Retrieval Algorithms for Atmospheric Attenuation in the Frequency Band 15 – 52 GHz From Two-Channel Microwave Radiometer Observations

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Introduction

Ground-based microwave radiometers operating in the frequency range 20 – 40 GHz have several applications using atmospheric remote sensing techniques. Often the basic idea is to measure the atmospheric sky brightness temperature on and off the water vapour emission line centred just above 22 GHz. These temperatures may be used to infer atmospheric transmission (or absorption) (Westwater, 1990) as well as the signal propagation path delay through the atmosphere in the direction of the observation (Klügel et al., 2019). Because the main atmospheric constituents determining the sky brightness temperatures are the integrated amounts of water vapour (IWV) and liquid water (ILW) also these quantities may be estimated. We will refer to this instrument as a water vapour radiometer (WVR). In this study the focus is on the estimation of atmospheric transmission along earth-space paths although we also present example results for the other applications mentioned above. We have developed these algorithms for a site at the Onsala Space Observatory on the Swedish west coast. A prototype WVR, developed by Omnisys Instruments, Gothenburg, Sweden, for which the derived algorithms are intended is shown at the test site in Fig. 1.

Fig. 1. The WVR at the Onsala Space Observatory

Simulations: input data and assumptions

The input data describing the atmospheric properties were taken from ERA-Interim via its web interface. The quantities used are: surface pressure, temperature profile, geopotential altitude, humidity profile, liquid water content profile (LWC) and low cloud fraction (LCF). Data were downloaded for the years 2000 – 2013. The position was selected to match the location of the Onsala Space Observatory, OSO. This database contained 20,456 cases.

The following assumptions were made about the WVR:

1. the instrument has two channels, at 23.8 and 31.4 GHz;
2. the antenna pattern is sufficiently narrow, that a pencil beam calculation represents the antenna temperature;
3. the instrument channels are sufficiently narrow that a monochromatic calculation represents the brightness temperature;
4. the magnitude of uncorrelated (thermal) noise is assumed to be 0.6 K, for both channels (including noise added by the atmosphere and the calibration process);
5. there are fully correlated errors between the two channels (0.37 K rms in channel 1 and 0.47 K rms in channel 2);
6. all instrument errors are assumed to be independent of the observed air mass.

More details are given in the proceedings paper.

Simulations: regression model

Measured brightness temperatures are used to model the atmospheric properties by polynomial expressions. The polynomials applied are of 2nd order (except for ILW which is of 3rd order) and include a cross-term:

$$t(\nu,\varepsilon) \;=\; a_0(\nu,\varepsilon) + a_1(\nu,\varepsilon)\cdot t_1 + a_2(\nu,\varepsilon)\cdot t_2 + a_3(\nu,\varepsilon)\cdot t_1^2 + a_4(\nu,\varepsilon)\cdot t_2^2 + a_5(\nu,\varepsilon)\cdot t_1\cdot t_2$$

where retrieval of the transmission, t, at the frequency ν and the elevation angle ε is used as an example; a_0, a_1 ... are the polynomial coefficients to be determined; t_1 and t_2 are the transmissions for channels 1 and 2. These are related to the measured brightness temperatures through the effective atmospheric temperatures. The forward model ARTS (Eriksson et al., 2011) is used to derive these relations. More details are given in the proceedings paper.

The retrievals are done for the Onsala site but can can easily be adopted to the conditions at other sites given that the atmospheric data used to determine the regression coefficients are taken from a global atmospheric model, such as the ERA-Interim. Selected output parameters both from the ERA-Interim dataset and from calculations by ARTS are illustrated in Fig. 2.

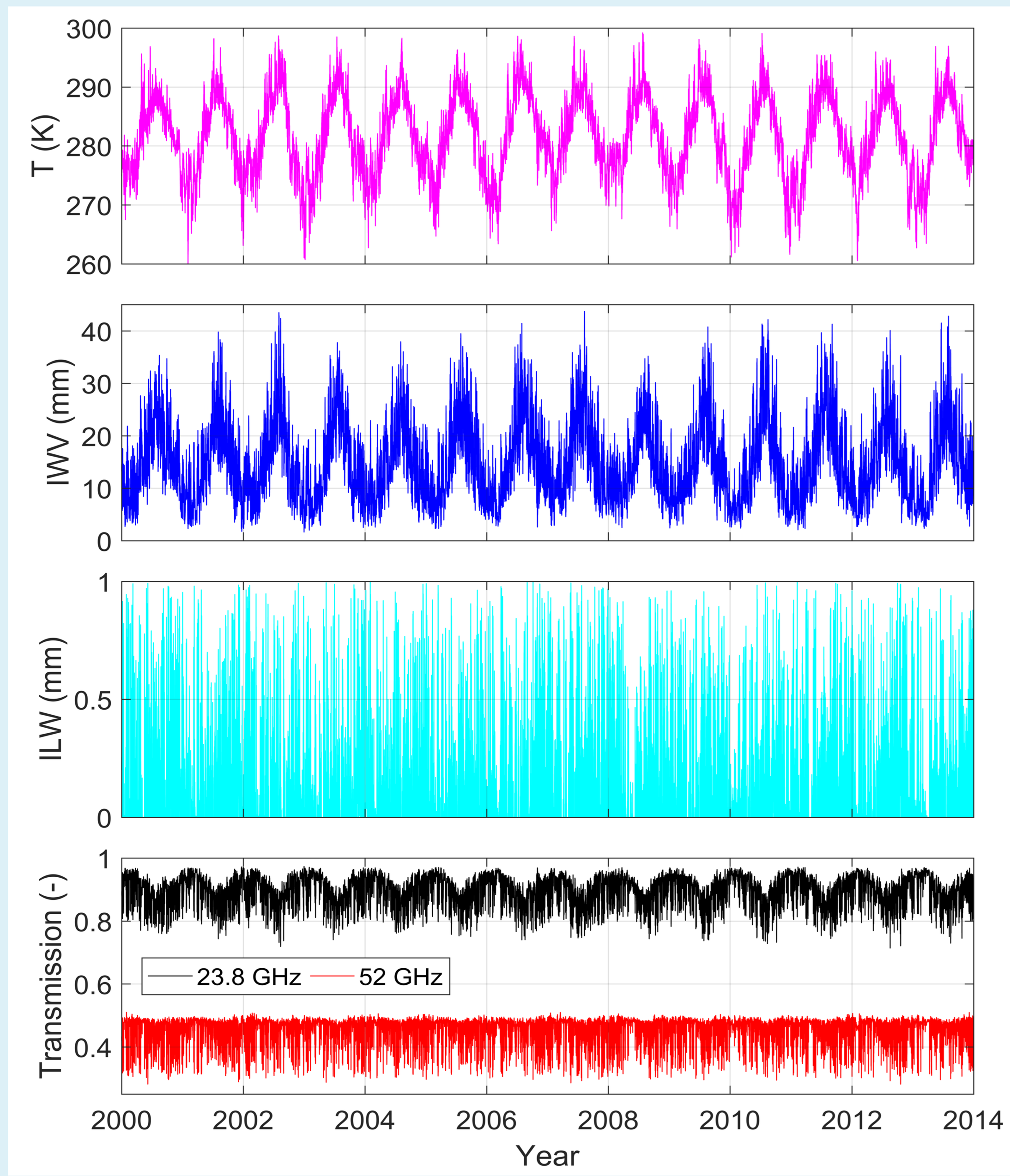

Fig. 2. Output parameters from ERA-Interim and the ARTS forward model (from top to bottom): ground temperature, IWV, ILW and the transmission at 23.8 GHz and 52.0 GHz for the studied time period. Only data when ILW < 1 mm are included.

Results: atmospheric transmissions

Fig. 3 depicts the zenith transmissions for the ERA-Interim dataset calculated with ARTS. The one standard deviation and the maximum total error are also shown. The steep gradient towards low transmissions above 45 GHz is explained by the band of oxygen lines in the frequency range 50 – 70 GHz.

We calculate the expected transmission error as a function of frequency. Fig. 4 includes several errors. The term "fit error" (blue lines) refers to the error in absence of measurement uncertainties, i.e. those that originates solely from basic limitations of the measurement. Limitations of the regression fit would also end up as a fit error, but this contribution appears to be very small compared to the intrinsic smoothing error. (This conclusion is drawn from observing that more complex fit models do not decrease the fit error.)

The ESA requirements for the accuracy of the inferred transmission is that that the one standard deviation total error shall be < 0.01, which is met with margins in the 15 – 52 GHz frequency range.

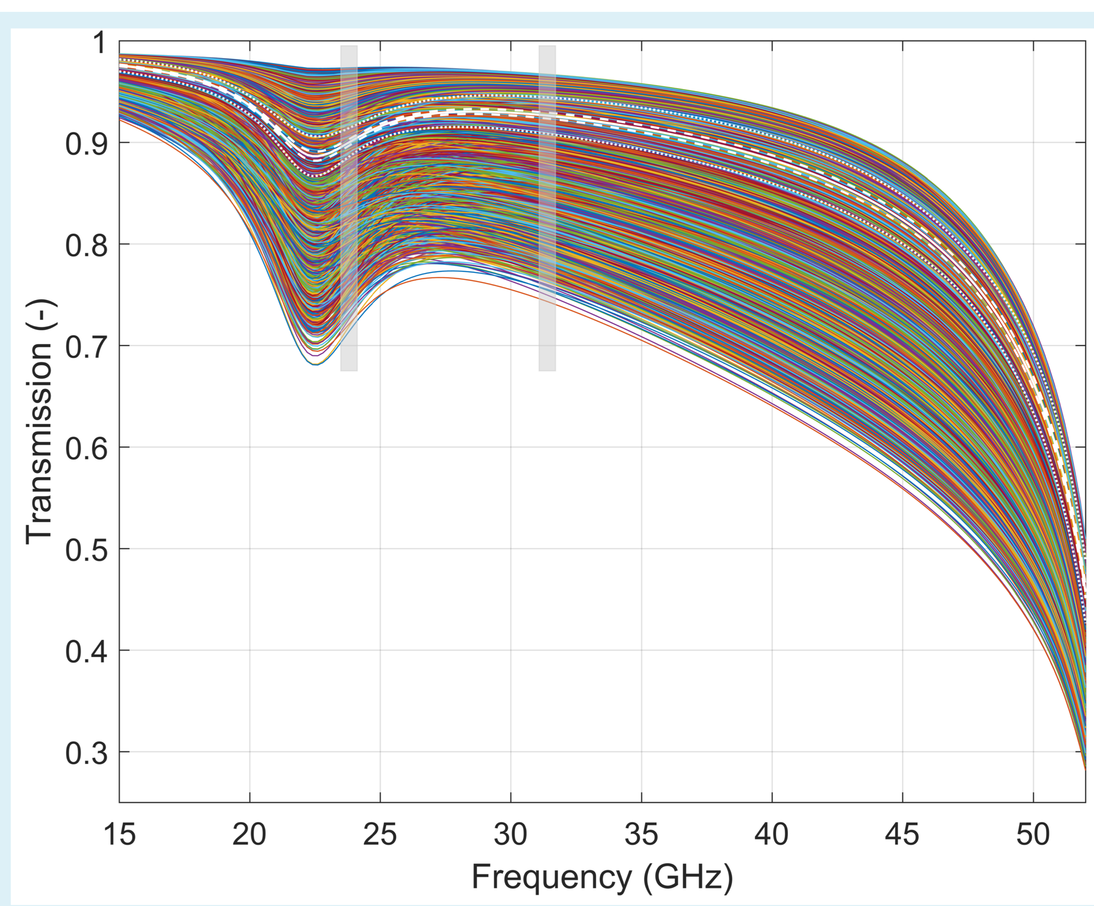

Fig 3. Transmissions at one air mass for the ERA-Interim profiles are shown for the cases when the zenith ILW < 1 mm. The solid white line shows the mean transmission; the dashed white lines show the standard deviation for the total error; and the dotted white lines show the interval for the maximum total error. The vertical grey bars show the two observed frequency bands.

References

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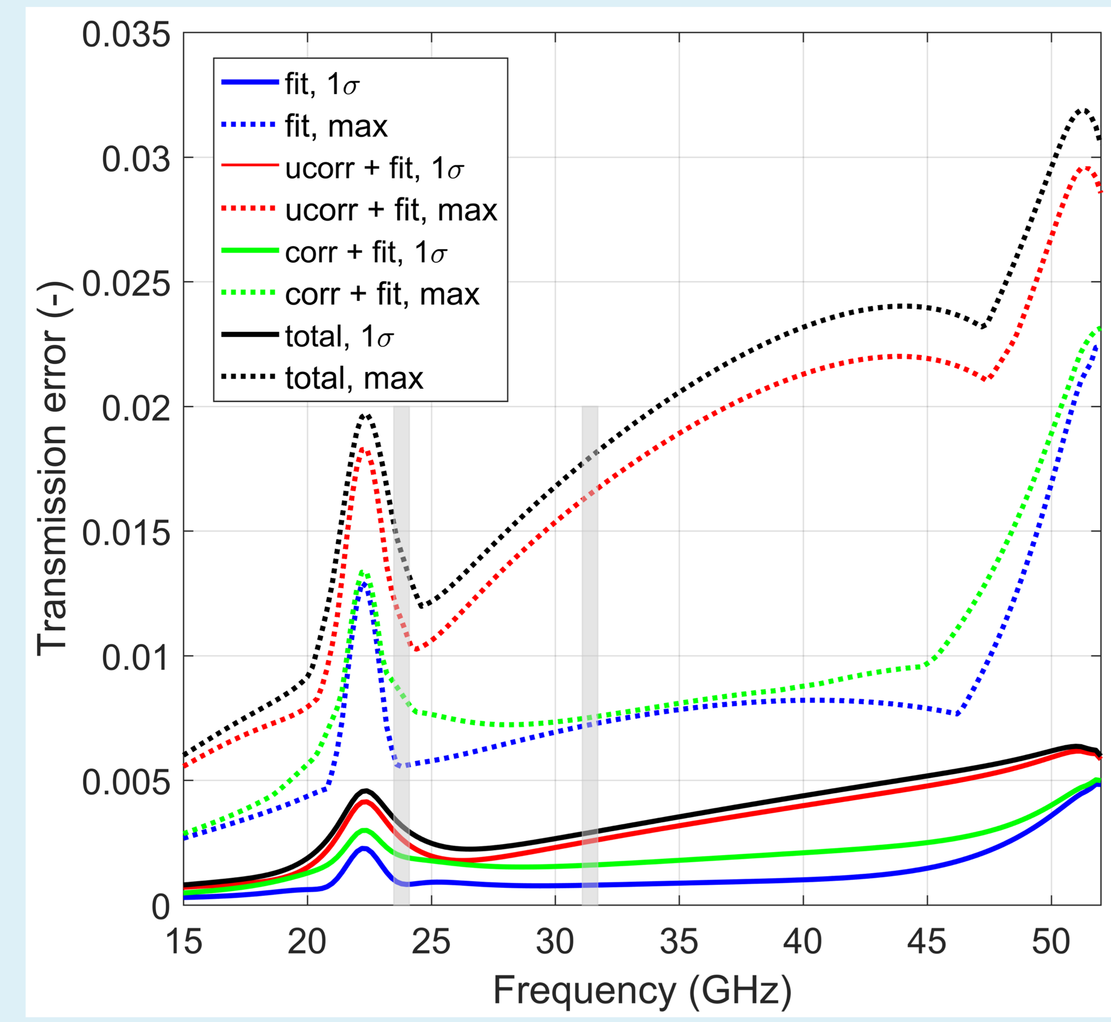

Fig. 4. Transmission errors for the ERA-Interim profiles, where profiles having the ILW < 1 mm are are included in the calculations. The vertical grey bars show the two observed frequency bands.

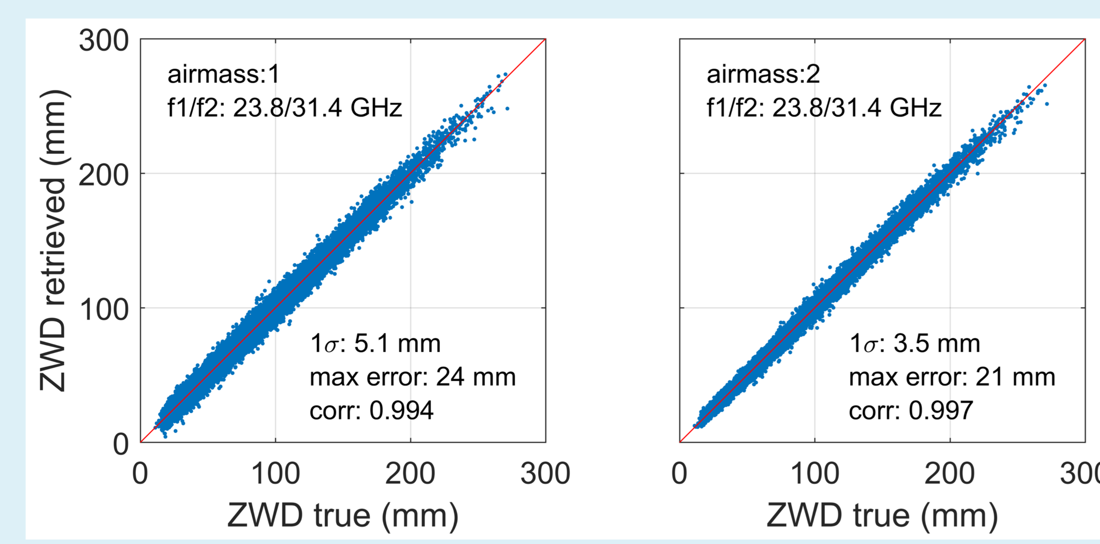

Fig. 5. Retrieval of zenith wet delays, ZWD, where the zenith ILW < 1 mm. In the left plot observations at one air mass are used and in the right plot observations at two air masses are used.

Results: ZWD, IWV, and ILW

In Fig. 5 we present the retrieval of ZWD using observations of the brightness temperatures at both one and two air masses. Observations at a high air mass (low elevation) gives higher brightness temperatures compared to observations at a low air mass. Since all errors are assumed to be independent of the observed air mass, the errors will have less relative importance when observing at two air masses instead of at one. This is clearly seen in Fig. 5.

Fig. 6 illustrates the retrieval of IWV and ILW. The observations are acquired at two air masses, but the IWV and ILW are referred to the zenith direction.

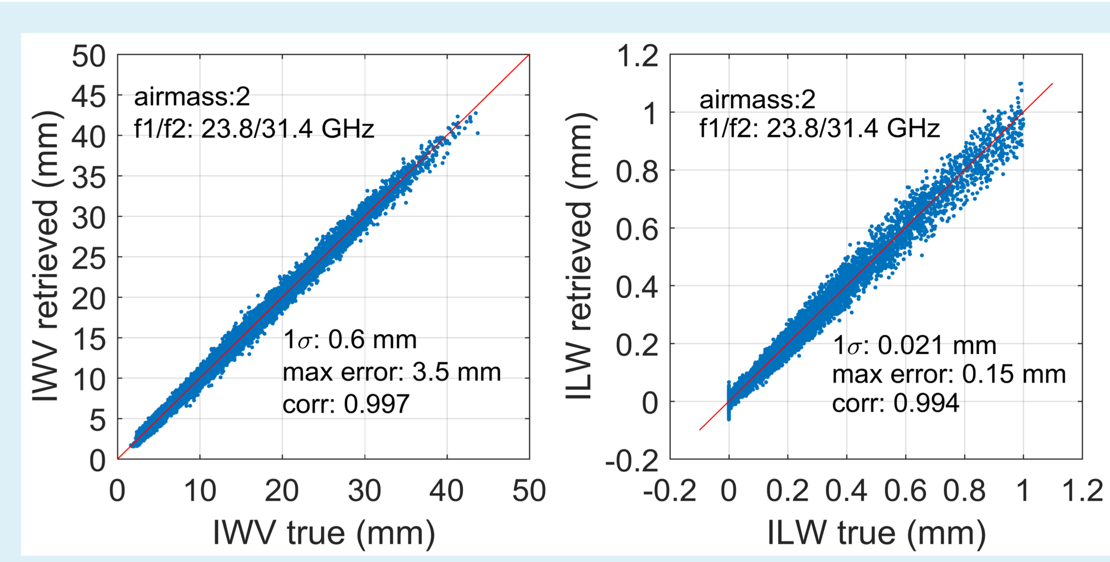

Fig. 6. The left plot depicts retrieval of the zenith IWV. The right plot depicts retrieval of the zenith ILW (when < 1 mm). Observations at two air masses are used.

Conclusions

A retrieval set-up based on the ARTS forward model and a polynomial regression model is presented. The Onsala Space Observatory site is used for testing and demonstration of the retrieval performance, but the retrievals can easily be adopted to the conditions at other sites as the atmospheric data used to determine the regression coefficients are taken from a global atmospheric model (ERA-Interim).

The errors found should be acceptable and match what is achieved by existing radiometers. The requirement specified for the transmission retrieval is met. In fact, the requirement is met with some margin implying that bias errors in the atmospheric attenuation coefficients — see e.g. Cimini et al. (2018) — and in the instrument, which have not been included in the simulations, can be tolerated to some extent.

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