R model in the tropical area is a well known issue that largely depends on the overestimation of the ECMWF predictions of the total mean yearly cumulated rain (one of the key input parameter of the ITU-R Rec. P.837-4). The shape of the curve predicted by the ITU-R model for the Columbian site is appropriate, though the mean yearly cumulated rain is not, which causes a shift of the prediction curve to higher rainfall values. A different consideration applies to the $P(R)_1$ in Prague: the total mean yearly cumulated rain provided by the ITU-R model seems to be adequate, but the distribution between low and high rain rate values does not, so that the discrepancies are mainly due to the wrong form of the curve.

4.2 First guess $P(R)_1$ extracted from the ITU-R Rec. P.837-1: The reasons why we present and discuss this second solution are on one side the wish to show how much the choice of the first guess $P(R)_1$ is not a critical point of the method and on the other side to derive and provide a global table of coefficients for the conversion law (1-hour to 1-min $P(R)$). In fact, the ITU-R Rec. P.837-1 divides the world into 15 rain zones and thus has the advantage of allowing the computation of a set of conversion factors for each zone, to be

easily and quickly accessed. On the other hand, however, the mentioned recommendation presents spatial discontinuities that cannot always be easily managed.

We have obtained the global grid of conversion factors from the ITU-R Rec. P.837-1, through the steps described in section 3.4, and in particular:

- the first guess $P(R)_{1,i}$ relative to rain zone i has been extracted from the ITU-R Rec. P.837-1 and used as input to the EXCELL model;
- the wind velocity at the 600 mb altitude for zone i , namely $\bar{v}_{600,i}$, has been calculated from the ERA-15 database, as the average value of all the $v_{600,i}$ samples relative to the grid points in the database belonging to zone i :

$$\bar{v}_{600,i} = \frac{1}{N_i} \sum_{zone\ i} v_{600,i} \quad (9)$$

being N_i the number of points, i.e. ERA-15 pixels, included in rain zone i .

Table 2 lists the resulting $\bar{v}_{600,i}$ values and parameters a , b , c , d of equation 8 for each rain zone. They have been obtained by fitting the calculated conversion factors in the probability range $10^{-3} \% - 1 \%$, except for rain zones A and B, for which the range is reduced to $10^{-3} \% - 10^{-1} \%$. In fact, in these latter zones, the associated $P(R)$ s provided by the recommendation span over a limited percentage interval ($10^{-3} \% - 2 \cdot 10^{-1} \%$ for zone A and $10^{-3} \% - 5 \cdot 10^{-1} \%$ for zone B). Moreover, since they are referred to the least rainy regions in the world, such $P(R)$ s are also less regular (especially for $P > 10^{-1} \%$) and therefore less suitable to be well fitted by the EXCELL model. Based on such considerations, Table 2 also shows, for each rain zone, the range of validity of the a , b , c , d coefficients.

Despite the big differences among the sets of coefficients in Table 2, which are the outputs of a fitting procedure, the associated conversion laws provide a similar trend as clearly visible in Figure 3, where equation 8 is plotted for all the 15 rain zones.

As an example, Figure 4 shows the results of the estimates provided by the model for two sites (Kuala Lumpur and Miami, respectively). The rain rate statistics predicted by the current ITU-R recommendation are also plotted for comparison. It can be noted that also in this case the predictions of the proposed conversion model are very satisfactory.

5. *Performance of the method:* A quantitative test of the performance of the conversion method has been carried out by considering a set of sites and by evaluating, for each of them, the error in the $P(R)_1$ estimate:

$$\varepsilon(P) = 100 \frac{R_{est}(P) - R_{meas}(P)}{R_{meas}(P)} \quad [\%] \quad (10)$$

where $R_{est}(P)$ and $R_{meas}(P)$ are the estimated and measured rain rate values of the $P(R)_1$, respectively, at the same probability level P , in the percentage interval $10^{-3} \% < P < 1 \%$.

5.1 *Overall performance:* Twenty five sites spread all over the world have been considered whose details are given in Table 3. The test has been carried out for both the proposed solutions.

The mean, standard deviation (STD) and the root mean square (RMS) values of $\varepsilon(P)$ are gathered in Table 4 where they are compared to the performance of the ITU-R Rec. P.837-4. Note that only two among all the available Colombian sites have been included in the test, and specifically those locations characterized by the lowest (Girardota) and the highest (Chorillos) altitudes in order not to bias the overall scores that appear at the end of the table. As it can be easily noticed both from the single error figures and from their average values, this conversion method allows a definite improvement in the $P(R)_1$ estimation when local rain rate measurements with poor time resolution are available. This result was expected as the method utilizes local information on rain rate statistics (with a long integration time) to estimate the $P(R)_1$, thus retaining as much of the climatic peculiarities of the considered site as possible. On the other site, the ITU-R Rec. P.837-4 is based on even longer term rainfall statistics which are themselves estimated by the ECMWF. In other words, the proposed conversion method can exploit point rainfall measured statistics, while the ITU-R recommendation is based on indicators of the rainfall statistics which are relative to a large area ($1.5^\circ \times 1.5^\circ$ pixels).

As one can appreciate from Table 4, in most of the considered cases, both the average and the RMS values of $\varepsilon(P)$ are lower than the ones obtained using the ITU-R Rec. P.837-4 predictions and, however, lower than 25 % and 35 %, respectively. On average, with some exceptions (Spino d'Adda,

Prague, Florida), the use of the ITU-R Rec. P.837-1 as first guess $P(R)$ does not provide results far different from the ones obtainable utilizing the ITU-R Rec. P.837-4. In the latter case, in fact, the RMS error decreases from 18.30 % to 16.14 %.

5.2 Sensitivity of the model to parameters $k_1(60)$ and $k_2(60)$: In order to assess the sensitivity of the proposed rain rate conversion method to the wind reduction factors $k_1(60)$ and $k_2(60)$, the overall performance of the model (ITU-R Rec. P.837-4 as first guess curve) has been evaluated by applying separately a percentage variation (from -75 % to 75 %) to $k_1(60)$ and $k_2(60)$. Namely, tests have been performed first by varying only k_1 from 0.55 to 3.85, keeping k_2 equal to 0.3. Afterwards, k_2 has been varied from 0.075 to 0.525, maintaining k_1 equal to 2.2. As a result, Figure 5 and Figure 6 depict the trend of the overall mean, standard deviation and root mean square values of the estimation error (the same quantities listed in the last row of Table 4). Figures clearly show a higher sensitivity of the model to k_1 with respect to k_2 ; this result was expected as k_1 affects the translation of convective cells, the ones with higher impact on the rain rate integration process. It is also worth noting in Figure 5 and Figure 6 that though the values $k_1 = 2.2$ and $k_2 = 0.3$ have been derived only from 6 $P(R)$ s, such choice guarantees the best performance of the model also on the whole dataset used in this study.

5.3 Spatial and temporal variability of the $P(R)$: Ten out of the 25 experiments listed in Table 3 are located in Colombia and belong to a limited ($6.17^\circ \text{ N} < \text{LAT} < 6.39^\circ \text{ N}$ and $-75.66^\circ \text{ E} < \text{LON} < -75.46^\circ \text{ E}$) but very mountainous and inhomogeneous area, where altitude ranges from 1360 m to 2353 m. We used this subset of experiments to assess how much the spatial variation of rain, in this case mainly due to the irregular topography of the zone, is trailed by the proposed method (in this exercise, only the ITU-R Rec. P.837-4 $P(R)$ has been chosen as input to generate the scaling factors). In Table 5, the results of the predictions are compared: the ITU-R Rec. P.837-4 is less sensitive to the $P(R)$ s modifications inside a limited area, since the basic input parameters of the model are defined on a $1.5^\circ \times 1.5^\circ$ geographical grid and the bilinear interpolation cannot provide input data sufficiently different to

change the resulting $P(R)_1$ significantly. Instead, the use of local data allows the 1-hour to 1-min conversion method to provide STD values of the estimation error that are quite limited and fairly well balanced among all the sites (from about 7 % to a peak value of 18 % in one site). In this case, in fact, in order to quantify the model performance, reference should be made to the STD values instead of to the customary RMS ones because, otherwise the ITU-R Rec. P.837-4 would be penalized by anomalous large mean values of $\varepsilon(P)$, likely due to the systematic overestimation of the mean yearly cumulated rain in that region.

Another test that we have performed emphasizes the ability of the conversion method in tracking the year-to-year variability of the rain rate CDF. Some years of rain gauge measurements collected in Spino d'Adda (from 1993 to 1999) have been considered separately. Also in this case (see Table 6) the conversion method reacts adequately and provides good results with respect to the ITU-R Rec. P.837-4, showing a maximum RMS error of 20.1 % (year 1997), usually limited between 5 % and 15 %. Note that the error figures reported in Table 6 relative to the ITU-R Rec. P.837-4 represent the difference between the annual and the long term rain rate CDF while the ones relative to the new scaling method derive from the application of the same conversion law, the one calculated for Spino d'Adda, to different input $P(R)_{60}$. In terms of overall performance, the proposed conversion method shows an RMS value of $\varepsilon(P)$ that is lower than one half of the competing one.

The results of this section assess the capability of the proposed method to adequately trail the spatial and temporal variation of rain rate CDFs, and emphasize the importance of using local information to obtain good estimates of rain rate statistics.

6. Conclusions: A method applicable worldwide to obtain the 1-min rain rate CDF ($P(R)_1$), required for applications related to propagation, from measured CDF with 1-hour integration time ($P(R)_{60}$) is proposed and tested here. The method, exploiting the Lowered EXCELL model and a first guess $P(R)_1$ to describe the precipitation characteristics of the location of interest, derives the coefficients of the conversion law that is assumed to have the analytical form proposed by Chebil and Rahman in [6]. Two different solutions for the

determination of the first guess $P(R)_1$ has been considered and tested: the ITU-R Rec. P.837-1 and the ITU-R Rec. P.837-4. Both the solutions generate accurate conversion factors, thus confirming that the choice of the first guess curve is not a critical point of the method (strictly speaking, slightly better results have been obtained using the ITU-R Rec. P.837-4 estimation as the first guess curve). In particular, the use of the ITU-R Rec. P.837-1 allowed the calculation of regional conversion factors, for all the 15 rain zones defined in that ITU-R recommendation. Tests have confirmed that wherever a direct rainfall measurement is available, although with poor time resolution, the use of a proper tool to convert τ -min into 1-min integrated rain rate CDF is far more effective than the use of prediction models based on general meteorological information. It has been also shown that the proposed method quite adequately trails the spatial (due to topography) and temporal (due to year-to-year variability) modifications of the $P(R)_1$.

Obviously, because of its physical derivation, the method could be enhanced by considering different integration times (for instance $\tau = 5, 10, 30$ min): in fact, only the coefficients $k_1(\tau)$ and $k_2(\tau)$ in equation 6, defining the effective velocities of cell translation (equations 4 and 5), need to be recalculated.

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Tables:

Table 1: locations where measured $P(R)_1$ and $P(R)_{60}$ have been used to determine $k_1(60)$ and $k_2(60)$ coefficients

Spino d'Adda	45.46° N	9.56° E	9 years data (rain gauge time series)
Rome	41.87° N	12.48° E	8 years data (rain gauge time series)
Miami	25.65° N	-80.43° E	40 years data (CDFs)
Chicago	41.9° N	-87.65° E	40 years data (CDFs)
Kuala Lumpur	3.16° N	101.71° E	3 years data (CDFs)
Sendai	38.27° N	140.87° E	9 years data (CDFs)

Table 2: coefficients of equation 8, providing conversion factors to calculate $P(R)_1$ from $P(R)_{60}$ for each rain region defined in the ITU-R Rec. P.837-1

	$\bar{v}_{600,i}$ (m/s)	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>P max</i> (%)	<i>P min</i> (%)
Zone A	11.9	-13.3055	0.0141	13.7663	0.0592	10^{-1}	10^{-3}
Zone B	12.1	0.3192	-0.2097	0.6404	-6.4445	10^{-1}	10^{-3}
Zone C	11.25	0.7112	-0.1239	0.0883	1.2319	1	10^{-3}
Zone D	15.1	0.8419	-0.1036	0.3928	-1.1172	1	10^{-3}
Zone E	10.4	0.4980	-0.1712	0.2635	0.4263	1	10^{-3}
Zone F	14.5	0.3624	-0.2606	0.5872	0.0210	1	10^{-3}
Zone G	13.4	0.5001	-0.1378	0.8409	-0.6725	1	10^{-3}
Zone H	13	-4.79	0.1169	5.11	0.1342	1	10^{-3}
Zone J	6.8	-0.26	0.0862	1.73	-0.3201	1	10^{-3}
Zone K	12.4	-3.03	0.1790	3.36	0.1448	1	10^{-3}
Zone L	11.4	-72.07	0.0054	72.51	0.0059	1	10^{-3}
Zone M	12	-3.38	0.0939	4.26	0.0162	1	10^{-3}
Zone N	6.8	0.8178	-0.1041	0.7126	-2.8874	1	10^{-3}

Zone P	5.9	0.8652	-0.1094	0.7163	-1.2835	1	10^{-3}
Zone Q	7	-52.00	0.0001545	53.61	-0.0078	1	10^{-3}

Table 3: characteristics of the 25 sites where rain data are available

Location	Country	LAT (° N)	LON (° E)	ITU-R Rec. P.837-1 zone	Duration (years)	Data type
Spino d'Adda	Italy	45.46	9.56	K	9	Rain gauge time series
Rome	Italy	41.87	12.48	K	8	Rain gauge time series
Miami	USA	25.65	-80.43	N	40	1-m and 1-h $P(R)$ s
Chicago	USA	41.9	-87.65	K	40	1-m and 1-h $P(R)$ s
Sendai	Japan	38.27	140.87	K	9	1-m and 1-h $P(R)$ s
Kuala Lumpur	Malaysia	3.16	101.71	P	3	1-m and 1-h $P(R)$ s
Rio de Janeiro	Brazil	-22.92	-43.5	N	10	1-m and 1-h $P(R)$ s
Madrid	Spain	40.45	-3.7	H	5	1-m and 1-h $P(R)$ s
Prague	Czech Rep.	50.1	14.44	H	5	Rain gauge time series
Montreal	Canada	45.52	-73.57	K	10	Rain gauge time series
California	USA	40.87	123.94	K	2	Rain gauge time series
LBA	Brazil	-10.35	-62.58	P	1	Rain gauge time series
Houston	USA	29.77	-95.73	M	8	Rain gauge time series
Kwajalein	Marshall Islands	8.79	167.62	N	8	Rain gauge time series
Florida	USA	28.34	-80.93	N	8	Rain gauge time

						series
Chorrillos	Colombia	6.3	-75.51	N	4	Rain gauge time series
S. Antonio de Prado	Colombia	6.19	-75.66	N	4	Rain gauge time series
S. Cristobal	Colombia	6.26	-75.55	N	4	Rain gauge time series
Girardota	Colombia	6.28	-75.64	N	4	Rain gauge time series
Ayurá	Colombia	6.39	-75.46	N	4	Rain gauge time series
Manantiales	Colombia	6.17	-75.57	N	4	Rain gauge time series
Cucaracho	Colombia	6.32	-75.54	N	4	Rain gauge time series
Convento	Colombia	6.29	-75.61	N	4	Rain gauge time series
Pedregal	Colombia	6.34	-75.52	N	4	Rain gauge time series
Gerona	Colombia	6.31	-75.58	N	4	Rain gauge time series

Table 4: mean, STD and RMS values of $\varepsilon(P)$ for the selected sites. Comparison between the ITU-R Rec. P.837-4, the conversion method with the first guess $P(R)_1$ extracted both from the ITU-R Rec. P.837-4 (labeled SF Rec. 837-4) and from the ITU-R Rec. P.837-1 (labeled SF Rec. 837-1)

Location	Mean value of $\varepsilon(P)$ (%)			STD value of $\varepsilon(P)$ (%)			RMS value of $\varepsilon(P)$ (%)		
	ITU-R P.837-4	SF Rec. 837-4	SF Rec. 837-1	ITU-R P.837-4	SF Rec. 837-4	SF Rec. 837-1	ITU-R P.837-4	SF Rec. 837-4	SF Rec. 837-1
Spino d'Adda	-16.83	3.41	15.69	7.63	6.90	12.98	18.48	7.70	20.36

Rome	-30.83	-5.19	-3.12	10.49	10.14	8.91	32.57	11.39	9.44
Miami	-22.38	2.82	-3.95	6.41	9.54	9.69	23.28	9.95	10.46
Chicago	-22.84	8.65	-0.309	12.35	4.59	5.57	25.96	9.79	5.57
Sendai	-25.12	-14.85	-22.73	14.32	10.01	8.61	28.92	17.91	24.31
Kuala Lumpur	-25.97	-6.95	0.29	12.23	6.38	3.83	28.71	9.43	3.84
Rio de Janeiro	-29.74	-25.57	-22.89	2.62	6.05	7.52	29.85	26.28	24.10
Madrid	-8.06	-9.02	16.35	0.82	12.57	8.42	8.10	15.47	18.39
Prague	23.84	-4.36	26.18	37.33	9.99	12.80	44.29	10.91	29.14
Montreal	34.02	25.27	14.91	59.79	26.48	24.53	68.79	36.60	28.70
California	-30.36	-7.03	-6.40	23.30	16.11	17.77	38.27	17.58	18.89
LBA	28.07	24.01	24.74	38.52	24.52	24.51	47.66	34.32	34.83
Houston	-26.14	9.88	-0.08	10.68	12.26	15.31	28.24	15.74	15.31
Kwajalein	86.34	-2.74	-17.04	30.34	14.15	8.79	91.51	14.42	19.17
Florida	-0.28	8.93	-1.06	2.55	6.42	22.33	2.56	10.99	22.36
Chorrillos	88.58	-2.79	-8.36	16.92	18.01	8.25	90.18	18.23	11.74
Girardota	134.10	-5.13	-10.59	15.50	5.81	9.82	134.99	7.75	14.44
Total	9.2	-0.04	0.09	17.75	11.76	12.33	43.67	16.14	18.30

Table 5: mean, STD and RMS values of $\varepsilon(P)$ for the Colombian sites.
Comparison between the ITU-R Rec. P.837-4 and the conversion method with first guess $P(R)_1$ extracted from the ITU-R Rec. P.837-4 (SF Rec. 837-4)

Location	Mean value of $\varepsilon(P)$ (%)		STD value of $\varepsilon(P)$ (%)		RMS value of $\varepsilon(P)$ (%)	
	ITU-R	SF Rec.	ITU-R	SF Rec.	ITU-R	SF Rec.
	P.837-4	837-4	P.837-4	837-4	P.837-4	837-4
Chorrillos	88.58	-2.79	16.92	18.01	90.18	18.23
S. Antonio de Prado	54.63	-9.42	6.18	9.86	54.98	13.64

S. Cristobal	107.95	-3.69	22.09	14.74	110.19	15.19
Girardota	134.10	-5.13	15.50	5.81	134.99	7.75
Ayurá	96.90	4.46	16.07	18.73	98.22	19.25
Manantiales	122.68	-3.58	23.56	6.68	124.93	7.58
Cucaracho	91.00	4.40	21.19	11.52	93.44	12.33
Convento	122.82	5.70	29.14	7.98	126.23	9.81
Pedregal	114.58	3.84	22.14	11.24	116.70	11.88
Gerona	100.55	0.76	25.15	13.41	103.65	13.44
Total	103.34	-0.55	19.74	11.80	105.35	12.91

Table 6: mean, STD and RMS values of $\varepsilon(P)$ for the yearly data in Spino d'Adda. Comparison between the ITU-R Rec. P.837-4 and the conversion method with first guess $P(R)_1$ extracted from the ITU-R Rec. P.837-4 (SF Rec. 837-4)

Year of the Spino d'Adda database	Mean value of $\varepsilon(P)$ (%)		STD value of $\varepsilon(P)$ (%)		RMS value of $\varepsilon(P)$ (%)	
	ITU-R	SF Rec.	ITU-R	SF Rec.	ITU-R	SF Rec.
	P.837-4	837-4	P.837-4	837-4	P.837-4	837-4
1993	-23.96	-3.44	8.64	6.79	25.47	7.61
1994	-19.94	7.09	2.39	7.05	20.09	10.00
1995	-21.43	9.48	20.14	12.30	29.41	15.53
1996	-20.99	-0.97	5.10	6.92	21.60	6.99
1997	0.68	10.58	7.38	17.13	7.41	20.13
1998	44.49	2.40	7.06	4.74	45.05	5.31
1999	-20.22	-5.88	4.79	13.08	20.78	14.34
Total	-8.77	2.75	7.93	9.72	24.26	11.42

Figures:

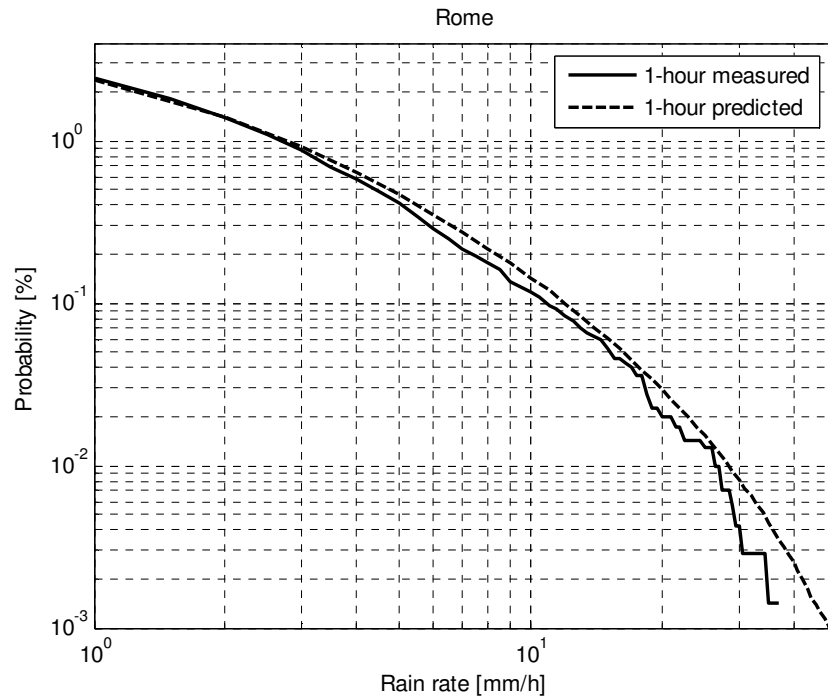


Figure 1: comparison between the measured $P(R)_{60}$ (bold line) and the one estimated from the measured $P(R)_1$ (dashed line). Data are relative to Rome

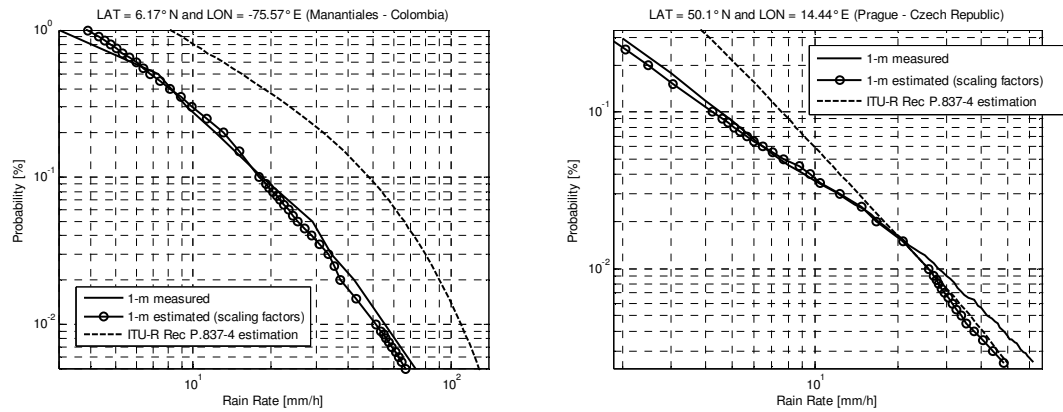


Figure 2: application of the proposed conversion method with the $P(R)_1$ provided by the ITU-R Rec. P.837-4 as first guess: data relative to Manantiales (Colombia, rain zone N) and Prague (Czech Republic, rain zone H)

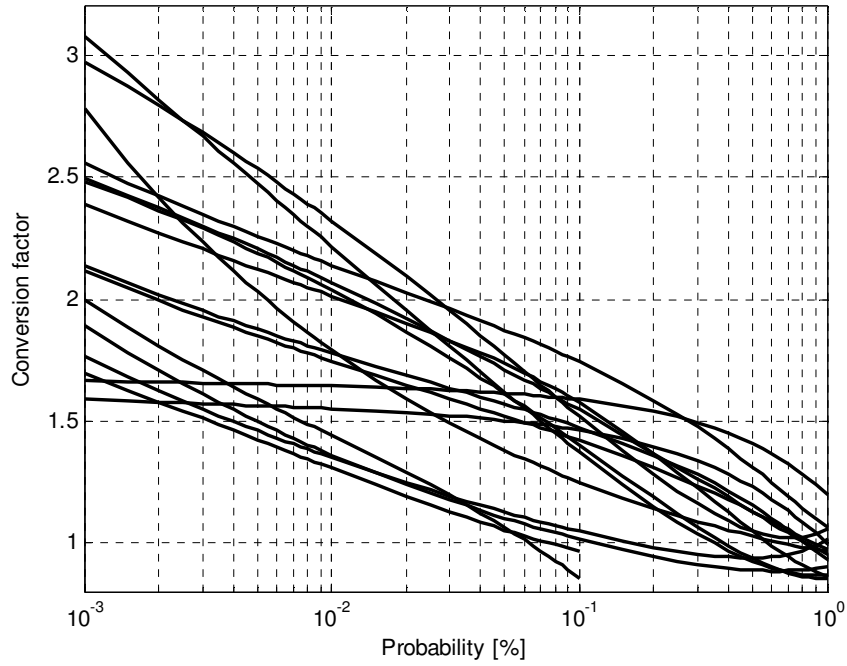


Figure 3: trend with probability of the conversion factor $\rho_{60}(P) = R_1(P)/R_{60}(P)$ for the 15 rain zones defined in the ITU-R Rec. P.837-1

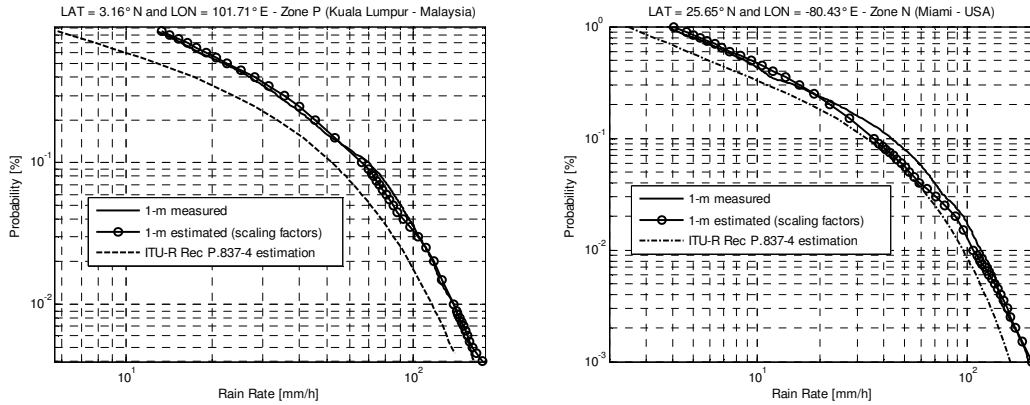


Figure 4: application of the proposed conversion method with the $P(R)_1$ provided by the ITU-R Rec. P.837-1 as first guess (coefficients of equation 8 derived from Table 2): data relative to Kuala Lumpur (Malaysia, rain zone P) and Miami (USA, rain zone N)

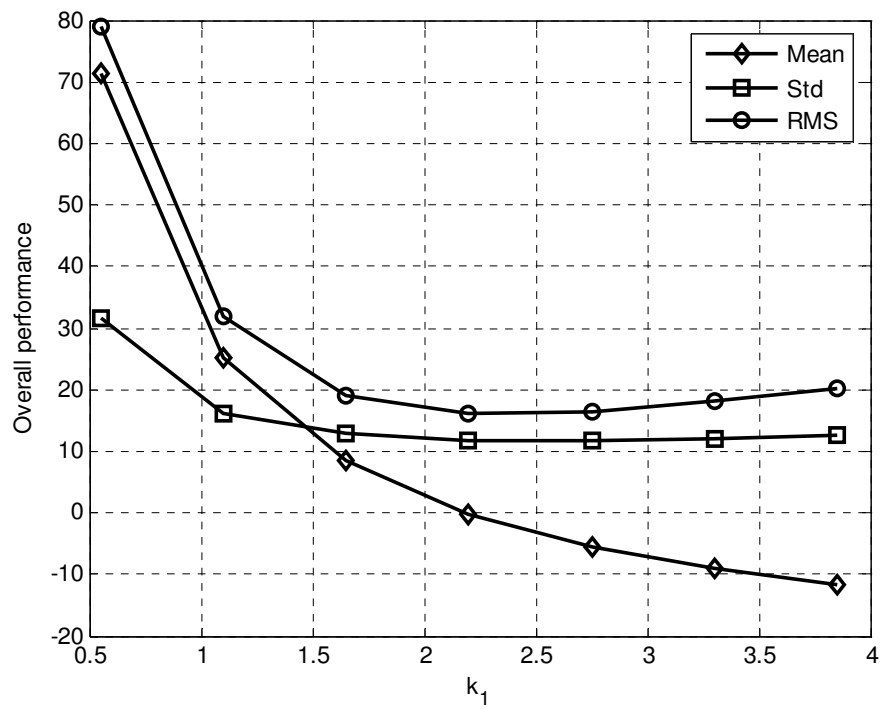


Figure 5: plot of the mean, standard deviation and RMS values of the estimation error for $k_1(60)$ equal to 0.55, 1.1, 1.65, 2.2, 2.75, 3.3 and 3.85. $k_1(60) = 2.2$ provides the lowest RMS value

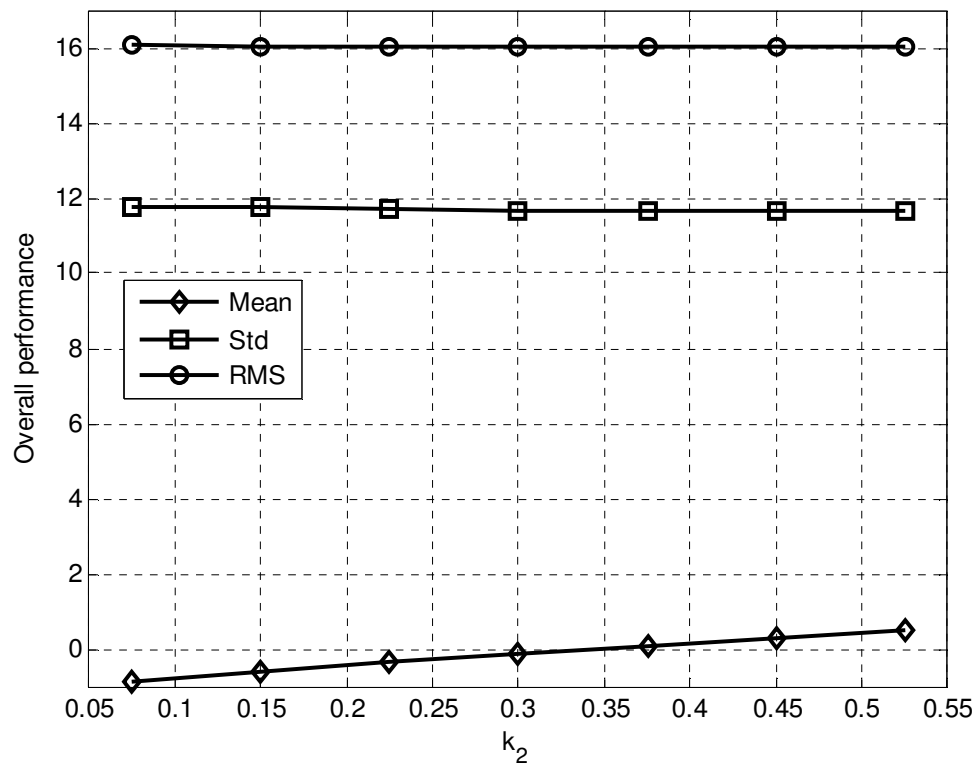


Figure 6: plot of the mean, standard deviation and RMS values of the estimation error for $k_2(60)$ equal to 0.075, 0.15, 0.225, 0.3, 0.375, 0.45 and 0.525. $k_2(60) = 0.3$ provides the lowest RMS value