European networks observing the atmospheric boundary layer: Overview, access and impacts

Chapter 2d: Microwave Radiometer (MWR)

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Introduction

This report provides a short overview of operating microwave radiometer, including introduction to sensor, products, manufacturers, instrument types, instrument setup and required regular maintenance on site, calibration, measurement configuration, data formats, QA/QC methods and retrieval methods.

Part 1 General overview

Introduction

Microwave radiometry is a well-established technology that has extensively been applied to observe thermodynamic profiles in the troposphere for several decades (e.g. Rose et al., 2005, Cadeddu et al., 2013, Illingworth et al., 2019). The instrument itself, the microwave radiometer (MWR), is a passive remote sensing device that measures the downwelling natural emission from the Earth's atmosphere. The common commercial units include receivers for channels in the 20-60 GHz frequency range to sample the atmospheric thermal emission from atmospheric gases, primarily oxygen and water vapor, and cloud liquid water with high temporal resolution. The measured microwave radiances, expressed as brightness temperatures (Tb), can be used to retrieve atmospheric temperature and humidity profiles, as well as integrated liquid water. The ability to derive atmospheric parameters depends on the selected frequency channels, on single or multi-channel observations, and on combined frequent elevation scans.

MWRs are robust instruments operating 24/7 fully autonomous under all-weather conditions. The long commercial availability and the sustainable support in operation make MWRs potentially suitable for operational use and network applications (Rüfenacht et al., 2021). Three commonly used instruments are presented (see Table 1) whose possible applications and measurements coincide with the interests and research questions in PROBE. Their manufacturers are involved in PROBE and provided input to this section to support the development of improved instrument operation procedures and standardised methods for a future establishment of MWR networks. Currently, European MWR networks exist within the Research Infrastructure for Aerosol, Cloud and Trace Gases (ACTRIS) and EUMETNET's observation programme E-PROFILE, which is funded by National Meteorological Services. In ACTRIS the focus is on harmonized long-term data sets and instrument synergy products, whereas E-PROFILE is aiming for provision of near real-time data (for more details see Chapter "Overview of existing networks").

Products

The basic measured quantities of a MWR are microwave radiances in W/(m2·sr·Hz) at selected frequencies near the water vapor resonance centered at 22.235 GHz and at frequencies in the band of oxygen resonances between 51 and 60 GHz. The microwave radiometer specifications and the selected frequencies of each MWR type are summarized in Table 1. Integrating the spectral radiances over the antenna aperture, the antenna aperture angle and the bandwidth of the receiving system, results in received powers (raw data output or level 0 data in Table 1). These powers are usually converted into brightness temperatures (Tb) using Planck's law (level 1 data files in Table 1). For the processing of atmospheric thermodynamic variables (level 2 data files in Table 1), such as temperature and humidity profiles, but also integrated quantities, such as cloud liquid water path (LWP) and integrated water vapor (IWV), a retrieval procedure is required. Commercial microwave radiometers use statistical algorithms such as Artificial Neural Networks (ANN) to provide temperature and humidity profiles based on the observed Tbs. The training of such ANN utilizes databases of atmospheric profiles, from which the simulated measurements of the radiometer and the atmospheric state are available. The observed Tbs have a complex and nonlinear functional dependence on the atmospheric state. The ANN is inverting this function by a nonlinear regression of input data (microwave observables) to output data (atmospheric/meteorological variables).

Since the retrieval problem is ill-posed by nature (different atmospheric states may produce the very same set of observed data and thus turn out to be indistinguishable), the underlying data base for retrieval creation is in most situations a localized data set fitting to climatology and height above sea level. Such approach makes use of statistical background data and largely improves the quality of retrieved data.

Manufacturers/Instrument types

The following table summarizes specifications and operating parameters for three microwave radiometer models provided by their manufacturers.

Table 1: Overview of MWR manufacturers and instrument types, including specifications and operating parameters.

Manufacturer	Radiometrics Corporation (RDX)	RPG Radiometer Physics GmbH	RPO Attex/IfU GmbH
Company website	http://radiometrics.com	https://www.radiometer-physics.de	http://attex.net http://mtp5.ru
Model	MP3000-Series	Hatpro-Series	MTP5-Series
Product URL	http://radiometrics.com/mp-series	https://www.radiometer-physics.de/products/microwave-remote-sensing-instruments/radiometers/humidity-and-temperature-profilers/	http://attex.net/EN/mtp5.php http://temperaturprofile.de
Number of receivers, frequency range and channels	2 receivers: 22-30 GHz (K-Band) 51-59 GHz (V-Band), 35 Channels	2 receivers: 22-31 GHz (K-Band) 51-58 GHz (V-Band), 14 Channels	1 receiver: V-Band, 1 channel
Receiver technique	Spectrum analyser (Synthesizer): single detection of each channel (sequential)	Filterbank system: parallel detection of all channels (simultaneous)	
Channel frequency (GHz)	22.000, 22.234, 22.500, 23.000, 23.034, 23.500, 23.834, 24.000, 24.500, 25.000, 25.500, 26.000, 26.234, 26.500, 27.000, 27.500, 28.000, 28.500, 29.000, 29.500, 30.000, 51.248, 51.760, 52.280, 52.804, 53.336, 53.848, 54.400, 54.940, 55.500, 56.020, 56.660, 57.288, 57.964, 58.800	22.24, 23.04, 23.84, 25.44, 26.24, 27.84, 31.4 51.26, 52.28, 53.86, 54.94, 56.66, 57.3, 58.0	56.6
Viewing angle	Zenith/All-sky elevation scanning (available with optional azimuth positioner)	Zenith/All-sky elevation scanning (available with optional azimuth positioner)	Zenith/All-sky elevation scanning
Beamwidth (HPBW)	4.9 - 6.3° (K-Band) 2.4 - 2.5° (V-Band)	3.0° - 4.2° (K-Band) 1.8° - 2.2° (V-Band)	2.5°
Raw data output (Level 0)	Received power at channel frequencies (V)	Received power at channel frequencies (V)	Received power at channel frequency (V)
Measured quantity (Level 1)	Brightness temperatures at channel frequencies (K)	Brightness temperatures at channel frequencies (K)	Brightness temperature at channel frequency (K)
Stated accuracy or uncertainty	Radiometric Resolution (rms @ .25 sec): 0.25 K Absolute brightness temperature: 0.2 + 0.002*|TkBB-Tsky|	Radiometric resolution (rms @ 1 sec): 0.10 K (22-31 GHz), 0.15 K (51-58 GHz) Absolute brightness temperature accuracy: 0.5 K	Radiometric resolution (rms @ 1 sec): < 0.1 K Absolute brightness temperature accuracy: 0.5 K
Sampling rate	Integration time: 200 µs per channel	≥ 1 sec (user selectable)	5 min (user selectable)

Standard Retrievals (Level 2)	Temp profiles (K)	Humidity profiles (g/m3)	LWP (kg/m2)	IWV (kg/m2)	Temp profiles (K)	Humidity profiles (g/m3)	LWP (kg/m2)	IWV (kg/m2)	Temp profiles (K)
Stated Accuracy or uncertainty	1 K	0.2 - 1.5	0.02	1.0	1 K	0.2 - 1.5	0.02	1.0	0.2 K
Range	0-10 km	0-10 km			0-10 km	0-10 km			0-1 km
Observation cycle for standard retrievals	15 s (for zenith observation retrievals) < 120 s (boundary layer elevation scans @2 off zenith angles for additional temperature retrieval)				≥ 1 s (zenith observation for standard retrieval) < 180 s (boundary layer elevation scans @11 off zenith angles for additional temperature retrieval)				300 s (boundary layer elevation scans @XX off zenith angles for temperature retrieval)
Retrieval methods from manufacturers	Artificial Neural Networks (ANN)				Artificial Neural Networks (ANN)				Statistical regularization technique (Ilyin 2017)
Supplementary measurements	Automatic surface weather station: Atmospheric temperature, relative humidity, pressure Rain sensor: yes GPS: yes IR Radiometer: Upward Looking,(9.6-11.5 µm) Optional: Surface Wind Speed and Direction				Automatic surface weather station: Atmospheric temperature, relative humidity, pressure Rain sensor: yes GPS: yes IR Radiometer: Viewing direction user selectable, (9.6-11.5 µm) Optional: Surface Wind Speed and Direction				Automatic surface weather station: Atmospheric temperature, relative humidity, pressure Rain sensor: No IR Radiometer: No
Absolute calibration methods	Manual: K-Band: Tip Calibration V-Band: LN2 Calibration				Manual: K-Band: LN2 Calibration V-Band: LN2 Calibration				Automatic: Self-correction by using signal from atmosphere between scans
Internal operational calibration methods	calibration of receiver noise temperature on ambient Black Body Target (period is user selectable)				Hot load calibration on ambient Black Body Target (period is user selectable), Gain calibration through rapid noise switching (50 Hz), available from HATPRO generation 5 on				
Operating Software	External Control Computer (Windows™ 10): Comprehensive software provides command and control interface as well as data visualization, health status and data archiving.				External Control Computer (Windows™ 10): Comprehensive software provides command and control interface as well as data visualization, health status and data archiving. MWR internal control Computer (Windows™ 10): is used for data acquisition.				External Control Computer (Windows™ 10): Comprehensive software provides command and control interface as well as data visualization, health status and data archiving.
Output data formats	ASCII (csv files)				Binary, ASCII, NetCDF				ASCII, NetCDF
Independent analysis of performances	Güldner, https://doi.org/10.5194/amt-6-2879-2013				Löhnert and Maier, https://doi.org/10.5194/amt-5-1121-2012				Baxter et al., 2011, National Air Quality Conference MTP5 at ZUERICH-AIRPORT in Switzerland, FINAL

			REPORT, markasub ag, 2006 Quality assurance audit report, AMSTech, 2010
References of existing research	Cimini et al, https://doi.org/10.5194/amt-8-315-2015	Martinet et al, https://doi.org/10.5194/amt-10-3385-2017 Martinet et al, https://doi.org/10.5194/amt-13-6593-2020 Rose et al.,2005	Banakh et al, https://doi.org/10.3390/rs12060955

Part 2 Recommendations for network operation

2.1 Instrument setup

Microwave radiometers are passive remote sensing instruments and hence do not emit any radiation. Therefore, usually no permission for the operation is required.

The site needs to provide a shelter for the instrument's host computer. For network operation, a reliable internet connection is strongly recommended. The site also needs to be accessible for regular liquid nitrogen calibrations (a roof only accessible by a steep ladder is not recommended).

Observations are both performed zenith looking as well as at different elevation angles. All instruments perform elevation scans into one azimuth direction where unobstructed view to the horizon is necessary (if possible to the north in the northern hemisphere to avoid contamination by pointing directly at the sun). Some instruments are also equipped with an azimuth-scanning device. Uncertainties due to the instrument setup, as described in Böck et al. (2024), include horizontal inhomogeneities of the atmosphere, pointing errors or a tilt of the instrument, and physical obstacles (mountains building, power lines)) in the line of sight of the instrument. Also external sources, like radio frequency interference (RFI, microwave links), could impact the measurements and can be detected with a MWR having azimuth and elevation-scanning capabilities.

2.2 Required regular maintenance on site

The instruments can operate unattended 24/7 during extended periods of time. Regular maintenance works on-site include radome change (every 6-12 months, depending on the radome conditions) and absolute calibrations (every 6 months). Please refer to the instruments' manual for more details.

2.3 Calibration

The calibration of microwave radiometers is of great importance, since uncalibrated radiometers do not provide any useful data. Microwave radiometers are calibrated by several different methods, which can be divided into absolute and relative calibrations.

- Absolute calibrations provide a complete characterization of the system by using two blackbodies at reference temperatures. Usually, a blackbody target at ambient temperature inside the instrument as well as a cold target filled with liquid nitrogen are used. This procedure has to be repeated every 6 months on-site. The procedure itself takes about one hour including preparation. It requires two people and 10-40 litres of liquid nitrogen (depending on instrument type).

- Automatic relative calibration can be performed via the software. The choice of calibrations depends on instrument manufacturer and type. More details are provided in the instrument manuals as well as in a special document for network operation of instruments.

2.4. Measurement configuration

Usual scan patterns include a mix of several observation modes for different purposes:

- Zenith observations with high temporal resolution (if possible 1 second) for IWV/LWP to detect short-term fluctuations, especially of clouds.
- Elevation scans are performed to provide more information about the boundary-layer temperature profile. These observations are performed under 6-10 different elevation angles down to about 4° above horizon with a longer integration time of 10-30 seconds per angle to reduce noise. Usual frequency of scans is 15-30 minutes.
- Some instruments are equipped with an azimuth scanning opportunity to provide information on horizontal inhomogeneities of water vapor and/or clouds.
- Requirements for scan patterns in networks (E-Profile and ACTRIS) include one elevation scan every 15-30 minutes and zenith observations in between, in order to obtain both temperature profiles and integrated quantities in an optimal way.

Further requirements can be found in the ACTRIS Standard Operating Procedures (SOPs): https://www.actris.eu/topical-centre/ccres/microwave-radiometer

2.5 QA/QC methods

Recommendation for housekeeping data: Always store all data, and take warning messages from the software seriously.

All instruments provide data flags that are based on rain conditions, receiver stability, threshold values, etc. Within the networks of ACTRIS and E-Profile, automatic housekeeping data checks and calibration monitoring will be performed. This includes data quality analysis via thresholds, spectral consistency checks and O-B (observation minus background) monitoring, i.e. comparison to model profiles (Marke et al. 2024b). With this information, biases and drifts can be detected and analysed.

The quality of absolute calibration can be analysed by comparing cold load observations directly before and after the calibration, and observations of a blackbody are also used to determine random and correlated noise via a covariance matrix of the different channels (BOCKTO-VM-W3-MWR in preparation).

A monitoring tool for the radome hygroscopic properties can be used to evaluate the radome condition and therefore help with instrument maintenance (Löffler 2024). The method is available on GitHub (https://github.com/igmk/mwr_radome) and was successfully tested for quality assurance and to identify the need of replacing the radome (Tonka 2024).

Part 3 Data formats and file standards

3.1 Data formats

Data formats differ between manufacturers. However, it is recommended to always store the raw data in the native manufacturer's format.

- Radiometrics instruments: LV0 and LV1 data (csv files). The atmospheric products are stored in LV2 files and can always be reproduced from the LV1 files.
  - LV0: raw data output
  - LV1: brightness temperatures
- MTP-5 provides raw data (signals, self-test, etc.) in ASCII format (.cod). In addition, daily files are generated with brightness temperatures (.tbr) at different elevation angles. From these observations, temperature profiles are generated (.txt)
- RPG radiometers: Level-1 binary files (BRT, BLB/BLS, HKD, IRT, MET, (LV0), LOG). The other products (such as IWV, LWP, TPB, TPC, HPC, etc.) can always be reproduced from the level-1 files
  - BRT: Brightness temperatures (single angle)
  - BLB/BLS: Brightness temperatures from multi-angle elevation scans
  - HKD: Housekeeping data
  - IRT: Infrared radiometer brightness temperatures
  - MET: Meteorological sensor data
  - LV0: Raw voltages
  - LOG: Automatic calibration log files

The instrument software also allows to convert data to different formats (e.g. ASCII, NetCDF, BUFR, etc.). This is not recommended in network operation for RPG instruments as this process might slow down the Host-PC software.

3.2 File standards

In E-Profile and ACTRIS networks, data processing will be performed centrally. The individual stations only need to transfer above mentioned raw data files to the data hub. There, Level 1 data and all the products (IWV, LWP, profiles, etc.) are generated and converted to NetCDF format for further use. The E-PROFILE file format, as well as the one in ACTRIS, share most of the file content (variable names, metadata, units).

E-PROFILE:

- Level 1: https://github.com/MeteoSwiss/mwr_raw2l1/blob/master/mwr_raw2l1/config/L1_format.yaml
- Level 2: https://github.com/MeteoSwiss/mwr_l12l2/blob/master/mwr_l12l2/config/L2_format.yaml

ACTRIS:

- Level 1: https://github.com/actris-cloudnet/mwrpy/blob/main/mwrpy/level1/lev1_meta_nc.py
- Level 2: https://github.com/actris-cloudnet/mwrpy/blob/main/mwrpy/level2/lev2_meta_nc.py

Part 4 Processing algorithms and retrieval codes

Retrieval methods

Retrieval algorithms to derive atmospheric parameters from brightness temperature observations use several approaches. The most common are statistical methods, such as multiple regression (e.g. Löhnert et al., 2012) or neural network algorithms (e.g. Marke et al., 2016). But also physical retrieval approaches, like optimal estimation (Rodgers, 2000), are widely used (e.g. Martinet et al., 2020), due to the physical consistency and provision of a full characterisation of retrieval uncertainties. Statistical retrievals on the other hand are computational less expensive and hence better suited to run on a high temporal resolution to capture atmospheric and cloud variabilities.

Retrievals are trained by using a dataset of atmospheric profiles from radiosondes or models (reanalysis) that are representative for the climate at the measurement site.

For commercial instruments, the manufacturer usually provides one set of algorithms that are specific for the deployment site.

In future, E-Profile and ACTRIS will apply harmonized retrieval algorithms for the whole network. In E-PROFILE the "Tropospheric Remotely Observed Profiling via Optimal Estimation" (TROPoe, https://hub.docker.com/r/davidturner53/tropoe) approach is used, while in ACTRIS a neural network retrieval based on reanalysis training data is planned.

Below is an overview on all single MWR retrieval, including methods that are being used as standard algorithms in the E-PROFILE and ACTRIS networks. For a complete overview (including all references) on all available single instrument and synergy retrieval approaches to derive temperature and humidity profiles (also applicable for IWV and LWP in case of the MWR) see the "Temperature and Humidity profiling, inversion strength and position" chapter in the "PROBE COST ACTION WG2 "Advanced ABL profiling" - Deliverable 2.1" document.

Products	**Temperature profile**	**Humidity Profile**
Existing algorithms	- IPT (Cologne University): OEM retrieval using a climatology as the "a-priori"	- IPT (Cologne University): OEM retrieval using a climatology as the "a-priori"

	- Net1D (Météo-France/IMAA): OEM retrieval using a NWP model short-term forecast as the “a priori” - Statistical regularization method (Single channel MWR): physically-based retrieval using temperature autocorrelation matrix calculated from a climatology of radio soundings as the "a-priori” - TROPoe (NOAA): OEM retrieval using a climatology as the “a-priori” - Neural network: provided by manufacturers for each MWR unit and implemented in the MWRpy processing chain; trained from either a climatology of radiosoundings or model re-analyses - Linear / quadratic regressions trained either from a climatology of radiosoundings or model re-analyses: can be provided by manufacturer or the MWRpro chain provided by the university of Cologne	- Net1D (Météo-France/IMAA): OEM retrieval use a NWP model short-term forecast as the “a priori - TROPoe (NOAA): OEM retrieval using a climatology as the “a-priori” - Neural network: provided by manufacturers for each MWR unit and implemented in the MWRpy processing chain; trained from either a climatology of radiosoundings or model re-analyses - Linear / quadratic regressions trained either from a climatology of radiosoundings or model re-analyses: can be provided by manufacturer, or the MWRpro chain provided by the university of Cologne
Assumptions needed	- horizontal homogeneity in area around ~2 km from the instrument when using measurements at low elevation angles	
Accuracy of existing products	- Statistical retrievals: 0.2 to 2 K within 4 km - Regularization method (single-channel MWR): 0.2 to 1.5 K up to 1 km - Up to 6 km altitude with Net1D, IPT: 0.5 to 1.5 K	- 0.2 to 1.5 g/m3
Uncertainty estimates existing?	- Net1D chain: provides full error covariance matrix - IPT chain: provides full error covariance matrix - TROPoe chain: provides full error covariance matrix	- Net1D chain: provides full error covariance matrix - IPT chain: provides full error covariance matrix - TROPoe chain: provides full error covariance matrix

Temporal resolution	- depends on scanning strategy: 2 to 5 min averaging time typically every 20 minutes	- 1 second
Timeliness	depends on scanning strategy: - < 20 min for statistical retrievals or OEM method - < 1 hour for OEM based on model forecast	- < 5 min
Data availability	- 24/7 in non-heavy precipitation conditions	- 24/7 in non-precipitating conditions

Processing algorithms

As an advancement of the IDL based processing algorithm mwr_pro (https://zenodo.org/records/7973553), the Python code MWRpy (Marke et al. 2024a; https://actris-cloudnet.github.io/mwrpy/) is designed to address the needs in ACTRIS to provide centralised processing, quality control of MWR raw data, and provision of standardised output of meteorological variables. The code is designed as a stand-alone software, since it covers the full processing chain of reading in raw data to higher level products and visualisation (Fig. 1), but it is also implemented in the Cloudnet algorithm CloudnetPy (Tukiainen et al. 2020). Within Cloudnet, the output of MWRpy is then harmonised and used to derive synergy products with other remote sensing instruments, like cloud radar. In this way, MWRpy is replacing the previous mode of operation of relying on pre-processed and non-harmonized data streams.

As part of the MWRpy QA/QC chain, the monitoring tool (Löffler 2024; https://github.com/igmk/mwr_radome) will give valuable insights into radome degradation. In addition O-B statistics (Marke et al. 2024b) are evaluated to detect long-term trends of instrument uncertainties, as well as help with the detection of faulty absolute calibrations.

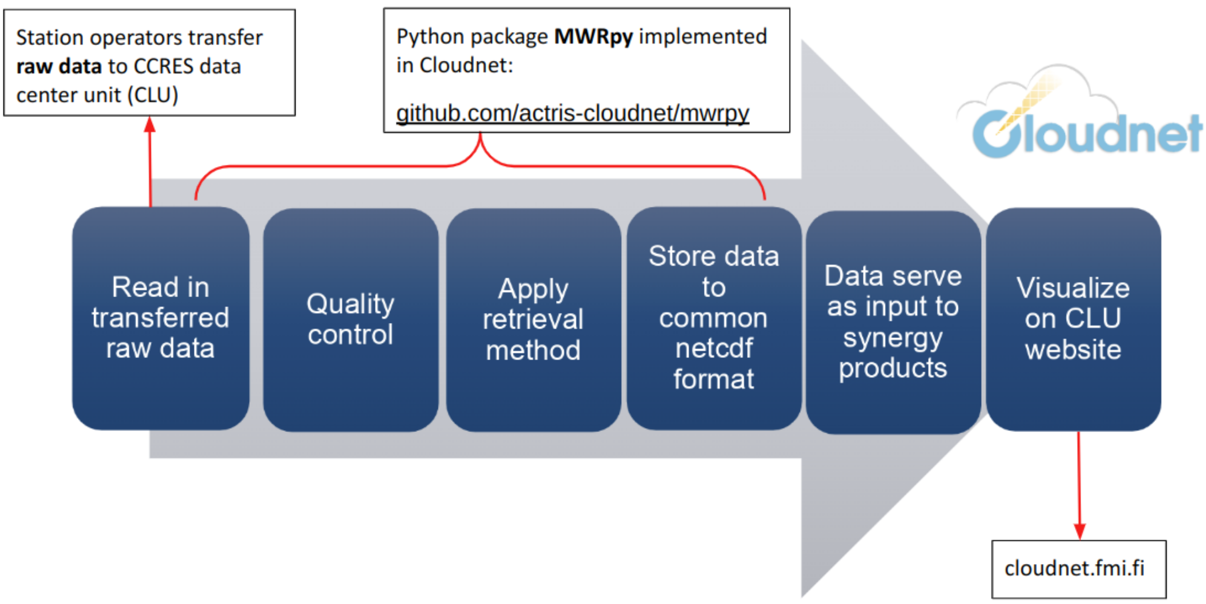

Figure 1: Flowchart of the MWRpy processing chain, with the last two steps being exclusive for the CloudnetPy implementation.

In E-PROFILE, Python tools for generating Level 1 NetCDF files from raw data (https://mwr-raw2l1.readthedocs.io/en/latest/), as well as a package for centralised near real-time retrieval application (by running TROPoe, https://mwr-l12l2.readthedocs.io/), are available for operational use (see Fig. 2). The centralised processing takes place on the European Weather Cloud (EWC), which is a distributed cloud infrastructure from ECMWF and EUMETSAT, and allows fast access to ECMWF data needed for the retrieval approach.

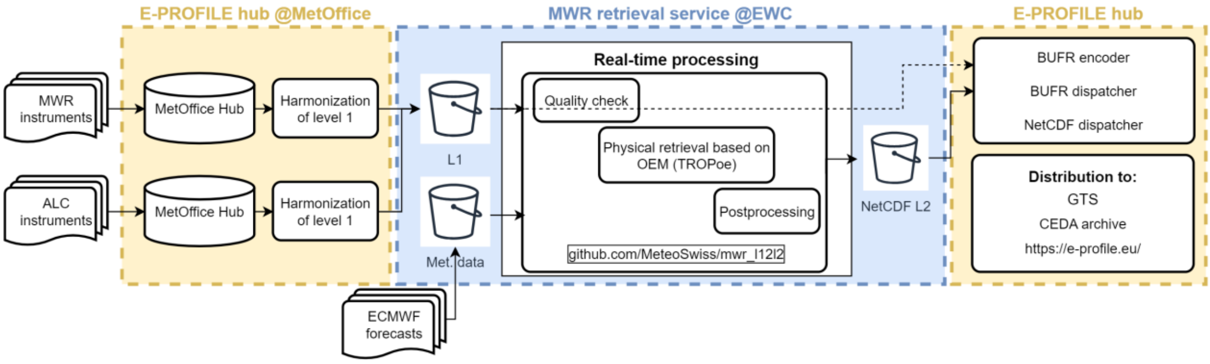

Figure 2: Flowchart of the E-PROFILE MWR processing chain.

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