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Identification of dry and rainy periods using telecommunciation microwave links

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1 INTRODUCTION

A microwave link consists of a transmitter communicating with a receiver through a microwave signal. Such links are widely used for data exchange between base stations of mobile phone networks. Because of the range of frequencies (roughly 15 to 50 GHz) used for data transmission, the link signal is attenuated when rainfall occurs along the link path. Working with operational telecommunication microwave links, Messer et al. (2006) and Leijnse et al. (2007) have shown that the path-integrated rain rate can be estimated from such attenuation measurements. A critical issue in this approach is the ability to distinguish the attenuation due to rainfall from the attenuation occurring during dry periods (referred to as the attenuation baseline). The difficulty lies in the fact that the attenuation baseline is not constant over time and fluctuates due to changes in water vapor concentration, temperature, wind effects on the antenna, losses during transmission and reception, interferences and possible multipath effects. Moreover, attenuation measurements are rounded (usually at 1 dBm) which results in additional uncertainty and makes it very difficult to distinguish noise from light rain.

Using dual-frequency links specifically designed for rainfall estimation, Rahimi et al. (2003) and Holt et al. (2003) proposed to identify dry and rainy periods using the correlation between the link signals at 2 different frequencies. Following the same idea, Goldshtein et al. (2009) proposed to identify dry and rainy periods using the correlation between local and remote signals (each antenna acting both as a transmitter and a receiver). For dual-polarization links, Ruf et al. (1996) and Aydin and Daisley (2002) showed that the attenuation baseline can be removed by considering the difference of attenuation between the two polarizations. Unfortunately, many operational telecommunication microwave links only use single-polarization signals and the frequencies of local and remote signals are often too close (about 1 GHz apart) for dual-frequency considerations.

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In this paper, we propose a method to identify and separate dry from rainy periods and fit a time-varying attenuation baseline using attenuation measurements from single-polarization and single-frequency telecommunication microwave links. This wet/dry information nicely complements data from rain gauge and radar networks, and can be useful for many applications in agriculture, road-traffic management and outdoor activities.

2 Data

Measurements of instantaneous transmitted and received power, expressed in dBm, from 3 operational telecommunication links are provided by Bouygues Telecom, a French telecommunication company. The length, frequency and polarization of each link are given in Table 1. Note that link 13 and 14 are dual-polarization links, but only the horizontal polarization has been used in this study. The attenuation along the link path is obtained by subtracting the received power to the transmitted one (in dBm). The sampling resolution is 30 s from May to August 2008 and 6 s since January 2009. All power measurements are rounded at 1 dBm.

Table 1: Length [km], frequency [GHz] and polarization of the considered telecommunication microwave links.

Link	Length	Frequency	Polarization
1	3.7	26	V
13	7.1	19	H/V
14	2.4	26	H/V

Ten rain events of various intensities and durations have been selected and are considered as representative of the local rainfall climatology. The dates, durations, rain amounts and maximum rain rates (as estimated by a near-by C-band weather radar) of these events are given in Table 2. The selected events represent about 90 h of rain and about 150 mm of rain amount.

The performance of the proposed method is investigated by comparing the link estimates with independent radar rain-rate maps provided by Météo France. The radar rain-rate maps have a spatial resolution of 1×1 km^2 and temporal resolution of 5 min.

They are derived from measurements of an operational C-band weather radar located in Trappes, about 20-30 km from the links. All rain rate maps are obtained by combining different scans at different elevation angles using a technique described in Tabary (2007) which corrects for the main sources of error (e.g., ground clutter, beam blocking, vertical variability and advection).

Since microwave links provide path-integrated measurements, the corresponding radar path-averaged rain-rate values are calculated by averaging the radar pixels crossed by the link beam with weights given by the length of the link in each pixel.

Table 2: Date, duration [h], rain amount [mm] and maximum rain-rate [mmh^{-1}] of the considered events.

No.	Date	Duration	Amount	R_{max}
1	27-28 May 08	8	40	60
2	22 Aug 08	23	25	20
3	18 Jan 09	10	12.5	10
4	27 Apr 09	7	11.5	5.5
5	29 Apr 09	3	10	18
6	25-26 May 09	1.5	5	12
7	06-07 Jun 09	2	1.5	2.5
8	07 Jun 09	2	3.5	12.5
9	09-10 Jun 09	16	18.5	12.5
10	10-11 Jun 09	15	21.5	20

3 Method

Figure 1 shows the raw attenuation measurements recorded on 22 August 2008 by link 14 (2.4 km and 26 GHz). Rainy periods are clearly characterized by a local increase of the signal attenuation (e.g., between 17:00 and 18:00 GMT). It is also important to note the significant (54-56 dB) and time-varying attenuation of the signal during dry periods. This variability must be taken into account when trying to separate dry from rainy periods.

Let $A(t)$ be the total attenuation affecting a given link at time t. Because of the variability affecting the link signal and because all measurements are instantaneous, $A(t)$ can be seen as a random variable rather than a deterministic quantity. Furthermore, let us suppose that $A(t)$ can be expressed as:

$$A(t) = A_B(t) + A_R(t) \tag{1}$$

where $A_B(t) = a_b(t) + \varepsilon_B(t)$ represents the attenuation baseline and $A_R(t) = a_r(t) + \varepsilon_R(t)$ the attenuation caused by rainfall. The variables $a_b(t) = \mathrm{E}[A_B(t)]$ and $a_r(t) = \mathrm{E}[A_R(t)]$ represent respectively the deterministic parts of the attenuation

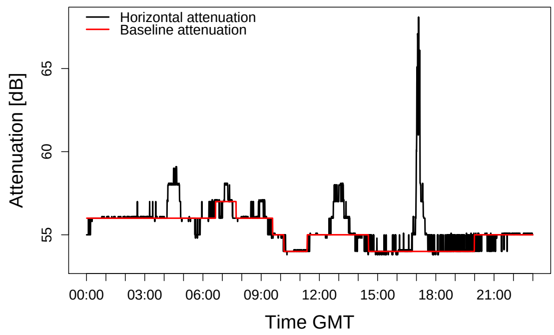

Figure 1: Attenuation measurements and attenuation baseline for link 14 during rain event 2 (22 Aug. 08).

baseline and of the attenuation caused by rainfall. The local variances $\sigma_B^2(t) = \mathrm{Var}[A_B(t)]$ and $\sigma_R^2(t) = \mathrm{Var}[A_R(t)]$ are supposed to be finite. For dry periods we set $a_r(t) = 0$ and $\sigma_R^2(t) = 0$. Furthermore, we assume that $\varepsilon_B(t)$ and $\varepsilon_R(t)$ are independent with zero mean and zero autocorrelation. Hence

$$\mathrm{Var}[A(t)] = \sigma_B(t)^2 + \sigma_R(t)^2.$$

For a moving time window $W_t = [t-w, t]$ of duration $w > 0$, we define

$$\bar{A}_{W_t} = \frac{1}{N_W} \sum_{k \in W_t} A(k) \tag{2}$$

$$S_{W_t}^2 = \frac{1}{N_W} \sum_{k \in W_t} \left(A(k) - \bar{A}_{W_t}\right)^2 \tag{3}$$

where N_W represents the number of measurements in W_t. The proposed method to separate dry from rainy periods is based on the assumption that during dry periods, the local standard deviation S_{W_t} is bounded by some constant value that does not change with time and only depends on the physical characteristics (frequency, length, type of antenna,...) of the considered link. On the other hand, periods with higher values of S_{W_t} are more likely to be rainy periods. Indeed, for dry periods with $a_r(k) = 0 \ \forall k \in W_t$, one can show that

$$\mathrm{E}[S_{W_t}^2] = C < \sigma_B^2 > + < a_b^2 > - < a_b >^2 \tag{4}$$

where $<>$ denotes the arithmetic mean over W_t and $C = (N_W - 1)/Nw$. On the other hand, rainy periods are characterized by

$$\mathrm{E}[S_{W_t}^2] = C < \sigma_B^2 + \sigma_R^2 > + < (a_b + a_r)^2 > - < a_b + a_r >^2 \tag{5}$$

which tends to be higher than during dry periods because of the additional variability resulting from $a_r(t)$ and $\sigma_R^2(t)$.

This leads to a simple decision rule given by:

$$\text{Decision rule: } \begin{cases} \text{rain if } S_{W_t} > \sigma_0 \\ \text{dry if } S_{W_t} \leq \sigma_0 \end{cases} \quad (6)$$

for a given threshold σ_0 that has to be estimated from the link data.

The threshold value σ_0 determines the performance of the algorithm with respect to the percentage of true and false rain/dry detections. However, there is also a physical limitation in the detection process which depends on the variability of the baseline. In particular, equations (4) and (5) show that dry periods with a highly variable baseline cannot be distinguished from periods of light rainfall because both exhibit a similar variability.

The value of σ_0 can be estimated by considering the attenuation measurements collected during an extended dry period (typically 24 h). If D denotes this dry period, a possible value for σ_0 is given by:

$$\sigma_0 = q_{99}\{\, S_{W_t} |\ t \in D \,\}, \quad (7)$$

where q_{99} denotes the 99% quantile. This choice of σ_0 is preferred to the maximum because it limits the effect of outliers and link failures. Combining several dry periods is recommended for more robustness since one single dry day may not adequately represent all the variability affecting the link signal during dry periods. Note also that for short links, most of the variability occurring during dry periods is due to the 1 dBm rounding in the attenuation measurements. In this particular case, $\sigma_0 = 0.5$ dBm.

The choice of the window size w is a delicate tradeoff which depends on the natural variability of rainfall. For small values of w, the algorithm tends to be less efficient because of the higher probability of having nearly constant rainfall during short periods of time. In this case, the variability of the rain signal is too small compared to the variability of the baseline. Larger time windows do not have this limitation because it is very unlikely to have very regular rainfall over extended periods of time. On the other hand, w should not be chosen too large since it determines the shortest dry period that can be identified using this algorithm. In practice, time windows between 15 min and 35 min adequately represent the dynamics of rainfall. In particular, a 25-min time window has been chosen for the evaluation in Section 4.

Once w has been chosen and σ_0 estimated, the previously described decision rule can be applied to the entire data set to identify dry (D) and rainy time periods (R). The attenuation baseline $B(t)$ can then be estimated in real-time using the following algorithm:

(1) For each time index $t \in D$, set $A_B(t) = \bar{A}_{W_t}$.

(2) For each $t \in R$, set $A_B(t) = A_B(t - k)$ where k is the smallest value such that $t - k \in D$.

Finally, the baseline is used as a reference to remove all rain detections for which the attenuation is below the baseline. This is a necessary step in the procedure because the proposed decision rule cannot distinguish between strongly increasing and decreasing attenuation signals (e.g., Figure 1 from 09:00 to 10:00 GMT).

4 Application

In this section, the performance of the proposed method is evaluated using 3 different microwave links and 10 different rain events between May 2008 and June 2009 (see Section 2). Independent radar rain-rate maps provided by Météo France are used to validate the classification into dry and rainy periods obtained with the links. These maps are used to separate dry from rainy periods and to quantify the total amount of rain identified by the links. Note that the comparison between link and radar measurements cannot be perfect because of the different sampling volumes, altitudes and resolutions.

For comparison with radar estimates, a 5-min time step is considered rainy if at least one link measurement during this period is identified as rainy. Otherwise, the period is considered dry.

After several tests, the authors decided to compute S_{W_t} using a 25-min moving time window (see Section 3) which enables to catch most of the dynamics of rainfall as well as the variations in the attenuation baseline. The corresponding rain detection thresholds σ_0 as described in Section 3 are 0.53 (link 1), 0.55 (link 13) and 0.50 (link 14). These threshold were computed using three different dry days (23 August 2008, 21 January 2009 and 16 April 2009).

In order to quantify the performance of the algorithm, 5 different criteria are used: (1) the percentage of correct rain detections during rainy periods, (2) the percentage of correct dry detections during dry periods, (3) the percentage of type I errors (rain detections during dry periods), (4) the percentage of type II errors (dry detections during rainy periods) and (5) the detected rain amount assuming the rain-rate estimates from the links are identical to the radar rain-rate estimates. While the first 4 criteria define the contingency table between the link estimates and the radar data, criterion 5 is important for hydrological applications for which the total rain amount plays a major role.

Finally, the proposed algorithm is compared to an alternative method proposed by Leijnse et al. (2007). In this method, the attenuation baseline is assumed constant and equal to the mode (the most observed value) of all attenuation measurements. All periods for which the attenuation exceeds the mode are considered rainy. The rest is considered dry.

Figure 2 shows the performance for criteria 1-4 for both the proposed method and the fixed "mode" baseline. The results show that, on average, during rainy periods, the new algorithm identified 91% to 94% of all rainy periods with worst-case performance about 75% (link 13 event 8). On the other hand, the fixed "mode" baseline only identified 68 % to 83 % of all rainy periods on average with worst-case performance down to 40 % (link 13 event 2).

During dry periods, the proposed algorithm identified on average 81 % to 93 % of all dry periods with worst-case performance about 67 % (link 1 event 1). This is better than the fixed "mode" baseline which identified only 67% to 83% on average with worst-case performance about 14% (link 13 event 7).

The percentage of type I errors (rain detection during dry periods) for the new method is between 6 % and 17 % on average with worst case performance up to 27 % (link 1 event 8). For the fixed "mode" baseline, the type I errors are between 15% and 33% on average with worst case performance up to 83 % (link 13 event 7).

The percentage of type II errors (dry detection during rainy periods) for the new method is between 6 % and 9 % on average with worst case performance up to 24% (link 1 event 9). For the fixed "mode" baseline, the percentage of type II error is between 21 % and 42 % with worst case performance up to 59 % (link 13 event 5).

Although the proposed algorithm is not perfect, it significantly reduces the error (both type I and II) compared to the fixed "mode" baseline. Also, the variability of the error is much lower than for the "mode" method. The algorithm obviously performs best for links at high frequencies during intense rain events and worst during light rainfall. Furthermore, the performance of the proposed algorithm depends both on the length and the frequency of the considered link. Longer links tend to produce less reliable results because their attenuation baseline exhibits more variability. Links at higher frequencies are more sensitive to rainfall but also exhibit more variability during dry periods.

Finally the proposed algorithm detected about 98 % of the total rain amount on average with worst case performance of 83 %, meaning that most of the high rainfall intensities are captured by the algorithm. For comparison, the fixed "mode" baseline only detected 95 % of the total rain amount on average with worst case performance of 76 %.

5 Summary and conclusions

Telecommunication microwave links can be used for rainfall estimation. A critical issue in this procedure is the ability to separate the attenuation during dry periods from the attenuation due to rainfall. In particular, this requires to identify and separate dry from rainy periods.

In this paper, we proposed a simple method to identify dry and rainy periods and fit a time-varying attenuation baseline. The proposed method can be applied in real-time on a single-polarization single-frequency link and does not require any additional data for calibration. Rain identification is performed by analyzing the local variability of the link signal. The attenuation baseline is estimated using the classification into dry and wet periods.

The main limitation of the proposed method is its inability to identify changes in the attenuation baseline during rainy periods. Also, the 1 dBm power resolution in the attenuation measurements makes it difficult to separate light rain from noise.

Future work will mainly focus on the analysis of the intermittency as seen by microwave links at high sampling resolution and on the seasonal variability in the link signal during dry periods.

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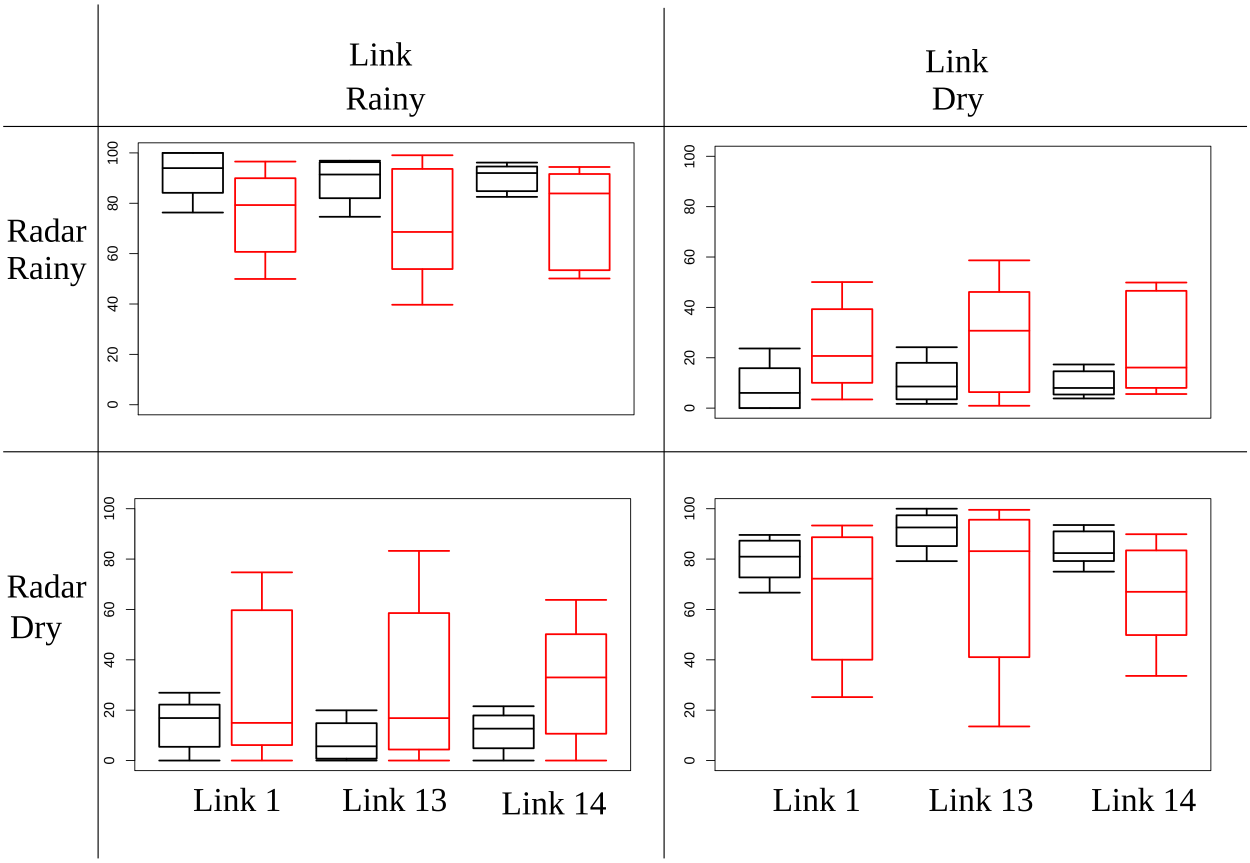

Figure 2: Performance evaluation for all links and all rain events. Black box-plots represent the performance of the new algorithm. Red box-plots represent the performance of the fixed “mode” baseline method. Each box-plot represents the minimum, 25% quantile, average value, 75 % quantile and maximum over all 10 rain events.