CEST 2017

15th International Conference on Environmental Science and Technology

Rhodes, Greece, 31 August to 2 September 2017

Vertical Precipitation Estimation Using Microwave Links in conjunction with Weather Radar

Raıch R.[1,*], Alpert P.[2] And Messer H.[1]

[1]School of Electrical Engineering, Tel Aviv University, Tel Aviv, Israel

[2]Department of Geosciences, Tel Aviv University, Tel Aviv, Israel

*corresponding author:

e-mail: roiraich@gmail.com

Abstract

Precipitation measurements taken at a specific height, e.g., by weather radar, may not represent the precipitation amount that actually reaches the ground because of a Virga phenomenon, which particularly happens when the air below the cloud base is dry, and continues until humidity increases. In this paper we suggest a method of combining data from several weather radar beams and from a near ground Commercial Microwave Links (CMLs) in order to create a vertical profile of the rain-rate measurements. We propose an estimation method and demonstrate it on real-data measurements in the dead-sea area, and verify the validity of the estimation near ground by comparing the results with Rain Gauges' (RGs) actual measurements. The suggested method provides the best correlation results, with a correlation of up to 0.9615, when correlated with real measurements of RGs.

Keywords: Precipitation Estimation, Commercial Microwave links, Virga

1. Introduction

Over the past decade, the rain-induced-attenuation over Commercial Microwave links (CMLs) has been the source of many studies, and is part of an on-going research of precipitation estimation based on the their Received Signal Level (RSL) measurements. In particular, the attenuation of the signal over cellular networks links due to rain, which can be calculated as the Transmitted Signal Level (TSL) at one antenna minus the RSL in the opposite antenna, after compensation of a baseline level, has shown to be directly connected to the rain-rate over the link via Power-Law relation (Olsen *et al*, 1978). The ongoing research produced many tools, particularly for rainfall monitoring, such as but not limited to, rainfall estimation (Messer *et al*, 2006; Messer 2007; Leijnse *et al*, 2007), rainfall mapping (Zinevich *et al*, 2008; Goldshtein *et al*, 2009), rain detection (David *et al*, 2009; Harel and Messer 2013). However, all of these studies focus on rainfall monitoring at near ground level, where their performance is often compared with Radar. While such comparison is reasonable though radar measures rain much above ground, as there is no much variance along the vertical axis once the relative humidity is nearing 100%, it is not the case when dealing with arid and even semi-arid regions. As was shown in previous studies (Evans *et al*, 2011), when measuring precipitation at an arid region, precipitation particles, rain, or snow flakes, may evaporate before reaching the ground while creating visible precipitation shafts below the cloud base level. The precipitation shafts will be observed at height by the weather radar beams, but will not actually be measurable at ground level. This evaporation is regarded as the Virga phenomenon (Fraser and Bohren 1992) and is occurring naturally when the air below the cloud is dry, and will continue until humidity below the base of the cloud is high enough to decrease the evaporation and then precipitations will reach the ground (Sassen and Krueger 1993). The Virga phenomenon, in a semi-arid zone, may lead to considerable over-estimation of rainfall by the weather radar, while the ground might remain nearly dry. Current ground monitoring devices such as Rain Gauges (RGs), are usually sparse and represent an area of less than 1 square meter. Moreover, although the Virga phenomenon is rare, it is much likely to occur in arid and semi-arid regions such as found, for example, in the east and south of Israel. As CMLs are very widespread with high density, and cover long areas mainly across lengths of 1-30 [km], in this paper we suggest a method of profiling the vertical rain-rates in arid areas using a combination of several radar beams, observing at different heights along with cellular links in order to achieve more accurate above ground level rain-rates where the Virga may affect the radar measurements of rain. The rest of the paper is organized as follows: Section 2 provides the necessary background and the methodology used. Section 3 details the experimental setup and the outcome results. Lastly, section 4 concludes this paper.

2. Theory and Methods

2.1. Theory

In order of using CMLs for the sake of rain rate monitoring, we need apply the power law equation (Olsen *et al*, 1978), which connects the CMLs' power attenuation $A[dB]$ caused by the effect of rainfall at a specific rate $\mathrm{R[mm/hr]}$:

$$\mathrm{R} = \sqrt[\mathrm{b}]{\mathrm{A/aL}} \tag{1}$$

Where $\mathrm{a, b}$ are parameters that are affected by the CML's frequency, polarization and the Drop Size Distribution

(DSD), and can be found at publications by the International Telecommunication Union (ITU-R 2005), and $L[km]$ is the CML's length.

Next, the rate of rainfall (in [*mm/hr*]), at distance Z below Cloud Base level (Cl_B), can be written as: (Schlesinger *et al*, 1988)

$$P(Z) = P(0) - CP^{\alpha}(0)\Psi(Z) \qquad (2)$$

Where $P(0)$ is the rain rate at the height of Cl_B, C and α are constants that are affected by the DSD, and $\Psi(Z)$ can be presented as:

$$\Psi(Z) = \frac{(1-S_0)Z}{K_1+K_2}\ ;\ constant\ relative\ humidity\ S_0 \qquad (3)$$

And K_1, K_2 are affected by the surrounding environment's parameters, and are calculated by:

$$K_1 = \frac{L^2\rho_l}{kR_vT^2} \qquad K_2 = \frac{R_vT\rho_l}{D_we_s(T)} \qquad (4)$$

When ρ_l is the density of liquid water, k is the thermal conductivity of air, L the latent heat of condensation, R_v is the gas constant for water vapor, T the temperature, $e_s(T)$ the saturation vapor pressure and D_w the diffusivity of water vapor in air. Assuming constant relative humidity along the Z axis, **eq. (2)** could be written as:

$$\mathrm{P(0) - C^*P^{\alpha}(0)(1-S_0)Z = P(Z)} \qquad (5)$$

Where $(C^* \triangleq C/(K_1+K_2))$. Our aim is to find the unknown parameters in **eq. (5)**, so the vertical profile of the rain from the cloud base to the ground level can be determined. That is, using the available measurements we need to estimate the parameters vector $\underline{\Theta} = (P(0)\ \alpha\ C^*\ Cl_B)^t$, in effort of achieving an equation that will define the vertical profile of the rain rate below the Cl_B and downwards. Exactly how we suggest of doing so will be explained in the following subsection.

2.2. Methods

For the sake of estimating our parameters vector $\underline{\Theta}$, we suggest using CML data in conjunction with different radar beams, and later validate our results with RGs nearby. First, need present our measurements vector $\underline{y}$, which is provided by using various rain rate monitoring tools : weather radar sampling the rain rate at different heights, and CMLs sampling at the antenna height. Second, we show how we estimate $\underline{\Theta}$ from the measurements. Finally, we show how the RGs' rain rate could be calculated from $\underline{\Theta}$ to validate the results. In addition, the relative humidity S_0 is considered given and is provided by weather stations in the vicinity. Given a CML at a height of H_{CML} above ground level, the CMLs' rain rate measurements P (in [*mm/hr*]), when following eq. (5) and eq. (1) can be presented as:

$$P(Cl_B - H_{CML}) = P(0) - C^*P^{\alpha}(0)(1-S_0)(Cl_B - H_{CML}) = \sqrt[b]{\frac{A}{aL}} \qquad (6)$$

Next, we need to introduce a method to present the weather radar rain rate. Since the radar beams have an opening of a certain degree, when monitoring at a distance this translates to integration and averaging of the precipitations $P(Z_1 \to Z_2)$, by the radar, along the vertical axis, where the beam is observing from height Z_1 to height Z_2 above ground level. The integration of a specific radar beam can be written as:

$$P\left(Z_1 \to Z_2\right) = \frac{1}{Z_2-Z_1}\int_{(Cl_B-Z_2)}^{(Cl_B-Z_1)}(P(0) - C^*P^{\alpha}(0)(1-S_0)Z)dz = P(0) - C^*P^{\alpha}(0)(1-S_0)\left(Cl_B - \frac{(Z_2+Z_1)}{2}\right) = P\left(Cl_B - \frac{(Z_2+Z_1)}{2}\right) \qquad (7)$$

To summarize the above, the samples vector $\underline{y}$ can be represented, as: $\underline{y} = \underline{\Theta_1} - \underline{\Theta_3{\Theta_1}^{\Theta_2}}(1-S_0)(\underline{\Theta_4} - \underline{z}) + \underline{n}$,

when $\underline{n}$ is the added measurement noise, but as one can see it is problematic to differentiate between $\Theta_2, \Theta_3, \Theta_4$, this is where additional prior knowledge is required. We suggest using the values of α and C that were derived according to the research done by Schlesinger *et al*, (1988), and calculate C^* by using the surrounding environment parameters K_1, K_2. Next, we can present a new, and of lesser dimension, parameters vector:

$$\underline{\Theta}^n = \begin{pmatrix} P(0) - C^*P^{\alpha}(0)(1-S_0)Cl_B \\ C^*P^{\alpha}(0)(1-S_0) \end{pmatrix}$$

And the samples vector is:

$$\underline{y} = \Theta_1^n \cdot \underline{1} + \Theta_2^n \cdot \underline{z} + \underline{n} \qquad (8)$$

This problem's solution is known and can easily be solved using a Least Squares Estimation (LSE) to extract $\underline{\widehat{\Theta^n}}$. After doing so, our estimated values for $P(0)$ and Cl_B could be calculated by:

$$\widehat{P(0)} = \sqrt[\alpha]{\frac{\widehat{\Theta}_2^n}{C^*(1-S_0)}}\ ;\ \widehat{Cl}_B = \frac{\widehat{P(0)} - \widehat{\Theta}_1^n}{\widehat{\Theta}_2^n} \qquad (9)$$

Finally, for the sake of validating the results, we can calculate, from the estimated parameters, the rain rate at the RG location and height, and compare it with the actual RG measurements. Given a RG height above ground level is less than a few meters and is roughly at ground level, the rain measurements in [*mm/hr*], when following eq. (5) and using the estimated parameters from eq. (9), can be represented as:

$$\widehat{P(Cl_B)} = \widehat{P(0)} - C^*\,\widehat{P(0)}^{\alpha}(1-S_0)\,\widehat{Cl}_B \qquad (10)$$

Where S_0 is taken from the measurements at the specific weather station where the RG is located. In the next section the experiment and measurements selected in order to solve our estimation problem will be presented, as well as the corresponding results.

3. Experiment and Results

3.1. The experimental setup

The experiment site chosen to demonstrate our method is in southern Israel, in the semi-arid region near the city of Arad, where a CML of the length of 16 [*km*] and temporal resolution of 4 samples per hour, at the average height of 43 meters above ground level was used. In addition, we used radar samples from the Israeli Meteorological Service (IMS) with the temporal resolution of 12 samples per hour, and at two different elevation ranges: 355-1940 meters and 1275-2862 meters above ground level. After implementing the suggested method described in the previous section using the radar and the CML, we can calculate the localized rain rates for the RGs locations and compare the results with the actual RGs' measurements. The test site location, the available RGs for validation purpose (with a resolution of 6 samples per hour), the CML and the radar are displayed in **Figure 1.** The storm of May 7th-8th 2014 was selected to be analyzed, since the month of May is generally a dry month in Israel in this region and the humidity could drop dramatically, thus creating good conditions for significant evaporation of rain drops. Moreover, when using our CML to extract rain rate values, the a, b power-law parameters were chosen according to a recently made calibration for this specific CML(Ostrometzky *et al*, 2016). Since this CML saves the maximum and minimum RSL values from the last 15 minutes and not the temporal RSL values, the calibrated power-law parameters were used. The base line attenuation for the CML was measured when there was no rain, right before the beginning of the tested storm and was deducted from the attenuation measured during the storm, since it represents base attenuation due to dry air, water vapor etc. (Harel and Messer 2013). In addition, we needed to be able to compare the CML with the radar beams time-wise and location-wise. Since there are different sampling rates in time for each device, we averaged the samples over the smallest common denominator, which, when including the RGs rate, added to 2 samples per hour. And when trying to compare the location of the CML with the radar beams, we used an Averaged Radar Cells Over Microwave Link (ARCOML) (Eshel 2017) location, which added to 124 different radar cells to be averaged above the CML. In total, there are three measurements sources, two radar beams and one CML, but only two parameters to estimate, so we can extract: $P(0)$ and the Cl_B by using LSE, as suggested in the previous section, under the assumption of the same values of α and C that were calculated previously (Schlesinger *et al*, 1988), and when using the averaged relative humidity values taken from both weather stations at Arad and Shani. The values of $P(0)$ and Cl_B were calculated every 30 minutes for this specific event. Then, based on the estimated parameters, we created two series of local near ground rain rate samples, for both Shani location and Arad location, using the corresponding relative humidity values for every 30 minutes by using eq. (10). The next subsection presents the results of the aforementioned experiment.

3.2. Results

As described in the previous subsection, we conducted an experiment to calculate rain rates using multimodal measurements, in addition to using our suggested method, to interpolate measurements near ground, at the Shani and Arad RGs locations. The estimated values for $P(0)$ for the duration of the storm, above the CML, ranged between 0 and 18.2 [mm/hr] while the Cl_B was between 475 and 6598 meters and averaged at 3773 meters above ground level. Even though, the estimated values for $P(0)$ and Cl_B were physically within reason for a storm at this season and for this specific area, in the absence of real measurements for $P(0)$ and Cl_B, we decided to validate the results by calculating the rain rate near ground at the RGs: $\widehat{P(\mathrm{Cl}_B)}$ and correlate it with actual RGs data. Table 1. illustrates the correlation between the different measurement sources of rain rate (RGs, CML, ARCOML at 2 different elevations, and the suggested method estimated rain rate near ground - $\widehat{P(\mathrm{Cl}_B)}$) over the duration of 25 hours on May 7th-8th 2014 in southern Israel. Our method produced the highest correlation values except for the correlation with Arad RG, where the CML was slightly better correlated but by a very negligible margin: 0.9627 vs. 0.9615. When comparing the results of our method vs. Shani RG, we got a correlation of 0.5569, more than 10% over the second best correlation value. When observing the time series, displayed in Figure 2., our suggested method in comparison with the CML, the ARCOML, or average of the two RGs, a higher correlation is found between our method and the CML than with the RGs, this could be mainly attributed to the pin-pointed location of the RGs which is not representing well it's surrounding rain rate, and the fact that both the CML and our method show results at near ground while the ARCOML is not. In Figure 2., it is also noticeable that when comparing the near ground methods to the ARCOML at the heights of 355-1940 meters, as long as the relative humidity is around 50% the radar beam overestimated rain rates as expected, and nearly matches the other methods in the second half of the storm when the relative humidity rises to near 100%. This is because the Virga effect diminishes significantly with 100% of relative humidity.

4. Conclusions

There are some issues when trying to estimate near ground rain rates at semi-arid regions from current commonly used methods such as weather radar and RGs: while RGs may produce relatively accurate near ground rain amounts, they are very pin-pointed and are not necessarily representative of the surrounding rain amounts, particularly in a semi-arid region, while the weather radar cover large areas with high resolution when measuring rain rates, but when measuring at a high altitude above ground, some evaporation may occur and then the radar overestimates the rain rates at ground level. In Figure 2. we can observe both of this issues as we can clearly see that the RGs provide localized rain rates that do not match throughout all the duration of the storm to the other methods, while the ARCOML shows significant over estimations when the relative humidity is still low at around 50%. Moreover, when correlating Shani RG with Arad RG we get a value of 0.4768, emphasizing the pin-pointed representation of the RGs, when compared to the other methods. In this research we provided a method of overcoming these issues by using several radar beams at different heights, in conjunction with a near ground CML, that covers a long distance. The resulted method yielded the highest correlation values (or second best by a very small margin in one case) when compared with the RGs, in comparison to other methods.

Acknowledgments

We wish to thank the help of our friends within cellular network service providers: Cellcom, Pelephone, and PHI for providing us data over the last decade**.** In addition, we thank all members of our research team in Tel Aviv.

Figure 1. The test site location: Southern Israel, the Israeli Meteorological Service(IMS) weather radar (white target), both Shani and Arad RGs (white triangles), and the microwave link represented by two black antenna markers and the actual link between them (purple)

Table 1. The correlation between the different measurement sources of rain rate (Rain Gauge (RG), Commercial Microwave Link (CML), Averaged Radar Cells Over Microwave Link (ARCOML) at 2 different elevations, and the suggested method of combining radar and microwave link data to estimate rain rate near ground) over the duration of 25 hours on May 7th-8th 2014 at the experiment area between the cities of Arad and Shani in southern Israel. Values marked in green show best values, values marked at yellow show second best values for a specific column.

	Correlation with Shani RG	**Correlation with Arad RG**	**Correlation with the avg. of Arad & Shani RGs**
Shani RG	1	0.4768	0.8259
Arad RG	0.4768	1	0.8894
CML	0.4636	0.9627	0.8586
ARCOML1 (0.35-1.94 [*km*])	0.3233	0.9060	0.7493
ARCOML2 (1.28-2.82 [*km*])	0.4911	0.9385	0.8574
The suggested method	0.5569	0.9615	0.8926

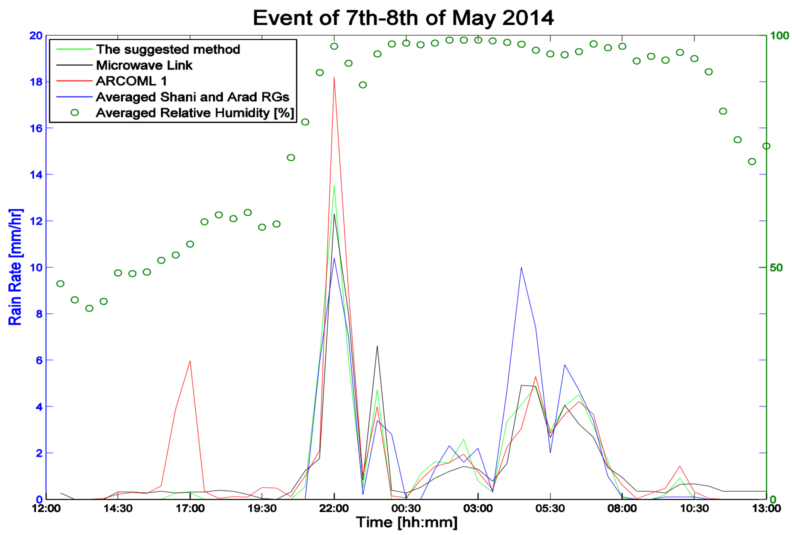

Figure 2. The temporal rain rate according to the average of Arad and Shani RGs (in blue), the rain rate according to the microwave link (in black), the lower weather radar beam (ARCOML 1, in red), as well as according to the suggested method (in green) in correspondence with the event's relative humidity averaged from the measurements at the weather station in Arad and Shani, over 25 hours in May 7th-8th at southern Israel.

University, led by Prof. Hagit Messer and Prof. Pinhas Alpert for their cooperation and beneficial discussions

References

Olsen, R. O. G. E. R. S., Rogers, D. V., & Hodge, D. (1978). The aR b relation in the calculation of rain attenuation. IEEE Transactions on Antennas and Propagation, 26(2), 318-329.

Messer, H., Zinevich, A., & Alpert, P. (2006). Environmental monitoring by wireless communication networks. *Science*, *312*(5774), 713-713.

Messer, H. (2007). Rainfall Monitoring Using Cellular Networks [In the Spotlight]. *IEEE Signal Processing Magazine*, *24*(3), 144-142.

Leijnse, H., Uijlenhoet, R., & Stricker, J. N. M. (2007). Rainfall measurement using radio links from cellular communication networks. *Water Resources Research*, *43*(3).

Zinevich, A., Alpert, P., & Messer, H. (2008). Estimation of rainfall fields using commercial microwave communication networks of variable density. *Advances in water resources*, *31*(11), 1470-1480.

Goldshtein, O., Messer, H., & Zinevich, A. (2009). Rain rate estimation using measurements from commercial telecommunications links. *IEEE Transactions on Signal Processing*, *57*(4), 1616-1625.

David, N., Alpert, P., & Messer, H. (2009). Technical Note: Novel method for water vapour monitoring using wireless communication networks measurements. Atmospheric Chemistry and Physics, 9(7), 2413-2418.

Harel, O., & Messer, H. (2013). Extension of the mflrt to detect an unknown deterministic signal using multiple sensors, applied for precipitation detection. *IEEE Signal Processing Letters*, *20*(10), 945-948.

Evans, E., Stewart, R. E., Henson, W., & Saunders, K. (2011). On precipitation and virga over three locations during the 1999–2004 Canadian Prairie drought. Atmosphere-Ocean, 49(4), 366-379.

Fraser, A. B., & Bohren, C. F. (1992). Is virga rain that evaporates before reaching the ground?. Monthly weather review, 120(8), 1565-1571.

Sassen, K., & Krueger, S. K. (1993). Toward an empirical definition of virga: Comments on "Is virga rain that evaporates before reaching the ground?". Monthly weather review, 121(8), 2426-2428.

Recommendation, I. T. U. R. P. (2005). 838-3. Specific attenuation model for rain for use in prediction methods. *ITU-R Recommendations, P Series Fasicle, ITU, Geneva, Switzerland*.

Schlesinger, M. E., Oh, J. H., & Rosenfeld, D. (1988). A parameterization of the evaporation of rainfall. Monthly weather review, 116(10), 1887-1895.

Eshel, A. (2017). *Commercial microwave links and radar integration in respect to flash floods in the dead sea area* (Unpublished master's thesis). Tel Aviv University, Tel Aviv, Israel.

Ostrometzky, J., Raich, R., Eshel, A., & Messer, H. (2016, March). Calibration of the attenuation-rain rate power-law parameters using measurements from commercial microwave networks. In *Acoustics, Speech and Signal Processing (ICASSP), 2016 IEEE International Conference on* (pp. 3736-3740). IEEE.