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Key Points:

- Quantifying convective rainfall in Sahel from a 7 GHz/29 km commercial link
- Excellent agreement between microwave link estimate and rain gauge
- Cost-effective method for monitoring rainfall in observation-poor tropics

Correspondence to:
M. Gosset,
marielle.gosset@ird.fr

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Rainfall monitoring based on microwave links from cellular telecommunication networks: First results from a West African test bed

Ali Doumounia[1], Marielle Gosset[2], Frederic Cazenave[3], Modeste Kacou[2,4], and François Zougmore[1]

[1]Laboratoire de Matériaux et Environnement/UFR-S.E.A, Université de Ouagadougou, Ouagadougou, Burkina Faso, [2]Geoscience Environnement Toulouse, GET (UMR 5563 CNRS, IRD, UTIII), Observatoire Midi-Pyrénées, Toulouse, France, [3]LTHE (IRD, Université Grenoble Alpes, CNRS), Grenoble, France, [4]Laboratoire de Physique de l'Atmosphère et de Mécanique des Fluides, Université Félix Houphouet-Boigny, Yamoussoukro, Côte d'Ivoire

Abstract Rainfall monitoring based on commercial terrestrial microwave links is tested for the first time in Burkina Faso, in Sahelian West Africa. In collaboration with one national cellular phone operator, Telecel Faso, the attenuation on a 29 km long microwave link operating at 7 GHz was monitored at 1 s time rate for the monsoon season 2012. The time series of attenuation is transformed into rain rates and compared with rain gauge data. The method is successful in quantifying rainfall: 95% of the rainy days are detected. The correlation with the daily rain gauge series is 0.8, and the season bias is 6%. The correlation at the 5 min time step within each event is also high. These results demonstrate the potential interest of exploiting national and regional wireless telecommunication networks for monitoring rainfall in Africa, where operational rain gauge networks are degrading and the hydrometeorological risk increasing.

1. Context and Objectives

Rainfall monitoring in Africa is an issue for many operational and research applications. In Sahel, droughts and floods are a threat to the economy and the population. There are hints that these extreme events may be increasing with a changing climate and a possible intensification of rainfall that need to be confirmed with accurate rainfall measurements. In addition, the population growth and rapid land use changes are increasing hydrometeorological risk, especially in urban areas. Precipitation needs to be accurately measured with high spatial and temporal resolution to study and monitor this changing risk. But the operational ground network is sparse and globally degrading in West Africa. Weather radar data are not available operationally, and the prospects for developing an operational radar network in Sahelian Africa are low. Despite a net improvement since the Tropical Rainfall Measuring Mission program and more to be expected from the Global Precipitation Measurement constellation, the satellite rainfall estimates are still imperfect. Biases remain, especially for real-time and high-resolution products, and ground measurements are still useful to adjust or to downscale satellite estimates.

Microwave links have been proposed as an alternative means for measuring rainfall [*Messer et al.*, 2006; *Overeem et al.*, 2011; *Zinevich et al.*, 2008]. The principle is to exploit the attenuating properties of rainfall in the microwave frequencies: the loss of signal due to rainfall attenuation along the link is quantified and used to retrieve the path-average rainfall over the link. The method can be applied to commercial links (telecommunication networks) as well as dedicated links. Several studies have demonstrated that rainfall maps could be derived based on this principle using cellular telephone networks [*Zinevich et al.*, 2008; *Overeem et al.*, 2013]. The accuracy of the rain maps depends on the network density, length of links and operating frequency, and on the temporal sampling and accuracy of the attenuation information [*Zinevich et al.*, 2010; *Leijnse et al.*, 2008, 2010]. The method has proven to be useful to complement gauge and radar networks in many European countries [*Overeem et al.*, 2013; *Schleiss and Berne*, 2010] and in Israel [*Messer et al.*, 2006; *Zinevich et al.*, 2008].

In African countries where the need for rainfall monitoring is high, while the operational network is degrading and simultaneously the cellular phone network is developing rapidly, rainfall measurement based on cellular networks is an extremely attractive prospect [*Hoedjes et al.*, 2014]. On the other hand, because of the relatively low frequency and long length of the terrestrial links encountered in Africa, the uncertainty in the microwave-link-based rainfall estimates is expected to be higher than for the higher frequency/shorter links found in Europe or Israel [*Zinevich et al.*, 2010; *Leijnse et al.*, 2008, 2010]. This paper presents the first quantitative evaluation of rainfall estimation based on a commercial link in West Africa. The work benefited from a collaboration between the Indo-French Megha-Tropiques Mission Ground Validation program (http://meghatropiques.ipsl.polytechnique.fr/), the Burkinabé Telecel Company, the University of Ouagadougou, and the Institut de Recherche pour le Developpement (IRD). A test bed has been set up to evaluate rainfall estimation from a cellular microwave link in Ouagadougou, Burkina Faso. During the monsoon season 2012, the data from one Telecel link were compared with a tipping bucket rain gauge, allowing the evaluation of the rainfall time series down to a 5 min time interval. The results are presented below.

2. Data and Method

Figure 1 presents the study region and the instrumental setup. The test bed is deployed around the city of Ouagadougou in Burkina Faso. The rainfall regime is typical of the southern Sahel, with 800 mm/yr on average. As in the rest of the region, the annual rainfall is explained mostly by organized mesoscale convective systems. Within these systems, 75 to 80% of the rainfall is due to relatively short-lasting (about an hour) convective fronts characterized by medium to heavy rain rates; the convective fronts are followed by longer-lasting stratiform trails with intensities below 10–15 mm/h [*Moumouni et al.*, 2008, and references therein].

The Ouagadougou instrumented site was initiated as part of the Megha-Tropiques satellite mission Ground Validation (MTGV) program (http://meghatropiques.ipsl.polytechnique.fr/). This MTGV West African supersite hosts a polarimetric radar and a network of 17 tipping bucket gauges since 2012. In addition to the satellite validation activities, it was decided to take advantage of the setup and the scientific interest of local partners to test other innovative methods for measuring rainfall. A collaboration started between the MTGV teams (funded by the French national space agency Centre National d'Etudes Spatiales and IRD), the University of Ouagadougou, the meteorological services, and the Telecel Faso cellular communication operator. The operator has agreed to provide the attenuation information for the three links that are displayed inside the purple circle in Figure 1; however, due to some technical problems with the initial data set, only one link could be exploited quantitatively for the 2012 monsoon season. This link, named "Korsimoro-Kaya," is indicated by the red ellipse in Figure 1. The tipping bucket rain gauge of "Boussouma" is located along the link.

The Korsimoro-Kaya link is 29 km long, and the operating frequency is 7 Ghz (one single horizontal polarization). The transmitted and received signals are recorded every second with a precision of 1 dB increment. The tipping bucket system records rainfall with a 0.5 mm increment. Both link and gauge information are processed to produce time series with a regular time interval of 5 min.

An example of the time series for the period 1 July to 10 August 2012 is displayed in Figure 2.

As discussed by previous authors [*Overeem et al.*, 2011, and numerous references therein], two delicate steps are necessary to convert the raw information from the microwave link into rainfall estimates with sufficient accuracy: (i) the path integrated attenuation (in dB) attributable to rain along the link must be extracted from the raw signal and (ii) the attenuation must be converted into an average rain rate along the link.

2.1. Extraction of Path Attenuation Along the Link

Attenuation by rain is not the only source of variation in the received signal. Depending on the operating frequencies, drops in the received signal can be due to changes in the air refractivity, dust, or technical problems such as antenna misalignment. Another source of attenuation is the water film that may deposit on the antennas during rainfall and can increase the apparent attenuation due to rain along the link [*Zinevich et al.*, 2010; *Leijnse et al.*, 2008]. This is not explicitly accounted for in the present work.

The so-called *baseline level*, from which attenuation due to rain can be subtracted, is therefore a time-varying signal and must be determined. After several sensitivity tests, the method recommended by *Schleiss and Berne* [2010], or "moving window variance method," was adopted and applied to 5 min time series. It consists in separating the *dry* periods from the *wet* periods on the basis of the signal (temporal) variance. When rainfall is present along the link, the signal drops rapidly due to rainfall attenuation, and the variance is higher than during the dry period. The baseline level for the dry periods is calculated from this principle, based on the 1 h long dry period that preceded the rainy period. The attenuation due to rain is then calculated as the

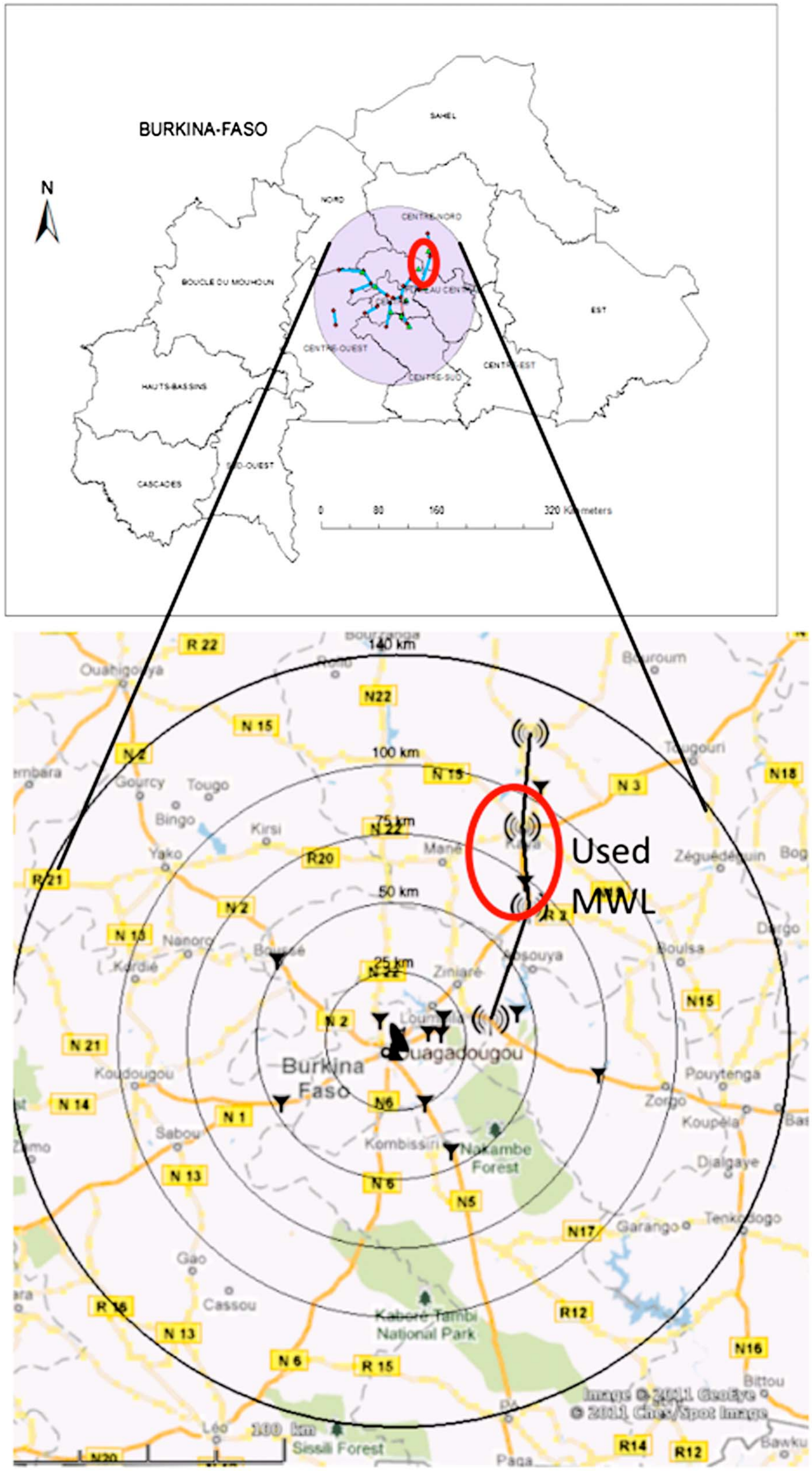

Figure 1. Location of the study area in Burkina Faso and instrumental setup. The red ellipse shows the Korsimoro-Kaya link and the Boussouma rain gauge used for this study. The purple circle and the blue segments are for the *X* band radar and link network that will be available for the analysis of the 2013 season.

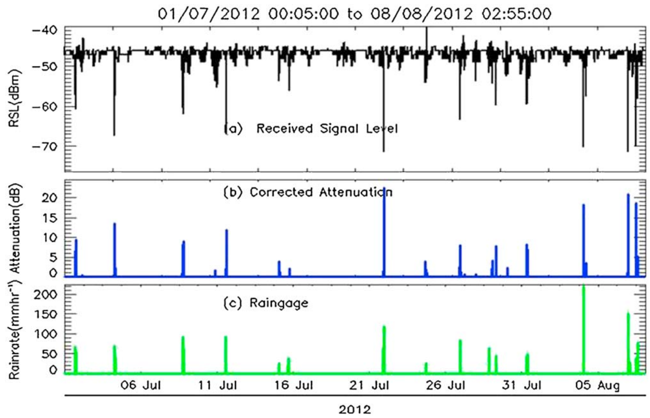

Figure 2. (a) Received minus transmitted raw microwave signal level. (b) Path attenuation due to rain. (c) Rain rate time series from the gauge situated below the link.

difference between the received signal and the baseline. The result is illustrated for the July–August time series in Figure 2, with the raw received signal in Figure 2a and the attenuation by rain itself in Figure 2b.

2.2. Conversion of Path Attenuation Into Rainfall Rate

The conversion from attenuation to rainfall is based on the power law relationship between the specific attenuation *A* (dB/km) and the rain rate *R* (mm/h):

$$A = a\,R^b \tag{1}$$

The prefactor *a* and exponent *b* depend on the microwave frequency and on the raindrop size distribution along the path. Drop size distribution data gathered during the African Monsoon Multidisciplinary Analyses (AMMA) campaign [*Moumouni et al.*, 2008] and a Mie scattering code were used to study the *A*-*R* relationship for West African convective systems, a temperature of 26°C and a frequency of 7 Ghz; with these assumptions, equation (1) becomes

$$A = 0.000159\,R^{1.827} \tag{2}$$

The microwave link provides the path integrated attenuation (PIA), which is the integral of the specific attenuation *A* along a path of length *L*. The averaged rainfall rate $<R>$ along the link can be deduced from

$$< R > = [(\mathrm{PIA}/L)/a']^{(1/b')} \tag{3}$$

Unless the rainfall is uniformly distributed along the link, or the exponent *b* is equal to 1, *a*′, *b*′ in equation (3) are different from *a*,*b* in equation (1). Because at 7 GHz the *A*-*R* relationship is far from linear (equation (2)) and due to the relatively long length of the link, these rainfall variability-induced effects are expected to be noticeable [*Leijnse et al.*, 2010]. High-resolution radar data were used to study the variability of the rainfall along the link and the relationship between the PIA and the path average rain rate, assuming that equation (2) is valid at the point scale. The corresponding values of *a*′, *b*′ is 0.000197, 1.854, thus a 25% increase in the prefactor. The results presented hereafter are based on these values.

With the values of *a*′,*b*′ above and a link length of 29 km, an increment of 1 dB is equivalent to a rainfall rate of about 16 mm/h. The imprecision in the rain retrieval due the quantization increment decreases to 2 mm/h and below for rain rates above 50 mm/h. Despite the high detection threshold due to the relatively low frequency of the link and because of the convective nature of rainfall in Sahel, the detection of rainfall over the Korsimoro-Kaya link was very successful in 2012. Indeed, Figures 2b and 2c illustrate that the attenuation measured by the link and the time series of rainfall measured by the gauges are in very good agreement at the daily time step. Quantitative details are given in the next section.

Table 1. Daily Rainfall Detection Statistics for the Period 27 June 2012 to 04 September 2012 (No Measurement From 9 to 20 August)

	Total Rainfall (mm)			Number of Rainy Days			
Threshold	Gauge	Link	Bias (%)	Gauge	Link	Probability of Detection	FAR
0 mm/d	609	645	6%	31	20	70%	5%
3.5 mm/d	600	645	7%	22	20	91%	5%
5 mm/d	596	645	8%	21	20	95%	5%

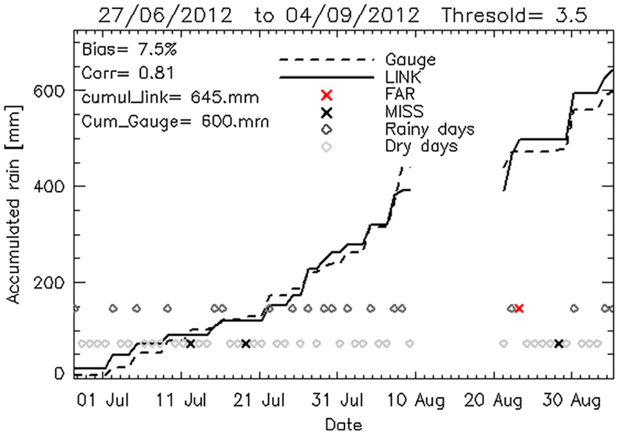

Figure 3. Cumulated daily rainfall series from the gauge (dash line) and the link (plain line). The black diamonds mark the days with correct detection of rain, the red cross for the false alarm (of the link compared to the gauge), the black cross for the missed rain, and the gray diamonds for the days with no rain detected by any sensors.

3. Results

3.1. Detection and Quantification of Rainy Days

Table 1 and Figure 3 illustrate the ability of the method to detect and quantify rainfall over the period of data availability (26 June to 4 September, with an interruption due to a technical problem on the link from 10 to 20 August). The agreement between the series of daily rainfall is high (correlation of 0.82), and the bias in the period's accumulation is 6%. When restricting to the days with 3.5 mm or above (which represent 99% of the season rainfall), the probability of detection is 91% (and 95% for rain above 5 mm/d). Only 1 rainy day out of the 20 detected by the link is a false alarm (thus, a false alarm ratio (FAR) of 5%). The detection skill and the bias are both very sensitive to the definition of the dry/wet spells and the baseline level (which might or not account for a possible wet antenna attenuation): for instance, a downward shift in the baseline level by a small increment of 0.5 dB increases the probability of detection of the 3.5 mm rainy days to 95% but causes a 20% bias. The optimal choice depends on the targeted application.

Given the differences in the nature and sampling of the two instruments, the agreement shown in Table 1 and Figure 3 is very satisfactory and as good or better than what has been reported when comparing gauge data with satellite estimates in this region [*Gosset et al.*, 2013].

3.2. Analysis of the 5 min Time Series

The analysis was carried out at the 5 min time resolution, as illustrated in Figure 4 and Table 2. Fifteen rainy events when both the gauge and the link detected at least 8 mm are reported in Table 2. The overall bias for this heavy precipitation cases is −3%. The mean absolute bias per event is 40% but is below 25% for 12 out of 15 events. Some of the bias can be explained by the differences in sampling between the two

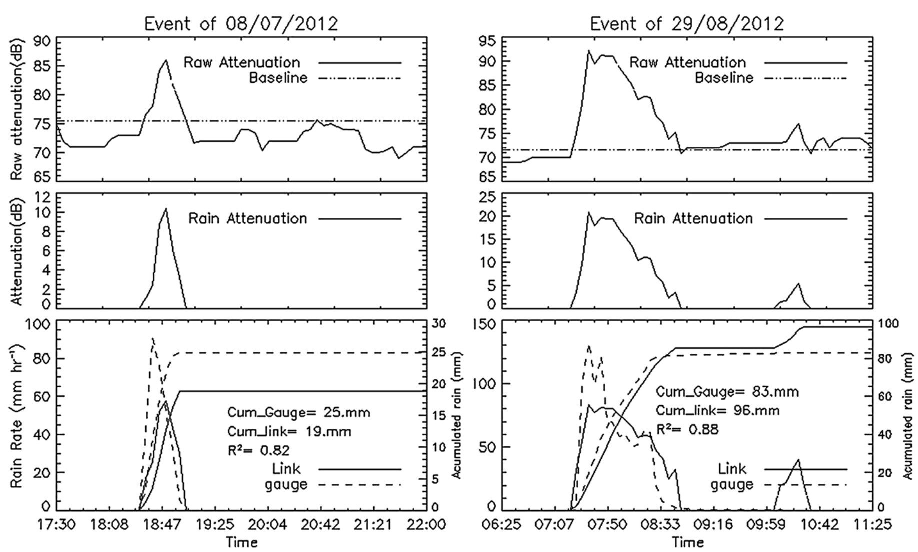

Figure 4. Five-minute resolution time series for two events (date as title). (a) Solid line: raw microwave attenuation (reception minus transmission). Dotted line: baseline (dry) attenuation. (b) Path attenuation due to rain. (c) Solid line: rain rates estimated from link. Dashed line: gauge rain rates.

Table 2. Detailed Analysis of 15 Main Rainy Events CO Detected by the Gauge and the Link[a]

	Gauge		Link				
Start Date/Time of Event	Maximum (mm/h)	Cumulative (mm)	Maximum (mm/h)	Cumulative (mm)	Bias (mm)	Correlation	Correlation Versus Radar
01/07/2012 17:10:00	67	16	61	28	15	0.75	
04/07/2012 06:05:00	69	29	76	22	−2	0.91	
08/07/2012 18:35:00	90	25	57	19	−4	0.82	
15/07/2012 15:50:00	39	15	40	12	−2	−0.05	
21/07/2012 22:05:00	119	43	94	32	−10	0.97	
24/07/2012 16:30:00	27	13	42	22	10	0.44	
26/07/2012 22:40:00	84	35	65	54	20	0.61	0.61
29/07/2012 07:30:00	45	8	55	17	9	0.58	0.79
31/07/2012 08:10:00	49	22	58	17	−4	0.88	0.82
04/08/2012 00:35:00	219	52	91	27	−24	0.92	0.69
06/08/2012 23:00:00	150	54	92	61	10	0.81	0.81
07/08/2012 12:15:00	76	35	32	13	−21	0.16	0.77
21/08/2012 11:55:00	103	33	67	25	−5	0.55	0.58
29/08/2012 07:25:00	132	83	83	96	17	0.88	
02/09/2012 07:40:00	89	29	69	32	4	0.78	
16 event series		506		477	−3%	0.82	

[a]The maximum rain rate and the event total recorded by the link and the gauge, the correlation of the 5 min time series, and the bias are indicated for each event. The scores for the series of event totals are given in the bottom line. The last column shows the correlation with the radar rainfall series when available.

instruments, as well as the uncertainty associated with the attenuation-rainfall conversion. For 12 of these events, the correlation between the 5 min time series within the event is above 0.58, with an average of 0.8, which is remarkable given the differences in the nature of the measurements. The lower correlations for 3 events could be explained by the difference in the sampling mode of the two instruments and/or associated with rain cells covering only partially the link and not the gauge. This is confirmed for the 7 August event, where the radar was operating and the radar-link correlation is 0.77 (Table 2, last column), while the gauge-link correlation is 0.16. More investigation of this effect will be possible with the 2013 data set that comprises several neighboring links and more radar data.

Figure 4 concentrates on two rainy events, 8 July and 29 August. On both dates, the microwave-link-based retrieval and the gauge rainfall are in very good agreement (correlation above 0.8 on both days; see also Table 2). The shape of the link-based time series is smoother, as expected when comparing a 29 km path average rainfall with a point-scale measurement from a gauge. The timing of the events is good and the biases is in the range of 15–25%. More work is planned on quantifying the uncertainties and sensitivities [*Leijnse et al*., 2008, 2010] for the specific link configuration and rain properties encountered in the region and providing a tentative error bar in addition to the rain occurrence and rain rate time series [*Zinevich et al*., 2010].

4. Conclusion

The first quantitative evaluation of rainfall measurement based on microwave links in Sahelian Africa has proved to be very convincing. Despite the relatively low frequency (7 Ghz) and long length (29 km) of the available link, the probability of detection of rainy days is very high (95% of the rain events above 5 mm/d are detected). This is due to the convective nature of the rainfall in the region, characterized by a high contribution of the medium to heavy rain rates. In addition to the detection, the quantification of rainfall amounts is also very satisfactory with less than 10% bias in the seasonal rainfall but with a strong dispersion in the event to event bias. The analysis of the 5 min time series reveals that the agreement within an event is also high for most cases, with correlations above 0.7 on average and above 0.75 for 9 events out of 15. These results prove that given an adequate sampling of the received signal, an operational telecommunication link can provide statistically robust information on rainfall for climatological studies in tropical regions like Sahel, where there is a deficit of observations.

The real potential of the method lies in exploiting networks rather than isolated links, because the consistency among neighboring links helps to eliminate false alarm/misses and above all because a network can provide rainfall maps [*Zinevich et al.*, 2008, 2010; *Overeem et al.*, 2013]. Applications are expected in tropical urban hydrology and monitoring of extreme hydrometeorological events, such as floods, which have impacted many African cities in the last years. The cellular networks are denser in urban areas, with shorter links and higher operating frequencies. They would thus allow good spatial resolution of the rainfields [*Zinevich et al.*, 2009].

As the operational ground networks are degrading and new questions are arising on the variability of rainfall, improved measurements over poorly monitored regions are needed. In rural areas, where the cellular phone network is sparse, the microwave link information can be combined with satellite data. Microwave link information may also be used to correct the biases in real-time satellite estimates.

A key issue will be the cooperation of cellular telecommunication operators and the access to data with sufficient sampling, if possible in real time. Following the success of the first Ouagadougou experiment, the Burkinabé Telecel operator has agreed to extend the test bed. The data from 14 links of the Ouagadougou region will be made available for the 2013 season and will permit the comparison of cellular-derived rain maps with radar data and a 17 gauge network. A conference and training program is planned in order to involve more countries and teams in a regional network for promoting rain measurement from cellular telecommunication networks in Africa.

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