BAMS
Meeting Summary

The Opportunistic Precipitation Sensing Network (OpenSense)

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First Conference on Opportunistic Sensing of Precipitation

***What*:** Meeting to summarize and present final outcomes of OpenSense and discuss future directions for coordination around opportunistic sensing (OS) of precipitation. Dissemination of knowledge took place during three conference and meeting days with discussion on the benefits of OS for National Weather Services during a panel debate.

***When*:** 24–26 June 2025

***Where*:** Headquarters of Deutscher Wetterdienst, Offenbach, Germany

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1. Introduction and background

The International Conference on Opportunistic Sensing of Precipitation (OpenSense) took place on 25–26 June 2025 at the Deutscher Wetterdienst (DWD) headquarters in Offenbach, Germany. Organized as the final meeting of the Cooperation in Science and Technology (COST) Action Opportunistic Precipitation Sensing Network (CA20136), the meeting brought together over one hundred participants from across Europe and beyond. The attendees represented a broad spectrum of the meteorological community, including researchers in hydrology, radar meteorology, atmospheric science, computer science, and representatives of several national meteorological and hydrological services (NMHSs). The overarching research topic of the conference was about the advances of opportunistic sensing (OS) for precipitation monitoring. OS uses signals or devices not originally designed for professional, high-quality meteorological purposes—such as commercial microwave links (CMLs), personal weather stations (PWSs), television-satellite microwave links (SMLs), and citizen-science contributions—as rainfall sensors. OS can either complement conventional observations from gauges, radars, and satellites or give observational data in regions with sparse rainfall data. The COST Action OpenSense, launched in 2021, has provided a framework for this community. It aimed to establish a coordinated scientific network, to harmonize processing methods, and prepare the ground for operational uptake of OS methods. Working groups within OpenSense focused on data management, methodological homogenization, data merging, and applications (https://opensenseaction.eu/). The conference was the kickoff of a meeting series on the scientific progress and institutional prospects of OS rainfall estimation. The second edition is already in preparation at the Royal Netherlands Meteorological Institute (KNMI) in De Bilt, the Netherlands, on 23 and 24 June 2026. This first edition of the conference served as the final meeting of OpenSense and also consisted of internal management committee and working group meetings preceding the two conference days. The conference program was structured into thematic sessions described in the following sections and consisted of oral and poster sessions as well as keynote lectures and a panel discussion. This report synthesizes the main themes, cross-cutting insights, and emerging challenges as discussed across the sessions.

2. Achievements of OpenSense

The main achievements of OpenSense were presented during all sessions of the conference and during dedicated working group meetings on the first day. Here, these achievements are structured into the five working groups (WGs) that OpenSense consists of. The first three of

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them coordinate the action's efforts on scientific topics, and the last two serve internal and external capacity building and communication. WG1 on data management and standardization focused on defining common data and metadata format conventions for different types of OS sensors and coordinated curation and sharing of individual OS datasets and identified benchmark datasets. This resulted in the definition of the OpenSense OS format based on NetCDF and Climate and Forecast conventions (Hassell et al. 2017) by Fencl et al. (2024) with an up-to-date version maintained on GitHub (https://github.com/OpenSenseAction/OS_data_format_conventions/). WG1 also curates and regularly updates a database of public and private OS datasets and identifies appropriate benchmark datasets for method intercomparison studies. Up to now, five different OS datasets were published openly and selected as benchmark datasets.

WG2 on method and software homogenization did review the state of the art of existing open-source processing tools for OS rainfall data. Based on this assessment, WG2 collaboratively developed three new software packages called poligrain, pypwsqc, and mergeplg to build a new software ecosystem with a robust foundation and interoperable implementations of methods (Chwala et al. 2025, manuscript submitted to *Hydrol. Earth Syst. Sci.*). At the core of this software ecosystem is a data model that follows the standards defined in WG1. One of the new software packages is devoted to methods for merging weather radar data with data from rain gauges and CMLs, which was developed in collaboration with WG3 to support their work on a method intercomparison. In parallel, WG2 carried out an intercomparison study of CML processing methods.

WG3 on merging and application reviewed the current state of OS applications and coordinated the integration of open datasets from WG1 with software tools developed by WG2 for benchmarking studies. Olsson et al. (2025) conducted a comprehensive review of the literature in which OS rainfall estimates were used in downstream applications and carried out a survey among OpenSense members to assess the readiness of OS rainfall for operational implementation. A key activity of WG3 involved benchmarking studies focused on CML processing, PWS quality control, and radar–CML merging methods, which are currently in progress. In addition, the WG has supported several NMHSs through projects aimed at incorporating OS into (test) operational routines, e.g., CML–radar adjustment at DWD (Germany) and PWS data utilization at Swedish Meteorological and Hydrological Institute (SMHI) (Sweden).

WG4 and WG5 worked jointly on all administrative tasks associated with the Action. WG4 on stakeholder involvement and WG5 on capacity building, knowledge exchange, and coordination focused on collaborating with key stakeholder groups, including researchers, data owners, NMHSs, telecommunication operators, international organizations, and hardware vendors. Among the Action members, participation particularly involved OS data researchers and data providers, such as those working with CMLs, SMLs (HD Rain, MBI, Ayecka), and other precipitation information (PWS as well as rain gauge and radar data from NMHSs). Engagement was strengthened through roundtable discussions on the Global Microwave Link Data Collection Initiative (GMDI), with representatives from WMO, ITU, GSMA, EUMETNET, NMHSs (e.g., DWD, Meteo Rwanda), mobile network operators (Telefónica, T-Mobile, Odido), private companies (RTC4Water, Hydro Meteo GmbH, HD Rain, Google Research, Aon Czech Republic), industry partners (Huawei), and academic institutions (CTU Prague, KIT, TU Delft, TAU). Discussions defined the technical, legal, and business frameworks for using CML data in rainfall monitoring, leading to the creation of a GMDI Working Group, initiation of an ITU recommendation on link metadata standards, and a pilot of the GMDI-CAP system. GMDI is funded by a COST Innovator Grant for 1 year starting in November 2025 under the name setGMDI. Knowledge exchange was advanced through bimonthly OpenSense short online conferences, two international training schools, four coding meetings, annual joint meetings, and the first International OpenSense Conference.

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During the Action, 29 Short-Term Scientific Mission grants supported exchange visits among scientists, particularly young researchers and innovators. OpenSense results are disseminated via the OpenSense website (https://opensenseaction.eu). In addition, WG4 also held the responsibility, in coordination with the Action Science Communication Coordinator (JO), to produce and disseminate the OpenSense Action outputs on various channels: flyers, leaflets, and slides for researchers to present during conferences and venues; an active YouTube channel to which short promotional clips and short online conference recordings were regularly uploaded; and Twitter (X) and Facebook/Instagram channels for updates regarding upcoming Action meetings, presentations at conferences, etc. All (social) media links are available from the OpenSense website.

The OpenSense community will maintain its core activities in the next few years after the COST Action ends in October 2025. WG1 will keep monitoring new OS datasets and support their standardization and long-term storage in public repositories. WG2 will maintain collaborative software development efforts, ensuring open and interoperable tools. WG3 will further engage in benchmarking studies and promote the uptake of OS approaches, for example, through contributions to EUMETNET's Expert Team on IoT. WG4 and WG5 will maintain the community's homepage and organize short online conferences on a quarterly basis. The core group plans to continue the OpenSense Conference as an annual series, serving as an anchor point of the community's activities.

3. Conference topics

a. Open datasets. Open-access OS datasets are crucial for intercomparison studies and for the robust testing of new processing methods. Although OS data are typically owned by private companies, several datasets were successfully published with the support of the OpenSense Action during its course and were presented in the dataset session. Generally, the OS datasets published after the first release of the OpenSense OS format adhere to it. Data acquisition for open datasets requires case-specific effort; related experiences and software were shared during the conference and panel discussion.

b. Processing methods. A central topic throughout the meeting was about various methods for processing OS rainfall data. The processing methods session was illustrated by examples of how far the community moved from proof-of-concept experiments to provide robust, reproducible, and scalable methods. A main theme was the necessity of rigorous quality control (QC). Opportunistic data, by nature, are noisy and often contain artifacts unrelated to precipitation. Contributions presented advances in QC algorithms for CMLs, PWS, and SMLs. Tackling QC but also other processing steps, artificial intelligence (AI) approaches are increasingly used with OS data. Talks highlighted generative adversarial networks (GANs) for rainfall estimation without paired training datasets, graph neural networks for fusing multisource precipitation data, and hybrid architectures for radar adjustment. The community recognizes both the value of established QC procedures and the promise of AI-driven innovations. It is agreed that QC and robust processing are necessary for the application of OS rainfall data. Participants stressed, however, that machine learning (ML) must be coupled with physical constraints to ensure transferability and interpretability, especially for extreme events.

c. Data merging. The data merging session addressed the question that is one of the main motivations for OS research in Europe: How to combine heterogeneous OS datasets to produce reliable precipitation estimates. National and regional meteorological services rely heavily on quantitative precipitation estimation (QPE) products derived from radar, gauge networks, and satellites. While radar provides spatial coverage, it is prone to biases; gauges provide

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ground truth but are sparse and have their own issues; and satellites offer global reach but at limited resolution. OS data, in contrast, are often abundant but noisy. The merging challenge lies in integrating these sources into coherent rainfall fields. A keynote contribution demonstrated the assimilation of near-surface temperature and humidity observations from PWS and attenuation data as a proxy for path-averaged rain rates from CML data into convection-permitting numerical weather prediction (NWP). Assimilation experiments with the Icosahedral Nonhydrostatic (ICON)-D2 ensemble system (part of DWDs forecasting system) showed positive impacts on convective initiation and short-term rainfall forecasts, a result consistent with earlier work on assimilating nontraditional data such as Mode-S aircraft and GPS zenith delays (de Haan 2011; Mahfouf et al. 2015). The presentation underscored how OS data can contribute directly to forecast skill when proper QC and bias corrections are applied. Other contributions presented open-source software frameworks for merging. The mergeplg package, developed as community software within OpenSense, enables radar adjustment with CMLs and gauges. Similarly, the pyRADMAN framework extends operational radar-gauge merging methods by including CML data in a real-time environment at an NMHS. The conclusion from this session was that merging methods have moved beyond conceptual demonstrations. With the emergence of open datasets and reproducible software, the community is well positioned to provide best practice examples for rainfall products that leverage both conventional and opportunistic sensors.

d. Comparative performance and uncertainty estimation. While processing and merging methods are advancing, their credibility depends on robust evaluation. The performance and uncertainty estimation session addressed this critical aspect. Several contributions examined the possible retrieval of information on drop size distributions from microwave link scintillations and the disaggregation of CML path-averaged rain rates into subpath estimates. These approaches highlight the increasing sophistication of OS retrieval algorithms. Yet the challenge remains to quantify uncertainties across diverse temporal and spatial scales. Discussions repeatedly emphasized that validation and benchmarking must be standardized. While case studies show promising results, comparisons are often based on limited datasets or inconsistent evaluation metrics. For OS methods to gain acceptance by NMHSs, uncertainty estimates must be transparent, reproducible, and statistically robust. A keynote lecture broadened the session's perspective by addressing AI in hydrometeorology. Applications ranged from enhancing radar rainfall estimation to bridging climate dynamics with local rainfall modeling. The presentation underscored the dual promise and challenge of AI: While it can extract patterns from complex, heterogeneous datasets, its "black box" character raises questions about interpretability and reliability (Liu et al. 2016; Reichstein et al. 2019). In the context of OS, AI methods may accelerate the development of robust retrieval algorithms but will require careful validation against physical benchmarks. The key outcome of this session was that uncertainty assessment in the sense of verification is central to the operational acceptance of OS. While methodological innovation is strong, convergence on shared protocols for validation and error quantification remains an urgent task for the community.

e. Applications. The applications session showcased the potential of OS to address real-world hydrometeorological challenges. One of the strongest messages was the value of OS in urban hydrology. Citizen-operated PWS networks, when properly quality controlled, provide dense observational coverage in cities. These data can improve rainfall interpolation, support flash flood forecasting, and enhance resilience to extreme events. A case study of the October 2024 Valencia floods illustrated how PWS data revealed localized rainfall intensities that were underrepresented by official networks, underscoring the contribution of citizen science

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to disaster response. Opportunistic sensors also offer a pathway to monitor rainfall in data-sparse regions. Satellite microwave links, mesh networks, and low-frequency CMLs were presented as promising options for regions with limited meteorological infrastructure. This global relevance was highlighted as a key reason why OS methods resonate beyond Europe. The synthesis outcome was that OS has moved into applied contexts, particularly in urban environments and for extreme event monitoring. While integration with operational decision-support systems remains limited, the direction of travel is clear: OS is increasingly recognized as a valuable component of climate resilience and hydrometeorological services, such as nowcasting.

f. Bridging the Gap to operations. Following the scientific sessions on methods, merging, performance, and applications, a central question of the conference was how to bridge research advances and operational uptake. This theme was explored in the Bridging the Gap oral session and in a panel discussion involving representatives of NMHSs and the research community. The discussions revealed both optimism and caution. On the one hand, OS offers clear benefits: higher density of observations, rapid availability, and low costs. On the other hand, NMHS representatives emphasized unresolved challenges: legal frameworks for data sharing, quality assurance, standardization, and the need to build trust with users. One keynote provided a European perspective, outlining EUMETNET's efforts to integrate nontraditional data sources such as GNSS water vapor, aircraft observations, and PWSs. These experiences suggest that operational uptake of OS is possible but requires concerted efforts on data interoperability, sharing agreements, and institutional buy-in. The synthesis of this session was that bridging the gap requires not just technical innovation but also institutional frameworks. The parallels with the assimilation of Mode-S and GPS observations into NWP (de Haan 2011; Mahfouf et al. 2015) were drawn, showing that nontraditional data can become operationally indispensable when systematic efforts are made to standardize and integrate them. In conclusion, the panel emphasized that OS has the potential to add value to NMHSs, especially for high-impact weather and in data-sparse regions. However, realizing this potential will depend on progress in data sharing, legal agreements, and long-term institutional commitment as well as the ongoing improvement in the QC, processing, and uncertainty estimation of OS rainfall data.

4. Conclusions and outlook

The First Conference on Opportunistic Sensing of Precipitation—OpenSense 2025 brought together people from the OpenSense community and beyond. Opportunistic precipitation sensing has moved from early proof-of-concept studies (Messer et al. 2006; Leijnse et al. 2007; Overeem et al. 2013) to a mature research domain providing reproducible methods, open datasets, and operationally relevant software. Three cross-cutting conclusions emerged:

1) Standardization and uncertainty quantification
   Progress across all sessions highlighted the need for common benchmarks and protocols with OpenSense presenting a valuable first step in standardization. Without standardized approaches to QC, merging, and validation, OS data cannot gain the trust of operational users.
2) Open data and software ecosystems
   Initiatives such as the OpenSense software packages (poligrain, mergeplg, pypwsqc) demonstrate the community's commitment to reproducibility and open science. Expanding such efforts will be essential to accelerate innovation and uptake.

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3) Bridging to operations
   Scientific advances must be matched by institutional progress. Data sharing frameworks, legal clarity, and cross-border coordination are prerequisites for operational integration, particularly in Europe but also globally.

The broader message is that OS is no longer a niche research topic. It is emerging as a credible component of future weather and climate services, with particular relevance for urban hydrology, extreme rainfall events, and data-sparse regions. With sustained collaboration and institutional commitment, OS has the potential to transform how rainfall estimates are obtained and applied for societal benefit in a changing climate.

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Data availability statement. All open OS datasets and software tools can be found at https://opensenseaction.eu/outputs/datasets/ and https://github.com/OpenSenseAction.

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