For each specify progress made within the action and challenges still remaining

1 Hardware characterization

The retrieval process is based on simulation of radiometer measurements. Therefore, a realistic characterization of the instrument?s hardware imperfections benefits the quality of the retrieved products. Realistic simulations consider the radiometer?s specific properties, like the width and characteristic of the band pass filters, the antenna characteristic, and the noise performance.

Instead of assuming an ideal radiometer - with a pencil beam antenna and monochromatic frequency channels - simulations should consider the finite width of the beam and the band pass filters. (Meunieur et al. (2012)). The beam width is usually sufficiently characterized by the Half Power Beam Width (HPBW) of the antenna's main lobe. Its consideration is particularly important for multi-angle retrievals: For example, when channels start to saturate at low elevation angles, measurementes will pick up more radiation from below the nominal pencil beam. in this case, simulations based on the pencil beam assumption lead to underestimated brightness temperatures.

Similarly, band pass filters pick up radiation from a finite frequency range. Even when the channel mid-frequencies are well-known, non-linearities of the atmospheric absorption spectrum accross the band passes can lead to differences between measurements and simulations. This effect is relevant for V-band simulations and increases with deployment altitude. The band passes are provided with their Full Width Half Maximum (FWHM). The FWHMs can be used for measurement simulations that assume rectangular filter shapes. An advanced approached is to use the exact filter shapes - in case these are available. However, this approach is only beneficial, for V-band simulations for high altitudes.

Besides this, the retrieval algorithm needs a realistic estimation of the measurement noise. This noise is composed by the amplitude of the system noise and the calibration uncertainty. Furthermore, the stability of the system noise and the detector gain are important for the applied calibration schedule. This means calibrations have to be repeated on time scales below the typical time scales of detector drifts. The measurement stability can e.g. be determined and monitored by calculating the Allan Variance.

2 Retrievals

- OEM and 1DVAR

Commercial MWR make use of statistical algorithms to directly provide temperature and humidity profiles as well as higher order products like stability parameters. In addition to the different frequency channels sometimes further information on the environmental temperature, humidity or infrared temperature is input to the retrieval algorithms. These algorithms are simple to apply in real time but strongly rely on the underlying data set and cannot provide uncertainty estimates for an individual measurement. Optimal estimation methods (OEM) solve the inverse problem in a physically consistent way, optimally coupling MWR observations with a priori background knowledge, as well as with other instruments? observations, accounting for their error characteristics (Löhnert et al., 2004). OEM has the advantage to associate a dynamical error characterization to the retrieved atmospheric variables, at the expenses of more computations (iterative process), and thus are typically applied in post-processing. Examples are the Integrated Profiling Technique (IPT), developed to couple MWR with cloud radar, ceilometer, and other observations for temperature, humidity, and cloud water content profiling (Löhnert et al., 2004 and 2008) and the one-dimensional Variational Retrieval (1DVAR), developed to couple MWR observations with Numerical Weather Prediction (NWP) model output (analysis or forecast) for temperature, humidity, and cloud water content profiling (Cimini et al. 2006; Hewison 2006, 2007; Cimini et al. 2010). The main advantage of 1DVAR with respect to other techniques is the use of the NWP output as a first guess, as usually the NWP output is more representative of the present atmospheric state than a climatological mean. The use of 1DVAR was demonstrated in all-weather conditions during the Vancouver 2010 Winter Olympics (Cimini et al., 2011), providing temperature and water vapour density profiles within 1 K and 0.5 g/m3 from surface up to 10 km.

- Model-based regression retrievals

For operational applications of network data provided by microwave radiometers some non-trivial problems need still to be solved. The provision of comparable observations at any site of a network is of high priority in this connection. In particular nearly unbiased retrievals are required by the users. Practice, however, has shown that systematic differences in observations and retrievals are often obvious, mainly caused by calibration issues and/or uncertainties in the absorption model (Hewison et al. (2006), Löhnert and Maier (2012)). At the Lindenberg observatory an observation-based regression method using MWRP and radiosonde measurements from the past has been succesfully applied to calculate regression operators (Güldner and Spänkuch, 2001). Analogously, NWP model data and simultaneous brightness temperature observations can be used for operational applications.

On this account, the appropriateness of NWP model data was shown in a study of the LUAMI campaign (Nov 2008) applying microwave data from eight stations in Europe and during a campaign at Munich Airport in winter 2011/2012 (Güldner, 2012). This model-based regression method is a specific approach to the inversion of the radiative tranfer equation. Estimated profiles $\bar{x}$ are calculated using the equation:

$$\bar{x} = x_0 + C_{xy} C_{yy}^{-1} (y - y_0)$$

C_{xy} represents the covariance matrix of the profiles x, extracted from the forecast model, and the simultaneous MWRP measurements y. C_{yy} is the autocovariance matrix of y.

Comparisons performed during the campaign in 2011/2012 show that errors of the retrievals calculated by the model-based regression operator for the temporary site in Munich and of temperature / humidity profiles derived at the reference site Lindenberg where the observation-based retrieval method had been applied, are in a similar order of magnitude. It demonstrates the usefulness of a model-based regression method to redraw systematic errors and to provide comparable results within a network. The method offers good prospects for a continuous and partially autonomuous updating of model-based regression operators at a multitude of radiometer sites.

3 Online data flow

Currently different MWR delivery observations and retrievals using a variety of file formats. The format of MWR output data should be harmonized. Ideally, numerical data should be provided with metadata to facilitate their spread use. The candidate for a common format with metadata should be chosen among the well established and understood by NWP and climate communities data formats. It is recommended to inquire the NWP community what file format they would be willing to process/ingest (it may be BUFR through the GTS). Data format (NetCDF) and structure/metadata used at ARM could be taken as a starting point. The file naming (e.g. nsamwrpC1.b1.20070215.000635.cdf) reflects site, instrument, data level, date. Ideally, the netCDF files should comply with the NetCDF Climate and Forecast (CF) Metadata Convention

Data files shall be divided in levels as follows:

- lv0
    - raw voltages
- lv1
    - calibrated data, such as TB for the microwave channels, but also IR-temperatures, T/RH/P readings from MET sensors, GPS information
- lv2
    - quality controlled retrieved data obtained from application of a retrieval to lv1 data
- lv3
    - added-value products

For providing general high quality products, it is strongly recommended that quality control and calibration monitoring is done in a standardized way in a centralized server.

4 Forward operator

A fast forward modelling operator for ground-based MWR is needed in future to comply with data assimilation demands and standards from the atmospheric modelling community. The widely used RTTOV fast radiative transfer model, developed and maintained by the MetOffice, has been developed for the simulation of passive, downward-looking satellite sensors operating from the infrared to the microwave region. First developments have been commenced within EG-CLIMET to modify RTTOV to also handle the ground-based observational geometry. This will be an important step toward using ground-based microwave radiometer measurements in data assimilation.

The work carried out sofar consisted of three equally important parts:

- calculation of LBL transmittances for an exemplarily ground-based microwave radiometer in a suitable format for the standard RTTOV regression software
- modification to the RTTOV regression coefficient generation software in order to account for the ground-based perspective
- changing central routines in the main RTTOV code for the ground-based observation geometry.

Although extensive testing of the modified routines is still needed the LBL calculations, generated coefficients and modifications to the main RTTOV code are an important step that was only possible due to the excellent cooperation with the MetOffice. In the future, more extensive testing must be done. Once the clear-sky changes have been proved to work properly, the modifications will be expanded to the cloud routines e.g. modifying the cloud predictors and related subroutines.

5 Networking

MWR technology has matured so far that hundreds of systems operate continuously world wide. However, there is lack of coordination of MWR operations worldwide, causing underutilization of MWR data. Recent attempts that tried to address this issue include the LUAMI campaign and MWRnet. The LUAMI (Lindenberg Upper-Air Method Intercomparison) campaign was carried out to demonstrate the capabilities of MWRP systems for their use in operational meteorology, deploying a test network of MWRP supplying quality-proven data in real-time to a network hub at the DWD Atmospheric Observatory in Lindenberg. The temporary network of 8 MWRP operated reliably and data were collected for 1 month. A common retrieval algorithm, a statistical regression based on MWRP observations and NWP model output, was applied to data from all the 8 MWRP; this method effectively removed absorption model and calibration issues, producing weak-biased retrievals with respect to NWP.

More recently, efforts are being made towards the establishment of a permanent international network of microwave radiometers MWRnet. The MWRnet initiative started within this COST action EG-CLIMET and proposed the following goals:

- Establishing the ?best practice? for making MWR observations and retrievals
- Defining procedures for optimum calibration and quality control
- Developing common retrieval algorithm with error analysis (from observations to retrievals)
- Implementing metadata and data handling protocols
- Facilitating the registration and access of well documented and quality controlled MWR observations and retrievals with errors
- Providing near-real-time MWR data and retrievals (with errors) for NWP Data Assimilation (DA) and Observation System Experiments (OSE).

In Europe, nowadays the number of operational MWR is larger than the number of radiosounding sites. This is expected to happen in other countries soon, as China, India, and U.S.A.