Rainfall detection by tomographic inversion of commercial radio link data: a pilot project in Italy

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Abstract

Within MOPRAM project, we investigate the use of a network of microwave radio links to a) improve the accuracy and reliability of precipitation fields detection and rainfall estimation and b) to enhance the knowledge of river basins answer, and in particular the prediction of river discharge, based on the availability of more accurate space-time precipitation measurements. A tomographic technique is applied for the first time to reconstruct rain fields from link data collected by the backhauling network of a major mobile phone company operating in Italy. The raw data are a network's by-product, available at almost no-cost, once the network software is properly updated. The tomographic method has to be fine-tuned on the network's topology, to be stable even in the presence of noisy measurements and perform consistently. The proposed methodology could guarantee more accurate information about the rainfall fields with respect to weather radars (lacking in terms of quantitative reliability) or rain gauges (lacking in terms of spatial resolution).

Keywords: radio link, rainfall, tomography, flood

1. Introduction

The accurate knowledge of rainfall fields is of great importance for several purposes, including agriculture, weather forecast, water management, climate change and, last but not least, mitigation of floods and landslides. All hydrological models, whether they are used for real-time flood forecasting, flood risk mapping, or water resources planning and management, rely on accurate information about the spatial and temporal distribution of rainfall, and its exact amount. Inaccurate rainfall data compromise the predictions of hydrological models and the decisions based on their outputs (Berne and Krajewski (2013)). Thus, there is an urgent need to collect reliable rainfall data at high spatial (say, a few km or less) and temporal (hourly or less) resolution. Rainfall estimates are usually obtained either from ground (i.e. rain gauges) or airborne measurements (i.e. radars). Rain gauges provide direct measurement of rain intensity, they are cheap and easy to deploy. However, extrapolating the spatial distribution of precipitation from a sparse network of rain gauges might result in large errors, especially during convective events. On the other side, radar data give spatial distributions and provide a good basis for short-term forecasts, but their quantitative reliability is questionable (McKee and Binns (2015)). An alternative methodology for estimating rainfall is based on the power loss (i.e., the attenuation) that rain induces on the signals transmitted across microwave radio links. Several experimental studies confirm the potential of this approach: for instance, D'Amico *et al*. (2006) estimated the path-averaged rainfall rate from ad-hoc point-to-point link measurements. Overeem *et al*. (2013) derived rain fields over Netherlands from attenuation data gathered on a country-wide scale network by a simple kriging method. Advantages and drawbacks of different measurements methods of rainfall are summarized in Table 1. Highly accurate rainfall estimates can be obtained through the tomographic techniques firstly proposed by Giuli *et al* (1991). Even though tomography was widely simulated in the past (Cuccoli *et al*. (2009); Zinevich *et al*. (2008)), the technique was applied on real data only recently by D'Amico *et al*. (2016) exploiting attenuation measurements collected from a small set of operational microwave links. Moreover, to the authors' knowledge, the tomographic technique has never been applied to a dense network of commercial operational links. Improving the description of the space-time variability of rainfall events by tomographic inversion and assessing its impacts on the flood response are the main challenges of MOPRAM (MOnitoring of Precipitation through A network of microwaves RAdio Links) project. In this contribution, the project objectives and its novel aspects are described and the methodology used to achieve the above objectives is detailed.

2. The MOPRAM project

MOPRAM is a multidisciplinary project, which couples together expertise of radio propagation, meteorology and hydrology. It is funded by Fondazione Cariplo, a philanthropic organization that devises research programs in different areas such as arts and culture, environment, social and human services and scientific research.

Table 1. Comparison between different methods for measuring rainfall.

	Rain Gauge	Weather Radar	Microwave Link
Advantages	-Direct measurement of rain rate -Relatively low cost with respect to radars	-A single radar covers areas up to 100 km (C-band)	-Infrastructure deployed in many countries in urban and mountain areas (e.g. backhauling networks managed by ISPs)
Drawbacks	-Single-point measurement: need many sensors to detect heavy localized events -Sensors must be connected into a network to get real time measurements -Not easy to deploy in rural and mountain areas -Electromechanical device that requires constant maintenance -Must be located in a protected site to minimize exposure to wind and turbulence.	-Indirect measurement of rain rate from radar reflectivity. -Quantitative estimates of rainfall are an issue due to clutter contamination, partial beam-filling, beam-shielding, etc. -Volume averaged measurement (typical radar map resolution: 1 x 1 km) -Measurements are taken aloft -Cannot operate in areas surrounded by mountains -Radars are expensive and require high operating costs	-Indirect measurement of rain rate from microwave attenuation -Path-averaged measurement (link length: 1-10 km) -Operational links are optimized to transmit high-speed data and network control data rather than for purposes of rain measurements

The MOPRAM team includes researchers from Consiglio Nazionale delle Ricerche and Politecnico di Milano. Microwave link data have been courtesy provided by Vodafone Italia S.p.A. The data are produced by the Vodafone cellular network monitoring tool I-Veritas, designed and operated by SIAE microelettronica S.p.A. The latter will support the analysis and interpretation of the microwave data in the frame of the project. MOPRAM kicked-off in April 2017 and will go through three years of activity. MOPRAM aims at investigating the potential of a commercial network of microwave radio links for quantitative assessment of rainfall through simulations and a measurement campaign over selected areas within the territory of Lombardy (Northern Italy). There are several arguments in favor of this project:

- Networks of microwave links are deployed worldwide nowadays. They would be the cheapest way to monitor precipitation in those areas where networks of ad-hoc sensors are not present.
- When compared with rain gauges and radars, microwave links have specific and somewhat complementary skills, hence they could be a valuable support tool even in those areas where the classical sensors are present (see Table 1).
- The observation area includes a variety of terrain conditions and environments and several areas of interest for hydrogeological purposes.
- A few networks of rain gauges are deployed throughout Lombardy. One of them will be used as ground truth for assessing the methodology. Weather radar data are available as well.

The main goals of the project are:

- The improvement of the accuracy and reliability of the precipitation fields detection using a tomographic method, which guarantees high space and time resolution without implying high costs.
- The progress in the knowledge of river basins answer, and in particular in river discharge prediction, thanks to the availability of more accurate precipitation measurements in both space and time.

It is important to point out that the data will not come from an ad-hoc sensor network, but from an operational network that is routinely used to convey traffic. These type of data are a network's by-product, and can be available at almost no-cost, once the network software is updated and "instructed" to collect and forward them to a central server. This project moves from two fundamental assumptions that have been demonstrated by previous research:

- Path-averaged rainfall rate estimates can be gathered through commercial microwave link measurements. It has been shown that the precipitation cumulated on a daily basis agrees fairly well with the one measured by co-located rain-gauges (D'Amico *et al*. (2016)).

- If a dense mesh of microwave links is available, such as the backhauling links of a commercial cellular network, the 2D rain field can be generated over large areas through simple interpolation techniques (Overeem *et al*. (2013)).

Building further on the above hypotheses, MOPRAM will explore the following issues:

- Are simplified models used to convert microwave attenuation into rainfall accurate enough for the purposes of the project? Do these measurements permit to identify solid precipitation?
- Do relatively more complex techniques such as tomographic inversion improve substantially the 2D rain field pattern with respect to ordinary kriging used by Overeem *et al*. (2013)?
- Is there a minimum mesh density required for quantitative estimates of the spatial distribution of rain?
- Which is the impact of the 2D rain field obtained by the microwave network on the output of hydrological models?

3. Methodology

The outcomes of previous experimental campaigns will serve as useful preliminary information for addressing the critical aspects of the method, developing algorithms and comparing the results of MOPRAM. Two benchmark experiments will be considered here: first, the European Commission Framework V project MANTISSA (Microwave Attenuation as a New Tool for Improving Stormwater Supervision Administration), aimed at investigating the potential of microwave links for rainfall estimation, included extensive field campaigns in Germany and in Italy (MANTISSA (2004)). Second, the concept of a network of commercial links for 2D rain field reconstruction has been applied to map precipitation over the Netherlands by Overeem *et al*. (2013).

In order to meet the projects objectives, the scientific activities of MOPRAM are divided into three major workpackages as sketched in Figure 1. In WP1, we will start investigating the preliminary data available with three different aims. First, we will carry out data quality control, cross-validation of rain gauge datasets and comparison with disdrometer data, highlighting the issues related to the usage of each dataset. A preliminary set of microwave link data will be processed to elaborate signal models useful for extracting the meteorological information. Moreover, we will investigate the relation between microwave link attenuation and rain intensity considering different kinds of events (convective and stratiform rain and possibly solid precipitation) and testing different models for the drop size distribution (Cugerone and De Michele (2015)). Finally, the field trials will be planned: suitable areas will be identified and measurement requirements will be defined.

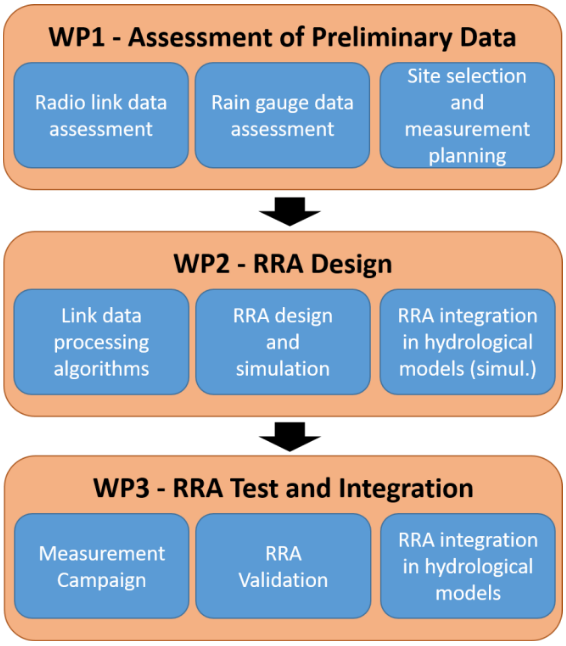

Figure 1. Breakdown structure of the scientific activity in the frame of MOPRAM project.

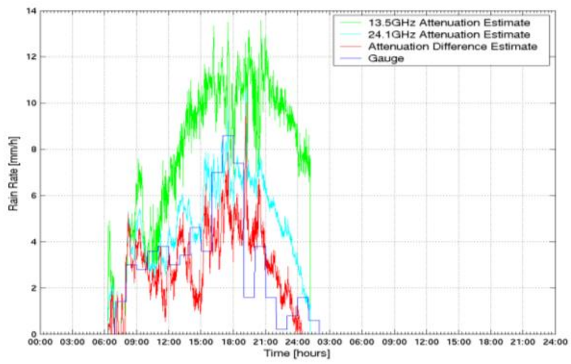

Figure 2. Time series of rain intensity estimated by a dual-frequency radio link as compared with that collected by a co-located rain gauge.

The theoretical principle behind the derivation of rain intensity from the signal transmitted through a microwave wireless link is the following: the received signal is rather stable in "clear sky" conditions (i.e. dry weather), hence it can be taken as the reference signal level. On the other side, when precipitation is present, part of the energy associated with the propagating electromagnetic wave is absorbed and scattered by the hydrometeors, which causes a reduction in the received signal strength (i.e. fading). The excess signal attenuation above the reference level can be related to the average rain rate intensity along the link. This task is not trivial, since a) the signal is affected by noise and disturbances and b) attenuation depends on rain intensity through a complex (and non-univocal) relation. However, by applying clever inversion algorithms, the problem can be effectively tackled. Figure 2 shows the time series of rain rate estimated from a dual-frequency radio link, compared with the one collected by a co-located rain gauge. As can be inferred from the figure, when two frequencies are available, the difference in attenuation between the two channels can be a better estimator of rain rate, since some sources of errors due to the uncertainties on the drop size distribution are removed. In WP2, we will design, implement, and test the Rain field Reconstruction Algorithm (RRA) - based on a tomographic inversion technique - within a controlled scenario, i.e. using synthetic rainfall fields gathered from an historical set of radar maps collected from the Spino d'Adda weather radar. As an example, Figure 3 shows a comparison between a 2D rain map obtained from radar measurements (top) and one generated by applying the tomographic technique on 252 simulated microwave links (bottom). In particular, the event shown was recorded by the Spino d'Adda radar on 11 August 1989; a total of 260 radar maps were acquired during this event, and they have been cumulated to obtain the total accumulated rain shown in Figure 3. We will perform a statistical analysis in order to test the agreement between the reconstructed rainfall fields and the radar rainfall fields (assumed as truth) investigating such issues as extremes (maximum and minimum values) and space-time intermittency (i.e., wet and dry areas) of the rain fields (Pavlopoulos and Gupta (2003)) and scale invariance (Pavlopoulos and Krajewski (2014)). Finally, the synthetic maps obtained by the RRA will be assimilated into hydrological models and the outputs will be checked against the ones obtained from the radar maps. Finally in WP3, we will apply the RRA to observed rainfall fields using the data collected during MOPRAM measurement campaigns. Six-month field trials have been scheduled over two test areas representative of different hydrological scenarios in Lombardy. The ground truth will be provided by selected rain gauge datasets and the use of disdrometers. The RRA-based maps of rainfall will feed different hydrological models (namely, GUH, HBV, TOPKAPI) with different level of complexity and description of the hydrological response, and the corresponding outputs will be compared with the ones obtained from classical inputs (McMillan *et al*. (2011)).

4. Conclusions

The multidisciplinary project MOPRAM intends to use new measurements deriving from a network of microwave radio links to improve the characterization of the space-time variability of rainfall and its impact on the flood response. MOPRAM is expected to contribute significantly beyond the state of the art in the area of hydrometeorology, with the following novel aspects: a) application of a tomographic inversion technique to the inverse problem of rain field reconstruction from a mesh of commercial microwave radio links, 2) investigation of space-time variability of precipitation in mountain areas through microwave radio links, and 3) assimilation of 2D rainfall estimates into hydrological models and comparison with the outputs gathered from classical inputs. The results of this project can help to address other problems, as the triggering of shallow landslides, or the soil erosion that is important for agricultural purposes. In addition, the methodology implemented in MOPRAM could be easily extended to other areas of Lombardy, or national territory, especially those being scarcely equipped, or completely ungauged (like small mountain basins), where the methodology is particular appealing.

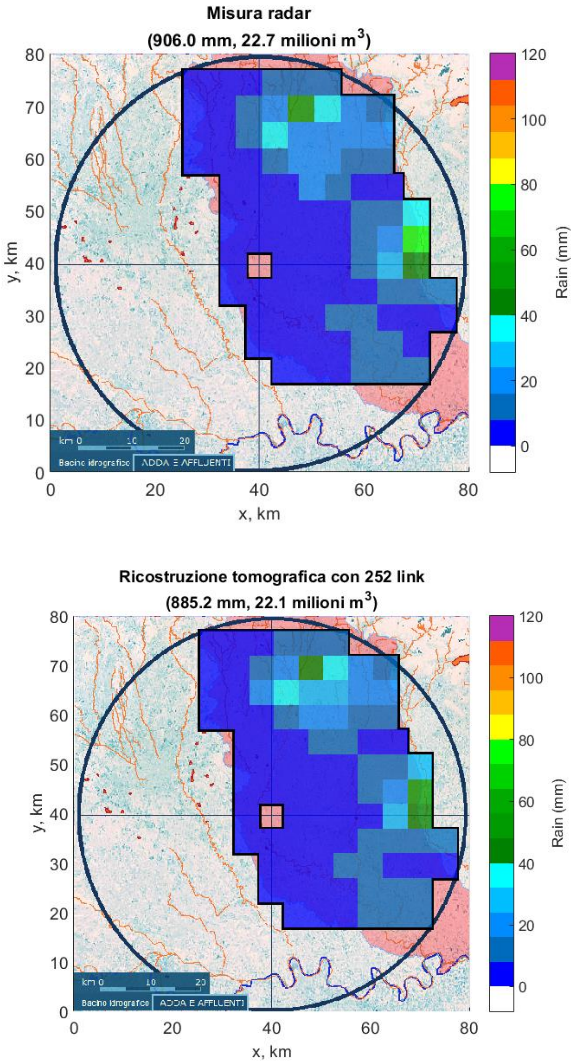

Figure 3. Comparison between a 2D rain map obtained from radar measurements (top) and one generated by simulating a number of microwave link across the test area (bottom).

Acknowledgement

The authors are grateful to Fondazione Cariplo for funding the MOPRAM project.

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