# Microwave Links Improve Operational Rainfall Monitoring in Gothenburg, Sweden

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**Abstract**

Microwave links (MWL) in operational telecommunication networks provide new opportunities to improve rainfall monitoring, especially in cities and low-income countries. We used signal strength data from 364 MWLs sampled every 10s to estimate rainfall in Gothenburg. We compared these estimates with conventional gauges and weather radar. We found that MWLs improve monitoring by providing: higher temporal resolution (1min vs. 15min), greater surface coverage (364 MWLs covering 1040km vs. 10 gauges covering $0.2m^2$), higher spatial resolution of rainfall maps ($0.25km^2$ vs. $4km^2$ for radar), better ability than radar to capture peak intensities at local scale, near-surface measurement (30m vs. 1200m for radar), and more robust sampling (10s vs. 15-min snapshots for radar). The MWLs captured temporal dynamics very well (correlation: 0.8), but generally overestimated accumulated volumes (+31%). We used the MWL data to build an operational real-time prototype providing 1-min rainfall maps online. MWLs could be combined with other sensors and models to improve flood forecasting and infrastructure design. Short-duration rainfall extremes are projected to increase in the future, increasing the risk of fast flood events. Hence, MWLs offers a timely opportunity to adapt current monitoring to the future climate, contributing to building more resilient and sustainable societies.

**Keywords:** accuracy, intense precipitation, opportunistic sensor, real-time monitoring

## 1. Introduction

High-intensity rainfall can cause severe flooding in cities, often leading to damaged infrastructure, buildings, power plants, etcetera. Sometimes the sewer system capacity is surpassed, leading to release of untreated sewage and consequential peaks of environmental pollution downstream. Several cases of severe flooding has happened in Sweden over the last 5-10 years, and a major flooding disaster took place in Copenhagen in July 2011 when 120 mm of rain in 2 hours led to damages associated with estimated costs of up to 1 billion EUR (Tolstrup, 2012). Furthermore, climate projections suggest that short-duration rainfall intensity in Sweden may increase by 30-40% until the end of the century (e.g. 10-year intensities, Olsson & Josefsson, 2015). Forecasting this type of sudden flood events requires accurate and up-to-date information on how much rain has fallen in different parts of the city watershed, since rainfall varies substantially in space and time (Fencl *et al*., 2013). This is used to obtain accurate starting conditions in urban drainage and flood forecasting models as close as possible to the time of the forecast. Current operational rainfall monitoring typically consists of gauges and weather radar. Rainfall gauges measure with high accuracy but only locally; they are not always representative for the surrounding areas. Weather radar indirectly estimates rainfall at higher resolution and with full spatial coverage, but the estimates are uncertain. Operational telecommunication networks, which are particularly dense in urban areas, provide a novel opportunity to monitor rainfall utilizing signal fluctuations in MWLs (Leijnse *et al*., 2007; Messer *et al*., 2006). The objective of our study was to test the potential of MWLs to monitor rainfall in the city of Gothenburg, Sweden.

## 2. Material and methods

Since May 2015 we have been collecting signal strength data from 364 MWLs (Ericsson MINI-LINK) in the Hi3G network covering the greater Gothenburg area (Figure 1). We sample each MWL every 10 seconds, and collect data for analysis every hour using a custom-made data collection tool. See Bao *et al*. (2017) for more details on the MWL data set and collection approach. We estimated average rainfall intensity at 1-min resolution from the signal strength data based on published algorithms (Chwala *et al*., 2012; e.g. Messer *et al*., 2006; Schleiss *et al*., 2013), combined with our own magnitude correction method based on link length. We derived rainfall intensity maps over Gothenburg at $0.25km^2 \times$ 1-min resolution, by interpolating between all MWLs. The MWL rainfall estimates were compared with 10 conventional rainfall gauges from Gothenburg municipality and SMHI (9 of which operate at 1-min resolution and one at 15-min resolution), and the national weather radar system (operating at $4km^2 \times$ 15-min resolution). We used all links within 500m of each gauge, and the nearest radar pixel in the comparisons. We compared both 1-min rainfall intensities, 15-min accumulated rainfall amounts, and spatial distributions for the period 1-31 July 2015.

## 3. Results and discussion

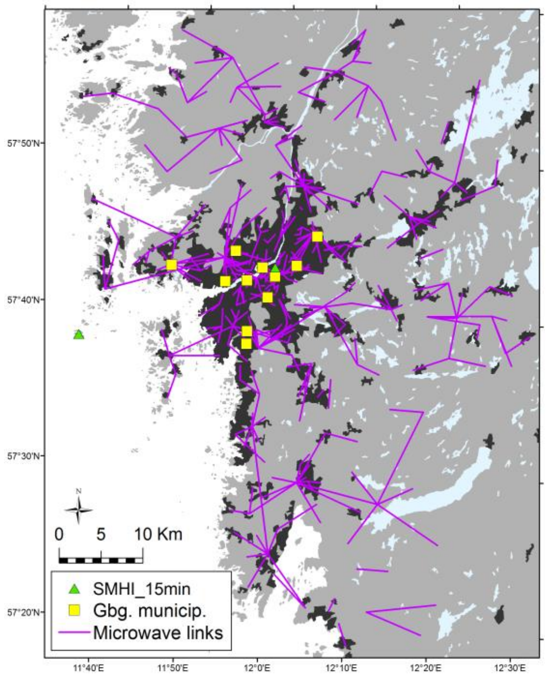


**Figure 1.** Map of the greater Gothenburg area (ca. 4000 km$^2$) showing the location of the 364 microwave links, SMHI's 15-min gauges, and Gothenburg municipality's 1-min gauges.

The performance of MWL and radar relative to the gauges is presented in Table 1 and Figure 2. The MWL rainfall generally correlated very well with the local gauges, significantly better than radar (Table 1). The correlation compares well with expected deviations due to spatial variability (i.e. comparing gauges located nearby each other). Hence, the temporal dynamics of rainfall can be better captured with MWLs than radar. MWLs typically overestimate rainfall amounts (due in part to the wet-antenna effect, Schleiss *et al*., 2013), but reasonable values were obtained in this study through magnitude corrections (Table 1). Peak rainfall intensities estimated by the MWLs were more similar than the radar to the peak intensities measured at the gauges (Figure 2a). Hence, the MWLs provide a better ability than radar to capture peak intensities at local scale. The MWL sampling (10s) is much higher than the operational radar (15-min). This allowed us to create a more robust and higher-resolution time series (1-min resolution with 6 samples per minute). As a consequence, some short-duration cloudbursts were better monitored by the MWLs than the radar (Figure 2b).

**Table 1.** Average performance of microwave links and radar for 15-min accumulated rainfall relative to 10 conventional rainfall gauges. We also include the average similarity of three gauges located within a 3km radius of SMHI's Göteborg A gauge to illustrate expected deviations due to local spatial variability in rainfall.

| | Correlation | Bias |
|---|---|---|
| Microwave links | 0.82 | + 31% |
| Weather radar | 0.57 | – 20% |
| Gauge-gauge similarity | 0.80 | – 10% |

The MWL network offer some additional advantages compared with gauges and radar (Table 2). The 364 MWLs monitor 1040 km in the greater Gothenburg area, while the gauges only cover 0.2m$^2$. Hence, the MWL network provides the opportunity to monitor rainfall in ungauged areas. This is possible also with radar, but the MWL network provides this coverage at higher temporal and spatial resolution and near the ground surface. As a consequence, the MWLs can better represent the temporal variability and the highest intensities of rainfall on local scale (Table 1, Figure 2). Moreover, the high density of MWLs covering Gothenburg provides the opportunity to map rainfall at 16 times higher spatial resolution than radar, again providing more localized information (Figure 3). However, the uncertainty of the mapped rainfall increases with increasing distance from each MWL.

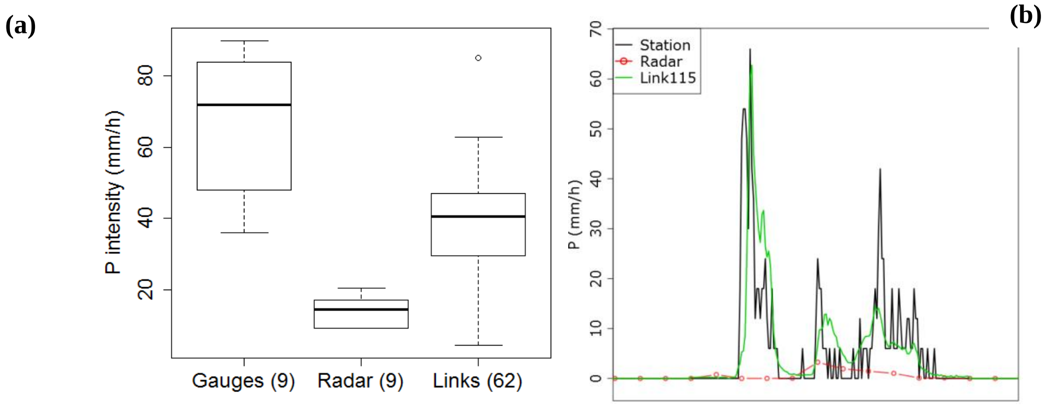


**Figure 2.** (a) Highest recorded rainfall intensities during July 2015 at nine 1-min gauges compared with the nearest radar pixel and microwave links. (b) Example of a fast high-intensity event from Torslanda 27 July 2015. The highest intensities were measured at around 15:05 UTC at the Torslanda 1-min. gauge. This was captured well by a nearby microwave link (sampling every 10s), but was completely missed by SMHI's weather radar (sampling with 15-min snapshots). Note the x-axis in (b) covers a 4-hour timespan.

**Table 2.** Characteristics of the microwave links, weather radar and gauges available for Gothenburg.

| | Coverage | Temporal resolution | Spatial resolution [a] | Sampling height [b] |
|---|---|---|---|---|
| Microwave links | 1040 km | 10 s [c] | 0.25 $km^2$ | 30 m [e] |
| Weather radar | 4000 $km^2$ | 15 min [d] | 4 $km^2$ | 1200 m [f] |
| Gauges | 0.2 $m^2$ | 1-15 min | - | 2 m |

[a] Spatial resolution of maps produced from the underlying data. Note that we did not interpolate the gauges to produce maps in this study. This is however done operationally at SMHI at a 4$km^2$ resolution.

[b] On average, above ground level.

[c] Here averaged to 1-min resolution to increase sampling robustness (6 samples per minute). Instantaneous mapping at 10s resolution is also possible.

[d] The operational Swedish radar also provides a complementary 5-min scan but only at one vertical level, which makes it less reliable than the 15-min scans used here (sampling multiple vertical levels).

[e] On average, and generally below 100m.

[f] Over Gothenburg. Generally the height increases with increasing distance from the radar.

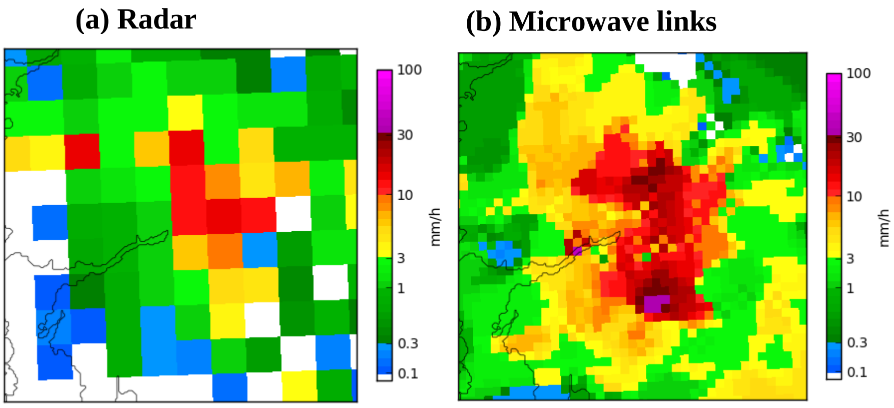


**Figure 3.** Maps of Gothenburg city during a rainfall event (2015-07-08 00:45 UTC) based on the radar (a, 4$km^2$ × 15-min. resolution, lowest sampling at 1200m above ground) and the microwave links (b, 0.25$km^2$ × 1-min resolution, average sampling at 30m above ground).

The MWLs are already installed and operational with negligible downtime in the mobile operator network. This means that it is straightforward to create operational near-real-time services, with very small additional cost. To illustrate this, we built an operational prototype providing 1-min rainfall maps over Gothenburg city (http://www.smhi.se/om-webbplatsen/om-smhi-se-lab/microweather-livedata/). The prototype provides both live data (updated every hour) and historic data (from April 2016). This can be used both to analyze historic events (e.g. to improve urban drainage design) and to visualize the current evolution of rainfall (in real-time management). In the future, this could be extended to deliver near-real-time data to stormwater drainage and flood forecasting models, which has been explored in e.g. Prague (Fencl *et al.*, 2013). Many cities already have operational rainfall monitoring systems. In these cities, the best rainfall information will likely be obtained by combining MWLs with the other operational sensors, utilizing their respective strengths and compensating for their weaknesses (e.g. providing redundancy during operational downtimes). MWL-based rainfall is a relatively young technology, which still requires more research and development to become a mature operational service. However, the MWL network can already now improve rainfall monitoring by providing operational information at ground level covering a larger surface area than gauges, at higher temporal and spatial resolution than radar, with higher sampling frequency than radar enabling better capture of high-intensity rainfall events at local scale. Given that high-intensity events are expected to become more frequent in the future, MWLs offers a timely opportunity to adapt the monitoring system to the future climate, contributing to building more resilient and sustainable cities of the future. MWLs also offer a great opportunity to improve monitoring in developing countries, where radar is typically not available and where sparse gauge measurements often only become available weeks-months after the actual rainfall event occurred. The great expansion of operational mobile phone networks in these countries has the potential to provide an unprecedented source of information to improve forecasting, water management, agricultural production etc. and, in extension, peoples' livelihood.

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