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MWRpy: A Python package for processing microwave radiometer data

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Summary

Ground-based passive microwave radiometers (MWRs) are deployed to obtain information on the vertical structure of temperature and water vapor mostly in the lower troposphere. In addition, they are used to derive the total column-integrated liquid water content of the atmosphere, referred to as liquid water path (LWP). MWRs measure radiances, given as brightness temperatures (T_B), typically in two frequency ranges along absorption features of water vapor and oxygen, as well as in window regions where the observations are sensitive to liquid water clouds. Profiles of temperature and humidity are retrieved together with the vertically integrated water vapor content (IWV) and LWP (e.g., Crewell & Löhnert (2003), Löhnert & Maier (2012)). A specific elevation scanning configuration allows for an improved resolution for temperature profiles in the atmospheric boundary-layer (Crewell & Löhnert, 2007). The instruments can be operated continuously and provide temporally highly resolved observations of up to $1s$, which makes them a valuable tool for improving numerical weather forecasts and climate models by studying the atmospheric water cycle, including cloud dynamics (Westwater et al., 2004).

One widely used application exploiting MWR data is the synergistic algorithm Cloudnet (Illingworth & Coauthors, 2007), which classifies hydrometeors in the atmosphere by combining several ground-based remote sensing instruments. As part of the European Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS, Laj & Coauthors (2024)), the Centre for Cloud Remote Sensing (CCRES) is aiming to provide continuous and long-term data of cloud properties and the thermodynamic state of the atmosphere, with Cloudnet being one of the key tools. For atmospheric observatories, MWRs are therefore mandatory to qualify as an ACTRIS-CCRES compatible station. The ACTRIS Central Facility responsible for MWRs in the network is hosted within ACTRIS Germany (ACTRIS-D).

The European cloud remote sensing network will encompass around 30 stations, including mobile platforms, and covering different climatological zones. This network configuration enables investigations of similarities of atmospheric processes and long-term trends between those sites. Some of the participating stations have been operational for more than a decade and Cloudnet products were derived based on their individual setups and processing algorithms. To ensure that the generated data sets are comparable, station operators are required to follow the ACTRIS-CCRES standard operating procedures and send raw data files to the central cloud remote sensing data center unit (CLU, http://cloudnet.fmi.fi). CLU provides data storage and provision, but also the centralized processing, including visualization, in order to harmonize the data streams.

Statement of need

MWRpy addresses the needs of a centralized processing, quality control of MWR raw data, and deriving standardized output of meteorological variables. The Python code is an advancement of the Interactive Data Language (IDL)-based processing software mwr_pro (Löhnert, 2023) and is able to handle raw data from HATPRO manufactured by Radiometer Physics GmbH (RPG, https://www.radiometer-physics.de/), which is so far the only instrument type in the network. The output format, including metadata information, variable names, and file naming, is designed to be compliant with the data structure and naming convention developed together with the EUMETNET Profiling Programme E-PROFILE (Rüfenacht et al., 2021), which is establishing a MWR network with the focus on near-real-time data provision. The processing chain in E-PROFILE consists of a package to convert instrument generated files into a common netCDF format using the convention shared with MWRpy (mwr_raw2l1) and a second tool to run an optimal estimation retrieval approach for advanced products (mwr_l12l2). Both modules are designed to be implemented in the central data hub of E-PROFILE for operational near-real-time data processing in the network of the European Meteorological Services[1]. As a research infrastructure, ACTRIS is pursuing a different approach for the product generation, which is based on statistical retrieval, while still allowing stations to be part of both networks. In this way, MWRpy improves data compatibility and fosters cross network collaborations.

The processing chain of MWRpy is replacing the mode of operation in Cloudnet, which previously relied on pre-processed and non-harmonized MWR data, and therefore contributes to more ACTRIS data consistency. Statistical analysis of these consistent long-term data sets is expected to be beneficial not only for atmospheric studies, but also for improving knowledge on instrument operation and maintenance by monitoring key parameters from the instrument and mandatory regular absolute calibrations (approximately every 6 months). Future developments include the support of further instrument types, if present in the network. Furthermore, the flexible design of the code enables updating the retrievals of meteorological variables, which will be derived from a common statistical approach. For that, a training data set is derived from a climatology of the atmospheric state (e.g. profiles from radiosondes or model reanalysis) and simulated T_B coming from a microwave radiative transfer model like `PyRTlib` (Larosa et al., 2024). `PyRTlib`, as a Python library for non-scattering atmospheric microwave radiative transfer calculations, takes various input profiles to compute down- and upwelling T_B for microwave sensors from different observational platforms using built-in atmospheric absorption models. This output, together with the climatology, can then be used for retrieval training (not included in MWRpy) to update existing coefficients in the ACTRIS network.

Code design

MWRpy is designed to be used as a stand-alone software since it covers the full processing and visualization chain from raw data to higher level products, but it is also embedded in the Python implementation of the Cloudnet processing scheme `CloudnetPy` (Tukiainen et al., 2020). At first, data quality control is performed on the mandatory data fields of measured T_B at various frequencies and instrument specific housekeeping data to generate quality flags. In the next step, auxiliary data (e.g., from a weather station) are combined to produce daily netCDF files. Subsequently advanced meteorological variables are derived by applying coefficients from the statistical retrieval approaches and are stored as separate daily files for variables originating from elevation scans (e.g., temperature profiles) and all remaining measuring modes (including vertical stare for e.g., LWP). Within the Cloudnet processing framework the output of MWRpy is then harmonized and utilized by `CloudnetPy`, together with data streams from other ACTRIS-CCRES instruments, like cloud radar, to derive synergy products. All files, including calibration and retrieval information, and corresponding visualizations are stored in

[1]E-PROFILE developed code for MWR processing (mwr_raw2l1, mwr_l12l2) can be found at https://github.com/MeteoSwiss

the Cloudnet data portal and accessible through an API.

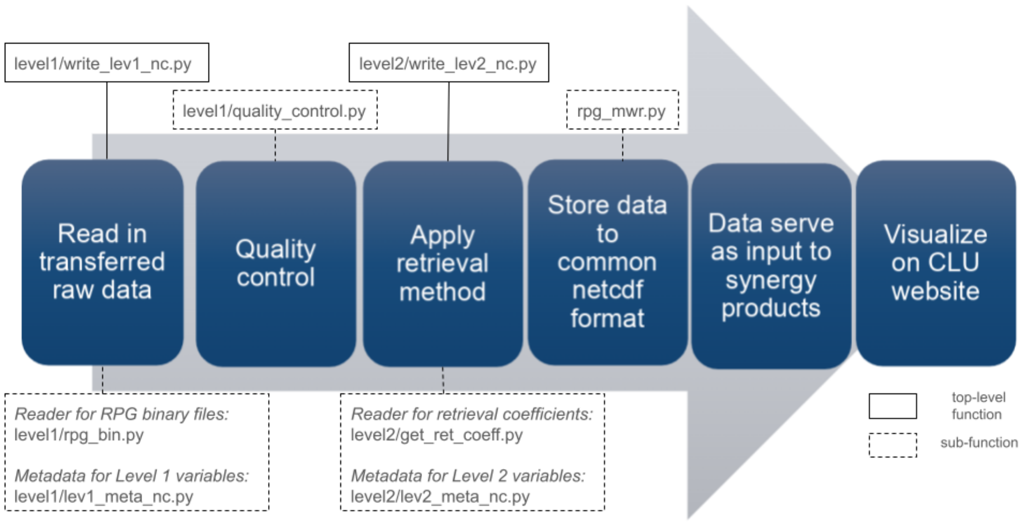

Figure 1: Flowchart of the `MWRpy` processing chain (including main functions), with the last two steps being exclusive for the `CloudnetPy` implementation.

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