Quantification of the metrological model chain

The metrological model chain visualizes the set of uncertainties (both from random and systematic effects) on the instrument outputs. The presumption is that all processes have been included and have an estimate of an uncertainty. For the uncertainty estimates, evidence for the magnitude must be provided and documented, where possible. If no measured uncertainty is available for a process, then at least an upper limit to its magnitude must be provided with a rationale for its size.

In the following, a brief explanation of the uncertainty displayed in Figure 5 is given. Uncertainties are divided in two groups: those affecting the MWR calibration (i.e. from atmospheric radiance to calibrated Tb) and those affecting the retrieval method (from calibrated Tb to MWR retrievals).

Uncertainties affecting the MWR calibration

For estimating the uncertainties affecting the MWR calibration, the uncertainties of the calibration parameters are propagated through the two commonly used calibration procedures, i.e. the liquid nitrogen (LN2) and tipping curve procedures (Maschwitz et al., 2013; Han and Westwater, 2000). The impact is summarized in **Table 1**.

The **LN2 calibration** is affected by the following sources of uncertainty:

LN2 refractive index: The refractive index of the LN2 target (n_{LN2}) determines the reflectivity of its surface. n_{LN2} is derived from laboratory measurements with an uncertainty of ±0.03 (Benson et al., 1983). The resulting Tb uncertainty decreases linearly with higher Tb values. For the opaque channels in the V-band the uncertainty reduces to 0.1 K, and it disappears at the hot calibration point.

Temperature sensor: Calibration uses an internal target at ambient temperature as a hot reference. The main source of uncertainty is the in-situ temperature measurement of the target. An uncertainty of ±0.2 K is considered for the in-situ temperature measurement, reflecting the maximum deviation between two temperature sensors within the ambient target. The resulting Tb uncertainty is approximately ±0.2 for V-band opaque channels. All other channels are affected by approximately ±0.1 K.

Target emissivity: Additional uncertainty is given by the target emissivity. Targets are assumed to be ideal black bodies, while their emissivity and reflectivity slightly differ respectively from 1 and 0. Manufacturers specifications give target reflectivity levels lower than -40 dB for frequencies higher than 8 GHz (i.e. $r<0.0001$ and $\varepsilon>0.9999$). The effective Tb is within 0.01 K if the ambient temperature varies from -30 to 40 °C. Therefore, the impact is assumed negligible. However, specifications in the spectral range of the observed MWR channels are not available to our knowledge.

Resonance: During the calibration, LN2 evaporates and its level diminishes, changing its distance to the receiver and the resonance conditions. This affects the uncertainty of the calibration point. The maximum uncertainty is estimated to be twice the amplitude of the oscillation observed at each channel, because the integration time within the LN2 calibration is small compared to the oscillation periods. K-band channels show oscillation amplitudes of 0.1 to 0.6 K. In the V-band the amplitudes are 0.1– 0.3 K.

Non-linearity parameter: The detector non-linearity is accounted in the four-point calibration solving for the non-linearity parameter α. The uncertainty in determining α is 0.1–0.2 % of the mean α value of each channel. The effect does not exceed ±0.04 K and is therefore negligible.

The **tipping curve calibration** is affected by the following sources of uncertainty:

Mean radiative temperature**:** The tipping curve method requires knowledge of the frequency-dependent mean radiative temperature (T_{mr}) of the atmosphere. T_{mr} is usually estimated from either a climatological mean or a linear regression based on ambient surface temperature (T_{srf}), both derived from prior atmospheric profiles processed with radiative transfer calculations. Regression on T_{srf} is more accurate, with a rms ranging from 3.4 to 1.1 K from the K- to V-band channels. Assuming the uncertainty on T_{mr} to be on 1-rmse level, it affects negligibly the K-band and by ≈ 0.1 K the V-band channels.

Pointing: The tipping-curve methods relies on the knowledge of the elevation angle at which the antenna is pointing. A mispointing of 1° can easily lead to a calibration error of several Kelvin. This systematic error is explained by a tilt and can be balanced by averaging measurements of symmetric elevation angle prior to the tipping curve procedure. The correction results in a residual pointing uncertainty of 0.05. This uncertainty has no effect on the K-band, and results in a ±0.1 K Tb uncertainty in the V-band.

Atmospheric inhomogeneity: The quality of the tipping curve method degrades with increasing atmospheric inhomogeneity. This variability is induced by random processes such as atmospheric turbulence. This has been estimated as the standard deviation of Tb over a set of scans, resulting in 0.1–0.2 K for the K-band and 0.3-0.4 in the V-band.

Beam width: A MWR is characterized by an antenna with a finite width. The effects of the finite width can be modeled using a Gaussian-shaped lobe. The contribution from outside the angular range of two half-power beam widths (HPBW) and the remaining uncertainty are negligible. The impact on calibrated Tb would be less than 0.1 K at three air masses for all channels.

Repeatability and validity: The repeatability and validity of the calibration have been evaluated for one particular instrument (Maschwitz et al., 2013). For repeatability is intended the capability of a calibration to reproduce the calibration parameters. It is assumed that the repeatability is characterized by the stability of the noise diode temperature T_N, which is determined with every calibration. The impact of the repeatability is estimated to be negligible for opaque channels, whose calibration is dominated by the ambient target temperature, and ranging between 0.2 and 0.4 K for the non-opaque channels. The validity is intended as the period over which a calibration is maintained stable, which again is characterized by the stability of the noise diode temperature T_N. As the LN2 calibration is impractical to perform frequently, this aspect is rather important for V-band channels which cannot be calibrated by the tipping curve calibration. A trend analysis of these calibrations reveals significant trends of TN (+0.006 to +0.010 K per day and +0.054 to +0.072 K per day in the K- and V-band respectively). The impact on calibrated Tb is estimated to be less than 0.01 K/day at all channels. Most affected channels are the relative transparent V-band channels, with an estimated drift of 0.3 K per month.

Table 1: Estimated uncertainty for liquid nitrogen (LN2) and tipping curve calibrations. Last column indicates the estimated validity of the calibration in terms of calibration drift (adapted from Maschwitz et al., 2013).

	LN2 calibration					Tipping curve calibration				
ν [GHz]	**n_{LN2} [K]**	**Res [K]**	**Hot [K]**	**α [K]**	**Total [K]**	**T_{MR} [K]**	**Poi [K]**	**Atm [K]**	**Total [K]**	**Drift [K/d]**
22.24	±0.7	±0.4	±0.1	±0.04	±1.2	±0.0	±0.0	±0.2	±0.2	−0.03
23.04	±0.7	±0.8	±0.1	±0.04	±1.6	±0.0	±0.0	±0.2	±0.2	−0.02
23.84	±0.7	±0.2	±0.1	±0.03	±1.0	±0.0	±0.0	±0.2	±0.2	−0.03
25.44	±0.7	±0.1	±0.1	±0.03	±0.9	±0.0	±0.0	±0.1	±0.1	−0.03
26.24	±0.7	±0.3	±0.1	±0.03	±1.1	±0.0	±0.0	±0.2	±0.2	−0.03
27.84	±0.7	±0.2	±0.1	±0.03	±1.0	±0.0	±0.1	±0.1	±0.1	−0.03
31.40	±0.7	±0.2	±0.1	±0.02	±1.0	±0.0	±0.0	±0.2	±0.2	−0.00
51.26	±0.6	±0.3	±0.1	±0.03	±1.0	±0.1	±0.1	±0.4	±0.6	−0.05
52.28	±0.6	±0.1	±0.0	±0.00	±0.7	±0.3	±0.1	±0.3	±0.7	−0.06
53.86	±0.4	±0.1	±0.0	±0.00	±0.5					−0.04
54.94	±0.1	±0.0	±0.1	±0.00	±0.2					−0.02
56.66	±0.1	±0.0	±0.2	±0.00	±0.3					−0.01
57.30	±0.1	±0.0	±0.2	±0.01	±0.3					−0.01
58.00	±0.1	±0.0	±0.1	±0.01	±0.2					−0.01

Uncertainties affecting the MWR retrieval method

The uncertainty of the retrieval method, that is the analysis algorithm to transform the calibrated Tb into the atmospheric products, contributes to the total uncertainty affecting the MWR atmospheric products. Some of the uncertainty sources are discussed below and the impact is summarized in **Table 2**. A variety of methods are currently used to solve the inverse problem, with somewhat different implementations, and their performances have been compared at some degree (Solheim et al. 1998; Cimini et al., 2006). Statistical algorithms, including multivariate statistical regression and neural networks, are usually exploited as they are suitable to be applied in real time. Conversely, physical retrieval methods, such as optimal estimation methods (OEM), are more computationally expensive as they solve the inverse problem in a physically consistent way. OEM optimally couples MWR observations with a priori background knowledge, accounting for and propagating statistical errors from both the observations and background. An estimate of the uncertainty on the retrieved profiles can be derived by assuming the errors are normally distributed about the solution and that the problem is only moderately non-linear. An example of the estimated retrieval uncertainty based on OEM method is shown in the **Figure** below.

The OEM retrieval method is affected by the following sources of uncertainty:

<u>Uncertainty due to absorption model</u>: Retrieval relying on radiative transfer model (RTM) calculations are affected by uncertainties in the atmospheric absorption model. These uncertainties are often estimated as the difference in zenith Tb calculated by two or more different absorption models, though a rigorous approach would require to propagate uncertainties in line parameters to uncertainty in absorption (Boukabara et al. 2005).

Profile discretization: The discretization of the background profiles introduces uncertainty in Tb calculated by the RTM. To evaluate this, a set of high-resolution radiosondes can be used as input to the RTM and the calculated Tb compared with Tb calculated using the same profiles reduced by a discretization method, as for example that used for numerical weather prediction (NWP) models.

Smoothing error: An important component of the total uncertainty is related to the vertical resolution. Although there are different definitions for its quantitative evaluation, the vertical resolution of MWR profilers for temperature and humidity retrievals is limited. A commonly accepted definition of the vertical resolution builds on the averaging kernel matrix (AKM) concept (Rodgers, 2000). The averaging kernel matrix defines the sensitivity of the retrieved quantities to the true atmospheric state. The broadness of the averaging kernels gives information on the vertical resolution, e.g. a perfect vertical resolution corresponds to averaging kernels in the form of delta functions. OEM provides the estimate of the AKM.

Spectral response function: RTM calculations require the knowledge of the channel spectral response function (SRF). In fact, MWR channels have finite bandwidths and thus are not monochromatic. As the atmospheric absorption may change non-linearly across the bandwidth of each channel, Tb evaluated at the channel's center frequency may be biased with respect to band-averaged Tb obtained convoluting the SRF with high-resolution RTM calculations. To avoid the expensive multiple RTM computations, it is often used an equivalent monochromatic frequency (EMF) for each channel. The EMF is determined as the monochromatic frequency that minimizes the difference with the band-averaged Tb for a representative data set of atmospheric profiles. The EMF does not always correspond to the nominal central frequency. Once the EMF is accurately determined, e.g. within 1 MHz uncertainty, the impact on Tb is small.

Table 2: Estimated uncertainty for MWR retrieval method (adapted from Hewison, 2007).

ν [GHz]	Absorption model [K]	Discretization [K]	SRF [K]
22.24	0.22	0.65	0.15
23.04	0.21	0.65	0.01
23.84	0.18	0.62	0.01
25.44	0.13	0.55	0.01
26.24	0.11	0.52	0.01
27.84	0.10	0.51	0.00
31.40	0.09	0.50	0.00
51.26	0.47	0.80	0.03
52.28	0.56	0.65	0.05
53.86	0.42	0.16	0.05
54.94	0.09	0.02	0.01
56.66	0.06	0.01	0.00
57.30	0.06	0.01	0.00
58.00	0.06	0.00	0.00

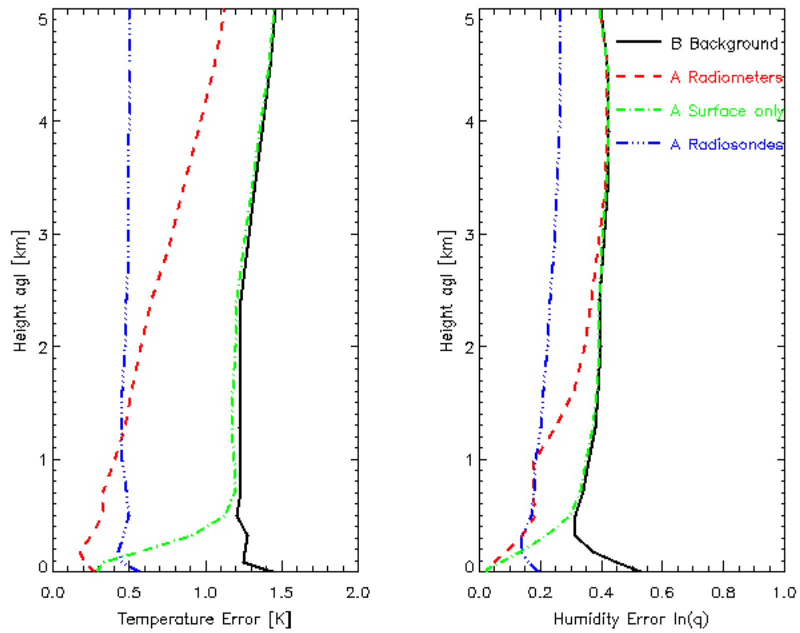

Figure: Uncertainties on background from mesoscale model (black) and retrieved profiles, using surface sensors only (green), MWR and surface sensors (red), and radiosonde only (blue). Left panel: temperature. Right panel: specific humidity (adapted from Hewison and Gaffard, 2006).

Outlook

The aim is to develop a technical document where each box in the chain is expanded and hence to produce traceable uncertainties.

References

Benson J., Fischer J. and Boyd D. A.: Submillimeter and Millimeter Optical Constants of Liquid Nitrogen, Int. J. Infrared Milli., 4, 145–152, doi:10.1007/BF01008973, 1983.

Boukabara S. A., S. A. Clough, J.-L. Moncet, A. F. Krupnov, M. Yu. Tretyakov, and V. V. Parshin, Uncertainties in the Temperature Dependence of the Line-Coupling Parameters of the Microwave Oxygen Band: Impact Study, IEEE Trans. Geosci. Rem. Sens., 43, 5, doi: 10.1109/TGRS.2004.839654, 2005.

Cimini, D., T. J. Hewison, L. Martin, J. Güldner, C. Gaffard and F. S. Marzano, "Temperature and humidity profile retrievals from ground-based microwave radiometers during TUC", Met. Zeitschrift, Vol. 15, No. 1, 45-56, 2006.

Han Y. and E. R. Westwater: Analysis and Improvement of Tipping Calibration for Ground-based Microwave Radiometers. IEEE Trans. Geosci. Remote Sens., 38(3), 1260–127, 2000.

Hewison T. and C. Gaffard, Combining Data From Ground-Based Microwave Radiometers And Other Instruments In Temperature And Humidity Profile Retrievals, TECO-2006.

Hewison T., “Profiling Temperature and Humidity by Ground-based Microwave Radiometers”, PhD Thesis, Department of Meteorology, University of Reading, 2006.

Maschwitz G., U. Löhnert, S. Crewell, T. Rose, and D.D. Turner, 2013: Investigation of Ground-Based Microwave Radiometer Calibration Techniques at 530 hPa, Atmos. Meas. Tech., 6, 2641–2658, doi:10.5194/amt-6-2641-2013

Solheim F., J. Godwin, E. Westwater, Y. Han, S. Keihm, K. Marsh, R. Ware, “Radiometric Profiling of Temperature, Water Vapor, and Liquid Water using Various Inversion Methods,” Radio Science, 33, pp. 393-404, DOI: 10.1029/97RS03656, 1998.