



International Conference on Opportunistic Sensing of Precipitation

Wednesday, June 25, 2025 - Thursday, June 26, 2025

German Weather Service, Offenbach, Germany

<https://indico.kit.edu/event/4624/>

Book of Abstracts

www.opensenseaction.eu

This publication is based upon work from COST Action CA20136, supported by COST (European Cooperation in Science and Technology).

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation.



www.cost.eu

Book of abstracts from **1st International Conference on Opportunistic Sensing of Precipitation - OpenSense** organized by Deutscher WetterDienst, Offenbach, Germany.
Editors: Vojtěch Bareš, Maxmilian Graf, Jonatan Ostromet-zky

Contents

Program and local organizing committees	1
Keynotes	2
Opportunistic weather observations in EUMETNET: past, present and future	2
Enhancing Numerical Weather Prediction with Opportunistic and Crowdsourced Observations: Insights from NetAtmo and Microwave Link Assimilation	2
AI in hydrometeorological applications: From now-casting to climate modeling	3
Opening and welcome session	4
Oral Session #1: Processing methods	5
Enhancing Quantitative Precipitation Estimation in Urban Areas Using IoT Sensors and Radar Data	5
Enhanced quantitative rainfall estimation using dual-channel TV-SAT microwave links: Progress and Experimentation	7
Improved CML-derived rainfall maps at city scale by introducing quality control algorithms	8
Rain Estimation Over a Region Using CycleGan	9
Oral Session #2: Bridging the gap	10
Commercial Microwave Links for Precipitation Monitoring: The Experience of Arpae-SIMC in Emilia-Romagna	10
Potential applications of opportunistic sensing data in operational precipitation products at Deutscher Wetterdienst - from first steps to visions	11
Oral Session #3: OS data merging	12
Disaggregating path-averaged rain rate estimates from commercial microwave links with multiplicative random cascade model	12
Temporal Super-Resolution, Ground Adjustment and Advection Correction of Radar Rainfall using 3D-Convolutional Neural Networks	13
Weather radar adjustment with commercial microwave links at DWD	14
Merging weather radar fields with data from commercial microwave links using mergeplg	15
The EURADCLIM gauge-adjusted radar precipitation dataset	16
Oral Session #4: Comparative performance analysis and uncertainty assessment	17
Comparison between terrestrial and satellite microwave links as opportunistic rainfall sensors	17

Exploring Rain Scintillation Spectra from Microwave Links for Raindrop Size Distribution Retrieval . . .	18
Insights in the rainfall dynamics preceding and during the 29 October 2024 Valencia floods using rainfall observations from personal weather stations	19
Do citizen science data improve the reconstruction of heavy rainfall events?	20
Oral Session #5: Application of OS rainfall data	21
Applications of opportunistic rainfall observations: a review	21
Precipitation field reconstruction and tracking using opportunistic rain sensors: the Summer 2021 catastrophic event in Germany as a case study	22
Exploiting a dense Commercial Microwave Link (CML) network in Nigeria for high-resolution near-surface rainfall estimates	23
Runoff predictions in combined sewer system of the city of Prague using raw attenuation data from commercial microwave links	24
Large-scale hydrological modeling with CML rainfall data	25
Flood forecasting based on personal weather station rainfall data	26
Poster Session #1	27
ISRaCML	27
OpenMesh: Wireless Signal Dataset for Opportunistic Urban Weather Sensing in New York City	28
Rainfield Monitoring and Extracting Natural Phenomena Combining CML with Graph Signal Processing	29
Unsupervised Fault Detection and Classification in Microwave Links for Opportunistic Weather Detection: Differentiating Weather-Induced and Non-Weather Faults	30
Optimizing Wet Antenna Attenuation Models for Improved Rainfall Estimation Using Commercial Microwave Links	31
The OPENSENSE software ecosystem	32
Citizen observations via the RMI smartphone app in Belgium: data collection and applications	33
Sensing from the Grassroots: How Environmental Measurement Software is Being Developed by Citizen Scientists	34
Satellite microwave link open data for rainfall estimation	35
Refining baseline and wet antenna models for improved rainfall estimation from CML data	36
Beyond Cellular Networks: Rainfall Estimation Using Low-Frequency and Short-Distance Commercial Microwave Links	37
Improving Precipitation Estimates from Commercial Microwave Links Using Deep Learning: A Comparative Study on OpenMRG Data	38
. GNN-Based Data Fusion for Precipitation Estimation Using Opportunistic Sensors	39
A toolbox for real time data acquisition and quality control of personal weather station rainfall data	40
Publicly available four-year CML dataset for the Netherlands	41
pypwsqc: A new tool for quality control of personal weather station data rainfall data	42
Poster Session #2	43

Periodic Noise	43
What you should be aware of when nowcasting rainfall in the tropics using CML-based rainfall estimates only	44
Relationship between Precipitable Water Vapor and heavy rainfall over Lombardy region in Northern Italy using GNSS and CML sensors network	45
Evaluation of the Dutch real-time radar precipitation product	46
Can we estimate the amount of rain water during disastrously large flood events with high resolution? . .	47
Commercial Microwave Link research at the Climate and Earth Lab (Ghent University)	48
Added value of Personal Weather Stations for Precipitation Estimates in the Lazio Region, Italy	49
Using Commercial Microwave Links to Estimate Rainfall Intensity and Variability in Rwanda	50
E-band rainfall observation: uncertainties in quantitative measurements and long-term statistics of outages	51
Enhancing Dry-Wet Classification in CML/SML Time Series by Integrating NWC-SAF PC Products and Commercial Microwave Links with Cloud Microphysical Satellite Data	52
Opportunistic rainfall observations in Gothenburg, Sweden: open data and real-time service	53
Including PWS gauge data in radar merging improves real-time precipitation estimates: Methodology and 1-year evaluation for the Netherlands	54
Hydro-Climatological Thresholds to Enhance Early Warning Systems for Landslides in Rwanda	55

Program and local organizing committees

Program Committee

Chair

Vojtěch Bareš (Czech Technical University, Prague, Czech Republic)

Vice-Chairs

Hagit Messer-Yaron (Tel Aviv University, Tel Aviv, Israel)

Tanja Winterrath (Deutscher Wetterdienst, Offenbach, Germany)

Members

Christian Chwala (Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany)

Martin Fencel (Czech Technical University, Prague, Czech Republic)

Filippo Giannetti (University of Pisa, Pisa, Italy)

Marielle Gosset (IRD/CNRS/Université Toulouse III/CNES, Toulouse, France)

Maximilian Graf (Deutscher Wetterdienst, Offenbach, Germany)

Congzheng Han (Institute of Atmospheric Physics Chinese Academy of Sciences, Beijing, China)

Roberto Nebuloni (National Research Council of Italy, Milano, Italy)

Jonatan Ostrometzky (Tel Aviv University, Tel Aviv, Israel)

Aart Overeem (Royal Netherlands Meteorological Institute, De Bilt, The Netherlands)

Magdalena Pasierb (National Research Institute, Warsaw, Poland)

Jochen Seidel (University of Stuttgart, Stuttgart, Germany)

Flavia Tauro (University of Tuscia, Viterbo, Italy)

Remko Uijlenhoet (TU Delft, Delft, The Netherlands)

Remco Van de Beek (Swedish Meteorological and Hydrological Institute, Norrköping, Sweden)

Local Organizing Committee

Matthias Gottschalk (Deutscher Wetterdienst, Offenbach, Germany)

Maximilian Graf (Deutscher Wetterdienst, Offenbach, Germany)

Natalia Hanna (TU Vienna, Vienna, Austria)

Petra Koudelová (Czech Technical University, Prague, Czech Republic)

Tanja Winterrath (Deutscher Wetterdienst, Offenbach, Germany)

Keynotes

#1: Opportunistic weather observations in EUMETNET: past, present and future

Speaker: Alex Priestley

Opportunistic observations form an important part of the networks operated by EUMETNET. Some of these observations are now mature operational networks, giving important benefits to weather forecasting models, such as GNSS-derived water vapour measurements and derived aircraft observations. Other sources of information, such as personal weather station data, are used widely on a national basis, but unlocking their wider benefits is currently held back by the ability to share data across Europe. In this talk I will cover some of EUMETNET's past work to help exploit opportunistic observations across Europe, and some plans for future opportunistic data use including webcams and smartphone data.

#2: Enhancing Numerical Weather Prediction with Opportunistic and Crowdsourced Observations: Insights from NetAtmo and Microwave Link Assimilation

Speaker: Stefanie Hollborn

The integration of opportunistic and crowd sourced observations into numerical weather prediction (NWP) presents a promising path toward enhancing high-resolution, short-term forecasting.

This talk explores the potential of crowd-sourced weather data—specifically from NetAtmo personal weather stations and Commercial Microwave Links (CMLs)—to improve NWP skill.

We will present findings from two recent research projects that evaluate the assimilation of these novel data sources using state-of-the-art ensemble data assimilation systems.

First, results from a study on NetAtmo near surface temperature and humidity observations demonstrate the added value of high-density data in regional NWP

through assimilation into the convection-permitting ensemble system ICON-D2 with the KENDA data assimilation framework.

Assimilating NetAtmo with proper quality control and bias corrections shows a positive impact, underlining the feasibility and benefit of integrating citizen weather observations into operational systems.

Second, we report on the RealPEP project, which focuses on assimilating CML attenuation data as a proxy for path-averaged rain rates.

Using the ICON-D2 model and EMVORADO radar forward operator, CML-specific attenuation is assimilated via the Localized Ensemble Transform Kalman Filter (LETKF).

Case studies and statistical evaluation reveal that CML assimilation effectively enhances convective initiation and short-term precipitation forecast skill.

Improvements in fractional skill scores (FSS) for radar reflectivity forecasts further quantify these benefits.

Together, these results underscore the growing importance of opportunistic sensing—both crowd-sourced and infrastructure-derived—in modern meteorology, providing valuable complementary information in data-sparse regions and enhancing the resilience of forecasting systems.

#3: AI in hydrometeorological applications: From now-casting to climate modeling

Speaker: Li-Pen Wang

In recent years, Artificial Intelligence (AI) has led to significant breakthroughs across many research fields, including hydrometeorology. However, its broader application remains constrained by its “black box” nature. In this talk, Dr Li-Pen Wang will present his team’s latest work on developing data-driven approaches to tackle hydrometeorological challenges. He will highlight how AI can enhance radar rainfall estimation and now-casting, and how it can help bridge climate dynamics with local rainfall modeling. Dr Wang will also explore how OpenSense project can open new opportunities with help from AI for future research.

Opening Welcome Session

Speaker: Maximilian Graf

The OpenSense network - ideas, goals and achievements

Speakers: Vojtech Bares and Hagit Messer

WG1 on data management and standardization

Speakers: Roberto Nebuloni and Martin Fencel

WG2 on method and software homogenisation

Speakers: Christian Chwala and Aart Overeem

WG3 on merging and application

Speakers: Maximilian Graf, Jonas Olsson and Remko van de Beek

Oral session #1: Processing methods

Session Chair: Filippo Giannetti

Enhancing Quantitative Precipitation Estimation in Urban Areas Using IoT Sensors and Radar Data

Authors: Thomas Einfalt¹; Annika Jahnke-Bornemann¹; Bruno Castro¹; Philipp Lampert¹

¹ *hydro & meteo GmbH*

Corresponding Authors: b.castro@hydrometeo.de, einfalt@hydrometeo.de, p.lampert@hydrometeo.de, a.jahnke-bornemann@hydrometeo.de

In the city of Lübeck, 50 optical sensors from NIVUS were installed as part of the mFund project heavyRAIN. These measurements, combined with radar-derived precipitation data, aim to improve quantitative precipitation estimation (QPE) through additional information from many measurement points (Einfalt et al., 2024). A key aspect of the study was the careful selection of sensor locations to optimize data quality in the challenging urban environment. To achieve this, a set of quality criteria was defined to guide the placement of the sensors (Jahnke-Bornemann & Einfalt, 2023). Together with the radar measurements, these measurements serve to better understand the spatial and temporal relationships between radar and ground measurements during heavy rainfall events. This leads to an improvement of the adjustment by estimating the adjustment error in space and time.

Heavy rainfall events often exhibit high spatial gradients in radar measurements due to small-scale precipitation cells. Since radar measures precipitation at altitudes ranging from several hundred meters to a few kilometres, two critical questions arise:

- When does the precipitation measured at higher altitudes reach the ground? Depending on the altitude and droplet size, which determines the fall velocity, raindrops can take up to 10 minutes to reach the surface (WMO, 2024).
- Where does the precipitation reach the ground? Wind conditions between the radar measurement height and the surface can cause precipitation to drift horizontally, sometimes over distances equivalent to the measurement altitude (Lack & Fox, 2007).

A comparison with a ground-based measurement network, such as the IoT sensor system, can help address these questions. The study involved a comprehensive quality assessment by classifying IoT sensor precipitation data into seven categories and comparing them with radar pixels at the corresponding locations. Initial efforts focused on handling data gaps and erroneous values in the IoT measurements. Subsequently, an extensive spatiotemporal analysis was conducted using a data cube approach to improve the correlation between radar and sensor data. The data can be shifted spatially and temporally in the data cube.

The findings demonstrate that integrating IoT sensors with radar data enhances the knowledge on small-scale rainfall patterns. The improved correlation between ground and radar measurements supports the development of more accurate adjustment techniques. These results contribute to the advancement of high-resolution precipitation monitoring and, as a consequence, forecasting in complex urban environments.

Literature

Einfalt, T., Jahnke-Bornemann, A., Jasper-Tönnies, A., Kupzig, J., Neumann, J., Oppel, H. (2024) Weather radar and IoT sensor networks: which information from which source? Book of Abstracts, International Conference on Urban Drainage ICUD 2024, Delft. https://www.hydrometeo.de/wp-content/uploads/202406_ICUD_IoT_sensors_Poster.pdf (besucht am 26.02.2025)

Jahnke-Bornemann, A. and Einfalt, T. (2023) heavyRain - Use of IoT rain sensors to improve heavy rain forecasts in Lübeck. UrbanRain23 Book of Abstracts, P. Molnar, Switzerland, <https://ethz.ch...BOOK-OF-ABSTRACTS.pdf> (besucht am 26.02.2025)

WMO (2024): WMO Guide to Operational Weather Radar Best Practices, WMO-No. 1257. <https://community.wmo...>
(besucht am 28.11.2024)

Lack, S. A., & Fox, N. I. (2007). An examination of the effect of wind-drift on radar-derived surface rainfall estimations. *Atmospheric Research*, 85(2), 217–229.

Enhanced quantitative rainfall estimation using dual-channel TV-SAT microwave links: Progress and Experimentation

Authors: Aymeric CHAZOTTES¹; Cecile MALLET¹; François Mercier-Tigrine²; Laurent BARTHES¹; Louise Gelbart²; Maxime Turko²; Nicolas VILTARD¹

¹ LATMOS

² HD Rain

Corresponding Authors: cecile.mallet@latmos.ipsl.fr, maxime.turko@hd-rain.com,

louise.gelbart@hd-rain.com, francois.mercier@hd-rain.com, nicolas.viltard@latmos.ipsl.fr,

laurent.barthes@latmos.ipsl.fr, aymeric.chazottes@latmos.ipsl.fr

Opportunistic remote sensing with TV-satellite microwave links (SML) in the Ku-band offers a promising approach for rainfall estimation by leveraging signal attenuation as an indicator of rainfall intensity. However, a key challenge remains: differentiating rain-induced attenuation from atmospheric induced noise.

In this study, we use SML to evaluate their ability to retrieve rainfall rates, by taking into account the emission of the atmospheric background noise. This method exploits signal variation of two distinct frequency channels coming from the same satellite - one with full-band satellite transmission, and the other without any signal emitted on the band. In this latter case, the receiver behaves like a radiometer, capable of measuring atmospheric radiation. To implement this approach, we establish a baseline for each channel (i.e., its signal level in dry conditions), which is automatically determined using a deep learning binary classification model. Additionally, we apply corrections for wet antenna, which significantly impacts light rainfall estimates, as well as for attenuation effects in the melting layer.

We apply this dual-channel measurement approach at Cadarache, France, where seven Ku-band sensors are co-located with six rain gauges. This setup allows for detailed validation of rainfall. Preliminary results indicate strong consistency between the rain gauge and the Ku-band sensors with dual channel method applied. The corrections for wet antenna and the melting layer effectively mitigate their respective biases, though further investigation is needed to refine their parameterization. The dual-channel algorithm produces highly consistent and unbiased results across the rainfall intensity range, significantly improving accuracy. In contrast, the standard method underestimates heavy rainfall by ignoring atmospheric radiation effects.

In addition, we will present the experiment that we have recently set up on the SIRTa platform observation in Palaiseau, France, to further refine our understanding of the factors influencing rainfall estimation with satellite microwave links. Three Ku-band sensors have been installed close to several disdrometers, rain gauges, the 95 GHz BASTA cloud radar, and, above all, the 9.4 GHz ROXI rain radar aimed in the same direction as the sensors. The objective is to better quantify uncertainties in our measurements, particularly related to melting layer height and thickness, drop size distribution, and vertical and horizontal heterogeneity of rain. These experiments will help improve error correction strategies and enhance the reliability of precipitation retrieval from TV-SAT links.

Improved CML-derived rainfall maps at city scale by introducing quality control algorithms

Author: Xin Zheng¹

Co-authors: Anna Špačková²; Martin Fencl²; Vojtěch Bareš²

¹ Hohai University, Nanjing, China

² Czech Technical University In Prague, Czech Republic

Corresponding Author: baresvoj@cvut.cz

The use of opportunistic sensing (OS) devices for rainfall monitoring, such as commercial microwave links (CMLs), has attracted the attention of urban hydrologists and drainage engineers in the recent decade. However, the devices are neither originally designed for rainfall monitoring nor properly maintained or installed. Therefore, they can be affected by various factors other than rainfall, such as environmental conditions and technical issues and thus appropriate quality control (QC) is essential. By implementing QC, potential errors and uncertainties in the data can be identified and corrected, and the accuracy and precision of the estimated rainfall fields can be improved.

Previous studies suggested QC algorithms for single links (SL) removing artefacts from the time series of their signal levels leading to improved rain rate estimates and more accurate reconstructed rainfall maps. In this study, we propose a QC method relying on neighbouring links (NL) and compare it with SL algorithm at city scale with high density of CMLs and short correlation lengths. We also investigate the synergy of simultaneously utilizing both QC methods for short time steps of 5 minutes.

A dataset of CML measurement was obtained from the T-Mobile network in Prague, Czech Republic. The selected period is between July 2014 and September 2014. The CML network has 173 links. Two datasets were used as the reference. The first reference dataset was generated by interpolating the measurements from 23 local RGs using the inverse distance weighting. The second dataset consisted of C-band radar data that was adjusted using the measurements from these 23 RGs.

The overall results show clear improvements of performance metrics when combining both QC algorithms. For validation period RMSE decreased from 2.38 to 1.57 mm/h and Pearson correlation increased from 0.45 to 0.74. The results demonstrate that NL method can be effectively applied for CML-derived rainfall estimates, resulting in larger data availability compared to SL method. NL performs better than SL when the CML density is high, and the superiority diminishes as the CML density decreases. Simultaneously applying both types of QC methods can further reduce errors in the results, but there may be a trade-off with data availability. The results also indicate that performing simple QC operations on the CML measurement before applying NL can retain more data while achieving favourable results. The findings of this study provide guidance for improving the accuracy of retrieval and rain field reconstruction results.

Rain Estimation Over a Region Using CycleGan

Authors: Hagit Messer¹; Jonatan Ostrometzky¹; Sagi Timinsky¹

¹ *School of Electrical and Computer Engineering, Tel Aviv University*

Corresponding Author: sagitiminsky@gmail.com

Accurately measuring rainfall is essential for weather forecasting, flood prediction, and water resource management. Traditional methods rely on rain gauges for direct measurements, radar systems for broader coverage and satellites. However, these methods face challenges due to sparse sensor distribution and data coverage.

A promising alternative is using wireless commercial microwave links (CMLs)—the infrastructure behind cellular networks. CMLs experience signal attenuation when it rains, allowing them to serve as cost-effective, high-resolution rainfall virtual sensors. However, current training machine learning models require paired CML-rain gauge data, which limits their applicability due to missing or misaligned measurements.

To overcome this limitation, we propose a CycleGAN-based framework that enables rainfall estimation without requiring paired datasets. Instead of relying on direct matches between CMLs and rain gauges, our method learns the relationship between the two through an unpaired training strategy. We introduce two mapping functions:

- $G:A \rightarrow R$ (Converts attenuation to rain rate).
- $F:R \rightarrow A$ (Converts rain rate to attenuation).

By enforcing cycle consistency, the model ensures that translating between the two domains preserves data structure, even in the absence of direct pairing between a CML and a gauge.

Our method offers several key advantages:

- Works with missing or sparse data.
- Adapts to different regions without direct alignment.
- Enhances rain estimation accuracy with a built-in detector.

We evaluated our approach on real-world CML datasets and rain gauge data from Israel and the Netherlands, demonstrating high accuracy in estimating accumulated rainfall, especially in heavy rain events.

This framework expands the capabilities of deep learning for rainfall estimation by enabling models to learn from unpaired datasets. It provides a scalable and flexible solution that overcomes the limitations of traditional supervised approaches.

Oral session #2: Bridging the gap

Session Chair: Remko Uihlenhoet

Commercial Microwave Links for Precipitation Monitoring: The Experience of Arpae-SIMC in Emilia-Romagna

Author: Elia Covi¹

Co-author: Giacomo Roversi²

¹ *Arpae-SIMC, Bologna (IT)*

² *Ca' Foscari University of Venice and CNR-ISAC Rome (IT)*

Corresponding Authors: ecovi@arpae.it, g.roversi@isac.cnr.it

Commercial Microwave Links (CML) offer advantageous properties compared to conventional sensors: they provide greater spatial representativeness than individual rain gauges and are positioned closer to the ground than the atmospheric volumes observed by weather radars. Moreover, CMLs are monitored in real time, and a well-designed opportunistic dataset can achieve latencies of less than 15 minutes. These factors make a CML network a valuable operational tool for precipitation measurement.

This objective is being pursued in Emilia Romagna (Italy) by Arpae-SIMC, through the activities of the EU LIFE CLIMAXPO project and the MODMET agreement between Arpae-SIMC and the Italian Civil Protection Department.

Real-time CML data are acquired and stored from the Hydro-Meteorological and Climate Structure of the Region (Arpae-SIMC). The data are shared by the company Lepida ScpA and consist of couples of instantaneous transmitted (TSL) and received (RSL) signal power levels (expressed in dBm) at one minute resolution, integrated by metadata about the locations of the antennas and the signal properties.

The purpose of this presentation is to report the experience developed within our regional weather service regarding the use of CMLs. In detail, it is intended to show the details of CML acquisition and related difficulties; the activities of the projects involved, in relation to the techniques developed within the COST action OPENSENSE.

Potential applications of opportunistic sensing data in operational precipitation products at Deutscher Wetterdienst –from first steps to visions

Author: Tanja Winterrath¹

Co-authors: Maximilian Graf¹; Hannes Konrad¹; Markus Ziese¹

¹ *Deutscher Wetterdienst*

Corresponding Authors: tanja.winterrath@dwd.de, maximilian.graf@dwd.de, markus.ziese@dwd.de, hannes.konrad@dwd.de

High-quality precipitation analyses represent key operational products of national meteorological services that serve several applications spanning from weather prediction, flood forecasting, and drought monitoring to disaster management and climate change studies. In Germany, the Deutscher Wetterdienst (DWD) plays a major role in providing regional to global scale quantitative precipitation estimates (QPE) for real-time applications as well as climatological analyses. All these products rely on ground-based precipitation measurements for either interpolation, adjustment, or validation. Opportunistic sensors (OS) - not originally designed for high-quality hydrometeorological observations - such as commercial microwave links (CML) and private weather stations (PWS) increase the density of ground-based sensors and may therefore constitute an important additional source of information that is still neglected in most operational data products.

We will introduce exemplary DWD precipitation products and discuss the yet identified and potential benefits, respectively, of considering OS data: a radar-based QPE for real-time and climate applications (RADOLAN/RADKLIM), the Global Precipitation Climatology Centre's (GPCC) gridded products based on interpolated station data, and the solely satellite-retrieved precipitation estimate GIRAFE.

The radar-based QPE products RADOLAN and RADKLIM use ground-based observations to adjust remotely-sensed indirect information to quantitative precipitation values. Classical pluviometers, however, due to the relatively low network density miss a significant fraction of local heavy precipitation events. Within the project HoWa-PRO, DWD has established a multi-source data merge including CML data to overcome this limitation and provide improved QPE to the flood forecasting centers of the German federal states in charge.

GPCC operates under the auspices of the World Meteorological Organization (WMO) collecting and archiving world-wide station data, performing quality control, and providing interpolated gridded precipitation fields and derived products for monitoring as well as climate change studies. Together with an increasing demand for higher temporal and spatial resolution a high spatial density of observations becomes more important - especially in data-sparse regions. A complementary inclusion of OS data is a promising option to support this plan.

GIRAFE is a solely satellite-based precipitation estimate by the EUMETSAT Climate Monitoring Satellite Application Facility (CM-SAF) operating at DWD. GIRAFE uses ground-based precipitation data for validation purposes. As validation is challenging in data-sparse regions like e.g. on the African continent, OS data may serve as additional ground truth for product quality measures.

Oral session #3: OS data merging

Session Chair: Jonas Olsson

Disaggregating path-averaged rain rate estimates from commercial microwave links with a multiplicative random cascade model

Author: Martin Fencel¹

¹ *Czech Technical University in Prague*

Corresponding Author: martin.fencel@cvut.cz

Commercial microwave links (CMLs) measure total attenuation along their path. Thus when used as opportunistic sensors, they provide path-averaged rainfall estimates. This poses a challenge for rainfall map reconstruction and potentially for rainfall estimation itself, as the conversion of attenuation to rain rate implicitly assumes uniform rainfall along the CML path.

We propose a new algorithm called CLEAR (CML Segments with Equal Amount of Rainfall) for disaggregating path-integrated rain rates along a CML path using a multiplicative cascade model. This model redistributes rain rates by successively dividing the CML into segments with equal rainfall amounts but varying segment lengths. The redistribution is driven by a cascade generator, with variance dependent on the rain rate of the parent segment and its length. Spatial consistency of the disaggregated rain rates across the entire network is ensured by a spatial coherence rule, which determines which segment receives a higher rain rate using information from neighbouring CMLs. The algorithm is tested on CML path-averaged rain rates obtained from 210 virtual rainfall fields, simulated for a real network topology in Prague, CZ, consisting of 67 CMLs. In addition, the performance of the algorithm is demonstrated in a case study where real observations from the same CML network are used.

The CLEAR algorithm is efficient in estimating rainfall maxima and minima along a CML path, achieving RMSE values of 2.8 and 1.3 mm/h, respectively, compared to 4.7 and 3.5 mm/h for the original path-averaged rain rates. It also outperforms the benchmark GMZ algorithm, which has for estimated rain rate maxima and minima along a CML path RMSE values of 6.8 and 1.8 mm/h, respectively. While the results are slightly worse when considering the exact position of the disaggregated rain rates, CLEAR still outperforms GMZ in this aspect. Additionally, due to the stochastic nature of multiplicative cascades, CLEAR is capable of providing uncertainty estimates. The evaluation shows that CLEAR tends to underestimate uncertainty, as reflected in the width of the uncertainty bands. This is partly due to shortcomings in reproducing rainfall intermittency and partly because the ensemble variance is driven by a cascade generator model that does not account for uncertainties in the spatial coherence rule.

Multiplicative cascades used in the CLEAR algorithm have proven to be efficient for 1D disaggregation and are applicable even for sparse CML networks. However, further research is needed to enhance CLEAR's uncertainty estimation and improve the estimation of rainfall intermittency.

Temporal Super-Resolution, Ground Adjustment and Advection Correction of Radar Rainfall using 3D-Convolutional Neural Networks

Author: julius polz¹

Co-authors: Christian Chwala²; Harald Kunstmann²; Hiob Gebisso²; Luca Glawion²; Lukas Altenstrasser²; Maximilian Graf³; Stefanie Vogl⁴

¹ *KIT/IMK-IFU*

² *KIT (IMK-IFU)*

³ *Deutscher Wetterdienst*

⁴ *OTH Regensburg*

Corresponding Authors: harald.kunstmann@kit.edu, h-gebisso@t-online.de, christian.chwala@kit.edu, maximilian.graf@dwd.de, julius.polz@kit.edu, stefanie.vogl@oth-regensburg.de, luca.glawion@kit.edu, lukas.altenstrasser@hm.edu

Ground-adjustment of weather-radar derived precipitation information is a common practice to correct for a variety of errors related to for example advection, size sorting or melting processes. Historically, this is mainly achieved by using point-like rain gauge observations which have a high temporal resolution and accuracy, but lack spatial representativeness and observation density, e.g. with one rain gauge per 330km² in Germany. In this study, we combine two novel approaches to enhance quantitative precipitation estimation (QPE) with weather radars.

First, we use Commercial Microwave Links (CMLs) as an additional source of information. CMLs provide path-integrated attenuation estimates close to the ground which yields a higher spatial representativeness than rain gauges. Due to their large abundance, they also largely increase the density of near-ground observations.

Second, we present a novel probabilistic deep-learning-based framework to combine radar, rain gauge and CML data. The presented perceiver architecture is generic and can easily be extended by additional input modalities.

Our study is based on the RADOLAN-RY precipitation product, derived from the C-band radar network of the German Weather Service (DWD), and a German-wide CML network with 3900 link paths. The results are compared to ResRadNet [1](#), a deep-learning model that only relies on radar input for ground-adjustment.

Weather radar adjustment with commercial microwave links at DWD

Author: Maximilian Graf^{None}

Co-authors: Christian Chwala¹; Malte Wenzel; Matthias Gottschalk²; Tanja Winterrath; julius polz³

¹ *KIT (IMK-IFU)*

² *Deutscher Wetterdienst*

³ *KIT/IMK-IFU*

Corresponding Authors: julius.polz@kit.edu, malte.wenzel@dwd.de, tanja.winterrath@dwd.de, matthias.gottschalk@dwd.de, maximilian.graf@dwd.de, christian.chwala@kit.edu

Weather radars provide high-resolution precipitation data but are subject to uncertainties due to their indirect measurement high above ground. To improve data quality, national meteorological services calibrate radar observations using ground-based station measurements for both operational and climatological applications. The emergence of opportunistic sensors (OS), data sources not originally designed for high-quality hydrometeorological observations, such as commercial microwave links (CML) and private weather stations (PWS), offers the potential to increase the density of ground-based sensors for the radar adjustment.

As part of the HoWa-PRO project, the Deutscher Wetterdienst, in collaboration with Ericsson, has established a real-time CML data flow for radar adjustment. To facilitate this, the Python framework pyRADMAN was developed, enabling low-latency merging of radar, station, and CML data. Built upon the existing RADOLAN methodology, pyRADMAN extends its capabilities by incorporating CML observations and testing advanced methods such as kriging with external drift, conditional merging, and radar pre-correction techniques. These enhancements improve precipitation estimates and reduce latency compared to traditional RADOLAN products, tested up to a temporal resolution of 15 minutes.

Looking ahead, the modular architecture of pyRADMAN enables the seamless implementation of future calibration techniques. The integration of opportunistic sensor data gives opportunities for accurate, high-resolution precipitation estimation, both in an operational and research setting.

Merging weather radar fields with data from commercial microwave links using *mergeplg*

Authors: Erlend Øydvin¹; Maximilian.Graf@dwd.de Graf^{None}; Christian Chwala^{None}; Elia Covi^{None}

¹ NMBU

Corresponding Authors: erlend.oydvin@gmail.com, christian.chwala@kit.edu,
maximilian.graf@dwd.de, elia.c.covi@gmail.com

Quantitative precipitation estimates are important for monitoring the water balance. Consequently, there exists a wide range of rainfall measurement methods. Weather radar has good spatial coverage, but the estimates can be biased. Ground observations, like rain gauges and commercial microwave links (CMLs), provide more accurate estimates, but have less good spatial coverage. Adjusting the weather radar field to fit the ground observations (merging) can provide more accurate rainfall precipitation fields.

Within OPENSENSE we have developed a python package, *mergeplg*, that implements different methods for merging weather radar fields to ground observations. In this work we provide results and insights from merging weather radar data to ground observations, with a focus on CML data, using two open access datasets OpenMRG and OpenRainER. In general, CMLs improve the raw radar estimates for both datasets.

The EURADCLIM gauge-adjusted radar precipitation dataset

Author: Aart Overeem¹

Co-authors: Else van den Besselaar ¹; Gerard van der Schrier ¹; Jan Fokke Meirink ¹; Emiel van der Plas ¹; Irene Garcia-Marti ¹; Lotte de Vos ¹; Hidde Leijnse ¹

¹ *Royal Netherlands Meteorological Institute*

Corresponding Authors: irene.garcia.marti@knmi.nl, emiel.van.der.plas@knmi.nl,

gerard.van.der.schrier@knmi.nl, overeem@knmi.nl, hidde.leijnse@knmi.nl,

lotte.de.vos@knmi.nl, jan.fokke.meirink@knmi.nl, else.van.den.besselaar@knmi.nl

EURADCLIM is a publicly available climatological dataset of 1-h and 24-h precipitation accumulations covering Europe at a 2-km grid over the period 2013 –2022. It is based on the surface rain rate composites from the EUMETNET programme OPERA. Algorithms are applied to remove remaining non-meteorological echoes as much as possible. The 1-h accumulations are merged with rain gauge accumulations from the European Climate Assessment & Dataset (ECA&D). Details on the employed datasets and algorithms are presented. The quality and shortcomings of EURADCLIM version 2 (<https://doi.org/10.21944/ymrk-mr24>) are assessed by comparisons to (independent) rain gauge data and are presented by means of scatter density plots, a spatial verification, and case studies. EURADCLIM clearly has a higher quality than the original OPERA product. The potential of EURADCLIM for deriving a pan-European precipitation climatology is shown.

EURADCLIM could serve as a reference dataset for precipitation estimates from opportunistic sensing. We demonstrate this by comparing a merged dataset based on radar (the OPERA product) and rain gauge data from personal weather stations (PWSs) over Europe to version 1 of EURADCLIM. The results show a better agreement of the merged dataset with the EURADCLIM ground truth than the version without PWS data, thus highlighting the potential of crowdsourced rain gauge data for improving radar precipitation products.

Finally, the newest findings from research and development on EURADCLIM are presented including what can be expected from version 3.

Oral session #4: Comparative performance analysis and uncertainty assessment

Session Chair: Remko Uijlenhoet

Comparison between terrestrial and satellite microwave links as opportunistic rainfall sensors

Authors: Filippo Giannetti¹; Fabiola Sapienza¹; Vincenzo Lottici¹; Giovanni Scognamiglio²; Attilio Vaccaro²; Elia Covi³; Carlo De Michele⁴; Christian Gianoglio⁵; Matteo Colli⁶; Roberto Nebuloni⁷

¹ *Department of Information Engineering, University of Pisa*

² *MBI*

³ *Arpae-SIMC*

⁴ *Politecnico di Milano*

⁵ *Department of Naval, Electrical, Electronic and Telecommunications Engineering, University of Genoa*

⁶ *Artys, Darts Engineering Srl*

⁷ *CNR*

Corresponding Authors: roberto.nebuloni@cnr.it, gscognamiglio@mbigroup.it, avaccaro@mbigroup.it, carlo.demichele@polimi.it, m.colli@artys.it, fabiola.sapienza@ing.unipi.it, vincenzo.lottici@unipi.it, ecovi@arpae.it, christian.gianoglio@unige.it, filippo.giannetti@unipi.it

The backhauling links of terrestrial wireless networks (Commercial Microwave Links, CMLs) and the downlink of satellite broadcasting/broadband services (Satellite Microwave Links, SML) operating in the Ku-band and above, say >10 GHz, proved effective opportunistic systems for rainfall sensing. CMLs and SMLs exhibit, indeed, features that make them suitable to complement conventional measurements carried out by rain gauge networks, weather radars, and Earth observation satellites. Based on the experience achieved by several research teams active on this topic in Italy since 2017, this paper compares CMLs and SMLs as opportunistic rainfall sensors from different perspectives. We address technical aspects (complexity of data acquisition and processing), performance (spatio-temporal resolution, accuracy, sensitivity and benefits brought by AI techniques), data accessibility and ownership, and deployment and operational costs. Finally, the perspectives of such opportunistic sensors and their potential as operational tools are also assessed in accordance with the evolution of wireless networks: in particular, the increase of fiber backhauling and the shift towards mmWave bands for CMLs will be important aspects for the future of CMLs, whereas the deployment of large and mega constellations of LEO satellites may be beneficial to SMLs.

Acknowledgment - This work was supported by the following projects: SCORE, funded by European Commission's Horizon 2020 research and innovation programme under grant agreement no. 101003534; Space It Up, funded by the ASI, the MUR –Contract no. 2024- 5-E.0 - CUP no. I53D24000060005; FoReLab (Departments of Excellence), funded by the Italian Ministry of Education and Research (MUR); COST Action CA20136 OPENSENSE, funded by COST (European Cooperation in Science and Technology); MODMET agreement between DPC and ARPAE.

Exploring Rain Scintillation Spectra from Microwave Links for Raindrop Size Distribution Retrieval

Authors: Peiyuan Wang^{None}; Arjan Droste¹; Marc Schleiss¹; Remko Uijlenhoet²

¹ *Delft University of Technology*

² *TU Delft*

Corresponding Authors: r.uijlenhoet@tudelft.nl, a.m.droste@tudelft.nl, p.wang-3@tudelft.nl, m.a.schleiss@tudelft.nl

Rainfall has been monitored with microwave links opportunistically for nearly 20 years. So far, most studies have focused on retrieving rainfall rates using the mean received signal, based on the power-law relation between specific attenuation and rainfall rate. However, theories and measurements have indicated that the power spectral density (PSD) of received signal contains extra information about rainfall. The drop size distribution (DSD) and the motion of raindrops both play a role in determining the scintillation spectrum of rain. To evaluate the feasibility of making use of rain spectra for retrieving information about DSDs, measurements from different experimental datasets are investigated. Initial results indicate that some information about rainfall (e.g. rainfall rate) is indeed retained in the spectra measured by a radio link at 26 GHz and a scintillometer at 160 GHz. Furthermore, a simulation of the PSD of the received voltage during rain is made to gain understandings of its behavior. The simulation, based on Ishimaru's work (1978), allows for the customization of various settings (e.g., wavelength, geometry, antenna gain functions) of radio links, as well as the DSD at different locations along the links. It is shown that large raindrops generally have more influence on the PSD of received voltage than smaller raindrops. A theoretical method to retrieve DSD from the PSD of the received voltage is proposed and its performance is assessed by simulation. Results show that the concentration of the tiniest raindrops is hard to retrieve because of their minor impacts on PSD. In the simulation, the concentration of larger raindrops can be relatively reliably retrieved, even when a large variation of DSDs is present along the microwave link.

Insights in the rainfall dynamics preceding and during the 29 October 2024 Valencia floods using rainfall observations from personal weather stations

Author: Nathalie Rombeek¹

Co-authors: Markus Hrachowitz¹; Davide Wüthrich¹; Remko Uijlenhoet¹

¹ *Delft University of Technology, Faculty of Civil Engineering and Geosciences*

Corresponding Authors: n.rombeek@tudelft.nl, r.uijlenhoet@tudelft.nl

On 29 October 2024 torrential rainfall exceeding locally 300 mm within less than 24 h, triggered devastating flash floods in the province of Valencia in Spain. Rainfall sums equivalent to more than half a year's total precipitation occurred within just a few hours. In this region, more than 200 low-cost weather observation devices, referred to as personal weather stations (PWSs), are located. The network density of PWSs in this region is seven times higher than that of the Spanish Meteorological Agency (AEMET), being able to provide more detailed insights in the rainfall dynamics. Another advantage is that rainfall observations from PWSs have a high temporal resolution (~5-min) and are available near real-time for everyone.

In this study we used rainfall observations from PWSs to get local insights into the rainfall event of October 29. Several PWSs measured already more than 180 mm of rainfall in parts of the Magro catchment (1661 km²) in the morning, consequently generating a flash flood in the upstream parts of this rapidly responding catchment. Areal rainfall maps, based on interpolating the PWS data, indicated daily catchment averaged rainfall sums exceeding 150 mm d⁻¹ across an area of more than 2500 km². Daily rainfall sums recorded by the PWSs showed a slight underestimation of the rainfall with a bias of 4% and a high correlation ($r = 0.94$) when compared to reported rainfall from AEMET. This presentation shows the relevance of utilizing PWSs for near real-time rainfall monitoring and potentially flood early warning systems.

Do citizen science data improve the reconstruction of heavy rainfall events?

Author: Hannes Müller-Thomy¹

Co-authors: Franca Meyer²; Kai Schröter¹

¹ *LWI, TU Braunschweig, Braunschweig, Germany*

² *Hamburg Wasser, Hamburg, Germany*

Corresponding Authors: h.mueller-thomy@tu-braunschweig.de,

kai.schroeter@tu-braunschweig.de, franca.meyer@magenta.de

Rainfall-runoff processes are highly dynamic in urban areas. For flood risk management an accurate estimation of spatial and temporal rainfall distribution are essential. In view of increasingly available data sources for rainfall observations we investigate the benefits that additional data sources can bring to the reconstruction of convective heavy rainfall. In this study we focus on the heavy rainfall event in Brunswick (Germany, 205 km²) during storm Lambert in June 2023 and compare rainfall data from different sensors: the German Weather service (DWD, 1 rain gauge), the municipal wastewater management and the university (BS, 8 rain gauges), citizen scientists (CS, 4 rain gauges) and rain gauge-corrected radar (YW). Rainfall information are compared regarding estimates of the spatial distribution of absolute rainfall intensities and resulting return periods for durations ranging from 5 minutes to 24 hours. As 'truth' we consider the interpolated rainfall product derived from all rain gauges. With ordinary kriging an areal rainfall of 113 mm over 24 hours is estimated. Since the rainfall field of the storm event did not hit the only DWD rain gauge located in the region directly, the derived areal rainfall is 72 mm only. Since the radar data is routinely corrected with the closest DWD rain gauges, the radar-based areal rainfall is even smaller (69 mm). Considering the CS rain gauges only leads to higher areal rainfall estimate (91 mm).

Also the spatial representation of the rainfall intensities is superior using CS data in comparison to DWD data or radar data alone. For each raster field (1 km x 1 km) the maximum rainfall intensities for durations $D=\{5, 10, 30, 60, 360, 720, 1440 \text{ min}\}$ were determined and return periods T based on the national extreme value catalogue assigned. For $D=30 \text{ min}$, using all rain gauges results in $T=100 \text{ yrs}$, while using CS rain gauges only leads to a slight underestimation with $T=50 \text{ yrs}$. However, strong underestimations are identified for the usage of the sole DWD rain gauge leading to $T=2 \text{ yrs}$, and for radar leading to $T<1 \text{ yr}$.

The study underlines that CS data may add useful information for the reconstruction of heavy precipitation events and should be used to increase the spatial density of rainfall information particularly in data sparse regions.

Oral session #5: Application of OS rainfall data

Session Chair: Martin Fencel

Applications of opportunistic rainfall observations: a review

Author: Jonas Olsson¹

Co-authors: Aart Overeem²; Andrijana Todorovic³; Carlo De Michele⁴; Christian Chwala⁵; Jochen Seidel⁶; Laura Horváth-Varga⁷; Magdalena Szaton⁸; Martin Fencel⁹; Maximilian Graf¹⁰; Nejc Bezak¹¹; Remco van de Beek¹; Vojtech Bares⁹

¹ *Swedish Meteorological and Hydrological Institute*

² *Royal Netherlands Meteorological Institute, The Netherlands*

³ *University of Belgrade, Faculty of Civil Engineering, Serbia*

⁴ *Politecnico di Milano, Italy*

⁵ *Karlsruhe Institute of Technology, Germany*

⁶ *University of Stuttgart, Germany*

⁷ *Budapest University of Technology and Economics, Hungary*

⁸ *Institute of Meteorology and Water Management, Poland*

⁹ *Czech Technical University, Czech Republic*

¹⁰ *German Weather Service, Germany*

¹¹ *University of Ljubljana, Slovenia*

Corresponding Author: jonas.olsson@smhi.se

Accurate rainfall observations, particularly with a high resolution in space and time, are of paramount societal importance for several reasons. They are needed to derive statistics of rainfall extremes used for planning and designing infrastructure. They are used to establish the best possible initial state for subsequent weather forecasts and rainfall nowcasts. They are crucial for developing numerical weather and climate models as well as for assessing climatic trends.

Today, most National Meteorological and Hydrological Institutes use meteorological stations, often together with weather radar, for rainfall observations. However, station networks are often sparse and rainfall observations by weather radar notoriously uncertain. As a complement, opportunistic rainfall observations have been advocated for several years by now. The most investigated and commonly used types are observations based on attenuation in signals between Commercial Microwave Links (CML) and observations from Personal Weather Stations (PWS). Both types are associated with distinct errors and uncertainties, but owing to their high spatial density faulty data may be discarded and useful signals filtered out.

Many proof-of-concept studies have demonstrated the potential of opportunistic rainfall observations for different applications, and in this effort performed within COST Action OpenSense we review the applications carried out. The applications are divided into two categories; rainfall mapping (further divided into single opportunistic sensor or merged opportunistic/conventional sensors) and subsequent applications (further divided into rainfall nowcasting and hydrological prediction). We will present the results of this review as well as discuss some remaining challenges and potential solutions concerning practical applications of opportunistic rainfall observations.

Precipitation field reconstruction and tracking using opportunistic rain sensors: the Summer 2021 catastrophic event in Germany as a case study

Author: Filippo Giannetti¹

Co-authors: Fabiola Sapienza¹; Elisa Adirosi²; Luca Baldini²

¹ *University of Pisa*

² *CNR-ISAC*

Corresponding Authors: l.baldini@isac.cnr.it, elisa.adirosi@artov.isac.cnr.it,

filippo.giannetti@unipi.it, fabiola.sapienza@ing.unipi.it

Quantitative precipitation estimates are usually derived based on the measurements collected by professional instruments, such as weather stations, weather radars, disdrometers, and rain gauges, with different time/space resolutions, and accuracies.

Recently, the opportunistic use of pre-existing microwave communication links has been investigated to retrieve precipitation estimates. In particular, satellite-based opportunistic systems for rain monitoring, are particularly appealing due to: i) the widespread presence of existing DTH satellite receivers across the territory, which can potentially function as rain-sensing devices, offering significant geographical coverage, especially in densely populated areas; ii) the ease of installation of new terminals to obtain higher spatial density; and iii) the low cost of commercial-grade satellite receive equipment.

In this work, we present a practical application of an opportunistic technique for the estimation of rainfall intensity. It is based on signal strength measurements made by commercial-grade interactive satellite terminals. By applying some processing, the rain-induced attenuation on the microwave downlink from the satellite is first evaluated; then the rain attenuation is mapped into a rainfall rate estimate via a tropospheric model.

This methodology has been applied to a test area of 30x30 km² around the city of Dortmund (North Rhine-Westphalia, upper basin of Ermscher river), for the heavy rain event that devastated Western Germany in July, 2021.

A spatial and temporal reconstruction of the event was obtained from a set of satellite terminals deployed in the region, using a classical spatialization method, based on the inverse distance weighting interpolation. The resulting rainfall maps were successfully compared with those provided by radar climatology of the Deutscher Wetterdienst (DWD), the national German weather service.

Acknowledgements: This work was supported by the following projects: SCORE, funded by European Commission's Horizon 2020 research and innovation programme under grant agreement no. 101003534; Space It Up, funded by the ASI, the MUR –Contract no. 2024- 5-E.0 - CUP no. I53D24000060005; FoReLab (Departments of Excellence), funded by the Italian Ministry of Education and Research (MUR); COST Action CA20136 OPENSENSE, funded by COST (European Cooperation in Science and Technology).

Exploiting a dense Commercial Microwave Link (CML) network in Nigeria for high-resolution near-surface rainfall estimates

Author: Bas Walraven¹

Co-authors: Aart Overeem²; Arjan Droste¹; Luuk van der Valk¹; Miriam Coenders¹; Remko Uijlenhoet³; Rolf Hut¹

¹ *Delft University of Technology*

² *Royal Netherlands Meteorological Institute*

³ *TU Delft*

Corresponding Authors: r.w.hut@tudelft.nl, l.d.vandervalk@tudelft.nl, a.m.droste@tudelft.nl, overeem@knmi.nl, r.uijlenhoet@tudelft.nl, b.walraven@tudelft.nl, a.m.j.coenders@tudelft.nl

High-resolution rainfall data, in both space and time, is essential for a number of life sustaining (hydrological) applications, ranging from flood early warning to (small-holder) agricultural services. Interpolated rainfall maps based on path-averaged rainfall estimates from Commercial Microwave Links (CMLs) present a viable alternative for near-surface high-resolution gridded rainfall data in regions where weather radars are typically not present or not operational, most notably large parts of Africa.

Recent projects in Burkina Faso, Ghana and Rwanda, in addition to multiple proof of concepts in different African countries (Burkina Faso, Cameroon, Kenya, Niger and Zambia) over the past decade, show the added value of CML based rainfall retrievals is increasingly being recognized across the African continent. One of the major challenges in applying this technique over Africa, however, is the lack of adequate near-surface reference data from either rain gauges or weather radars. Although satellite rainfall products are generally available, their temporal or spatial resolution is often too coarse, and their accuracy can be low over the tropics.

In this study we use several months of CML data from a dense network in Nigeria consisting of more than 12,000 links, predominantly over four heavily urbanized areas, to estimate near-surface rainfall rates. The 15-minute minimum and maximum received signal levels, obtained from the network management system of one of the mobile network operators in Nigeria, are used to estimate the path-averaged rainfall intensities. As a point reference we use data from the few available rain gauges. Additionally, we compare interpolated rainfall maps from CMLs to available gridded (satellite) rainfall products on a seasonal basis. In doing so, our aim is to exploit this large CML network to quantify the uncertainty range in rainfall estimates amongst the CMLs themselves, and assess the effect of interpolating path-averaged rainfall intensities from such a dense network with many short links. We also show the locally added value for urban water management applications by using the CMLs to highlight the rainfall variability within a satellite rainfall product pixel.

Runoff predictions in combined sewer system of the city of Prague using raw attenuation data from commercial microwave links

Authors: Ying Song^{None}; Martin Fenc¹; Vojtěch Bares¹

¹ *Czech Technical University in Prague*

Corresponding Authors: yingsong@cvut.cz, martin.fenc@cvut.cz, baresvoj@cvut.cz

Commercial microwave links (CMLs) have recently shown great potential in urban drainage modelling due to their ability to provide rainfall-runoff dynamics. Previous studies typically used mechanistic hydrodynamic models driven by quantitative precipitation estimates (QPEs) derived from CML attenuation data. Naturally, some errors are introduced, primarily related to CML rainfall retrieval model, including uncertainties in wet antenna attention correction, as well as errors originated from path-averaged character of CML QPEs. These processing steps not only generate some new uncertainties but also result in a loss of valuable information contained in raw data. Besides, mechanistic models require high-quality pre-processed input rainfall data, which adds complexity to the application.

We address these issues by employing raw CML attenuation data without QPE derivation using data-driven rainfall-runoff models in the overall Prague catchment, where runoff is influenced by both rainfall and residential water use. We find that: (1) Raw CML attenuation data can be effectively used to obtain the discharges despite the additional influence of household water consumption, achieving $NSE > 0.7$ and $PCC > 0.85$ over all sub-catchments. (2) Compared with rain-gauge data as inputs, CML attenuation data outperforms in heavy and long-period rain events (e.g. reducing RMSE by 17% and increasing PCC by 18% respectively). (3) CML performs better in sub-catchments A and F, where CMLs are densely distributed, and rainfall is highly concentrated within the catchment. However, its performance in sub-catchment K is poorer, likely due to its larger area, sparser CML coverage, and longer rainfall-runoff concentration time. Additionally, the influence of non-rainfall-related flows becomes more pronounced, potentially reducing the predictive advantage of CML. (4) Models using CML data as input enable runoff prediction beyond the catchment's rainfall-runoff lag time, whereas models with rain gauge data deteriorate quickly. CML-based hydrological modelling is effective in purely rainfall-driven urban basins and adaptable to more complex systems influenced by human activities. This research underscores CML's potential as a robust alternative to traditional rain gauges, particularly for improving real-time runoff predictions in data-scarce urban environments.

Large-scale hydrological modeling with CML rainfall data

Authors: Andrijana Todorovic¹; Carlo De Michele²; Cristina Deida³; Greta Cazzaniga⁴; Roberto Nebuloni⁵

¹ *University of Belgrade, Faculty of Civil Engineering, Institute for Hydraulic and Environmental Engineering*

² *Politecnico di Milano*

³ *Vrije Universiteit Brussel*

⁴ *Laboratoire des Sciences du Climat et de l'Environnement*

⁵ *Cnr-Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni (CNR-IEIIT)*

Corresponding Authors: greta.cazzaniga@lsce.ipsl.fr, carlo.demichale@polimi.it, atodorovic@grf.bg.ac.rs, roberto.nebuloni@cnr.it

Accurate spatio-temporal representation of rainfall is essential for hydrological (i.e., rainfall-runoff) modelling, and for the later applications of hydrological models. Rainfall data are usually obtained from official raingauge networks; however, these networks are often sparse and/or even with declining number of stations. To improve spatio-temporal representation of rainfall, various opportunistic sensors have been considered, including commercial microwave links (CML). CML-based rainfall data have been used for hydrological modelling in small urban catchments for years, but their applications in large catchments is lagging behind. Development of hydrological models in large catchments requires long rainfall series, which is not the case when it comes to CML datasets. Thus, a thorough evaluation of hydrological model transferability across different rainfall inputs is essential for wider application of the CML data. In this study, a semi-distributed hydrological model developed for the peri-urban Lambro catchment in Northern Italy (Cazzaniga et al., 2022; doi: <https://doi.org/10.5194/hess-26-2093-2022>) is evaluated from the standpoint of its transferability across the rainfall inputs. To this end, the model is run with conventional input obtained from the raingauge network (RG), from the CML-based rainfall, and combination thereof (CML-RG). The model performance is evaluated over 12 flood events, four of which are low-rate events (maximum rain intensity below 15 mm/h), while maximum rainfall intensity exceeds 35 mm/h during four most extreme ones. The model performance significantly varies across the events. Although the RG model yields the highest performance in most instances, it is outperformed by the model forced with CML- and/or CML-RG data during the three most extreme events. There is no strong correlation between the peak rainfall intensity and model performance; however, the RG model outperforms the CML- and CML-RG models over the low-intensity events. The CML model is outperformed by the CML-RG and, especially, RG model according to Nash-Sutcliffe efficiency, relative error in peak flows and in runoff volume, however, CML model performs best in most cases according to the coefficient of determination, which suggests that this rainfall input best captures rainfall dynamics. This study clearly indicates a great potential of CML to improve hydrological model performance in high-flow range. It also suggests that further research is needed to reduce biases in rain depth estimation at a sub-catchment level. Further research is also needed to enable optimal combination of different rainfall inputs to hydrological model, as well as to improve spatial discretisation of hydrological models to better accommodate “linear” CML rainfall data.

Flood forecasting based on personal weather station rainfall data

Author: Jisca Schoonhoven¹

Co-authors: Claudia Brauer¹; Linda Bogerd¹

¹ *Wageningen University*

Corresponding Author: claudia.brauer@wur.nl

An increasing number of personal weather stations (PWSs) is installed by citizens, resulting in a large amount of real-time available precipitation data. This study assesses the applicability of these data for flood forecasting. We focussed on 30 catchments (total area 2474 km²) located in the management area of Water Board Rijn and IJssel, a water authority in the Netherlands which actually uses PWS data as input for their operational flood forecasting system.

We compared rainfall from a network of Netatmo PWSs (after applying a quality filter) and the real-time radar product from the KNMI (Royal Netherlands Meteorological Institute). Next, we used both products as input for the rainfall-runoff model WALRUS and compared the simulated discharges. These two datasets with almost no latency were validated with the final reanalysis KNMI radar product and discharge observations, for a full year (2023), using the Kling–Gupta efficiency (KGE).

For precipitation the KGE was higher for the real-time radar (0.80 for the entire area) than for the PWSs (0.68). For discharge simulations the KGE was lower for the real-time radar (median of the subcatchments: 0.46) than for the PWSs (0.70). This contrasting result can be explained by the bias, which was higher for the real-time radar than for the PWSs, and is amplified in the discharge simulations due to the memory in the hydrological system.

During ten selected high discharge events, the simulations with real-time radar approached the observations more closely than with the PWSs. The results indicate a potential of these devices to be used in hydrological applications, especially when initial hydrological model conditions are improved with data assimilation in operational flood forecasting systems.

Poster Session #1

Session Chair: Congzheng Han

ISRaCML

Author: Matan Antebi¹

¹ *Tel Aviv University*

Corresponding Author: matanantebi@mail.tau.ac.il

Accurate and continuous monitoring of precipitation and extreme weather events, such as heavy rainfall and flooding, is essential for mitigating their devastating impacts on both natural and built environments. The increasing frequency and intensity of such hydrometeorological events, exacerbated by climate change, necessitate the development of innovative and cost-effective observational methodologies to complement traditional ground-based measurement networks. Opportunistic sensors (OS), which leverage existing infrastructure for environmental monitoring, provide a valuable alternative for enhancing spatial and temporal precipitation assessments, particularly in regions with limited meteorological instrumentation. Cellular microwave links (CMLs), a prominent example of OS, offer an extensive and high-resolution dataset for rainfall estimation, making them particularly useful in diverse climatic regions such as Israel, which spans from hyper-arid zones in the south to temperate conditions in the north.

In this study, we will present ISRaCML dataset which includes frequencies ranging (17 - 23GHz) K-Band, path lengths varying (0.5 - 16km), presenting observations from CMLs deployed across Israel, sourced from a number of telecommunications providers, Cellcom, Pelephone and Orange, over the period of January 1, 2017, to August 31, 2017. The dataset is structured to include multiple temporal resolutions: 15-minute and 24-hour instantaneous values, min-max aggregates for 15-minute and 24-hour intervals, and min-max aggregates for 7-day 24-hour periods. Additionally, it integrates ground-based precipitation measurements from 85 rain gauges maintained by the Israel Meteorological Service (IMS), thereby furnishing a complementary dataset for validation and cross-referencing. This dataset constitutes a critical resource for enhancing precipitation retrieval algorithms, as it consists of, for the first time, CML measurements with different protocols by different network operators within the same time frame and area.

OpenMesh: Wireless Signal Dataset for Opportunistic Urban Weather Sensing in New York City

Author: Dror Jacoby¹

¹ *Tel Aviv University*

Corresponding Author: drorjacob@tau.ac.il

We introduce OpenMesh, a publicly available dataset of wireless links designed for high-resolution weather monitoring in dense urban environments. Collected from NYC Mesh—an initiative primarily aimed at providing affordable internet access—this dataset demonstrates how opportunistic usage can transform existing communication infrastructure into a platform for real-time meteorological observation.

Spanning eight months (November 2023–June 2024), the dataset includes measurements from 100 directional wireless links sampled at 1-minute intervals. These links operate across both lower (~5–6GHz) and higher V-band (40–70 GHz) channels. While higher frequencies undergo substantial atmospheric attenuation—especially during precipitation—this challenge doubles as an opportunity for real-time, localized weather sensing within mesh networks.

Centered on Lower Manhattan and Brooklyn in New York City, our dataset also incorporates regional meteorological records for validation, enhancing the evaluation process and advancing research in wireless-based atmospheric sensing. Aligned with ongoing efforts in opportunistic weather data, OpenMesh adheres to established environmental monitoring standards. By openly sharing these data, we invite further research and encourage practical applications leveraging 5G/6G capabilities for resilient, real-time urban-scale sensing—ultimately guiding next-generation networks (NGNs) toward more sustainable solutions.

Rainfield Monitoring and Extracting Natural Phenomena Combining CML with Graph Signal Processing

Author: Yaara Peled^{None}

Corresponding Author: yoyo7149@gmail.com

Measuring natural phenomena through opportunistic sensing is crucial for maximizing the use of existing data for research and weather warning systems. This research is an addition to existing work that has been done connecting CML information with rainfield monitoring. by integrating this signal attenuation-based rain estimation with graph signal processing techniques we can gain better rainfield monitoring and extract natural phenomena from anomalies in the graph. In this approach, graph vertices represent receiver (RX) measurements positioned at the midpoint of CML, functioning as single-point rain sensors. The edges and weights of the graph are determined by geographic proximity and correlation relations, establishing strong relationships between nearby and similar nodes.

By applying graph signal processing, this research aims to:

1. Detect anomalies in the graph, where anomalous links may indicate regions with heavy rainfall potential that could lead to floods (extract natural phenomenon).
2. Improve rainfield monitoring from the graph connectivity and build better interpolation.
3. Clustering the graph into meaningful categories:
 - 3a. Differentiating rain intensity levels.
 - 3b. Distinguishing between urban and rural rainfall characteristics.
4. Optimize computational efficiency, selectively utilizing only the most relevant CML to reduce power consumption and filter out redundant information.

This methodology has the potential to enhance existing rainfield monitoring based on CML information.

Unsupervised Fault Detection and Classification in Microwave Links for Opportunistic Weather Detection: Differentiating Weather-Induced and Non-Weather Faults

Author: Adi Green^{None}

Corresponding Author: adishafir@mail.tau.ac.il

Changes in communication signals due to weather conditions are often misclassified as faults, making it challenging to differentiate between meteorological effects and actual network malfunctions, such as physical obstructions (e.g., new construction blocking the signal path) or hardware failures. In this work, we propose an unsupervised learning framework for fault detection and classification in commercial microwave links (CMLs), distinguishing between weather-related and non-weather faults. Our approach is based on an autoencoder (AE) trained on mixed data to establish a reconstruction-based threshold for identifying potential fault regions. We then extract features from the encoder's latent space and combine them with domain-specific spatial and temporal features to enhance characterization. These enriched representations are clustered to capture both localized and regional fault patterns, allowing us to differentiate between faults caused by meteorological events—such as precipitation affecting multiple links simultaneously—and those resulting from structural or equipment-related issues. Beyond improving fault classification accuracy, our method enables opportunistic sensing of weather-induced signal variations, offering a valuable tool for both network maintenance and meteorological monitoring.

Optimizing Wet Antenna Attenuation Models for Improved Rainfall Estimation Using Commercial Microwave Links

Authors: Smit Doshi¹; Carlo De Michele²; Greta Cazzaniga³; Roberto Nebuloni⁴

¹ *Alfred Wegener Institute Helmholtz Center for Polar and Marine Research*

² *Politecnico di Milano*

³ *LSCE- CEA, CNRS*

⁴ *CNR*

Corresponding Authors: carlo.demichale@polimi.it, roberto.nebuloni@cnr.it, smitdoshi5@gmail.com, greta.cazzaniga@lsce.ipsl.fr

Accurate rainfall estimation using commercial microwave links (CMLs) is set back by wet antenna attenuation (WAA), which could lead to overestimation of rainfall intensity when not properly accounted. This study introduces a novel framework for minimizing WAA effects through an optimized calibration approach. The proposed methodological framework utilizes an effective distance metric to associate CML data with rain gauge (RG) assessment, integrating a weighted calibration process that gives more importance to high-intensity rainfall events. As a preliminary step, a comparative assessment of several existing WAA models - including Schleiss, Rieckermann, and Berne (SRB), Leijnse, Uijlenhoet, and Stricker (LUS), Kharadly and Ross (KR), Garcia-Rubia, Riera, Benarroch, and Garcia-del-Pino (GRBG), and Valtr, Fencl, and Bareš (VFB) was carried out. Most of the models that predict WAA from rainfall intensity, attenuation or rainfall attenuation are basically equivalent. The WAA compensation process was applied to data from 77 CMLs in the Seveso River basin (Northern Italy) across different types of rain events in 2019-2020. A modified version of VFB model (VGBm – calibrated VFB model), showcases analytically better performance across various CML lengths, frequencies, and rainfall intensities. In particular, VFBm model leads to much better results than SRB (a commonly used model that predicts a saturation of WAA to a relatively small 2.3 dB value) over all the relevant key performance indicators. These findings highlight that correcting WAA is important for accurate rainfall intensity estimates from CML data and emphasize the need to adjust the WAA models to local conditions for improved hydro-meteorological applications.

The OPENSENSE software ecosystem

Author: Christian Chwala¹

Co-authors: Maximilian Graf²; Bas Walraven³; Erlend Øydvin⁴; Elia Covi⁵; Jochen Seidel⁶; Louise Louise Petersson Wårdh⁷; George Schutz⁸; Martin Fencel⁹; Nico Blettner⁹; Abbas El Hachem⁹; Lotte de Vos¹⁰; Hai Victor Habi¹¹; Aart Overeem¹²

¹ KIT (IMK-IFU)

² German Weather Service, Germany

³ Delft University of Technology

⁴ NMBU

⁵ Arpa-e-SIMC

⁶ University of Stuttgart, Germany

⁷ 1) Swedish Meteorological and Hydrological Institute (SMHI), Folkborgsvägen 17, Norrköping SE-601 76, Sweden (2) Division of Water Resources Engineering, Faculty of Engineering, Lund University, P.O. Box 118, 22100 Lund, Sweden

⁸ RTC4Water

⁹ Czech Technical University In Prague, Czech Republic

¹⁰ Royal Netherlands Meteorological Institute

¹¹ Tel Aviv University

¹² Royal Netherlands Meteorological Institute (KNMI)

Corresponding Authors: ecovi@arpae.it, lotte.de.vos@knmi.nl, louise.petersson.wardh@smhi.se, erlend.oydvin@gmail.com, b.walraven@tudelft.nl, christian.chwala@kit.edu, aart.overeem@knmi.nl

The focus of working group 2 of OPENSENSE is on method and software homogenisation. We have reviewed the existing software available for processing opportunistic rainfall sensor data and did provide example applications executable online in the so called *OPENSENSE software sandbox*. There we have identified synergies but also implementation gaps. Based on this we have set a roadmap for developing individual new software packages to create an ecosystem of packages that work well together.

The foundation of our software ecosystem is the package *poligrain* which provides commonly used functionalities for loading data, plotting maps, comparing sensor data and for doing validation. All this is done with a focus on data provided on a grid, as point data, but also for line geometries. On top of *poligrain*, individual packages for processing data are being built. The existing CML processing package *pycomlink* was adapted to fit into this ecosystem and two new packages were created. The new package *pypwsqc* provides sophisticated methods for quality control of PWS data. The new package *mergeplg* provides different methods for merging point, line and grid data with a focus on merging weather radar and CML data.

In this contribution we will give an overview of this software ecosystem and briefly present the individual packages.

Citizen observations via the RMI smartphone app in Belgium: data collection and applications

Author: Maarten Reyniers¹

¹ *Royal Meteorological Institute of Belgium*

Corresponding Author: maarten.reyniers@meteo.be

To enhance meteorological data collection and nowcasting capabilities, the Royal Meteorological Institute (RMI) of Belgium integrated a citizen observation feature into its smartphone app in August 2019. This initiative has since accumulated over 3.3 million observations, including 56,000 user-submitted photos, significantly enriching RMI's meteorological datasets.

While the majority of user reports capture more general weather conditions such as sunny, overcast skies, or rain, the most valuable contributions focus on key weather phenomena like snow, hail, thunderstorms, and road conditions, providing real-time, localized insights. Each observation undergoes a plausibility check based on timestamp, location, and content, ensuring data reliability. A user reputation system further refines data quality, with 78% of users maintaining a reputation score of 90 or higher on a scale of 0 to 100.

This dataset has proven valuable for multiple applications at RMI, including the validation of weather radar estimates for hail detection, improving snow height model forecasts, and enhancing crisis response mechanisms. Specifically, citizen observations have been leveraged by regional hydrological and road management authorities for real-time flood monitoring and hazardous road condition assessments, respectively.

The integration of citizen observations into meteorological workflows marks a significant advancement in data collection, bridging gaps in traditional sensor networks and enabling better forecasting models. As the RMI continues to refine its methodologies, this approach holds promise for expanding the role of crowdsourced meteorological data across Europe.

Sensing from the Grassroots: How Environmental Measurement Software is Being Developed by Citizen Scientists

Author: Antti Knutas¹

Co-author: Nicolas Jullien²

¹ *LUT University*

² *IMT Atlantique*

Corresponding Authors: antti.knutas@lut.fi, nicolas.jullien@imt-atlantique.fr

There are a wide variety of opportunistic weather sensor networks, ranging from academic controlled to open source and commercial but individually owned and controlled personal weather stations. Individual participation to these networks through measurement and data sharing is a well-known method of engagement, sometimes referred to as citizen science. In addition to top-down measurement projects, there are several community-created and organised sensing efforts. Less well known, compared to citizen science efforts, is how grassroots or self-directed citizen scientists create measurement software and environmental data pools.

In this talk, we present a multiple case study of how volunteers have created a bottom-up environmental sensing software project with associated hardware, with case analysis based on several years of interviews and qualitative data collection. We apply the theory of open-source microeconomics by Jullien et al. and the lens of the commons by Ostrom et al., complemented by the concept of civic coding by Knutas et al. and the palette of participation to digital citizen science by Palacin.

The main contribution of the study, as presented in this talk, is an organisational growth model adapted for community environmental software projects with pitfalls that efforts must avoid during critical junctures, recommendations for setting up community sensing projects, and finally a discussion of how these findings could be used for community engagement in opportunistic weather sensing networks.

Satellite microwave link open data for rainfall estimation

Authors: Roberto Nebuloni¹; Maxime Turko²; François Mercier-Tigrine²; Greta Cazzaniga³; Maximilian Graf⁴

¹ *CNR - IEIIT*

² *HD Rain*

³ *LSCE- CEA, CNRS*

⁴ *Deutscher Wetterdienst*

Corresponding Authors: greta.cazzaniga@lsce.ipsl.fr, francois.mercier@hd-rain.com, maximilian.graf@dwd.de, maxime.turko@hd-rain.com, roberto.nebuloni@cnr.it

Opportunistic rainfall data collected through satellite microwave links (SML), such as the ones providing TV-SAT signals from Ku-band geostationary satellites, have the potential to complement conventional sensors, due to their flexibility and the relatively low-cost of the receiving equipment. However, opportunistic data must be properly processed and validated against ground truth. To this aim, the availability of large datasets of such data is crucial. This contribution presents an open SML dataset, courteously provided by the French company HD Rain, including 215 SMLs deployed in Southeastern France. The raw data are the received signal level (RSL) by each sensor expressed in dBm units and they cover a five month observation period from August to December 2022. Concurrent rain gauge and radar data from the Meteo-France operational network are provided as well. The radar data are aggregated in such a way that they spatially fit SML rainfall estimates, i.e. spatial averages across the propagation path. SML data provide indirect rainfall measurements based on the decrease of the RSL produced by raindrops falling across the path. As rain covers only a small fraction of the entire path from the satellite to ground, the height above ground where ice particles have melted into raindrops is a crucial input to derive rainfall estimates from SML data. Rain height data are supplied as well and a few techniques to derive this quantity are discussed.

Coffee Poster Session #1 / 48

Refining baseline and wet antenna models for improved rainfall estimation from CML data

Author: Erlend Øydvin¹

Co-authors: Christian Chwala ; Kristian Hovde Liland ; Maximilian Graf ; Elia Covi ; Mareile Astrid Wolff ; Nils-Otto Kitterød ; Vegard Nilsen

¹ *NMBU*

Corresponding Authors: vegard.nilsen@nmbu.no, erlend.oydvin@gmail.com, elia.c.covi@gmail.com, kristian.liland@nmbu.no, maximilian.graf@dwd.de, mareile.astrid.wolff@nmbu.no, christian.chwala@kit.edu, nils-otto.kitterod@nmbu.no

An important step in deriving precipitation estimates from commercial microwave links (CMLs) involves separating the attenuation caused by rainfall from the baseline attenuation and wet antenna attenuation (WAA). The baseline is usually estimated from the signal loss preceding a rainfall event, making the baseline sensitive to the estimated starting time for rainfall events. A rainfall event can either be detected by using external data, such as a weather radar, or by analysing the CML data itself. However, different rainfall detection methods capture different aspects of the rainfall event, causing different event timing and thus baseline estimates. Also, as the WAA model is typically estimated by calibrating it to nearby rain gauges, the estimated WAA models might overfit the data, leading to less generalizable baseline-WAA model combinations.

In this work, we explore different rainfall detection models combined with different WAA models. The models are trained and tested using data from CMLs and nearby rain gauges from Norway, Germany, Sweden and Italy. The results show that some baseline-WAA method combinations lead to better precipitation estimates when tested using cross-validation.

Beyond Cellular Networks: Rainfall Estimation Using Low-Frequency and Short-Distance Commercial Microwave Links

Authors: Jan Hajna¹; Lukáš Kaleta¹; Matěj Ištvanek¹; Miroslav Babel¹; Petr Mlýnek¹; Petr Musil¹; Štěpán Mikláněk¹

¹ *Brno University of Technology*

Corresponding Authors: xhejna02@vut.cz, matej.istvanek@vut.cz, xbabel02@vut.cz, musilp@vutbr.cz, stepan.miklanek@vut.cz, xkalte07@vut.cz, mlynek@vut.cz

Commercial Microwave Links (CMLs) have emerged as a promising tool for opportunistic sensing, particularly for rainfall estimation. However, most studies have focused on high-frequency cellular network links, leaving a gap in understanding the viability of CMLs operating at lower frequencies (10 GHz – 15 GHz) and over shorter distances (≤ 2 km). In this study, we analyze data from a private CML distributor and investigate the challenges and limitations that arise in this context.

The data from low-frequency and short-distance links present unique obstacles during preprocessing. Our dataset is influenced by a variety of environmental and infrastructural factors that introduce inconsistencies. Standard methods of opportunistic sensing, which usually rely on established models of attenuation and signal fluctuations, often fail due to the increased susceptibility to non-meteorological signal variations. In our study, we critically examine the nature of the data and assess the suitability of wet/dry classification and rain estimation methods at the lower limits of sensitivity.

We present an overview of the key challenges encountered during preprocessing, including baseline estimation and uptime utilization. Furthermore, we evaluate the performance of existing opportunistic sensing methods on this dataset, demonstrating their limitations and the need for novel approaches tailored to these conditions. Our preliminary findings underscore the importance of refining preprocessing techniques and developing new analytical frameworks to enhance the reliability of rainfall estimation from such data.

This extended abstract outlines our ongoing work and emphasizes the significance of addressing the challenges posed by non-traditional CML datasets. By improving the robustness of data preprocessing and refining methodologies for rain estimation, we aim to expand the applicability of CML-based precipitation monitoring beyond conventional cellular infrastructure. Future work will explore machine learning-based approaches to enhance the accuracy of rain rate retrieval and wet/dry classification from low-frequency, short-distance CMLs.

Improving Precipitation Estimates from Commercial Microwave Links Using Deep Learning: A Comparative Study on OpenMRG Data

Author: Nadia Ahmed Sharna¹

Co-author: İzzet Fatih ŞENTÜRK

¹ *Bursa Technical University*

Corresponding Authors: nadia.1.9.ahmed@gmail.com, izzet.senturk@btu.edu.tr

Compared to conventional methods, Commercial Microwave Links (CMLs) offer great spatial and temporal resolution, making them a viable opportunistic sensing technology for precipitation assessment. However, noise, ambiguity, and non-linear connections between signal attenuation and rainfall intensity make it difficult to reliably estimate precipitation using CML-derived attenuation data. In this work, we use the OpenMRG dataset, which contains metadata like frequency, link length, and polarization combined with CML-derived signal attenuation data, to investigate the potential of deep learning (DL) techniques to enhance precipitation estimations.

We assess the performance of various deep learning and machine learning models, such as Random Forest, Quantum Machine Learning (QML), Long Short-Term Memory (LSTM) networks, and Support Vector Regression (SVR). Our findings show that LSTM networks outperform conventional techniques like Random Forest (MAE: 0.530, R2: 0.026) with a Mean Absolute Error (MAE) of 0.529 and an R2 score of 0.074, capturing temporal correlations in the data. Additionally, we investigate the use of quantum-inspired models, demonstrating the potential of hybrid quantum-classical techniques for this job with an MAE of 0.507 and an R2 score of 0.125.

We suggest a novel deep learning framework that combines feature engineering, hyperparameter optimization, and ensemble techniques in order to overcome the shortcomings of current models. According to preliminary tests using polynomial features and sophisticated models like as XGBoost and SVR, performance can be further improved by meticulous preprocessing and model modification. According to our research, precipitation estimations obtained from CML data can be made much more accurate and reliable by using deep learning, especially LSTM and hybrid quantum models.

By showcasing the efficiency of DL approaches for processing CML data, this work adds to the expanding corpus of research on opportunistic sensing. We also highlight the possibilities for combining CML-derived precipitation estimates with conventional remote sensing techniques like radar and satellite data, and we talk about the implications of our findings for operational applications like nowcasting and hydrological modeling. In order to promote the use of CMLs for real-time, high-resolution precipitation monitoring, this work attempts to close the gap between data collection and useful insights.

GNN-Based Data Fusion for Precipitation Estimation Using Opportunistic Sensors

Author: ALI DAHER^{None}

Corresponding Author: ali.daher@uvsq.fr

Accurate precipitation estimation is essential for hydrology, meteorology, and climate studies. Traditional methods rely on rain gauges, weather radars, and satellite observations, each with inherent limitations. Opportunistic sensing through Commercial Microwave Links (CML) offers a promising complementary data source, especially in regions with sparse conventional observations. This work explores the use of Graph Neural Networks (GNNs) for fusing precipitation data from radars, rain gauges, and CML to improve rainfall estimation.

We propose a novel GNN-based approach that models the spatial and temporal dependencies among different sensing sources. By representing the measurement network as a graph, GNNs can effectively learn relationships between nodes and edges. The model is trained and evaluated using real-world precipitation datasets. Its performance is compared with other deep learning techniques, including Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), in terms of accuracy and robustness to missing or noisy data.

Initial results suggest that GNNs outperform conventional deep learning models by better capturing spatial correlations and leveraging the irregular distribution of sensing nodes. This study highlights the potential of GNNs for multi-source data fusion in precipitation estimation, paving the way for improved rainfall monitoring using opportunistic sensing.

A toolbox for real time data acquisition and quality control of personal weather station rainfall data

Authors: Nathalie Rombeek¹; Jochen Seidel²; Georges Schutz³

¹ *Department of Water Management, Delft University of Technology, the Netherlands*

² *Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Germany*

³ *RTC4Water s.à.r.l., Roeser, Luxembourg*

Corresponding Authors: georges.schutz@rtc4water.com, jochen.seidel@iws.uni-stuttgart.de, n.rombeek@tudelft.nl

The high network density of personal weather stations (PWSs), often exceeding that of official weather stations from national meteorological agencies, offers a large potential to improve precipitation estimates. Another advantage is that PWSs have a high temporal resolution (~5-min), are available in (near) real-time and can potentially be used for now-casting, flood forecasting or early warning system. For such purposes the latency and quality of the data are important aspects to consider.

We explored the real-time potential of rainfall data from PWSs from the private company Netatmo, which can be accessed via an application programming interface (API). We analysed the real-time accessibility and latency of the data and developed concepts of how existing quality control algorithms can be applied in the context of real-time applications. First results of these analyses and a road map for implementing this as a software package are presented.

Publicly available four-year CML dataset for the Netherlands

Author: Aart Overeem¹

Co-authors: Bas Walraven²; Hidde Leijnse¹; Remko Uijlenhoet³

¹ *Royal Netherlands Meteorological Institute*

² *Delft University of Technology*

³ *TU Delft*

Corresponding Authors: hidde.leijnse@knmi.nl, overeem@knmi.nl, r.uijlenhoet@tudelft.nl, b.walraven@tudelft.nl

We present a dataset of commercial microwave link (CML) received signal levels for the Netherlands. This can be used to estimate path-average rainfall between telephone towers. It contains microwave frequency, end date & time of reading, minimum & maximum received power, path length, coordinates, link identifier, errored seconds, and severely errored seconds. The dataset consists of on average 3070 sub-links over 1818 unique link paths covering the Netherlands, having a temporal resolution of 15 min. The dataset spans the period 13 January 2011 up to and including 15 March 2015, although data gaps exist. It contains part of the network from one of the three mobile network operators in the Netherlands during this 4-year period. The data have been provided by the mobile network operator (MNO) T-Mobile NL (since 5 September 2023 called Odido). Note that the transmitted signal levels were not available and are nearly constant. No adaptive power control (ADPC) was used.

The following characteristics of the dataset are presented: 1) timeseries of number of sub-links and link paths as a function of time; 2) a scatter density plot of microwave frequency versus link length; 3) map of the Netherlands with the CML locations and their availability per year; 4) an example of the application of the dataset: a 3-month rainfall map based on merged radar and CML accumulations, which is compared to two gauge-adjusted radar rainfall maps.

We hope that this CML dataset will contribute to the OpenSense goal of comparing the performance of CML rainfall retrieval algorithms on common datasets and will lead to improved algorithms. Moreover, a publicly available reference dataset of gauge-adjusted radar rainfall accumulations is available covering the same period and area.

Overeem, A., Walraven, B., Leijnse, H. (H.), & Uijlenhoet, R. (2024). Four-year commercial microwave link dataset for the Netherlands (Version 1) [Data set]. 4TU.ResearchData. <https://doi.org/10.4121/BE252844-B672-471E-8D69-27269A862EC1.V1>

pypwsqc: A new tool for quality control of personal weather station data rainfall data

Authors: Jochen Seidel¹; Louise Louise Petersson Wårdh²; Nicholas Illich¹; Lotte de Vos³; Christian Chwala⁴

¹ *Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Germany*

² *1) Swedish Meteorological and Hydrological Institute (SMHI), Folkborgsvägen 17, Norrköping SE-601 76, Sweden (2) Division of Water Resources Engineering, Faculty of Engineering, Lund University, P.O. Box 118, 22100 Lund, Sweden*

³ *Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands*

⁴ *Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Campus Alpin, Garmisch-Partenkirchen, Germany*

Corresponding Authors: lotte.de.vos@knmi.nl, louise.petersson.wardh@smhi.se, christian.chwala@kit.edu, st172541@stud.uni-stuttgart.de, jochen.seidel@iws.uni-stuttgart.de

The use of so-called opportunistic rainfall sensors like Personal Weather Stations (PWS) and Commercial Microwave Links has gained much attention over the recent year, as they clearly outnumber professional rain gauges which are operated by national weather services and other. However, the data quality of such sensors is typically low and thus their information cannot be used without thorough quality control. Various quality control algorithms for PWS rainfall data have been developed and published within the EU COST Action CA 20136 “Opportunistic Precipitation Sensing Network” (OPENSENSE) in the past years and are available on OPENSENSE’s GitHub (El Hachem et al. 2024).

These QC algorithms are now available in a Python package. The new functionalities of these QC filters include (1) an improved indicator correlation filter which was originally developed by Bárdossy et al. (2019) which now provides a skill score for the accepted PWS to assess quality of the indicator correlation with neighbouring references, (2) an algorithm to correct rainfall peaks in PWS data which may be caused by connection interruptions between the rain gauge and the base station and (3) a Python implementation of the QC algorithms for identifying faulty zeroes, high influxes and station outliers originally developed in R by de Vos et al. (2019).

These new functionalities are implemented in the ‘pypwsqc’ Python package (<https://zenodo.org/records/14177798>) which is currently under development in the OPENSENSE COST Action. In this contribution we present the new features and guidelines for usage.

Bárdossy, A., Seidel, J., and El Hachem, A. (2021), The use of personal weather station observations to improve precipitation estimation and interpolation. *Hydrol. Earth Syst. Sci.*, 25, 583–601.

El Hachem, A., Seidel, J., O’Hara, T., Villalobos Herrera, R., Overeem, A., Uijlenhoet, R., Bárdossy, A., and de Vos, L.W (2024), Technical note: A guide to using three open-source quality control algorithms for rainfall data from personal weather stations, *Hydrol. Earth Syst. Sci.*, 28, 4715–4731.

de Vos, L.W., Leijnse, H., Overeem, A., and Uijlenhoet, R. (2019), Quality control for crowdsourced personal weather stations to enable operational rainfall monitoring. *Geophysical Research Letters*, 46, 8820–8829.

/

Poster Session #2

Session Chair: Jochen Seidel

Periodic Noise

Author: Sagi Alon^{None}

Corresponding Author: sagialon1@mail.tau.ac.il

This work explores the phenomenon of periodicity (usually at 24-hour periods) in the received signal level observed in Commercial Microwave Links. We will present an overview based on several observations from different locations around the world (mainly in Germany, Israel, Sweden, and Italy) and from different sources (cellular backhaul commercial microwave links and smart-city wireless network of mm-wave links) which are collecting data with different characteristics (e.g. sampling methods like instantaneous and min/max samples at different sampling rates, using different quantization levels). We will share insights on how atmospheric factors (e.g., weather) as well as hardware characteristics might play a role in these signal fluctuations, relating to previously reported studies.

Preliminary results suggest that fluctuations during the daily cycle can reach a few decibels at a number of locations, regardless of whether or not precipitation is present.

Despite the obvious correlation with a number of daily phenomena such as temperature, air pressure, and absolute humidity, the exact causes are still not fully understood, as correlation does not mean causation.

We will present key observations and show that, while a daily cycle in atmospheric conditions seems to match the pattern of signal loss, there is not yet a definitive cause-and-effect pattern for why this happens. Understanding this phenomenon is important both from an opportunistic sensing point of view and from a practical point of view. On the opportunistic sensing side, a better understanding of how atmospheric changes affect wireless signals could help fill in the gaps in current theories and allow for more accurate opportunistic weather sensing. In practice, better insight into these effects could help communication service providers design more reliable networks.

What you should be aware of when nowcasting rainfall in the tropics using CML-based rainfall estimates only

Author: Bas Walraven¹

Co-authors: Aart Overeem²; Luuk van der Valk¹; Miriam Coenders¹; Remko Uijlenhoet³; Rolf Hut¹; Ruben Imhoff⁴

¹ *Delft University of Technology*

² *Royal Netherlands Meteorological Institute (KNMI)*

³ *TU Delft*

⁴ *Deltares*

Corresponding Authors: ruben.imhoff@deltares.nl, a.m.j.coenders@tudelft.nl, r.w.hut@tudelft.nl, b.walraven@tudelft.nl, aart.overeem@knmi.nl, l.d.vandervalk@tudelft.nl, r.uijlenhoet@tudelft.nl

Accurate and timely precipitation forecasts are crucial for flood early warnings and mitigating other rainfall-induced natural hazards like landslides. For forecasts up to three hours ahead, rainfall nowcasts are increasingly being used. Generally, these nowcasts statistically extrapolate real-time remotely sensed quantitative precipitation estimates, often based on weather radars. However, the global distribution of high-resolution (gauge-adjusted, ground-based) weather radar products is heavily skewed, largely favoring Europe, Northern America, and parts of East Asia. In many low- and middle-income countries, predominantly located in the tropics, weather radars are largely unavailable due to high installation and maintenance costs, and rain gauges are often scarce, poorly maintained, or not available in (near) real-time.

A viable and ‘opportunistic’ source of high-resolution space-time rainfall estimates is based on the rain-induced signal attenuation experienced by commercial microwave links (CMLs) in cellular communication networks. Based on received signal power levels, path-averaged rainfall intensities can be estimated, and then interpolated to produce high-resolution rainfall maps.

In this study, we delve into the opportunities and constraints that arise when using these rainfall maps as only input source of rainfall information in a nowcasting algorithm. Our aim is to emulate an operational setting and as such assess the feasibility and give insights into where, when and how CML-based rainfall estimates can be used for nowcasting in Sri Lanka.

We use 12 months of data from 2019 and 2020 from a Sri Lankan CML network that predominantly covers the northern half of the country, we create spatial rainfall fields at 15-minute intervals. Using the nowcasting algorithm pySTEPS, probabilistic nowcasts are created for leadtimes up to three hours for events with different durations ranging from 1 to 24 hours. The nowcasts (QPF) are evaluated against the CML rainfall fields (QPE) at the catchment scale. The performance of the nowcast is analyzed with regards to the catchment size, and the varying CML coverage and density per catchment. The results are further analyzed by season to determine the potential influence of rainfall intensity and dominant wind direction on the nowcasts accuracy. Hourly rain gauges, where available, are used as an independent (point) reference source of rainfall information.

With this novel application of CML-derived rainfall fields, essentially providing a ‘weather radar’ in the tropics, we identify the major sources of uncertainty in the nowcasts and highlight the potential impact of relying solely on CMLs for operational early warning services in regions that lack dedicated rainfall sensors.

Relationship between Precipitable Water Vapor and heavy rainfall over Lombardy region in Northern Italy using GNSS and CML sensors network

Authors: Christina Oikonomou¹; Roberto Nebuloni²; Giovanna Venuti³; Xiangyang Song³; Haris Haralambous⁴; Eugenio Realini⁵

¹ CLOUDWATER LTD & Frederick Research Center, Nicosia, Cyprus

² IEIIT, Consiglio Nazionale delle Ricerche, Milan, Italy

³ Politecnico di Milano - Department of Civil and Environmental Engineering, Milan, Italy

⁴ Frederick Research Center & Frederick University, School of Engineering, Nicosia, Cyprus

⁵ Geomatics Research & Development (GReD) srl, Lomazzo, Italy

Corresponding Authors: roberto.nebuloni@cnr.it, res.ec@frederick.ac.cy, giovanna.venuti@polimi.it, xiangyang.song@mail.polimi.it, eugenio.realini@g-red.eu, eng.hh@frederick.ac.cy

Nowcasting and understanding of locally evolving severe weather events is a demanding task that requires the combined investigation of different type (both ground- and space-based) of datasets. Atmospheric water vapor (WV) which is the most abundant greenhouse gas (accounting for ~70% of global warming) comprises a significant energy source which generates severe weather and climate phenomena. GNSS (Global Navigation Satellite System) WV has been proved a valuable data source for high-resolution limited area Numerical Weather Prediction (NWP) models. The rapid spatiotemporal variations of WV in the low atmosphere poses one of the main challenges to NWP models forecasting accuracy. Abrupt increase of WV several hours before extreme rainfall has been temporally correlated with rainfall in various studies, followed by a decrease after the event. Other studies have investigated the joint effect of GNSS-WV and atmospheric pressure on extreme rainfall. Though many studies have evidenced ongoing accumulation of WV before the heavy rainfall, there is still a great difficult to determine a tight relationship between rainfall and WV, that could be reproduced by a plain, physically motivated two-layer nowcasting model.

Lately, Commercial Microwave Links (CML), globally used in cellular telecommunication networks of base stations, are exploited as opportunistic sensors to estimate the average rainfall intensity along the radio path and to reconstruct rainfall maps over a region. Rainfall measured by the CML network has a vast application prospect in both densely populated and remote mountainous regions. Over tropical regions, such as Sri Lanka, the spatial comparison of CMLs with the high-quality satellite product GPM (global precipitation measurement) and with conventional rain gauge data confirmed the potential of CMLs to provide detailed monitoring of heavy rainfall events. The advantage of both the GNSS and CML opportunistic sensors networks is their high spatial and temporal resolutions. In this context, the present study attempts a first comparison of GNSS tropospheric products (Precipitable Water Vapor) with the respective CML-derived rainfall measurements with the ultimate aim to investigate the possible correlation between WV and heavy rainfall, during selected extreme precipitation events occurring at the period June 2019 – June 2020 over the Lombardy region in Northern Italy. To achieve this, we will exploit CML network, owned by Vodafone Italia S.p.A., ground-based GNSS receivers network owned by GReD srl, as well as meteorological observations available through the Lombardy-based Advanced Meteorological Predictions and Observations (LAMPO) project.

Evaluation of the Dutch real-time radar precipitation product

Author: Aart Overeem¹

Co-authors: Hidde Leijnse¹; Bastiaan Anker¹; Mats Veldhuizen¹; Jouke Jacobi¹; Tim den Dulk¹; Tim Vlemmix¹; Rik Noorlandt¹

¹ *Royal Netherlands Meteorological Institute*

Corresponding Authors: tim.den.dulk@knmi.nl, hidde.leijnse@knmi.nl, bastiaan.anker@knmi.nl, tim.vlemmix@knmi.nl, jouke.jacobi@knmi.nl, mats.veldhuizen@knmi.nl, rik.noorlandt@knmi.nl, overeem@knmi.nl

The Royal Netherlands Meteorological Institute (KNMI) produces a publicly available real-time gauge-adjusted radar precipitation product of 5-min accumulations on a 1-km grid covering 450000 squared kilometres of northwestern Europe every 5 min. It is employed for various applications, including nowcasting. The quality of the product has been much improved since 31 January 2023. The employed radar and rain gauge dataset are described, as well as the applied algorithms, such as (polarimetric) fuzzy logic clutter removal and the gauge adjustment method. The performance of the product to estimate precipitation is assessed for the last year of the old and the first year of the renewed radar product. Non-meteorological echoes are much less of an issue for the renewed product. Moreover, comparison against independent rain gauge accumulations shows that underestimation decreases by about ten percentage points to 15% for the land surface of the Netherlands. Extremes are better captured. A spatial evaluation over the entire domain generally reveals improvements in precipitation estimates. Current and upcoming developments are presented.

Here, the processing chain of the product and the product quality without employing opportunistic sensing data are explained. The evaluation also shows the limitations of the product. The product could be improved by employing crowdsourced rain gauge data, which is the topic of another presentation, that does not provide all the details on the processing chain.

The radar dataset is available at <https://doi.org/10.21944/5c23-p429> (real-time) & <https://doi.org/10.21944/e7zx-8a17> (archive).

Can we estimate the amount of rain water during disastrously large flood events with high resolution?

Author: Anna Jurczyk¹

Co-authors: Jan Szturc¹; Katarzyna Ośródka¹; Agnieszka Kurcz¹; Magdalena Szaton¹; Mariusz Figurski¹; Robert Pyrc¹

¹ *Institute of Meteorology and Water Management - National Research Institute*

Corresponding Author: magdalena.pasierb@imgw.pl

In September 2024, a very heavy and severe flood took place in the Upper and Middle Oder River basin - a mountainous area in southwestern Poland. The widespread rainfall lasted for about four days, reaching daily totals over 200 mm in some areas. Due to the necessity for real-time precipitation and runoff forecasts and subsequent analyses, an important issue is how precisely we can measure and estimate precipitation with high temporal and spatial resolution over an orographically diverse area. To answer this question, different measurement techniques were analysed: from rain gauges, weather radar-based, satellite-based, CML-based (non-conventional, currently tested at IMGW for their usefulness in real-time operational applications), and mesoscale numerical model simulations. Both data available in real and near real time, as well as reanalyses available later, were analysed. Various reanalyses based on satellite data (IMERG Final, PDIR-Now) and mesoscale simulations of ERA5 and WRF models were also examined. Data from manual rain gauges (for daily totals) and multi-source estimates (for hourly totals) were used as a reference to evaluate the results. On this basis, the reliability of various techniques for measuring and estimating precipitation was examined.

Commercial Microwave Link research at the Climate and Earth Lab (Ghent University)

Author: Kwinten Van Weverberg¹

¹ *Ghent University*

Corresponding Author: kwinten.vanweverberg@ugent.be

This poster presents an overview of our ongoing and future research at the Climate and Earth Lab (CLEAR) of Ghent University, where we leverage commercial microwave links (CML) to enhance precipitation monitoring. In Belgium, our efforts focus on the hilly terrain of southern regions, where we aim to improve existing radar–rain gauge merged products by integrating CML data. Using disdrometers, we are recalibrating the relationship between signal attenuation and rainfall intensity through detailed analyses of summer case studies. In the upcoming year, we will extend our investigations to winter conditions, exploring the synergistic use of CML and radar to identify surface frozen precipitation, in line with the approach proposed by Oydvin et al. (2024).

Additionally, our research extends to Equatorial Africa, with a particular emphasis on Rwanda. This region is characterized by large spatiotemporal variability in rainfall and a lack of radar observations, factors that complicate early-warning systems for flash floods and landslides and complicate the evaluation of high-resolution weather and climate models. Through the recently started Sensor² project (Supporting Early-warning systems and Nature-based Solutions using Opportunistic Rainfall monitoring in Rwanda), we will seek to enhance rainfall monitoring by integrating data from microwave links, automatic rain gauges, and satellite observations. Complementing this effort, the installation of three disdrometers in Rwanda will enable more accurate calibration of rainfall intensities, with a focus on tropical precipitation regimes.

Overall, our research demonstrates the potential of commercial microwave links as a complementary observational tool, promising advancements in precipitation estimation and early-warning capabilities across diverse climatic regions.

Added value of Personal Weather Stations for Precipitation Estimates in the Lazio Region, Italy

Authors: Jochen Seidel¹; Benedetta Moccia²; Elena Ridolfi²; Damaris Zulkarnaen¹; Louise Petersson Wårdh³; Francesco Napolitano²; Fabio Russo²; András Bárdossy⁴

¹ *Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Germany*

² *Dipartimento di Ingegneria Civile, Edile e Ambientale, Sapienza University of Rome, Italy*

³ *1) Swedish Meteorological and Hydrological Institute (SMHI), Folkborgsvägen 17, Norrköping SE-601 76, Sweden 2) Division of Water Resources Engineering, Faculty of Engineering, Lund University, P.O. Box 118, 22100 Lund, Sweden*

⁴ *Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Germany*

Corresponding Authors: elena.ridolfi@uniroma1.it, jochen.seidel@iws.uni-stuttgart.de, benedetta.moccia@uniroma1.it

In the Lazio region, there is a dense network of 230 trustworthy rain gauges with a high temporal resolution. In addition, data from more than 300 Netatmo Personal Weather Stations (PWS) are available. However, since these PWS do not meet professional standards in terms of installation and maintenance, they must first be quality controlled (QC). For this purpose, we will apply the latest QC filters and bias corrections developed in the Opensense COST Action. After the QC, the quality of the PWS data will be evaluated by comparing them with co-located professional rain gauges. To assess the added value of PWS in capturing the spatial variability of rainfall (extremes) and on precipitation interpolation, the PWS will be included in the interpolation process. For this, a copula-based approach will be compared with conventional interpolation methods to highlight the added value of PWS in the interpolation.

Using Commercial Microwave Links to Estimate Rainfall Intensity and Variability in Rwanda

Authors: Uijlenhoet Remko¹; Ricardo Reinoso Rondinel²; Aart Overeem³; Kwinten Van Weverberg⁴; Jean de Dieu Ndayisenga⁵

¹ *Hydrology and Quantitative Water Management Group, Wageningen University*

² *Department of Civil Engineering, Katholieke Universiteit Leuven*

³ *Royal Netherlands Meteorological Institute (KNMI)*

⁴ *Department of Geography, Ghent University*

⁵ *Ghent University/University of Rwanda*

Corresponding Authors: jeandedieu.ndayisenga@ugent.be, r.uijlenhoet@tudelft.nl, ricardo.reinoso-rondinel@kuleuven.be, kwinten.vanweverberg@ugent.be, aart.overeem@knmi.nl

This poster presents a first-time application of using commercial microwave links (CML) to predict rainfall intensity and variability in Rwanda, in the framework of a research project (Sensor²) with Ghent University, Rwanda Meteorology Agency, MTN Rwandacell and University of Rwanda. Similar research has shown global success in generating real-time data rainfall monitoring, particularly in areas with limited weather radar coverage. Rwanda, a country of hilly topography, located in a tropical region where weather patterns are complex and fluctuate easily, and with high population density and widespread mobile phone usage, could highly benefit from application of CML for rainfall monitoring. This research will identify the limitations of using CML to predict rainfall in a tropical region like Rwanda, with challenging meteorological conditions and a large variability in applied microwave frequencies. We will present a first analysis of a few case studies of extreme rainfall during the rainy season of 2025. The ultimate aim of the project is to generate calibrated, operational, high-frequency rainfall maps in real-time. To do so, an extensive calibration will be performed using dedicated disdrometers and automatic rain gauges. In addition, we plan to merge the CML-derived rainfall products with the existing automatic rain gauge network and satellite information. We will also investigate alternative approaches for dry-wet period identification using Meteosat Third Generation and optimal spatial interpolation methods. As such, this research will improve the accuracy of rainfall monitoring and early warning systems at the Rwanda Meteorology Agency reducing and mitigating risks associated with extreme weather events and improving Rwanda's disaster preparedness.

E-band rainfall observation: uncertainties in quantitative measurements and long-term statistics of outages

Authors: Anna Špačková¹; Martin Fencel¹; Vojtěch Bareš¹

¹ *Czech Technical University in Prague*

Corresponding Authors: martin.fencel@cvut.cz, anna.spackova@cvut.cz, baresvoj@cvut.cz

The deployment of E-band CMLs in high-capacity communication networks is increasing however, studies investigating how suitable they are for rainfall monitoring are still rare.

The analysis explores three-year long dataset from an E-band CML from the Prague network accompanied by five reference weather stations. The 4.5 km link, operating with two sublinks at 73.25 GHz and 83.25 GHz, offers a low rainfall detection threshold, making it sensitive to light rainfall intensities. However, the E-band signal is particularly susceptible to heavy rainfall attenuation leading to outages in rainfall monitoring.

The first objective of the study is to evaluate the impact of rainfall type and rainfall (non)uniformity on the accuracy and precision of the signal attenuation and rainfall intensity relationship. The second analysis focuses on the missing higher rainfall intensities in the observations and statistically assesses them.

The parameter sets were optimised for power-law approximation of the relation between attenuation and rainfall for convective and stratiform rainfall types (based on drop size distribution from nearby disdrometer). While improvements in correlation and RMSE for ITU and optimised parameters are negligible, the bias was reduced from -0.26 to -0.06 for convective rainfalls and from -0.05 to -0.03 for stratiform rainfalls in average for both sublinks. The variability of rainfall along the link path also influences the optimal parameter selection. For the most variable rainfalls (with CV of reference rainfall between 0.75 and 2), the relative bias improved from -0.20 to -0.04 in average for both sublinks.

CML outages caused by signal attenuation are clearly linked to rainfall intensity. During rainfalls exceeding path-averaged intensity 35 mm/h the outages occur about 75 % of time. Moreover, technically no E-band CML observation is available for rainfall intensities over 55 mm/h.

The study demonstrates that the suitability of E-band CMLs for rainfall observation is not fully explored, although these opportunistic sensors are becoming increasingly widespread. The employment of different parameter sets for different rainfall types reduces errors; however, it involves additional information about the rainfall type. Long E-band CMLs are prone to outages due to intense rainfall, this analysis addresses a knowledge gap regarding the distribution of outages in E-band CML data.

Enhancing Dry-Wet Classification in CML/SML Time Series by Integrating NWC-SAF PC Products and Commercial Microwave Links with Cloud Microphysical Satellite Data

Authors: Martin Fenc¹; TAOUFIQ SHIT¹; Vojtech Bares¹

¹ *CTU university, Prague*

Corresponding Authors: toufikshit95@gmail.com, martin.fenc@cvut.cz, vojtech.bares@cvut.cz

Abstract:

Accurate rainfall estimation benefits from combining various measurement methods. Commercial Microwave Links (CMLs) provide path-averaged rainfall rates through the attenuation of emitted radiation, offering valuable data, especially in regions lacking dedicated rainfall sensors, such as many parts of Africa. However, processing CML data presents challenges, notably in differentiating between wet and dry periods. Factors such as Wet Antenna Attenuation (WAA) and baseline drift due to environmental changes make conventional methods unstable and can lead to inaccuracies in rainfall estimates.

To address these issues, we propose integrating CML data with satellite-based cloud microphysics products to enhance wet-dry classification. In this study, we combine a hybrid CNN-LSTM model trained on commercial CML data with cloud microphysics data from the Meteosat Second Generation (MSG) Spinning Enhanced Visible and InfraRed Imager (SEVIRI), specifically the Precipitation Cloud (PC) and Precipitation Cloud-Phase (PC-Ph) products, for rain event detection. This integration aims to improve the accuracy of wet-dry classification in CML time series, assessing performance across varying rainfall intensities, frequencies, and durations. Data from 3,748 CMLs in Germany and 2,889 CMLs in the Czech Republic during June 2021 are analyzed, with validation against the RADKLIM-YW radar product.

By leveraging this hybrid approach, we anticipate improvements in dry-wet classification performance and plan to extend the use of these products for rainfall type classification and correcting errors related to the dependence of the attenuation-rainfall relationship on the Drop Size Distribution (DSD).

Keywords: Commercial Microwave Links, Satellite Data Integration, Rain Event Detection, Wet-Dry Classification, Cloud Microphysics, MSG SEVIRI, DSD, Rainfall Type

Opportunistic rainfall observations in Gothenburg, Sweden: open data and real-time service

Author: Remco van de Beek¹

Co-authors: Glen Nivert²; Jonas Olsson¹; Louise Petersson Wårdh¹

¹ *Swedish Meteorological and Hydrological Institute*

² *Sustainable Waste and Water, City of Gothenburg*

Corresponding Authors: jonas.olsson@smhi.se, glen.nivert@kretsloppochvatten.goteborg.se, louise.petersson.wardh@smhi.se, remco.vandebeek@smhi.se

Gothenburg City is located on the west coast of Sweden, which is the most rainy region in the country. The city with surroundings has experienced several flood events over the years, with both pluvial, fluvial and coastal components. In order to minimize the risk of flooding as well risks of treatment plant overload and sewer overflow, the sewer network is equipped with a system for real-time control (digital twin) that allows diversion of flows as the situation requires. The urban basin feeding the central treatment plant is large and it takes up to 20 hours from rainfall at the edge of the basin to reach the plant, therefore accurate rainfall observations are crucial for predicting the inflow in the near future.

Currently, Gothenburg relies on one rainfall station in the national network and X municipal stations distributed over the city for rainfall observations with a high temporal resolution (1 min). This is not sufficient for fully capturing the spatial variability of localized cloudbursts, and in order to improve the situation different types of opportunistic rainfall observations have been investigated. Early tests with observations from Commercial Microwave Links (CML) some 10 years ago were promising, but it turned out difficult to set up an operational service. More recently, observations from Personal Weather Stations (PWS) in the city have been collected and investigated.

In this presentation we will share some experiences from the collaboration between a city (Gothenburg) and a national service (Swedish Meteorological and Hydrological Institute), on applying opportunistic rainfall observations in a hydrological context. In particular, a prototype of a real-time service delivering high-resolution rainfall based on integrated observations from official stations, PWS and weather radar will be described. Furthermore, the extended version of the OpenMRG data set, with open high-resolution rainfall observations from stations, CML and radar in Gothenburg, will be presented.

Including PWS gauge data in radar merging improves real-time precipitation estimates: Methodology and 1-year evaluation for the Netherlands

Authors: Jiri Svatos¹; Aart Overeem²

Co-authors: Nathalie Rombeek³; Claudia Brauer¹

¹ *Wageningen University & Research*

² *Royal Netherlands Meteorological Institute (KNMI)*

³ *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Water Management*

Corresponding Authors: aart.overeem@knmi.nl, claudia.brauer@wur.nl, jiri.svatos@wur.nl, n.rombeek@tudelft.nl

Accurate precipitation estimation relies on adjusting radar data with rain gauge measurements to correct spatially and temporally varying errors. While official gauge networks are typically too sparse to sufficiently capture the precipitation variability in real time, recent studies have demonstrated the potential of using crowdsourced rain gauge data from low-cost personal weather stations (PWSs) which provide a much higher density of observations despite some quality issues.

Here we present a methodology for merging real-time radar data with both PWSs and professional rain gauges, explicitly considering the higher uncertainty of PWS observations. Combining crowdsourced data from >4000 Netatmo PWSs and 32 official KNMI automatic weather stations, we evaluate estimates of 1-hour and 24-hour precipitation accumulations for the period February 2023 – January 2024 in the Netherlands against an independent set of professional rain gauge measurements.

We show that including PWSs in the radar merging in addition to the official rain gauges improves real-time precipitation estimates even when applying only a simple and quick PWS quality control. The largest improvements are obtained during heavy rainfall and for areas far from the official stations. The benefit of including PWSs in the merging is also preserved for lower PWS densities, making this method potentially applicable in a wide range of other locations. These findings underpin the value of incorporating crowdsourced data into radar products and offer a pathway for more accurate operational precipitation monitoring.

Hydro-Climatological Thresholds to Enhance Early Warning Systems for Landslides in Rwanda

Author: Jean D'Amour DUSABIMANA¹

Co-authors: Ricardo Reinoso-Rondinel²; Olivier Dewitte³; Thom Bogaard⁴; Judith Uwihirwe⁵; Derrick Bugenimana⁶; John Musemakweri⁶

¹ *KU Leuven*

² *Department of Civil Engineering, Hydraulics and Geotechnics, KU Leuven, Leuven, Belgium*

³ *Department of Earth Sciences, Royal Museum for Central Africa, Tervuren, Belgium*

⁴ *Department of Water Management, Section Water Resources, Faculty of Civil Engineering and Geosciences, TU Delft, Delft, The Netherlands*

⁵ *Department of Mechanization and Irrigation Enterprise, Rwanda Institute for Conservation Agriculture (RICA), Gashora, Bugesera, Rwanda*

⁶ *Department of Irrigation and Drainage, School of Agricultural Engineering, College of Agriculture, Animal Sciences and Veterinary Medicine, University of Rwanda, Musanze, Rwanda*

Corresponding Authors: t.a.bogaard@tudelft.nl, ricardo.reinoso-rondinel@kuleuven.be, d.bugenimana@ur.ac.rw, john.musema2013@gmail.com, jeandamour.dusabimana@student.kuleuven.be, olivier.dewitte@africamuseum.be, uwihirwejudith@yahoo.fr

Landslides are rainfall induced geo-hydrological hazards that frequently occur in the mountains of Rwanda, a densely-inhabited region of the African tropics. In May 2023 alone, a heavy rainfall event triggered in a few hours a cluster of hundreds of landslides, which led to more than 100 fatalities and significant economic losses in the impacted communities. Although quite common, natural hazard disasters associated with the rapid occurrence of rainfall-triggered landslides are difficult to predict, especially in a data-scarce context such as that of Rwanda. The lack of accurate rainfall data plays an important role in this problematic situation, and a such prevents the issuance of timely and contextualized early warning systems (EWS). To tackle this issue, and considering the dense network of mobile phone antennas in Rwanda, the project entitled “Supporting Early-Warning Systems and Nature-based Solutions using Opportunistic Rainfall monitoring in Rwanda”(SENSOR2) has been initiated. This research, part of SENSOR2 project, aims to update the susceptibility-based hydro-climatic landslide thresholds that have been developed over Rwanda by integrating real-time rainfall monitoring, hydro-climatic data, and geospatial analysis. Specifically, this study will focus on the development of empirical landslide susceptibility models using updated hydro-climatic thresholds based on calibrated Commercial Microwave Link (CML) rainfall data from the mobile phone network of Rwanda. It is foreseen that CML-based thresholds will lead to improved landslide prediction models and thus enhance the performance of existing EWS for effective risk communication and preparedness for climate-induced geo-hydrological hazards in Rwanda.

Key words: Landslides, Hydro-climatic thresholds, Early Warning Systems (EWS), Commercial Microwave Links (CML)