

The OpenSat4Weather dataset: Ku-band satellite link data for precipitation monitoring

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Abstract. The TV-SAT signals received by the ground antennas of Satellite Microwave Links (SMLs) can be opportunistically used for detecting and quantifying precipitation. ~~Hence, SMLs can~~ Consequently, SMLs have the potential to serve as low-cost rainfall sensors ~~complementary to~~ complementing conventional instruments. However, a major challenge for opportunistic sensors, including both SMLs and their terrestrial counterpart—Commercial Microwave Links (CMLs)—is related to data ownership and accessibility constraints, possibly hindering progress in the development of processing tools and validation studies. This limitation highlights the importance of openly accessible datasets. While CML open datasets are already available, there are no large-scale SML datasets in public repositories. To ~~fill~~ address this gap, we introduce the OpenSat4Weather dataset, a comprehensive and openly accessible collection of measurements from 215 SML sensors deployed in Southern France, over a five-month period from August to December 2022. The dataset is accessible at <https://doi.org/10.5281/zenodo.16530166>. OpenSat4Weather also includes concurrent conventional measurements, namely, six-minute rainfall depths from 113 operational rain gauges, and radar-based estimates of rainfall intensity along each SML path. The radar data were derived from the gauge-adjusted weather radar product ~~Panthere~~ PANTHERE provided by Météo-France. Additionally, the dataset stores ERA5 reanalysis data of the 0°C isotherm height for rain height estimation, which are essential for accurately converting the received signal level into rainfall intensity.

In this paper, we overview the OpenSat4Weather dataset. We detail the data preparation process and draw statistics of data availability. ~~Furthermore, we present~~ We then provide a descriptive analysis of the dataset, ~~encompassing rain characteristics, based on the~~ including rainfall characteristics, derived from rain gauges, ~~SML received power statistics~~ statistical properties of the SML received signal levels, and a comparison between SML and radar data. ~~Finally, we provide~~ In addition, we illustrate examples of disturbances and anomalous patterns observed in raw SML signals. Finally, we provide some practical guidelines for processing and analyzing SML data. Our ultimate goal is to promote open research initiatives aimed at accelerating the development of SML-based applications. ~~Indeed, enhancing~~ Enhancing rainfall monitoring by opportunistic sensors ~~may has~~ the potential to provide substantial benefits, particularly in regions where conventional networks are sparse or unavailable.

1 Introduction

The impact of rainfall on ~~Satellite Communications (SatCom)~~ satellite communications has been investigated for decades as rain-induced signal fades can substantially degrade the performance of satellite links operating in the Ku band and above (Crane, 1996; ITU-R P.838-3, 2005). ~~The~~ On the other hand, the large deployment of geostationary fixed satellite services such as TV-SAT and satellite internet operating in rain-sensitive bands paved the way for the exploitation of satellite communication signals for rainfall monitoring. Satellite Microwave Links (SMLs) provide raw data in the form of time series of the Received Signal Level (RSL), corresponding either to the received power at the ground terminal (typically expressed in dBm) or the signal-to-noise ratio (in dB), averaged over an appropriate period of time. The RSL time series undergo a processing chain aimed at identifying the rainy periods, separating the effects of rain from the ones of disturbances, and finally converting the cleaned up signal into rainfall intensity estimates (Arslan et al., 2017).

Two distinct configurations have been proposed to implement the opportunistic sensing paradigm based on SMLs. The first approach relies on commercial-grade low-cost equipment consisting of a satellite dish antenna, a receiver and a data logger storing TV-SAT broadcast signals. The data collected in-situ by several of such devices are transferred to a central server for processing via cellular or Wi-Fi connectivity, thereby setting-up a real-time rainfall monitoring network (Colli et al., 2019; Gelbart et al., 2025). Flexibility is another key advantage of this approach as the sensors can be rapidly deployed wherever is needed, ~~for instance in areas where conventional sensors provide a poor coverage.~~ An alternative scheme relies on satellite-based IoT services or satellite internet systems, which use bidirectional links (Giannetti et al., 2019). In this case, the signal received ~~at the user terminal at ground~~ by the ground user terminal is transmitted back to the gateway ~~through the~~ via the satellite return channel. Measurements collected from many user terminals can be aggregated and processed by a centralized server. Please note the difference between the two approaches. In the first configuration, an additional infrastructure must be deployed and the raw data are accessible to anybody willing to install a ground receiver. In contrast, the second configuration does not require any additional infrastructure, as the RSL is transmitted through the return channel (alongside user traffic) for operational purposes, for instance, to optimize link performance according to current channel conditions. However, in this case, the satellite operator is the owner of the data. Both SML schemes provide very high temporal resolution data, in the order of 1-min or even less.

Research on SMLs as opportunistic rainfall sensors has been inspired by similar studies on terrestrial backhaul links, namely Commercial Microwave Links (CMLs), which emerged nearly twenty years ago (Messer et al., 2006; Leijnse et al., 2007a). A major advantage of CML data is their ubiquitous coverage, as wireless backhauling is employed in most mobile networks in the world. The balance between wired (i.e. fiber) and wireless backhaul in a network depends on factors such as cost of the infrastructure and environmental constraints. The exploitation scheme of CML data is similar to the one of bidirectional SMLs as in both cases data are generated as by products of network management activities conducted by the network operator. However, the processing chain of SML data differs from the one of CMLs in some important aspects. These differences depend on the geometry of the satellite link, which traverses the entire atmosphere, and on the characteristics of the transmitter, i.e., a geostationary satellite. In particular, only a small part of the link extending from the ground to the height where ice

particles have melted into raindrops is affected by rain. Therefore, the knowledge of the rain height is ~~ressential~~essential for the correct conversion process from RSL to rainfall intensity as signal attenuation is proportional to the rainy propagation path (Giannetti et al., 2017). The rain height can be estimated using ~~from~~ weather radar measurements or radiosoundings (when available), models, or forecasts produced by NWP. Moreover, significant errors in rainfall intensity estimates may be caused by the additional RSL loss due to the presence of the melting layer, that is, the thin atmospheric region above the rainy layer where frozen particles are melting. Finally, the transmitted power of the satellite is neither known nor constant and satellite perturbations induced by gravitational effects can introduce additional RSL fluctuations that may overlap the ones due to rain. Despite the complexity of data processing, several studies demonstrated the capability of SMLs to detect dry/wet periods (Angeloni et al., 2024; Gianoglio et al., 2024) as well as to quantify precipitation (Barthès and Mallet, 2013; Mercier et al., 2015; Colli et al., 2020; Adirosi et al., 2021). The reference data used in the validation process are direct measurements collected from operational networks of rain gauges, disdrometers, or radar-based precipitation maps.

It is very important to unlock CML and SML datasets, which may have ownership issues. Open data will help developing processing tools and carrying out validation studies, especially when concurrent datasets of conventional rainfall data are available. Research based on open data can assess the quality of opportunistic rainfall data and whether they can be used in operational scenarios, paving the way for implementing new business models. Several open CML datasets are already available in the literature. For instance, the OpenMRG dataset includes raw data collected from 364 bidirectional links deployed in the urban area of Goteborg (Sweden) over a three-month summer period (Andersson et al., 2022). Another large-scale dataset includes a countywide network of 1818 links covering the Netherlands and spanning the period from January 2011 to March 2015 (with gaps) (Overeem et al., 2016). These links are part of the network of one of the three mobile network operators active in the Netherlands. Two years of data (2021 and 2022) collected from about 150 CMLs in the region of Emilia-Romagna (Italy) are available for open access on the Zenodo platform (Covi, E. and Roversi, G., 2024). Finally, data from 100 links operated by the NYC Community Mesh network have also recently been published (Jacoby et al., 2025).

To the best of the authors' knowledge, however, no widespread SML open datasets are accessible. This ~~present~~ work fills the gap, presenting OpenSat4Weather (Nebuloni et al., 2025b), an open dataset ~~that includes comprising RSL~~ data from 215 SML sensors deployed in Southern France over a five-month period ~~from August to December in~~ 2022. ~~In addition, concurrent conventional data collected by rain gauges and weather radars are provided. Finally, a simple method for the evaluation of the rain height is proposed.~~ The dataset also includes concurrent rainfall intensity measurements and 0°C isotherm height data. OpenSat4Weather is presented in Section 2. Section 3 discusses preprocessing methods and data formats. Section 4 illustrates descriptive statistics of the dataset, while Section 5 shows examples of anomalous RSL patterns. Section 6 provides some practical recommendations for SML data processing, and, finally, the conclusions are given in Section 7.

2 Study area and data collection

The dataset ~~covers the period from August to December 2022 and partially includes~~ includes most of the coastal region near the Mediterranean Sea in southeastern France ~~(Figure and covers the period from August to December 2022 (Fig. 1).~~ The

case study area is characterized by a Mediterranean climate, with mild winters, hot and dry summers, and wetter springs and autumns. Rainfall exhibits a pronounced seasonal cycle ~~Mimeau et al. (2021)~~(Mimeau et al., 2021). In addition, rainfall is often associated with thunderstorms, which contribute approximately 40% of the annual ~~total-precipitation~~ and account for around 35% of ~~all~~ rainy days (Table 1). This proportion is significantly higher compared to northern France ~~(illustrated by the example of Paris in the table)~~. On the other hand, total ~~precipitation~~-accumulation is relatively low in the southeastern region compared to the southwestern region, with Biarritz being an extreme example(~~Table 1~~). In 2022, temperatures were above normal across most of France, contributing to record-breaking drought conditions that persisted until mid-November in Southern France. Precipitation, including snowfall, remained below average, and Southern France did not experience any major storms or significant Mediterranean episodes during this period. Nevertheless, several severe convective events were recorded, notably on 16–17 August (including episodes of hail), as well as on 6–7, 13–14, and 23–24 September (Météo-France, b).

~~In the-~~It is important to highlight that a dataset spanning a few months is insufficient to represent the full seasonal cycle and interannual variability of rainfall. This limitation has important implications for the use of OpenSat4Weather in the development and evaluation of rainfall retrieval algorithms. In particular, it increases the risk of overfitting during SML calibration, potentially resulting in biased model parameter estimates. Moreover, model validation is constrained by the reduced statistical robustness of key performance indicators

In the following subsections we describe the four different types of data that make up the OpenSat4Weather dataset.

Table 1. Average precipitation and average number of rainy days per year (1991–2020) for selected French cities (Météo-France, a).

City	Avg. annual precipitation (mm)	Rainy days >1 mm	Rainy days >10 mm	Proportion-Ratio of days >10 mm to days >10-mm-among >1 mm (%)
Biarritz	1473	141.1	49.9	35.4
Paris (Montsouris)	634.3	108.9	15.8	14.5
Montpellier (Airport)	639.2	57.8	17.7	30.6
Nîmes (Courbessac)	734.4	64.8	22.1	34.1
Marseille (Marignane)	532.3	53.5	15.8	29.5
Toulon	633.4	57.5	18.5	32.2
Nice	791.3	62.1	24.1	38.8

2.1 SML

SML data were ~~courteously~~kindly provided by HD Rain, a French company ~~offering-weather-specializing in weather monitoring and forecasting~~ services. The deployment of HD Rain terminals in this region is ~~driven-by-motivated by its exposure to significant environmental and meteorological risks. The area is highly exposed to hazards. The study area is affected by~~ “épisodes cévenols”, that is, intense Mediterranean rainfall events that can ~~cause-trigger~~ severe flash floods. Given the high flood risk, high-resolution precipitation measurements are essential for improving early warning systems and hydromete-
 orological ~~modelling-particularly-models. This need is particularly critical~~ in this region, which ~~includes-comprises~~ large

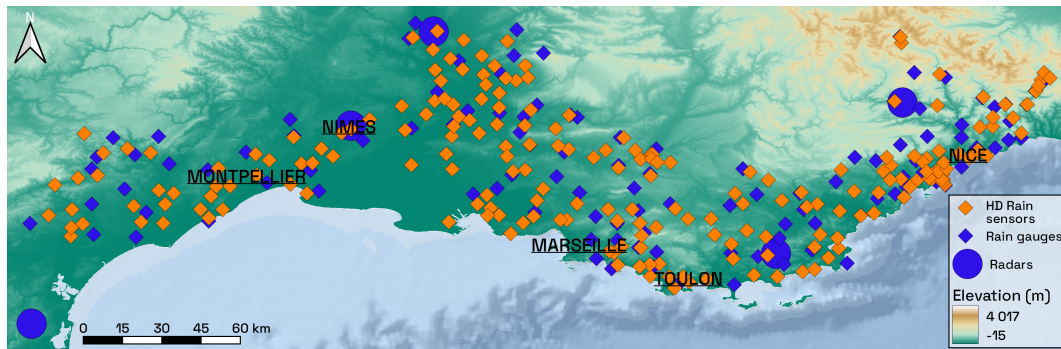


Figure 1. Position of the HD Rain SML stations, of rain gauges and radars in the coastal area near the Mediterranean Sea in southeastern France.

densely urbanized areas where pluvial flooding ~~poses major challenges~~ represents a major hazard. Additionally, the region's complex topography results in highly variable rainfall patterns, which ~~makes conventional measurements difficult~~ limits the representativeness of conventional rain gauge measurements. SML terminals ~~address this issue~~ help address this limitation by providing low cost decentralised fine-scale precipitation data, thereby enhancing meteorological observations in mountainous areas.

~~Beyond monitoring precipitation, integrating~~ environments. In addition to precipitation monitoring, the integration of temperature and humidity sensors into these devices (~~Figure 2~~) also enables them to contribute to ~~Fig. 2~~ enables their use in forest fire risk ~~management in this~~ assessment and management. This capability is particularly relevant in the study region, which is ~~particularly prone to such hazards~~ highly susceptible to wildfires.

~~By tackling these critical challenges, HD Rain terminals enhance both flood and wildfire risk management in the region.~~

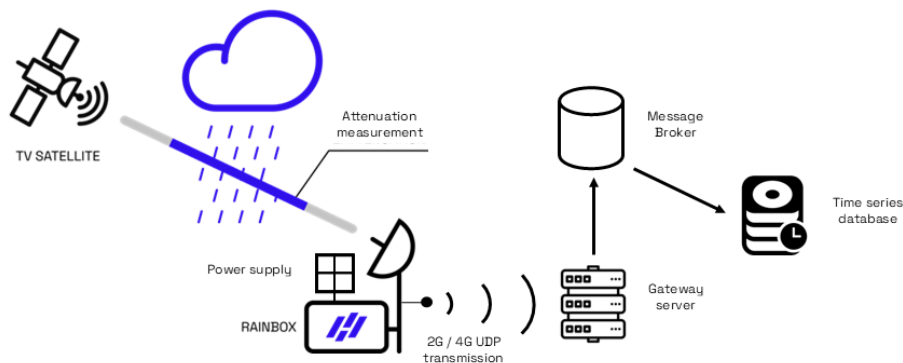


Figure 2. Sketch of SML configuration: HD Rain station and data transfer.

The SML sensor measures the loss of signal power, ~~namely i.e.,~~ rain attenuation, caused by rainfall ~~on the~~ along the propagation path of the microwave signal transmitted by a broadcasting satellite (Figure Fig. 2). The average rain intensity between the receiving ground station and the rain-snow ~~limit is proportional~~ transition level is directly related to rain attenuation. ~~At the studied frequencies (Ku-band), dry snow is entirely transparent to the signal. Consequently, the rain-snow limit is often set at the 0°C isotherm, although the transition between snow and rain is more gradual due to the presence of the melting layer.~~

Each HD Rain SML consists of a satellite dish (around 75 cm ~~of diameter~~) in diameter equipped with a standard TV Low-Noise Block (LNB) receiver, a solar panel ~~, ensuring the station's autonomy,~~ providing autonomous power supply, a GSM antenna, and a device called *Rainbox*. The ~~latter includes~~ Rainbox incorporates a data logger that enables high-frequency ~~measurement~~ measurements of the signal strength received from the satellite ~~, and~~ resamples these measurements by averaging them over ~~15-second intervals, and 15 s intervals.~~ It also contains a SIM card that ~~ensures connectivity with various~~ provides connectivity through multiple mobile operators worldwide. ~~These~~ The raw data are transmitted via the GSM network to a central server, where ~~they are processed by~~ a message broker processes and decodes them, making the information usable and storable before being stored in a time-series database for subsequent analysis.

Table 2. Satellite characteristics and associated HD Rain SML stations.

Satellite	Owner	Orbit (°)	Avg. elevations <u>satellite azimuth</u> in the <u>study area</u> (°)	Avg. azimuths <u>satellite elevation</u> in the <u>study area</u> (°)	Number of HD rain stations
Astra 1L	SES	19.2 East	161	37.8	147
Hotbird 13F	Eutelsat	13 East	169	39.1	67
Astra 3B	SES	23.5 East	156	36.9	1

The OpenSat4Weather dataset includes measurements from 215 HD Rain stations, ~~which are distributed as follows:~~ Among these, 147 ~~targeting the~~ receive the signal from the Astra 19.2°E (~~or~~ Astra 1L) satellite, 67 ~~targeting from~~ Hotbird 13°E (~~or~~ Hotbird 13F), and ~~1 targeting one from~~ Astra 23.5°E (~~or~~ Astra 3B). Since these three satellites ~~are located in a similar region of the sky, the~~ occupy nearby orbital positions, the satellite dishes have similar elevation and azimuth angles ~~of the satellite dishes are comparable across the stations~~ (Table 2). Two hardware versions are ~~present~~ represented in the dataset: RBV2 (23 stations) and RBV3 (192 stations). RBV3 is the ~~more recent model,~~ latest generation and, while providing the same measurements as RBV2, ~~but featuring features~~ updated electronic components and a larger solar panel to improve energy autonomy. The stations are deployed at ~~altitudes~~ elevations ranging from 0 to 1,622 m a.s.l., with a median ~~altitude~~ elevation of 94 m and an average of 173.3 m. Each station collects data at two ~~different~~ frequency bands and two ~~different~~ polarizations. For each ~~of the above four combinations~~ frequency-polarization combination, the Rainbox module ~~measures~~ records the total RSL ~~through the corresponding frequency band and polarization.~~ The OpenSat4Weather dataset includes ~~data~~ measurements from signals transmitted at horizontal polarization in the ~~high-part of the Ku frequency band.~~ This upper Ku-band. Specifically, the RSL in the dataset corresponds to the integration of the ~~raw signal received from the satellite~~ received satellite signal over

150 the 11.70–12.75 GHz interval, that is, the band where the RSL is the strongest frequency range, which provides the highest RSL for the broadcasting satellites active in France. The station names operating over France. Station identifiers follow the format “FRA-NNNNN”, where “FRA” represents denotes the country code and “NNNNN” is the a unique five-digit integer identifier of the station station identifier (e.g. “FRA-00002”).

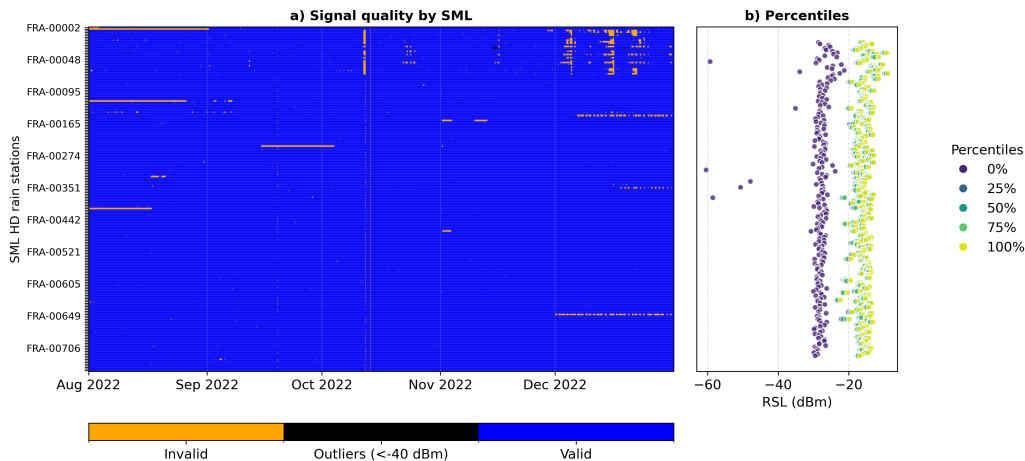


Figure 3. Quality assessment of the RSL data quality check for collected by the 215 HD Rain SMLs-SML stations during the five-month observation period. Each pixel on the left panel corresponds to Panel a) 1-minute-) shows the RSL time step for series as a two-dimensional matrix, where each pixel represents a 1 min observation from a single station. Missing data (NA) are shown in orange, outliers (i.e., RSL values below -40 dBm, are) in black, and values assumed to be problem-free are valid observations in blue. The right panel displays Panel b) shows the distribution of RSL values for each station in terms of selected quantiles (in dBm) of each SML. SML Stations are sorted by station ID in ascending numeric order increasing SML identifier from top to bottom.

The dataset consists of RSL time series in dBm recorded at a 1-minute 1 min temporal resolution with a precision of 0.01 dBm, and of together with the corresponding time stamps, expressed in UTC. The data cover the period from August-1 to December-August to 31 -,December 2022. Figure 3 shows-presents a 2D picture of all the-RSL-samplesRSL samples, labeled in three classes: missing values (NAs), outliers and valid data observations (Signal). It also reports a few-The figure also reports selected RSL quantiles. The-RSL-values-in-the-observation-period-and-all-the-SMLs-have-Considering all stations and the entire observation period, the RSL values exhibits a median value of -16.4 dBm, a maximum of -8.8 dBm and a minimum of -60.5 with minimum and maximum values of -60.5 dBm and -8.8 dBm, respectively. The absolute value-of-the-RSL-RSL value is not a critical parameter as long as-provided it remains within a given range, since an acceptable operating range, as it is directly affected-influenced by the antenna cable length between the dish and the Rainbox deviceunit. However, values that-are-too-low (typically below -40 dBm) are generally suspect. These-below approximately -40 dBm are generally considered suspicious. Such anomalously low values can-be-produced-by-different-factors, such-as-a-long-antenna-cable-, which leads-to-may result from several factors, including excessive cable length, which introduces additional signal loss, improper-inaccurate satellite

alignment, ~~defective LNB, etc~~ or a malfunctioning LNB, among others. In any case, an analysis of the magnitude of the RSL must be always considered in relation to its variability over time. Only five stations in the dataset (FRA-00038, FRA-00309, FRA-00332, FRA-00348 and FRA-00375) recorded RSL values below -40 dBm, ~~which can be considered and can therefore be regarded as~~ outliers. The proportion of missing values (NAs) varies between 0.04% and 20.6% ~~per-station across stations~~, with a median of 0.09% and a mean of 0.90%, respectively.

2.2 Rain gauges

The OpenSat4Weather dataset includes ~~ground-ground-based~~ rainfall measurements collected by ~~Météo-France's the~~ operational rain gauge network ~~of Météo-France~~. These data are freely ~~accessible via~~ available through the Météo-France API portal ~~or and~~ the open-data platform (~~meteo.data.gouv.fr: Rain gauges~~). Rain gauge measurements undergo a data quality control process, ~~which ends up in assigning one among the following quality codes (at every time stamp):~~ ~~which assigns a quality code to each observation as follows:~~ "9" denotes filtered data, "0" denotes protected data, that ~~is, validated by~~ have been validated through manual inspection, "1" denotes validated data either ~~by automatic procedure or by~~ automatically or through manual inspection, and, ~~finally,~~ "2" ~~are questionable data~~ indicates questionable observations (according to ~~an the~~ automatic procedure).

The rain gauge dataset provides ~~6-minute rainfall accumulation measurements~~ rainfall accumulations at a 6 min temporal resolution with a precision of 0.1 mm, covering the same period as the SML ~~data-dataset~~ (August 1 to December 31, 2022). A total of 113 rain gauges located within 10 km from ~~every SML receiver locations were included~~ at least one SML station were selected for inclusion in the dataset. The rain gauges are installed at ~~altitudes elevations~~ ranging from 1 m ~~to 1464 to 1.464~~ m a.s.l., with median and mean ~~altitudes elevations~~ of 184 m and 313 m a.s.l., respectively.

Figure 4 provides a summary of rain gauge sample statistics. ~~It has the same format~~ Figure 4 summarizes the statistical characteristics of the rain gauge observations using the same graphical representation as Fig. 3. ~~3. A total of 41% (46 out of 113) of the sensors contained invalid data, as shown in Figure 4a). The highest rain gauges contain invalid data. The maximum percentage of invalid data for a single sensor was 11.40%, with the average for affected sensors being an average of 1.1% . Furthermore, zero across all stations. Zero rainfall was recorded in from 86.7% to 99% of the 6-minute 6 min intervals, with the mean at an average occurrence of 97.5%. The maximum recorded value is rainfall accumulation over a 6 min interval was 26.9 mm in 6 minutes.~~

2.3 Weather radar

~~We used~~ We added to OpenSat4Weather the rain gauge-adjusted weather radar product ~~Panthere~~ PANTHERE from Météo-France as an additional ~~rainfall reference~~ reference for rainfall estimation. The product is gridded with a spatial resolution of 1 km and a temporal resolution of 5 minutes min. The data ~~can be downloaded in~~ are available in near real-time ~~from through the~~ Météo-France ~~at public API portal~~ (<https://portail-api.meteofrance.fr/web/fr/api/DonneesPubliquesPaquetRadar>. ~~The Panthere radar product is obtained~~). The PANTHERE product is generated from the data collected by ~~the French radar network called ARAMIS~~ ARAMIS, the French operational weather radar network. The network ~~consists of~~ comprises 20 C-band radars, five

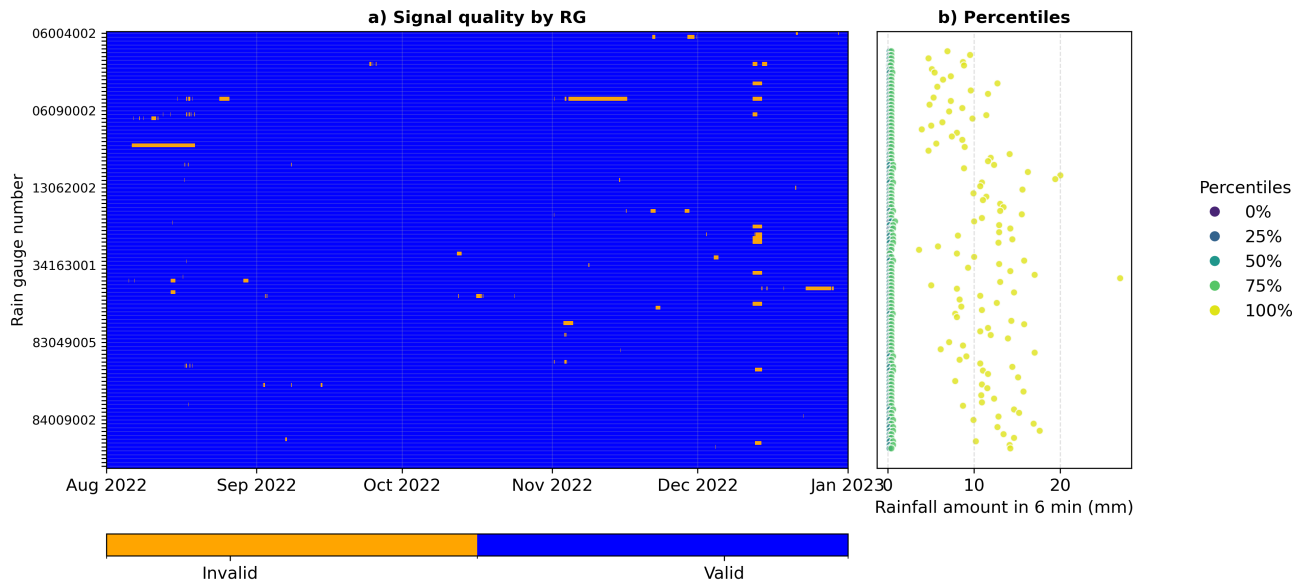


Figure 4. Rain-gauge Quality assessment of rainfall data quality-check-for-collected-by the 113 sensors-in-rain gauges during the dataset-five-month observation period. (Panel a) Data-shows the time series of the 6 min rainfall accumulation as a two-dimensional matrix as in previous Fig. 3 with colors representing data labels (missing-invalid and valid samples). (Panel b) Percentiles-shows the distribution of 6-min-6 min rainfall depth-accumulation values for each rain gauge in terms of selected quantiles, calculated-computed from the set of non-zero measurements-of-each-rain-gauge-time-series. Rain gauges are sorted by station-ID-in-ascending-numeric-order-by-increasing-sensor-identifier from top to bottom.

S-band radars, six X-band radars and two radars deployed at airports in Paris and Nice (Chochon et al., 2022). A description of the methodology to derive the Panthere-PANTHERE QPE product is available-from-Tabary-et-al-(2011). The above-radar products-do-not-have-gaps-in-the-period-where-SML-data-are-provided-provided-in-Tabary-et-al-(2011). The radar-derived precipitation fields used in this study contain no missing data during the period covered by the SML observations.

We did not include-directly-include the PANTHERE product in the Panthere product-as-it-is-into-the-OpenSat4Weather dataset. Rather-Instead, we further processed the data to derive radar-based rainfall estimates in-correspondence-of-along each SML path, as detailed in Section 3.2, and included-them-into-our-and these estimates were incorporated in the dataset. It is important to emphasize-that-Panthere-as-note that, as with most weather radar products, PANTHERE provides maps of surface rainfall intensity derived from radar scans acquired at multiple elevation angles. These measurements sample atmospheric volumes located at altitudes ranging from a-few-several hundred meters to several kilometers above ground level. To mitigate this limitation, the PANTHERE product has been corrected using ground-based rain gauge observations. Although gauge-based adjustment reduces uncertainties associated with radar measurements aloft, radar products still are only the best available estimate of the true structure of rainfall, as they are affected by multiple error sources (e.g. refraction, beam blockage, attenuation, and $Z - R$ relationship). For example, weather radar data often underestimate rainfall extremes (Schleiss et al., 2020)

. Therefore, comparing SML rainfall estimates and radar data, such as the ones provided here, should not be expected to yield perfect agreement.

215 2.4 ERA5

The knowledge of the 0°C isotherm is essential ~~to identify~~ for identifying the rain height, ~~i.e., the height of the part of the link where liquid precipitation occurs~~ defined as the upper limit of the portion of the propagation path where precipitation occurs in liquid form. ~~Here~~ In this study, we use ERA5, a global ~~scale reanalysis atmospheric dataset, which is available at atmospheric reanalysis dataset available through~~ the Copernicus Climate Data Store ~~—~~ (<https://cds.climate.copernicus.eu/datasets>). ~~The~~ ERA5 products are ~~derived from~~ generated using the integrated forecast model, ~~elaborated~~ developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), ~~by assimilating a number which combines model simulations with the assimilation~~ of meteorological observations from ~~different multiple~~ sources. The ERA5 single-layer ~~data include products provide~~ the 0°C isotherm height ~~with at an~~ hourly temporal resolution and ~~a~~ 0.25° spatial resolution (~~i.e. about approximately~~ 28 km). ~~The above This~~ variable represents the ~~height (in meters altitude~~ above sea level ~~) where the temperature of the air at which air temperature~~ reaches 0°C. ~~This, in turn, The 0°C isotherm height~~ is crucial for identifying the melting layer, ~~that is, the height interval namely, the vertical region of the atmosphere~~ where solid particles melt into raindrops, as discussed in Section 3.1.

ERA5 exhibits systematic errors in freezing-level height over complex terrain, primarily due to its limited spatial resolution (Schauwecker et al., 2022). Comparisons with aircraft observations show that ERA5 atmospheric temperatures are generally accurate, with maximum biases of approximately 0.4°C at upper atmospheric levels over the North Atlantic. Direct comparisons of ERA5-derived 0°C isotherm heights against aircraft measurements in Chile reported mean absolute errors of approximately 133–245 m (Quijada-Meza et al., 2026; Wolf et al., 2025).

3 Data preparation (Methods)

This section describes ~~how the raw data in the datasets listed~~ the processing applied to the raw data of the datasets described in previous Section ~~2 have been manipulated before being stored~~ 2 before their integration into the OpenSat4Weather dataset. In particular, the ERA5 temperature data ~~have been processed to extract the information on rain height (Section 3.1). The radar data have been~~ were processed to derive the 0°C isotherm height, which can be used to derive the contribution of liquid precipitation to SML attenuation, as described in Section 3.1. Additionally, radar data were spatially aggregated to provide rainfall estimates comparable to the ones that can be ~~extracted from the SML data (Section derived from SML observations (Section 3.2))~~. Finally, the ~~dataset~~ format and structure of the resulting dataset are briefly described in in Section 3.3.

3.1 Rain height

Even though a discussion of the methods for retrieving rainfall intensity from SML raw data is beyond the scope of this paper, nonetheless it is important to understand the role of rain height in SML data processing. The standard conversion formula

between rainfall intensity R (in $\text{mm/h} \cdot \text{h}^{-1}$) and rain attenuation γ per unit length is given by ITU-R P.838-3 (2005)

245 $\gamma = \kappa R^\alpha \text{ dB/km dB} \cdot \text{km}^{-1},$ (1)

where κ and α are coefficients dependent on SML signal frequency and polarization and on the link elevation angle. ~~If the path goes through~~ When the propagation path intersects a rainy layer with a vertical extent ~~equal to of~~ h_R km and ~~at~~ an elevation angle θ , R can be estimated as follows:

$$R = \left(\frac{A}{\kappa} \cdot \frac{\sin \theta}{h_R} \right)^{1/\alpha} \text{ mm/hmm} \cdot \text{h}^{-1},$$
 (2)

250 where A is the RSL attenuation (dB) ~~across caused by~~ the rainy layer ~~as~~ detected by the SML. Equation (2) assumes that rain is ~~uniform along the rainy~~ uniformly distributed along the propagation path up to h_R and that ~~there are no other relevant sources of attenuation besides rain. Both assumptions are not true in practice, hence no other significant sources of signal attenuation contribute to the observed attenuation. In practice, neither assumption is fully satisfied. Therefore,~~ h_R is ~~often considered generally interpreted~~ as an effective rain height rather than the physical ~~height altitude~~ up to which liquid particles are ~~found~~ present.

The physical rain height can be estimated by weather radar measurements. Radars detect the presence and the height of the melting layer, which appears as a thin vertical region of enhanced reflectivity ~~and named known as~~ bright band, typically located just below the 0°C isotherm. The bright band is produced by backscattering from snowflakes melting into raindrops (Thurai et al., 2003). Therefore, the top of the bright band corresponds to the 0°C isotherm height, while its lower boundary is the physical rain height (Fabry and Zawadzki, 1995). The characteristics ~~if of~~ the melting layer ~~depends depend~~ on the precipitation type. Stratiform precipitation is generally associated with large spatial scales, ~~low intensity values low rainfall intensities~~ and a well-defined ~~layered vertical structure (vertical structure composed of~~ a frozen layer, a melting layer and a liquid precipitation layer). In contrast, convective precipitation is characterized by vertical winds (downdrafts and updrafts), which generate high-intensity localized phenomena, and it does not exhibit a clear separation between frozen and liquid phase.

265 ~~Radar observations show that the 0°C isotherm stands 200-300 m above the bright band (Thurai et al., 2005), when the latter is visible and, in some cases, even 500 m above it. The rain height during convective events can extend much above the 0°C isotherm level when strong updrafts are detected, even though the vertical distribution of rain is not uniform. As a result, mixed type and mixed-phase precipitation coexist and the bright band disappears (Houze, 1997), which makes rain attenuation difficult to estimate.~~ In addition to radar observations, ~~rain height can be estimated from~~ radiosonde measurements or the ~~outputs of~~ Numerical Weather Prediction (NWP) ~~models as well as reanalyses of NWP data can also be employed for estimating the rain height over time scales comparable with rainfall dynamics~~ model outputs and atmospheric reanalyses, which provide estimates at temporal scales compatible with rainfall variability.

The rain height can ~~be also determined also be estimated~~ through models. For instance, ITU-R P.839-4 (2013) ~~statistical model predicts provides a statistical formula to retrieve~~ the mean annual rain height above mean sea level from the mean

275 annual 0°C isotherm ~~as~~ height h_0 :

$$h_R = h_0 + 0.36 \text{ km km},$$
 (3)

The above is ~~The output of (3) represents~~ an effective rain height ~~that can be used to predict rain attenuation across an Earth-satellite path on a statistical basis. The rain height level determined through (3) includes not only the contribution of liquid precipitation to path attenuation but also the one of the melting layer. Furthermore, (3) is an average between intended~~
 280 ~~for the statistical prediction of rain attenuation along Earth-satellite propagation paths. It accounts not only for the attenuation produced by liquid precipitation but also for the melting layer contribution. Moreover, this model provides an average of both stratiform and convective precipitation regimes. Capsoni et al. (2009) proposed a more refined statistical approach then that in (3) to estimate separate values deriving separate estimates~~ of h_R for stratiform and convective ~~rain, incorporating precipitation, while explicitly accounting for~~ the contribution of the melting layer. ~~This-Their~~ method is based on a weighted average of
 285 ~~the~~ monthly mean 0°C isotherm heights. ~~However, statistical methods are not suitable for deriving real-time rainfall intensity estimates from raw SML data, as they~~ Statistical methods primarily capture long-term features, such as ~~seasonal variations in the seasonal variability of~~ the 0 °C isotherm and rain height, rather than ~~instantaneous rainfall dynamics~~the short-term variability associated with individual precipitation events. Therefore, they are not appropriate for retrieving rainfall intensity from raw SML observations available in real time.

290 If the ~~current-actual~~ values of the 0°C isotherm and of the rain height are known, rainfall intensity can be estimated in real time ~~by using~~ electromagnetic models. ~~Typically, These models typically represent the atmosphere as~~ a two-layer ~~model (melting-layer + liquid-layer) is adopted~~medium consisting of a melting layer overlying a liquid precipitation layer. A straight-forward approach consists ~~in including of introducing~~ an additional attenuation term analogous to that in (1), which depends on both the rainfall intensity and the thickness of the melting layer, although with coefficients that differ from those ~~in rain~~
 295 ~~of liquid precipitation~~ (Matrosov, 2008; Giannetti et al., 2019). Alternatively, the length of the rainy path can be adjusted to incorporate the melting layer contribution (Xian et al., 2021). ~~During convective events, the effect of the melting layer is more challenging to model accurately~~Modeling the melting layer during convective precipitation is considerably more challenging, as updrafts ~~(or conversely, downdrafts) are more likely to transport liquid particles (or conversely, solid particles) to varying heights (see for instance (Giannetti et al., 2017)).~~ can transport liquid hydrometeors above their typical equilibrium levels and
 300 ~~viceversa for downdrafts with solid hydrometeors. As a result, the contribution of the melting layer contribution becomes more difficult to estimate accurately (Giannetti et al., 2017).~~

Time series of the 0°C isotherm height for each SML are included in the OpenSat4Weather dataset. These data were derived from the ERA5 reanalysis and are presented in ~~Figure~~Fig. 5. For each SML, the ERA5 grid cell corresponding to the SML receiver location was selected to approximate the atmospheric profile along the propagation path. Nevertheless, the spatial
 305 resolution of ERA5 is ~~not-optimal-insufficient~~ to fully capture ~~the~~ fine-scale topographic and meteorological variability ~~of the study area~~. Consequently, multiple SML receivers may fall within the same ERA5 grid cell ~~, resulting in and therefore share~~ identical 0°C isotherm time series despite differences in receiver ~~altitude~~elevation. As shown in ~~Figure 5~~Fig. 5, the 0°C isotherm ~~height~~exhibits significant temporal and spatial variability, primarily driven by seasonal changes and ~~terrain elevation. The overall trend indicates a gradual decrease of the orographic effects. The~~ 0°C isotherm height progressively decreases from
 310 late summer to winter, with peak values exceeding 5000 m above ground in August and minimum values as low as 360 m above ground ~~at winter~~. This variability is critical for rainfall retrieval from SMLs, as it ~~affects~~directly influences the estimation of

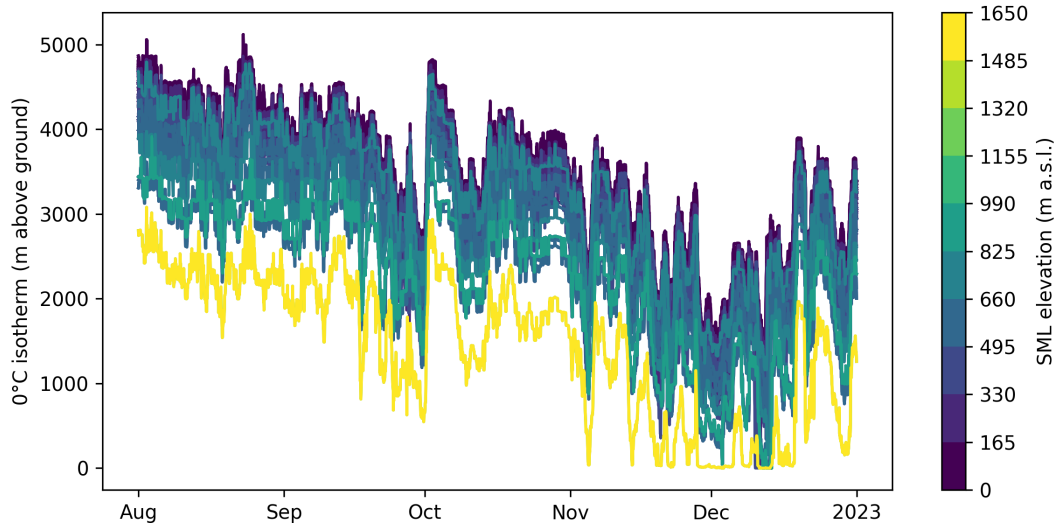


Figure 5. Time series of the 0°C isotherm height (in meters above sea level) from August to December 2022, derived from ERA5 reanalysis data. Each line represents the temporal evolution of the isotherm height at the ERA5 grid point corresponding to the location of an SML receiver in the study area. The line color denotes the elevation of the SML receiver, highlighting the dependence of isotherm variability on receiver altitude as well as on seasonal atmospheric dynamics.

the effective rain height. The color gradient scale in the figure ,representing indicates the elevation of the SML receiver locations, emphasizes that lower altitude areas generally correspond to reduced 0°C isotherm height. In general, lower receiver elevations are associated with lower isotherm heights, reflecting the influence of the regional topography on the atmospheric thermal structure.

3.2 Radar-based rainfall along SML path

We built-up derived the radar-based estimate of rainfall intensity rainfall intensity estimate in correspondence of each SML propagation path according to the rationale described hereinafter. We used the grid intersection method from poligrain (<https://github.com/OpenSenseAction/poligrain>) to compute the length of each SML path in the transecting radar pixels procedure described below. First, we determined the radar grid cells intersected by the SML path using the grid intersection method implemented in the poligrain package (<https://github.com/OpenSenseAction/poligrain>). As the SML rainfall estimate depends on the melting layer height, we calculated precomputed the intersections between radar pixels and SML path-paths for melting layer heights between 0 and 6000 m above ground in 250 m steps. Each radar grid cell intersected by the SML path was assigned a weight based-on proportional to the length of the path segment within that cell. For At each time step in the SML dataset, the current height of the melting layer was used to calculate all the intersected pixels. Finally, rainfall values from all intersected grid cells were averaged, with each cell's value weighted according to the above intersection weights. Thus, we derived a radar reference that matches the actual measurement of the SML through the rainfall in the atmosphere from the location of the SML receiver to the point where the

~~SML-path-reaches~~ the radar-based rainfall intensity estimate along each SML path was computed as the weighted average of rainfall intensity in the intersected radar cells, using the path-length weights.

330 The resulting radar-derived rainfall estimate is consistent with the SML measurement geometry, as it represents the path-averaged rainfall between the SML receiver and the point at which the propagation path intersects the melting layer. An example of the radar-based rainfall intensity along an SML path is shown in Section 4.

3.3 Data format

~~One issue~~ A major challenge associated with opportunistic data is ~~that there are not the lack of~~ standardized procedures for generating, formatting and storing the data. ~~However, a recent paper contributed to fill the gap, recommending~~ This issue has recently been addressed by (Fencl et al., 2024), who proposed a set of data format conventions for ~~different-several~~ types of opportunistic data, including SMLs (Fencl et al., 2024). ~~The above work is the result of the activity carried out by the researchers involved in the COST Action named~~. These recommendations are the outcome of the activities of the COST Action OpenSense (Opportunistic Precipitation Sensing Network), which aims to improve access to opportunistic precipitation observations (<https://opensenseaction.eu/>). ~~The Fencl et al. (2024) recommended the use of the NetCDF format for data storage~~ recommended by (Fencl et al., 2024) is *NetCDF*, basically due to its flexibility and portability. ~~The authors also provided~~ They also define a set of conventions for variable and metadata naming. Finally, their specifications distinguish names and for data and metadata structure, distinguishing between required and optional data and metadata elements, to ensure consistency and interoperability across datasets. The OpenSat4Weather dataset follows the above adopts these recommendations, including all the required SML data variables and data specified by Fencl et al. (2024).

The dataset includes the following three *NetCDF* files:

- *SML_data_2022.nc*: stores SML data;
- *radar_along_SML_data_2022.nc*: stores radar data;
- *rg_data_2022.nc*: stores rain gauge data.

350 In particular, the *SML_data_2022.nc* file hosts the following variables:

- The main variable is the RSL, stored in the file with the dimensions *sml_id* and *time*;
- The variable *deg0l* represents the 0°C isotherm height at the location of the HD Rain stations. ~~The isotherm data are extracted from the ERA5 reanalysis data.~~
- The required metadata ~~consists of~~ comprise the following variables:
 - 355 – SML ID;
 - time;
 - frequency;

- coordinates and height above sea level;
- azimuth and elevation angle;
- name of the satellite ~~the SML is pointing at~~ targeted by the SML.

The ~~radar-based rainfall estimate~~ radar-derived rainfall estimates along the SML path ~~is stored with~~ are stored using the same dimensions, format and naming convention as the SML data ~~itself. The meta-data of the SML.~~ The corresponding SML metadata are not included and ~~the variable is called~~ radar-derived rainfall is stored in the variable *rainfall_amount*. The rain gauge ~~station data dataset~~ contains the variable *rainfall_amount* ~~with together with the corresponding~~ time, coordinates and ~~the height elevation~~ above sea level. ~~Finally, the time-stamps of the~~ All timestamps in the three datasets are UTC. ~~Time-stamps of rain gauge and radar data~~ represent the end time of each 6-min integration interval and the ~~For the rain gauge data, each timestamp corresponds to the end of the 6 min accumulation interval. Similarly, the time stamps of radar data are the~~ end time of each ~~5-min radar scan, respectively~~ 5 min radar volume scan. Since the available radar product is rainfall intensity, the time stamp should be interpreted as nominal time rather than the exact acquisition time, because rain estimation is based on sweeps ~~at different elevations that generated data before the time stamp.~~

4 Results

Figure 6 presents an example time series of RSL collected by SML FRA-00332 (43.556° N, 6.967° E, ~~9 m amsl m asl~~) and corresponding meteorological data for ~~15-Dec-2022.~~ 15 December 2022. Panel a) displays the ~~1-minute-resolution RSL~~ RSL at a 1 min resolution, showing a prolonged rain event from approximately 07:00 to ~~approximately~~ 23:00, with ~~a peak the highest rainfall intensity~~ between 16:00 and 17:00. ~~At this rainfall~~ In correspondence of the rainfall intensity peak, the RSL drops by about 10 dB. Panel b) illustrates hourly aggregated rainfall intensity profiles from the nearby rain gauge and ~~radar from the radar data~~. These profiles generally correlate well with each other and with the RSL. ~~We remind the reader that It should be noted that~~ the radar data are ~~interpolated along the projection on ground of the SML rainy~~ obtained by spatially aggregating the PANTHERE radar product along the ground projection of the effective SML propagation path. While all three sensors capture the precipitation peak, the radar ~~indicates a smaller peak intensity compared to~~ exhibits a lower peak intensity than the rain gauge. Moreover, the minimum of the RSL profile ~~is delayed with respect to~~ occurs slightly later than the rainfall peak as observed by the radar. Panel c) shows the 0°C isotherm time series from ERA5 data, which drops by approximately 200 m during the event, influencing the rainy path length.

~~Fig. Figure~~ Figure 7 shows the ~~descriptive statistics of rainfall during~~ rainfall statistics over the five month observation period, ~~gathered from the~~ computed from the data collected by the 113 Météo-France rain gauges ~~located in the area where SMLs are deployed. within the study area.~~ The rain gauges are ~~sorted ordered~~ from left to right ~~in order of~~ according to increasing elevation above sea level. The ~~following four quantities are plotted for each rain gauge, aggregating the original 6 min rainfall accumulation into hourly periods, as suggested by (Andersson et al., 2022):~~ original 6 min rainfall accumulations were aggregated to hourly intervals, following Andersson et al. (2022). Four statistics are reported for each station: a) wet fraction,

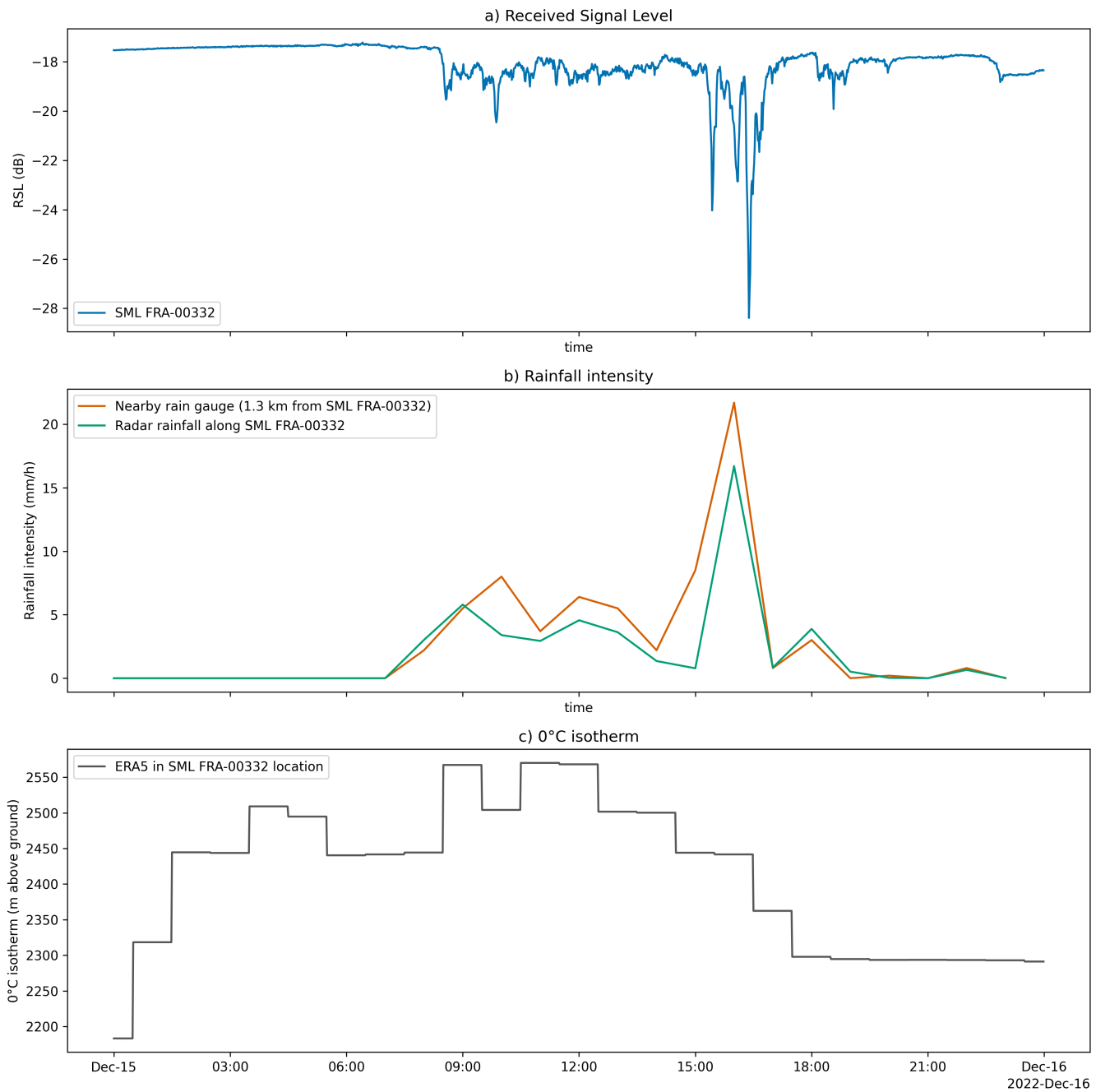


Figure 6. Example time series of RSL (a) from SML FRA-00332 (43.556° N, 6.967° E, 9 m ~~amsl~~^{asl}), with corresponding rainfall intensity from rain gauge and radar (b), and 0°C isotherm from ERA5 (c), for ~~15-Dec-2022~~^{15 December 2022}.

390 b) total rainfall accumulation ~~in the over the observation~~ period, c) maximum ~~value of the~~ hourly accumulation, and d) standard deviation of the hourly accumulation (~~wet hours only~~ computed over wet hours). An hourly ~~period interval~~ is flagged as wet if the accumulation exceeds 0.1 mm. ~~The mm. For 90% of rain gauges, the~~ wet fraction is comprised between 3.8% and 7.5% of time ~~in 90% of cases.~~, while the total accumulation ranges from approximately 204 to 526 mm. ~~The total accumulation in the period goes from about 204 to 526 mm in 90% of cases. The data highlight a weak trend towards the increase of wet percentage and of rain accumulation with the elevation~~ Overall, data indicate a weak positive relationship between station elevation and both the percentage of wet hours and the cumulative rainfall.

4.1 Descriptive Analysis of SML data

Figure 8 shows basic statistics per SML link, computed over the entire period. The first boxplot represents, for each link (y-axis), the median values (orange line) and several quantiles in dBm. In this Figure 8, links are ordered by altitude (from lowest on the left to highest on the right). At first glance, there appears to be no clear relationship between received power and altitude. Median received powers vary greatly, 8 presents descriptive statistics of the RSL measurements for the individual SML stations. In each boxplot, the box extends from the 25th to the 75th percentile (interquartile range), while the vertical lines indicate the 5th and 95th percentiles. The stations are ordered from left to right according to increasing elevation above sea level. Figure 8(a) reports the boxplots of the RSL (dBm) over the observation period with the median values highlighted in orange. No clear relationship is observed between RSL and SML elevation. Instead, the median RSL exhibits substantial variability across the network, ranging from -24 to -10 dBm. While particularly low values may sometimes indicate malfunction, one should not jump to conclusions: the main factor affecting average received power Although unusually low RSL values may, in some cases, indicate malfunctioning, the dominant factor affecting the median RSL is the length of the coaxial cable used during installation connecting the satellite dish to the Rainbox unit. Longer cables induce introduce greater losses, which shift the signal downward without necessarily compromising its quality. Therefore, resulting in lower median RSL values. Consequently, SML data analysis should focus on relative signal drops primarily on relative changes in the received signal (e.g., due to rain) rather than on the absolute values, which are highly variable strongly influenced by installation-specific characteristics.

To highlight some visual patterns without using advanced algorithms (e.g., baseline detection), we simply normalized each link by subtracting its mean received power over the period. The second boxplot in Figure 8 illustrates this. Here Figure 8(b) shows the normalized RSL, defined as the difference between the 1 min time series and the corresponding mean RSL value over the observation period. For the vast majority of SMLs, the boxplots are centered centered around 0 dB. A few links stand out—either because they are shifted (indicating a few extreme values affecting the mean but not the quantiles) or because they exhibit higher variability. This is a strong indicator of malfunctioning links. However, such cases are rare: for the vast majority, 90% of the values (represented here by the 5% to 95% quantiles) fall within a range of about -1 dB and exhibit a dynamic range within 1.5 dB. This suggests that rainfall (especially heavy rainfall which typically induces signal attenuation values above -1 dB (difference between the 5th and 95th percentiles). This indicates that rainfall, and, particularly moderate-to-heavy precipitation, is only marginally represented within the selected percentile range, as rain attenuation typically exceeds 1 dB) is not strongly visible in this representation. This is not surprising: radar data projected onto the SML link footprints show

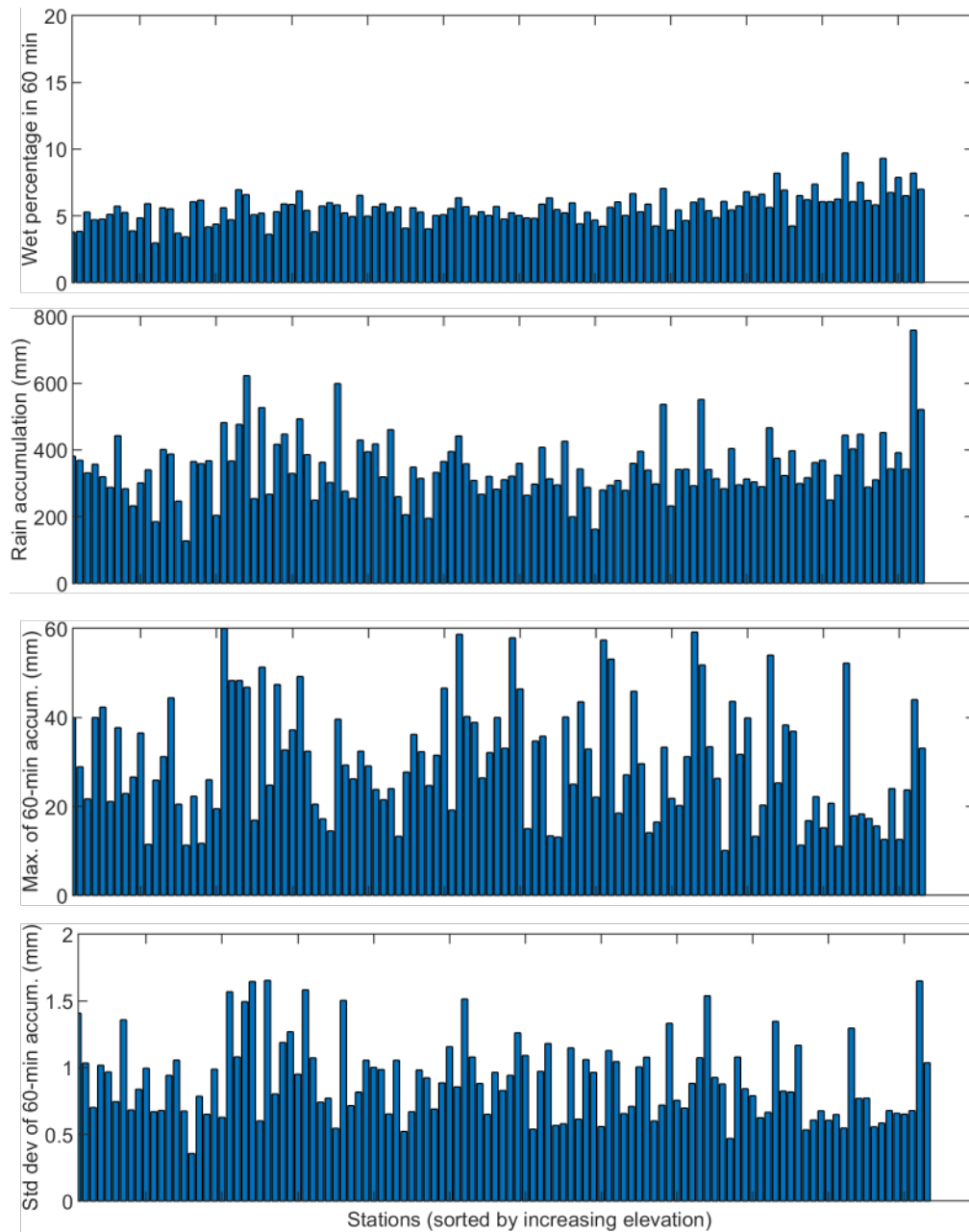


Figure 7. Descriptive Rainfall statistics of rainfall collected by the 113 available rain gauges within the study area during the five-month observation period.

rainfall occurrence between during intense precipitation events. Indeed, the radar-derived rainfall estimates along the SML propagation paths indicate that rainfall occurs during only 3.2% and to 7.4% of the time at 5-minute resolution, barely within

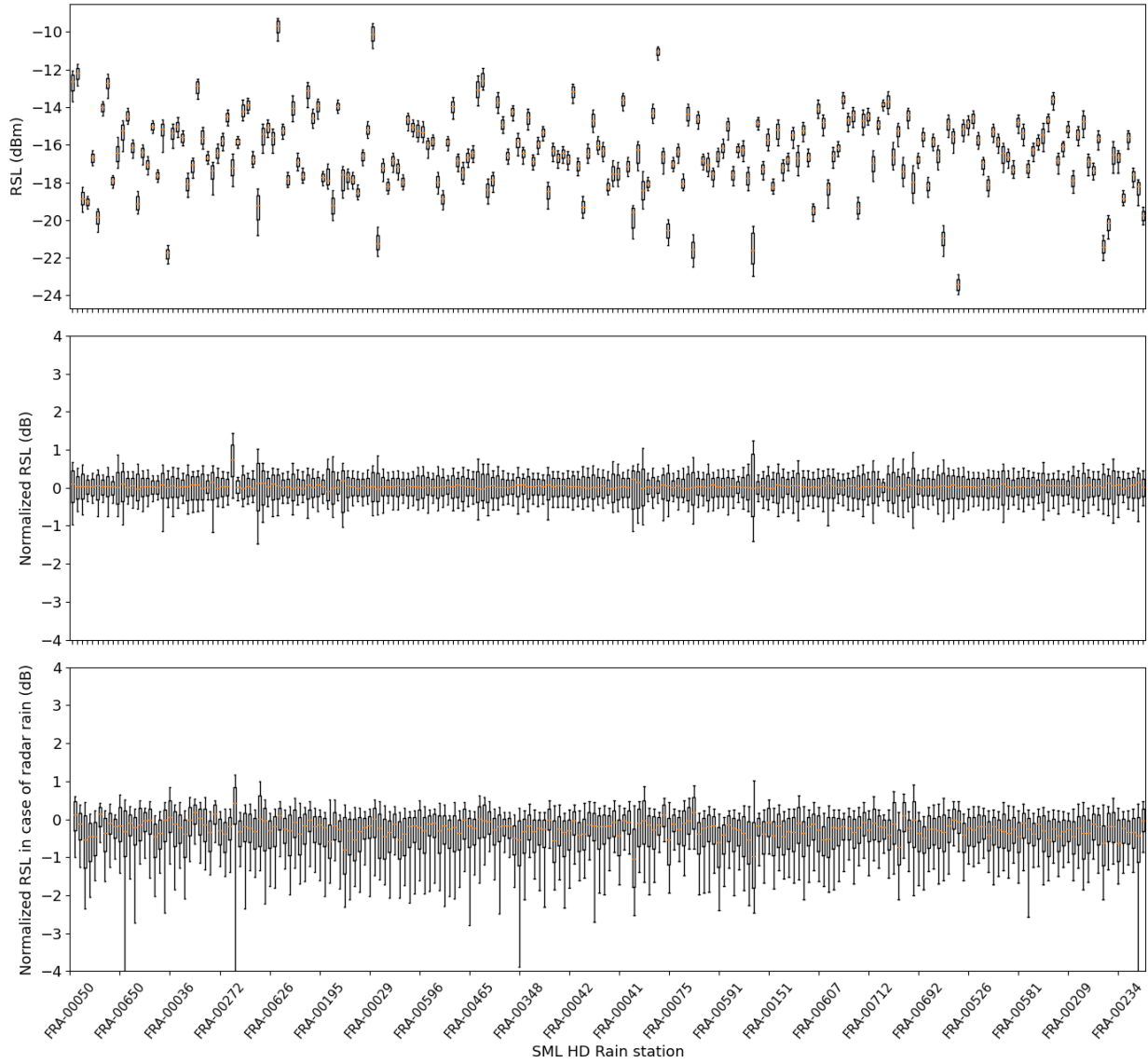


Figure 8. Descriptive statistics of SML data over the five-month observation period aggregating RSL data in 5 min temporal intervals. Each box (x-axis) corresponds to along the x-axis represents an individual SML link. In all cases, The box spans the statistics are computed over the entire five-month period at 5-minute resolution: the median interquartile range (orange horizontal line 25th–75th percentiles), the 25% and 75% quantiles (box), and the 5% and 95% quantiles (vertical lines) whiskers denote the 5th and 95th percentiles. The orange horizontal line indicates the median. Top: received-signal-level RSL (dBm). Middle: received-signal-level RSL normalized to its mean value for each link (dB). Bottom: same as above the middle panel, but restricted to the considering only time steps where during which the radar detects a detected rainfall accumulation greater than 0 mm (dB)-0.

the represented quantile range 5 min radar time intervals. Consequently, most rainy periods lie near or beyond the tails of the boxplot distribution. Furthermore, a large share portion of these rainy periods corresponds to light rainfall, which would in any case produce attenuation below generally produces attenuation values within 1 dB. For instance example, only 26% of rainy timestamps (5-minute resolution) show rain rates the 5 min rainy intervals in the radar dataset are associated with rain intensities above 2 mm/h according to radar data over the SML link paths mm h^{-1} . A small number of stations exhibit anomalous boxplots characterized by median values shifted away from 0 dB (indicating a few extreme values that affect the mean value but not the quantiles) or by a large variability, which is an indicator of unstable or malfunctioning links.

The third boxplot in Figure 8 shows the same normalized data, but restricted to time steps where radar along each link's path detects positive rainfall. This time boxplots in Fig. 8(c) show the normalized RSL, conditioned on the occurrence of rainfall, as identified by the radar-derived rainfall intensity along each SML path. In contrast to Fig. 8(b), the effect of rain is clearly visible. Although the median RSL is only slightly affected-reduced (generally between -1 and 0 dB), the lower quantiles (25% and 5% 25th and 5th percentiles) drop significantly across almost all stations—and variability increases, similarly to the radar data (with total accumulations ranging from for nearly all stations. The spread of the distributions also increases, consistent with the spatial variability of rainfall observed by the radar, whose total accumulation ranges from approximately 230 to 727 mm depending on the link). Again mm. Again, no clear altitude effect appears on this boxplot is observed.

Figure 9 presents statistics derived from radar and SML data, but this time time series of indicators aggregated across all SML links and in the form of time series. In the top plot, we show the average of the RSL values normalized per link (in stations and derived from SML and radar data. The top panel shows the mean normalized RSL across all SML stations (green), along together with the 95th percentile (links receiving the strongest signal at a given time relative to their own mean, in blue) blue), and the 5th percentile (weakest signals, in red). For comparison, we also display the average radar rainfall (in black) over all SML link paths the mean radar-derived rainfall along SML paths is also shown (black). The distance between the blue and the red curve measures the difference between the strongest and weakest RSL across all SMLs at each time stamp. The two lower plots are zoom-ins on two panels in the figure provide views of two selected 10-day periods.

We observe that during-
 During dry weather, there is a clear day/night alternation in the signal, which we will discuss the normalized RSL exhibits a pronounced diurnal cycle, which will be discussed later. This effect is especially pronounced in summer (i.e., at the beginning of the observation period). Rainfall periods are pattern is particularly evident during the summer months. Rainfall events are also clearly visible, particularly especially in the 5th percentile time series. In the September zoom-in, the 5th percentile drops sharply (nearly to approximately -3 dB), while the 95th percentile remains unaffected-essentially unchanged and the mean only slightly decreases. This suggests heavy but localized rainfall over part of behavior is consistent with heavy but spatially localized precipitation affecting a subset of SMLs across the French Mediterranean arc. In contrast, during the December period, the 5th percentile is less impacted (no more than -affected (1.5 dB attenuation), but even - dB). However, a slight decrease is observed also in the 95th percentiledrops slightly—indicating more-, indicating the presence of widespread but less intense rainfall precipitation.

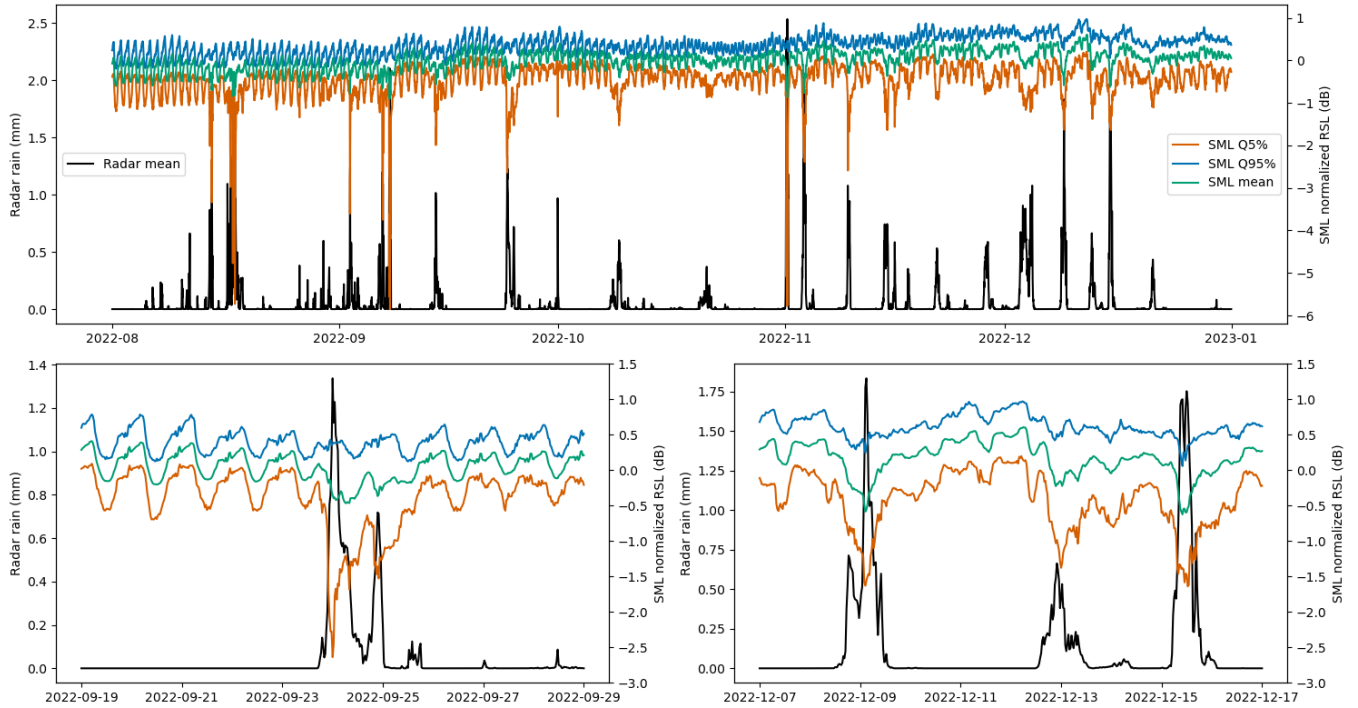


Figure 9. Temporal evolution from August to December 2022 Time series of radar RSL and rainfall aggregated over all the SML data stations. Top: full total observation period. Bottom: zoom-zoom-in on two 10-day periods. Green: average of all links' RSL values normalized by their link-specific mean; Blue: same for RSL averaged over all SML stations at each time stamp, the 95% quantile (high values); Red: same for blue curve is the 5% quantile (low values) 95th percentile time series and the red curve is 5th percentile time series. Black: Finally, the black curve is the average radar-radar-derived rainfall accumulation over along the SML link footprints, in mm paths.

460 4.2 SML - rain gauge association

The geographical distribution and proximity spatial distribution of rain gauges relative to SML sensors are crucial is a key factor for effectively leveraging opportunistic data, as the distance to the nearest rain gauge directly impacts comparative analysis for validation. Figure 10 illustrates, through boxplots, influences the reliability of validation analyses. Figure 10 shows boxplots of the distribution of distances to the three closest rain gauges for all the distances between each of the 215 HD Rain stations. In our dataset, the average SML stations and its three nearest rain gauges. The mean distance to the closest rain gauge is 5.87 km, with an interquartile range (IQR) of 5.16 km (25th percentile: 3.13 km, 75th percentile: 8.29 km), and values ranging. Distances range from a minimum of 0.06 km to a maximum of 19 km. For The mean distances to the second and third closest gauges, the mean distances nearest rain gauges are 10.43 km and 13.93 km, respectively, with interquartile ranges of 5.10 km and 6.76 km, respectively. Overall, 43% of SMLs have their closest a rain gauge within 5 km, and this percentage rises to 87%

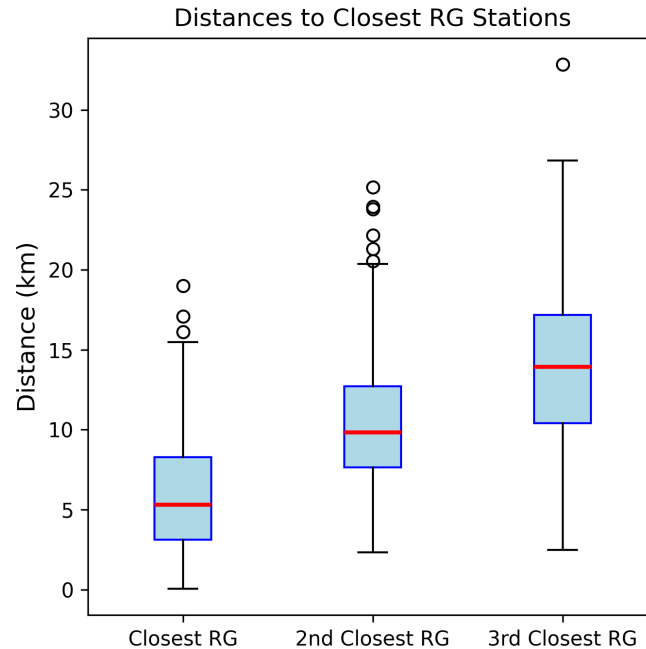


Figure 10. Boxplots representing the distribution of ~~distances~~ the distance between HD Rain SML stations and ~~their~~ the three nearest rain gauges.

470 ~~within a~~ are within 10 km ~~radius~~, indicating a relatively homogeneous distribution of both rain gauges and HD Rain stations across the ~~territory~~ study area.

4.3 ~~Analysis~~ Effect of the ~~radar along SML path based on ERA5 melting layer~~ 0°C isotherm height

There is a large variation of the melting layer height estimated by ERA5 over the observation area from over- Figure 11 illustrates the evolution of the 0°C isotherm from August to December 2022 (bottom panel), together with the RSL of a representative SML (top panel), and nearby rain gauge and radar-based rainfall intensity along the SML path (middle panel). The ERA5-derived 0°C isotherm height exhibits a large temporal variability, ranging from almost 5000m ~~above sea level~~ m asl in August to less than 1000m ~~m asl~~ m asl in December. ~~In general, the melting layer~~ It usually lies above 2000m ~~m asl~~ m asl from August to mid-October. ~~This results in an average SML path length of about 6000 m before reaching the melting layer~~ Consequently, the average SML propagation path of the SML signal below the melting layer is about 6 km. From November ~~onward~~, the path length ~~of the SMLs is generally below 3000 m~~ decreases to generally less than 3 km.

Figure 11 shows the altitude of the 0°C isotherm from August to December 2022 (bottom), along with the signal received by one of the SML links (top, in dBm), and rainfall intensities measured along the link path by a weather radar and by a nearby rain gauge (middle, in mm/h). Severe signal attenuation (around ~~Large signal attenuation values (up to about 12 dB)~~ are observed during the summer in correspondence of heavy

485 ~~precipitation events (rainfall intensities exceeding $75 \text{ mm} \cdot \text{h}^{-1}$), while the 0°C isotherm altitudes-being height remains around 4km. Around late October to early November, another combination of intense rainfall (40 to 50 mm/h), large attenuation km asl. A similar situation occurs between late October and early November (rainfall intensity peaks higher than $40 \text{ mm} \cdot \text{h}^{-1}$, attenuation around 10dB), and high dB, and 0°C isotherm altitude (height around 3500m) is observed. Later in the period, as the atmosphere cools, we see weaker rainfall events (10 to 25 mm/h) in early December, with lower m). As the atmosphere~~
490 ~~cools later in the observation period, rainfall events become less intense and the 0°C isotherm heights (height decreases to 1500–2000m), leading to much smaller attenuation values (around 1 dB).-~~

~~This highlights m. The observed signal attenuation is substantially reduced, reaching only about 2 dB. These results highlight a clear seasonal pattern in temperate regions: stronger rainfall tends to occur during warmer periods, when, typical of temperate regions. During the warmer months, rainfall events tend to be more intense and the 0°C isotherm is high, which results in stronger located at higher altitudes, resulting in stronger signal attenuation, due both to to both the higher specific attenuation and a longer integration the longer propagation path through the rainy liquid precipitation layer. Conversely, in winter, rainfall is often weaker (typically stratiform), with a winter precipitation is generally weaker and predominantly stratiform, which, combined with the lower 0°C isotherm height, thus, it produces a much produces substantially lower attenuation. This seasonality may complicate rainfall estimation: in-~~

500 ~~This seasonal variability has important implications for rainfall retrieval from SML data. During summer, strong attenuation can lead to saturation (may cause the RSL to decrease to the minimum detectable level of the LNB or result in complete signal loss), while, thereby limiting the ability to quantify heavy rainfall. Conversely, in winter, the weak attenuation and low variability in the signal can make it harder to detect and estimate rainfall reliably, as the baseline rainfall detection and estimation more challenging, as identifying the baseline signal level becomes more difficult to identify.-~~

505 ~~. However, these patterns are not universal. In the seasonal patterns have exceptions. In Mediterranean regions, for example, intense rainfall events can occur during convective events may also occur during the colder months, while stratiform rainfall may appear precipitation can occasionally be observed in summer.~~

~~Finally, it is worth noting important to note that the 0°C isotherm height exhibits substantial variability, not only at seasonal scale but also at shorter time scales: changes on seasonal time scales but also over much shorter periods: fluctuations of 1–2 km can occur over just a few days. For instance, Fig. 11 shows that the 0°C isotherm raises occasionally above 3000m can still occur m in late December, while values dropping below 2500m are already present m in early October. This variability calls for the use of dynamic 0°C isotherm data (rather than climatological averages), such as those provided by ERA5 reanalyses or by numerical weather predictions if real-time operation is needed.-~~

5 Discussion

515 As seen previously in Figure-Fig. 6, the RSL variation is strongly correlated with rain-rainfall intensity. However, additional effects may have a non-negligible impact on the received signal. Furthermore, hardware limitations and malfunctioning of the

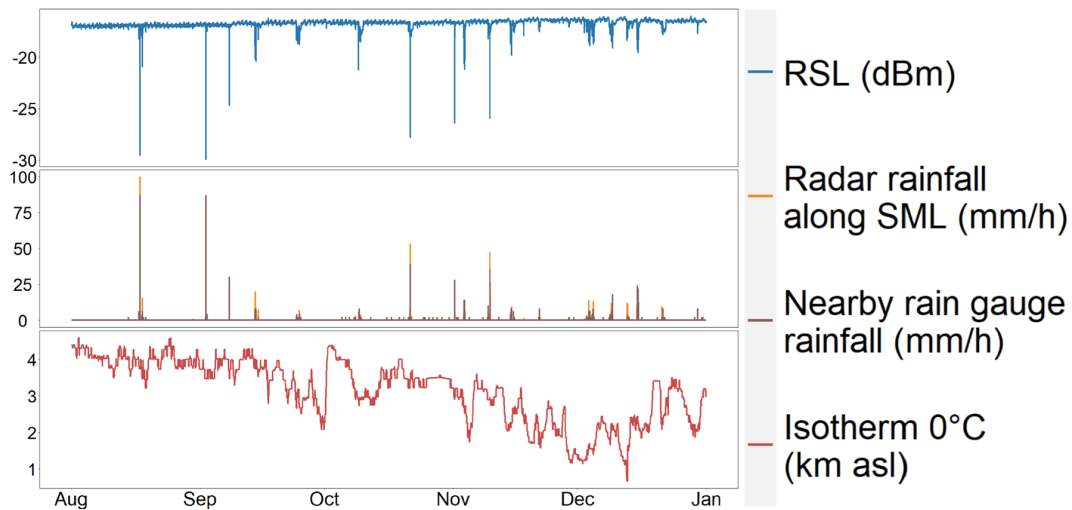


Figure 11. RSL signal (dBm) of collected from the SML station FRA-00410 (top), rainfall (mm/h) intensity from corresponding pixels radar data and from the closest-nearby rain gauge (middle), and the isotherm 0°C height above sea level for the location that SML asl from ERA5 reanalyses (bottom) are shown.

ground terminal can produce noticeable RSL patterns. These effects should be accounted for and, whenever possible, canceled, or, at least, identified, to prevent misclassification of such RSL variations as rain events.

For example, temperature significantly affects the RSL. Figure 12 shows distinct signal variations that are inversely correlated with the temperature increase observed on November 16 and 17, and, to a lesser extent, on November 13 and 18. These variations are primarily associated with sunny days, which are characterized by significant diurnal temperature fluctuations. A possible explanation is a temperature-dependent variation in the LNB gain. In contrast, the sharp and relatively short signal drops on November 14, late on November 15, and during the night between November 17 and 18 are rain events.

~~Temperature is not the only factor affecting the signal.~~ Interactions between raindrops and systems characteristics may also influence the quality of the received signal, thereby complicating its interpretation and the conversion into rainfall estimates, as shown in Figure illustrated in the example of Fig. 13. Panel a) shows the time series relative to a rainy day. The RSL is strongly correlated with the the rainfall intensity profile measured by the radar (and estimated along the SML path). Although precipitation ceases around noon, the RSL increases only gradually to get back to its level before the rain event several hours later. This signal behavior is likely attributable to the progressive drying of the antenna after the event. This phenomenon, known ~~has~~ "wet antenna" effect as wet antenna attenuation, has been reported for CMLs by several authors (see e.g. (Leijnse et al., 2007b) Leijnse et al. (2007b)). Panel b) highlights a short segment of an RLS a different RSL time-series. The nearly flat plateau visible between 12:25 and 12:35 corresponds to the received signal falling below the minimum detectable level of the LNB, during an intense rain episode. For this station, the maximum measurable attenuation is 14 dB. Beyond this threshold, the received signal becomes indistinguishable from noise. It is important to note that this maximum measurable attenuation is not

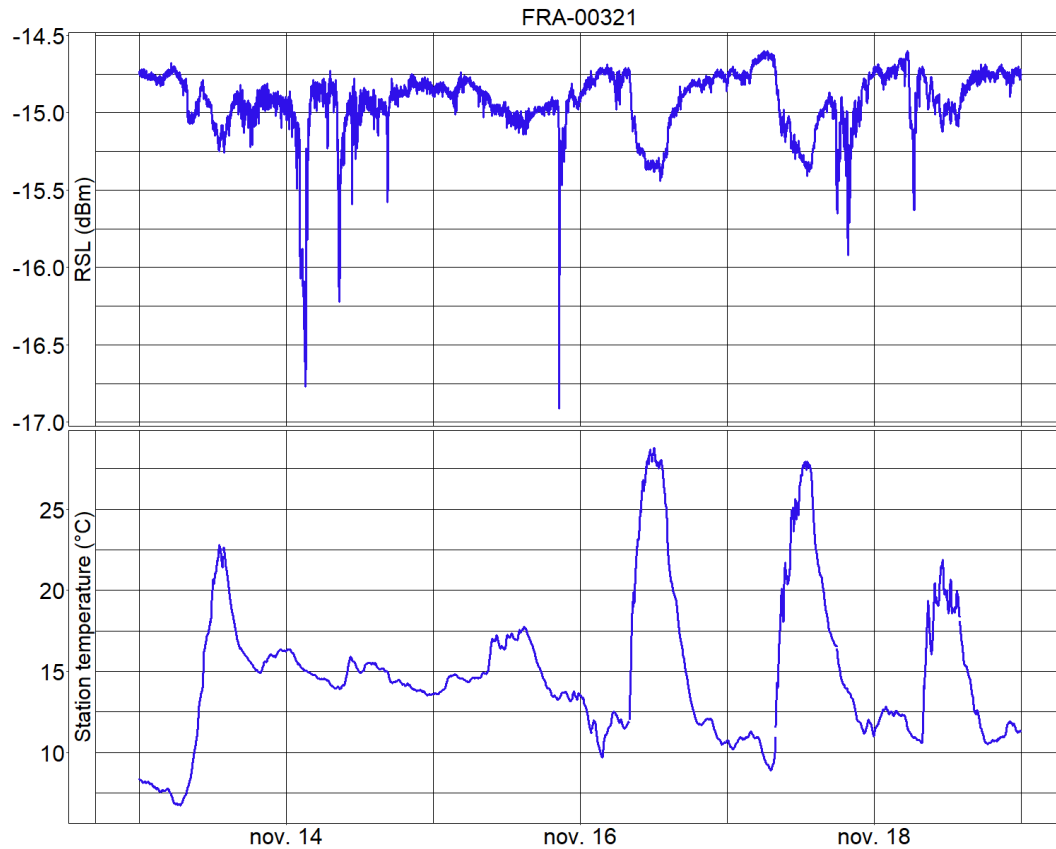


Figure 12. Example of RSL (dBm)-pattern and corresponding air temperature (°C)-measurements. Station SML station: FRA-00321.

535 equal to the one in clear-sky signal-to-noise-ratio conditions, but it is in fact lower, due to the significant increase in noise level during rain. This effect is produced by raindrops, which behave as radiating bodies. A small, yet not negligible, fraction of the emitted energy is radiated in the microwave spectrum and captured by the SML antenna, thereby introducing an additional noise contribution. Typically, for a clear-sky signal-to-noise ratio of about 18 dB, the maximum measurable rain attenuation is around 14 dB, corresponding to an increase in the background noise of about 4 dB (Gelbart et al., 2025). The maximum SNR

540 signal-to-noise ratio in clear-sky depends on the targeted satellite (i.e. the transmitted power level), on the size of the receiving dish (assuming optimal alignment), and, to a lesser extent, on the quality of the dish and on the LNB. The anomalous pattern in panel c) indicates an issue in the cable connecting the antenna to the LNB, resulting in complete signal loss ($RSL \approx -60$ dBm). Finally, panel d) shows two signal drops occurred in mid-September and in late November, respectively, which are attributed to misalignment of the satellite dish caused by wind or other mechanical factors.

545 These examples clearly demonstrate that the SML signal is not only influenced by rainfall intensity but also by multiple factors, thereby complicating the isolation of the rainfall contribution. Additional disturbances not reported here, such as the

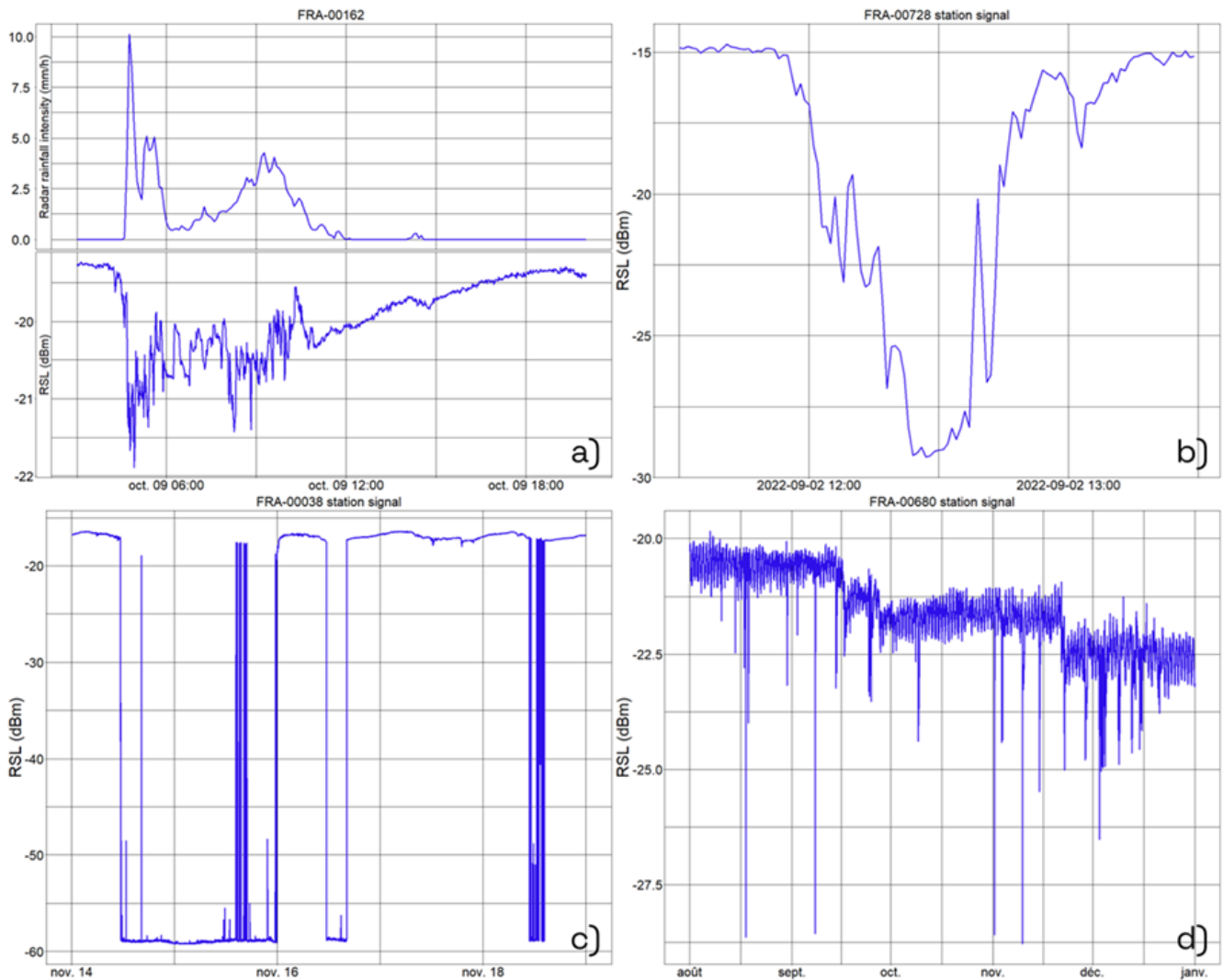


Figure 13. Examples of disturbances and anomalous RSL patterns a) sensor humidification after a rainfall event. b) saturation during an intense rainfall event. c) LNB cable disconnection. d) multiple cases of misalignment of the dish over time.

sun transit effect, are discussed in extensive surveys (Giannetti and Reggiannini, 2021; Nebuloni et al., 2025a). Furthermore, open SW packages are available for processing data collected by opportunistic rainfall sensors, such as the tools developed

6 Practical recommendations for working with SML data

550 While relatively few studies have addressed the processing of SML data, an extensive body of literature is available for CMLs. Since the processing of CML and SML data shares many common methodological aspects, insights and techniques developed

for CMLs can be adapted to SMLs. In addition to the references listed in the Introduction(Section 1), and based on our experience with SML and CML data, we provide the following recommendations for the processing and analysis of SML observations.

Interpolation of missing data over short time periods (e.g., a few minutes) can help obtaining a more complete dataset while reducing the risk of missing or inaccurately estimating rainfall events. The identification of anomalous links should rely on both the average RSL value and its temporal variability, as discussed in Section 2.1. In addition, cross-validation with nearby SMLs is recommended. The application of simple statistical filtering approaches, such as those proposed by (Blettner et al., 2025), may also enhance the overall quality of the dataset.

Accurate classification of wet and dry periods is essential for establishing an appropriate baseline for each rainfall event. Several methods have been developed for SMLs (see Nebuloni et al. (2025a) for a survey of methods), while additional approaches are available from the CML research community, including those implemented in the widely used Python package *pycomlink* (Chwala et al., 2025), developed within the COST Action OpenSense (~~OPENSENSE~~). Methods for estimating wet antenna attenuation are also available in *pycomlink*. However, these techniques were primarily developed for CMLs with two antennas, and should therefore be adapted when using them for SMLs, where only the ground antenna is affected by this disturbance.

~~In this context, the usage of neural networks-~~

Prior to deriving rainfall intensity from attenuation measurements, the portion of the propagation path containing liquid precipitation should be identified, and the contribution of the melting layer to total attenuation should be considered. Determining the 0°C isotherm height is a key step in this process (see Section 4.3). Owing to its substantial temporal variability, we recommend to use dynamic estimates of this quantity rather than climatological averages. Such information can be obtained from atmospheric reanalyses, such as ERA5, or from numerical weather predictions in real-time applications as provided with this dataset, by radiosonde, radar or other remote sensing observations. Rain attenuation can be converted into rainfall rates using the $\gamma - R$ relationship (1). The corresponding parameters are available from ITU recommendations (ITU-R P.838-3, 2005), or can be derived from local disdrometer measurements. To date, no studies have investigated the total attenuation of SML signals caused by heavy rainfall events, comparable to the analysis conducted for CML data by Polz et al. (2023).

Finally, the usage of machine learning methods in several steps of SML data processing appears particularly appropriate, as they are well-suited to capturing the amplitude, duration, and frequency of rain-induced ~~disturbances (Gianoglio et al., 2024)-~~ RSL patterns (see e.g., Gianoglio et al. (2024), Gelbart et al. (2025)).

7 Conclusions

We presented the OpenSat4Weather open access dataset, which provides SML data ~~aimed at for~~ the opportunistic sensing of precipitation. The ~~data are dataset consists of~~ the raw time series of ~~the~~ RSL collected by ~~the~~ low cost receivers used for TV-SAT ~~service reception. SMLs are easy to deploy, they have limited power consumption and data can be transferred from the sensors to~~ signal reception. SML sensors represent a cost-effective solution for precipitation monitoring, particularly in regions where conventional sensors are sparse or unavailable, due to their multiple advantages: ease of deployment, low power

585 ~~consumption, and the ability to transmit data to a remote server by a via Wi-Fi or 4G/5G network, hence they are suitable to monitor precipitation in areas where conventional sensors are scarce or unavailable. networks.~~

~~OpenSat4Weather includes RSL data for 215 SML sensors operating in the Ku-band and located in southern France are included in OpenSat4Weather. The data are sampled once every 1 min and extend over deployed across southern France. The dataset consists of 1 min sampled RSL time series covering a five month observation window (August–December 2022).~~

590 ~~The metadata (i.e. from August to December 2022. It also provides metadata for each SML, including the ground station coordinates, and satellite identifier, and antenna elevation and azimuth) are provided as well. The SMLs in the dataset work with horizontal polarizations and the angles. All the SMLs operate with horizontal polarization. The RSL should be considered a 1-min-1 min average of the signals received across the higher over the upper part of the Ku-band, i.e. 11.70-12.75 GHz. Moreover~~In addition, the dataset includes ~~corresponding hourly~~ time series of the 0°C isotherm height along each satellite-

595 ~~to-ground path at hourly intervals, which allow to quantify the length of the rainy part of the propagation path. The latter~~This information, in turn, is ~~used required~~ in the conversion process of RSL into rainfall intensity. Finally, OpenSat4Weather ~~features provides~~ conventional rainfall data collected by rain gauges and weather radars that can be used for ~~algorithm development, comparison and validation studies as well as into the RSL data. These data can also be used in the RSL processing chain, for instance for determining example for identifying~~ wet and dry periods of time.

600 The data are stored in the Netcdf format, which is supported by most of the computing platforms used by scientists and engineers. The dataset is openly available on Zenodo. OpenSat4Weather fulfills the guidelines for FAIR data (namely, Findable, Accessible, Interoperable and Reusable) (Wilkinson et al., 2016).

8 Data availability

The OpenSat4Weather dataset is openly available at <https://doi.org/10.5281/zenodo.16530166> under the Creative Commons

605 Attribution 4.0 International Public License (CC BY 4.0) (Nebuloni et al., 2025b). More details on the data structure and files are provided in the data repository. The OpenSat4Weather data covers the period August–December 2022. Additional data from the Météo-France ground weather stations can be downloaded at <https://meteo.data.gouv.fr/> (last access: 31 July 2025)

Author contributions. RN and MG conceived the idea and reached the agreement with data owners to openly share the SML dataset. MG and GC collected rain gauge, weather radar and ERA5 data, and converted these data as well as SML data into the NetCdf format. FM and

610 MT analyzed the SML data. RN analyzed the rain gauge data. MG analyzed the radar data. GC analyzed the ERA5 data. All the authors contributed to write and review the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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