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# Measurement of tropospheric/stratospheric transmission at 10–35 GHz for $H_2O$ retrieval in low Earth orbiting satellite links

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[1] Active microwave limb sounding is a possible technique for measuring water vapor in the upper troposphere and lower stratosphere, and here a first assessment of the retrieval capabilities of transmission measurements in the range 10–35 GHz is presented. The proposed observing system consists of a constellation of low Earth orbiters measuring atmospheric transmission at the frequencies 10.3, 17.2, and 22.6 GHz. The use of these relatively long wavelengths guarantees a minimal, for being a remote sensing technique, influence from scattering. The original objective of the measurements was to derive water vapor profiles, but the potential to retrieve the liquid water content of clouds was also identified during the study. Retrieval errors due to thermal noise, gain instability, and spectroscopic uncertainties were considered. With the assumed instrument characteristics a measurement precision for water vapor in the upper troposphere of 5–10% is obtained, with capability to observe through ice clouds and clouds with a low water content. *INDEX TERMS:* 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 0394 Atmospheric Composition and Structure: Instruments and techniques; 1640 Global Change: Remote sensing; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 6904 Radio Science: Atmospheric propagation; *KEYWORDS:* microwaves, atmospheric absorption, remote sensing, limb sounding

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## 1. Introduction

[2] The possible effects on the global climate caused by increased anthropogenic releases of greenhouse gases (such as $CO_2$, $N_2O$, $CH_4$ and CFCs) constitute a very complex problem, both scientifically and politically. Indications that the global climate can be affected by human activities exist [*Intergovernmental Panel on Climate Control* (*IPCC*), 2000], but any prediction about the future climate must be approached with caution as there are large uncertainties, for example, regarding water in the upper troposphere (UT) [*Kley and Russel*, 1999].

[3] Water vapor is the most important greenhouse gas [*Harries*, 1996]. Despite this importance, the distribution, variability and trends of water around the tropopause (TP) are not well known. The uncertainties connected with water vapor in the UT and the lower stratosphere (LS) can constitute the largest uncertainty when predicting a possible global warming. It has been estimated that the humidity in the UT must be known with an accuracy of 3–10% to maintain an uncertainty in the atmospheric radiative balance smaller than the effect of a doubling of the $CO_2$ [*Harries*, 1997]. The data set from the Microwave Limb Sounder (MLS) is maybe the most relevant for studies of water vapor in the UT, but the accuracy is only 20–50% below 150 hPa [*Stratospheric Processes and their Role in Climate* (*SPARC*), 2000], and the situation is far from satisfactory.

[4] Some primary demands on future water vapor observations in the UT are global coverage, good vertical resolution and high measurement precision. A further


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strong constrain is that the observations must be performed in the presence of clouds, preferably with the capability of observing through the clouds. Optical and infrared radiation is strongly scattered by clouds, a fact that makes observations at microwave frequencies (0–400 GHz) an interesting option, as proven by MLS. Good absolute accuracy is also of interest to enable rapid detections of water vapor trends in the UT. A positive trend has been found in the LS [*Oltmans and Hofmann*, 1995].

[5] Radio occultation, performed in a limb sounding mode, meets all these demands. This is an active technique where a signal is transmitted through the Earth's limb between two satellites. Compared to passive observations, radio occultation has the advantage of being able to perform measurements around the first (in frequency) molecular transition of water vapor with sufficient strength (22.235 GHz), and thus the longest possible wavelengths (>1 cm) are used, minimizing the influence of scattering. Passive limb sounding observations must be performed at higher frequencies, for example 180 GHz [*Waters et al.*, 1999] or 325 GHz [*Reburn et al.*, 2000], to obtain sufficient vertical resolution, this due to the relationship between the wavelength and the width of the antenna pattern for a given antenna size.

[6] The radio occultation technique is discussed further in the next section where a proposed satellite mission is presented. The forward model simulations are described in section 3. A first investigation of the retrieval performance for active limb transmission measurements at 10–35 GHz is given in section 4. Finally, section 5 gives the main conclusions.

## 2. WATS

[7] Active limb sounding has so far been restricted to observations of the path delay of the signal from GPS satellites (GPS/MET) [*Rocken et al.*, 1997; *Kursinski et al.*, 1997]. These observations, as any measurement of the limb path delay at microwave frequencies, yield information about atmospheric temperatures at high altitudes where the water vapor content is low, while at altitudes with higher water content additional information is needed to separate the contributions from water vapor and temperature. A possible way to resolve the ambiguity between temperature and water vapor is to also measure the atmospheric transmission. The measurement concept of WATS (Water Vapor and Temperature in the Troposphere and Stratosphere) is based on this approach.

[8] The WATS mission proposes 12 low Earth orbiting (LEO) satellites placed in two different orbital planes. The radio occultation technique will be employed to perform active limb sounding in such way that both path delay and transmission data will be obtained. Path delay will be measured from the LEOs to both GPS satellites and other LEOs, while transmission measurements will be restricted to LEOs in the same orbit plane.

[9] The transmission measurements consist of recording the change in signal strength during an occultation epoch. The atmospheric transmission is then determined by relating the recorded signal to the undamped signal obtained at the start of the occultation when the attenuation along the propagation path can be neglected. In other words, the gain of the transmitter/receiver system is calibrated at the start of the occultation. The transmission will be measured at three frequencies around the 22.2 GHz water vapor transition. The suggested set of frequencies is 10.3, 17.2 and 22.6 GHz, but other frequency combinations including 27.4 and 32.9 GHz have been discussed.

[10] In this context, the most important instrumental characteristics are the magnitude of thermal noise and gain variations during the occultations. The largest uncertainty in the transmission will result from gain drifts during the occultations. The individual sources of gain instability were not considered, all possible gain variations were instead treated as a single identity. As a conservative estimate, gain variations were assumed to be uncorrelated between the channels. The amplitude of the gain variations was assumed to have a normal distribution, where the amplitude stated is the standard deviation at the bottom end of the occultation. The gain drift is expected to be mainly of linear (as a function of time) nature, and as the reference case a linear gain drift of 0.025 dB was selected, but the impact of quadratic and sinusoidal gain variations have also been investigated. The standard assumption for the thermal noise was a SNR of 27 dB, for all channels, at a sample rate of 10 Hz. The SNR value refers to the ratio between the magnitude of thermal noise and the undamped signal. These assumptions were based on the usage of an existing GPS receiver system [*Bonnedal et al.*, 2001], and there should exist room for improvements regarding the thermal noise SNR.

[11] The WATS mission was suggested with only qualitative estimates on the measurement precision. This paper is based on a first assessment of the retrieval capabilities of the WATS transmission measurements, where the most general findings of that study are extracted.

## 3. Forward Model Calculations

[12] It was judged that, in the absence of rain, confined to the lowermost troposphere, scattering can be neglected while maintaining an acceptable accuracy. For example, the wavelength at 22.6 GHz is 13.3 mm, which is significantly larger than the particle sizes of liquid clouds (<0.1 mm). The size of the ice particles from cirrus clouds is more concerning as they can have a size >1 mm, but the number of such large particles should

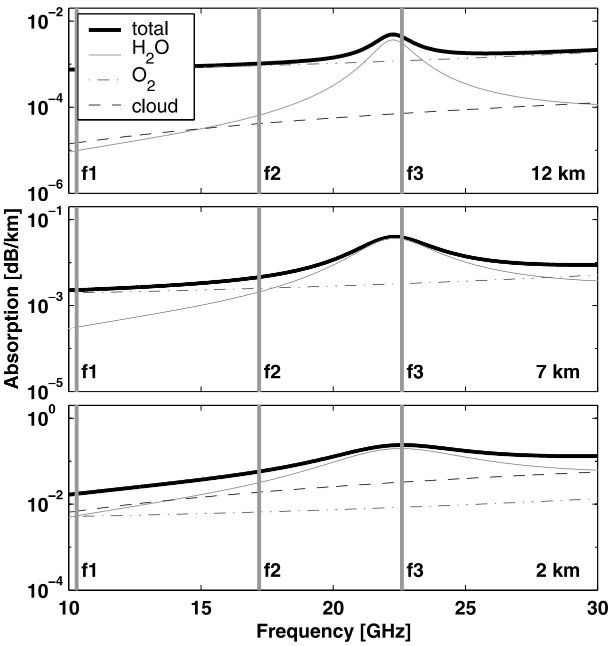


**Figure 1.** Absorption due to oxygen [*Rosenkranz*, 1993], water vapor [*Cruz Pol et al.*, 1998], and liquid/ice water [*Liebe et al.*, 1993] in the range 10–30 GHz. Calculated for summer midlatitude conditions and a cloud water content of 0.1 g/m$^3$. The clouds at 2 and 12 km consist of water and ice, respectively. The vertical shaded bars indicate the WATS observation frequencies.

be limited and possible scattering effects are expected to be small. For example, the importance of scattering increases with frequency, and the effects of cirrus ice on the water vapor measurements of MLS, where the frequencies are about a factor of 10 higher than for WATS, have been estimated as a retrieval error of less than ≈20% at 215 hPa [*SPARC*, 2000].

### 3.1. Absorption 10–35 GHz

[13] Absorption parameterizations were implemented for all constituents that could be of interest. It was found that the main gaseous absorbers at 10–35 GHz are water vapor and oxygen (Figure 1). Despite the fact that scattering can be neglected, liquid clouds will have a clear impact on the measurements by the absorption of liquid water at microwave wavelengths. The absorption decreases by more than two orders of magnitude if the water phase changes from liquid to ice and the absorption due to ice cloud particles can be neglected.

### 3.2. Limb Attenuation

[14] A general purpose forward model [*Eriksson et al.*, 2001] was used to simulate the measurements. The forward model is being developed mainly for passive observations and several simplifications were made. Only a single propagation path between the satellites was assumed (see further section 4.1). The vertical gradient of the refractive index gives, besides a bending of the line-of-sight, a divergent propagation. This effect is denoted as defocusing and was modeled by an additional absorption term, giving an attenuation close to the more detailed treatment performed by *Bonnedal et al.* [2001]. In addition, the atmosphere was assumed to have spherically symmetry (that is, to consist of homogenous layers). This applies also to clouds, but a scaling factor was introduced to compensate for partial cloud coverage. These simplifications are judged to be non-crucial for the main conclusions of the study but the simplified conditions must be noted when evaluating the results.

[15] For simplicity, the LEOs were assumed to be in the same orbit, at an altitude of 750 km, but going in opposite directions. A ray tracing scheme was applied to calculate the observing directions corresponding to the LEO-LEO link as a function of time. The lowermost altitude of the link, the tangent altitude, as a function of time, is given in Figure 2. The curvatures of the link obtained, measured by the bending angle, match closely Figure 1 of *Kursinski et al.* [1997]. The limb attenuation for different atmospheric scenarios is shown in Figure 3. The duration of an occultation (0–30 km) is in the order of 30 s.

### 3.3. Selection of Observation Frequencies

[16] It has been assumed that only three observation channels can be accommodated. A constrain for the observations is that the magnitude of thermal noise does not exceed the strength of the received signal. Accordingly, the lower limit of the operational range for a channel coincide here roughly with the point where the attenuation equals 27 dB. It is noteworthy that all frequencies are not

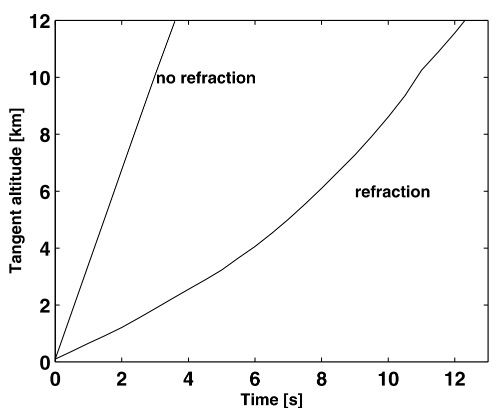


**Figure 2.** The tangent altitude as a function of time for an occultation when two satellites at 750 km are approaching each other. The synthetic case of no refraction is included for comparison.

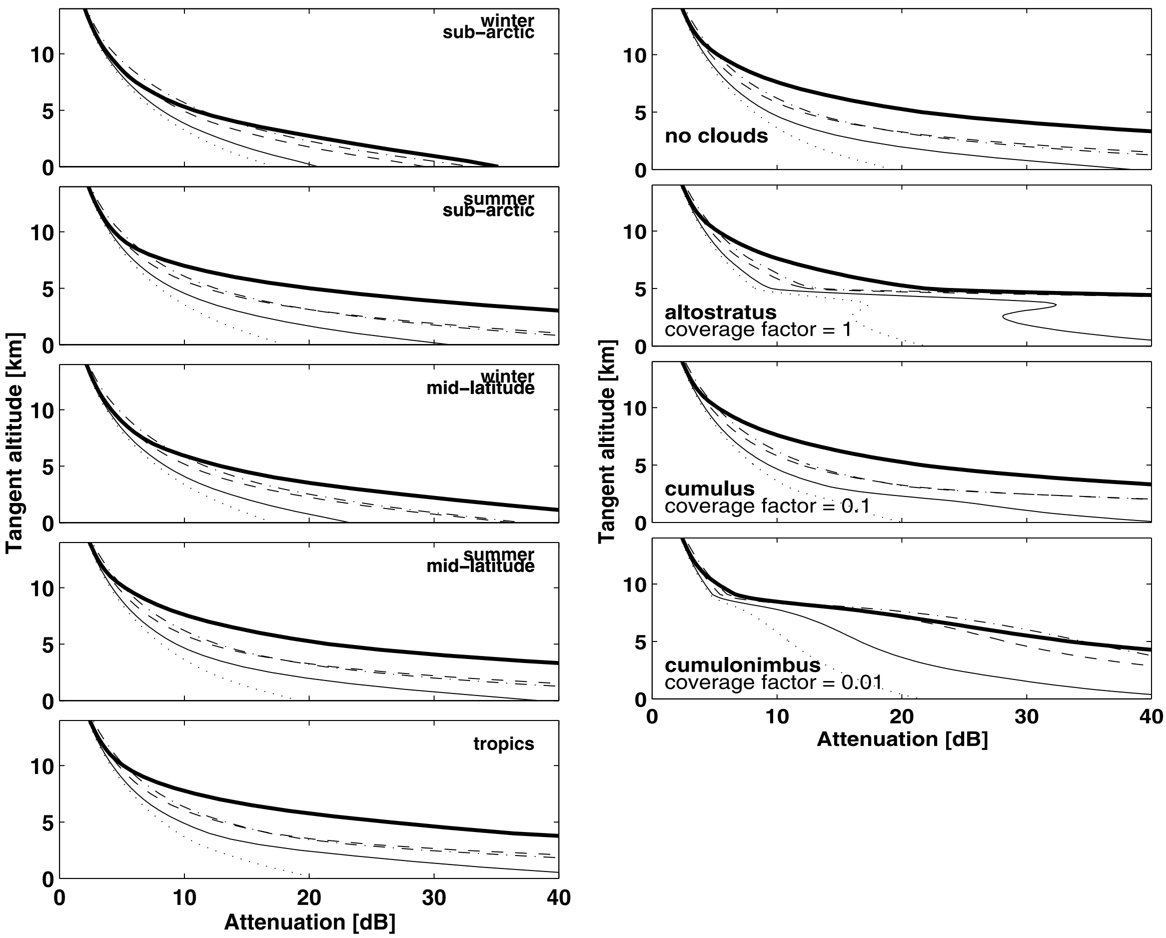


**Figure 3.** Limb attenuation for the considered frequencies and tangent altitudes 0–13 km. (left) Clear sky conditions and different atmospheric scenarios. (right) The midlatitude summer scenario with different cloud types. The cloud water content is scaled with the given factors to model fractional cloud coverage. The attenuation is plotted as dotted curves for 10.3 GHz, thin solid curves for 17.2 GHz, thick solid curves for 22.6 GHz, dashed curves for 27.4 GHz, and dash-dotted curves for 32.9 GHz.

open for active measurements, for example, a band around the 22.235 GHz water transition is protected for radio astronomy and passive remote sensing.

[17] The 22.6 GHz channel is needed to measure water vapor from about 8 km and above, the absorption of water vapor in the other channels is too low at these altitudes (Figure 1). To get sensitivity at low altitudes, the 10.3 GHz channel is the preferred channel, as it can be seen in Figure 3 (left). Then, the third frequency has to be selected from 17.2, 27.4 and 32.9 GHz. In Figure 3 (right) the effects of clouds in the signal attenuation is plotted. In order to separate water vapor and liquid water at least two "active" channels (the signal transmitted is not completely attenuated) are needed. As the high optical thickness at 22.6 GHz limits this channel to altitudes above ≈4 km, even for clear sky conditions, the less attenuated the third channel at low altitudes, the better. This rules out observation channels at 27.4 and 32.9 GHz, compared with 17.2 GHz, as the signal is more attenuated by the presence of clouds. The drawback of putting channels at higher frequencies was confirmed by retrieval simulations. In addition, use of higher frequencies requires more consideration to be given to the influence of scattering. Accordingly, the preferred frequency combination is 10.3, 17.2 and 22.6 GHz.

# 4. Retrieval Performance

## 4.1. Retrieval Setup

[18] The inversions were performed by the optimal estimation method [*Rodgers*, 2000], a standard method

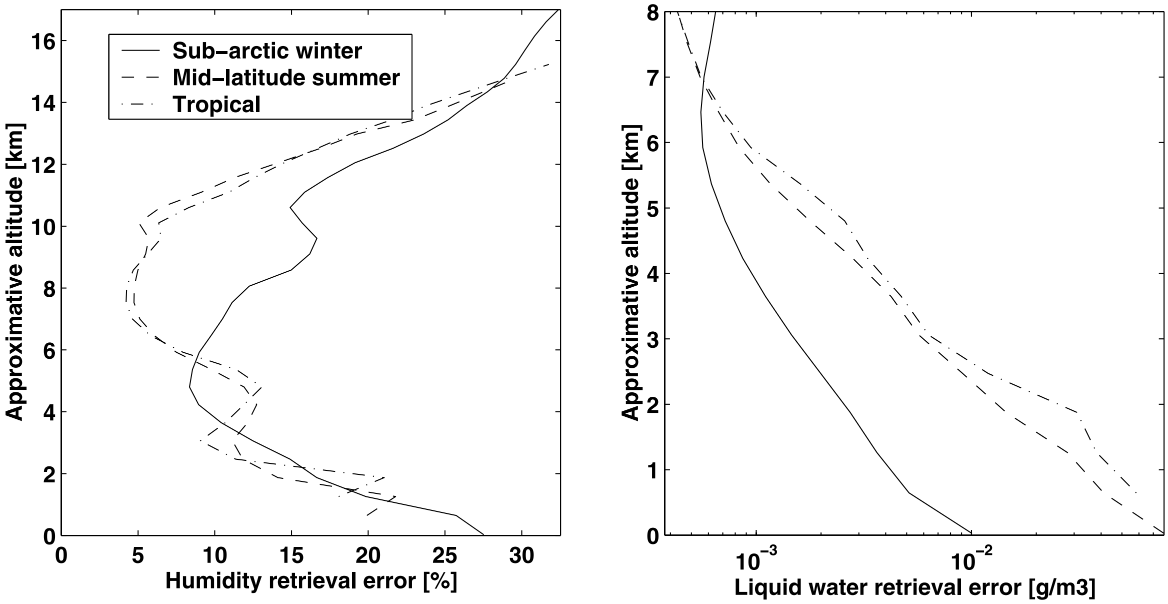


**Figure 4.** Retrieval error for (left) water vapor and (right) liquid water due to thermal noise and linear gain drift. Calculated with cloud-free conditions as a priori assumption, thermal noise SNR of 27 dB and linear gain drift of 0.025 dB. Only results corresponding to a measurement response ≥0.75 are displayed. Thermal noise is the dominating error source.

for passive atmospheric observations [*Eriksson*, 2000]. The method has also lately been used for inversion of GPS/MET data [*Palmer and Barnett*, 2001]. The retrievals were based on the atmospheric optical thicknesses as this gives a more linear inversion problem compared to using transmission values. As mentioned above, multipath propagation is neglected and in order to not overestimate the vertical resolution in absence of multipath effects, the minimum spacing of the retrieval grids was set to 500 m. The covariance matrix describing measurement uncertainties was set to model thermal noise and linear gain variations. See further section 4.3.

[19] The original WATS proposal discussed only retrieval of water vapor and temperature, but in this study liquid water was also identified as a retrieval quantity. The a priori uncertainty for liquid water was set to 0.5 g/m$^3$ up to 500 hPa and linearly decreasing above 500 hPa to reach zero at 300 hPa. The a priori uncertainty for water vapor was set to 1 (relative to a normalized water vapor profile) at all altitudes. An exponential inter-level correlation, with length 2 km, was assumed for water vapor, while no such correlation was applied for liquid water. The results displayed are throughout calculated using clear sky conditions as a priori assumption.

[20] Water vapor and liquid water were considered to be the target retrieval quantities, but for more realistic simulations, the temperature profile was also retrieved. As the information given by the path delay observations is here neglected, the a priori uncertainty for temperature was set to represent the accuracy that can be provided by meteorological offices, where the value 2 K was selected.

### 4.2. Some General Retrieval Characteristics

[21] The retrieval performance for the reference assumptions and clear sky conditions is given in Figure 4. The measurement response is defined as the area of the averaging kernels [see *Eriksson*, 2000]. A measurement response close to 1 indicates that the retrieval is mainly based on the measurement and that the influence of a priori information is small. The measurement response can be used to define the active retrieval domain and the response threshold was here set to 0.75. The lower retrieval limit is here discussed neglecting all problems connected with tracking the signal close to the ground level.

#### 4.2.1. Water Vapor

[22] The upper retrieval limit for water vapor is about 15 km. See further the discussion in section 4.3. The lower retrieval limit for cloud-free conditions varies between 0 and 2 km, depending on atmospheric scenario, but it is strongly affected by the presence of clouds. Observations can be made through ice clouds and clouds with a low water content. The tolerable amount of cloud water depends on atmospheric scenario, altitude, vertical extent and magnitude of thermal noise. For

example, the altostratus case in Figure 3 limits the water vapor retrievals to altitudes above 5 km for a SNR of 27 dB, but for a 10 dB better SNR, measurements through the cloud layer should be possible. However, even if the clouds are not thick enough to block out the signal, the measurement precision will be poorer in the presence of clouds, as the atmospheric attenuation is increased and the relative importance of thermal noise becomes higher. The vertical resolution (FWHM of the averaging kernels) is 0.5–1.0 km in the range 2–12 km, a resolution somewhat limited by the retrieval grid used.

#### 4.2.2. Liquid Water

[23] The vertical resolution for liquid water was found to mainly follow the selected retrieval grid. Tests with finer grids were performed with the same result. This indicates that the limiting factor for the vertical resolution can be multipath propagation and further studies are needed to determine best possible resolution.

[24] The measurements allow retrieval of liquid clouds up to at least 15 km and the practical upper retrieval limit is set by the atmospheric conditions, which limit the altitude range where such clouds can be expected. The lower retrieval limit is found close to the ground for smaller amounts of liquid clouds. For higher amounts of clouds, the limit is the altitude where the attenuation at 17 GHz becomes too high compared to the thermal noise SNR.

#### 4.2.3. Temperature

[25] The temperature measurement response is poor for the assumed instrument characteristics. Some information is gained only for a narrow range around 12 km and the temperature retrieval is not commented below. However, for considerably lower magnitudes of thermal noise (improvements of >10 dB) a good measurement precision can be achieved also for temperature, but this is not considered here.

#### 4.2.4. Error Correlation

[26] A considerable negative error correlation was observed between water vapor and liquid water, this especially for altitudes below 5 km. The error correlation above 6 km is in the order of $-0.6$, while below 4 km it is $\approx -0.9$. This means that if the water vapor content is over-estimated, most likely the amount of liquid water is under-estimated. The high correlation is caused by the fact that the spectroscopic features of water vapor and liquid water cannot be resolved perfectly. This separation is particularly difficult for tangent altitudes below 5 km where the 22.6 GHz channel is blocked out and only two channels are operational. Improved temperature information, for example by a joint inversion of the path delay data, will decrease the absolute value of the error correlation, but to what extent is an open question.

### 4.3. Measurement Retrieval Errors

[27] If a linear gain drift exists, but this fact is neglected during the inversion process, the resulting retrieval error can be large, while if the gain drift is included in the covariance matrix describing observation uncertainties [see *Eriksson*, 2000], the error is decreased considerably. The importance of feeding the inversion method with information about the gain drift increases with improved thermal noise SNR. A retrieval of the gain drift was not attempted, but the clear decrease in errors shows that such a retrieval is possible. In fact, for a linear OEM inversion there is no difference between retrieving a variable or treating it is an observation uncertainty. The standard retrieval setup was accordingly extended to include the linear gain drift as an observation uncertainty.

[28] The retrieval performance for levels of thermal noise deviating from the reference assumption was investigated. The noise was changed in steps of 5 dB, with the same change for all three observation frequencies (Figure 5). A first aim should be to reach a measurement precision better than 10% for the UT (see section 1), and to meet this demand a thermal noise SNR around the reference level of 27 dB is needed, as also shown by Figure 4. However, an improvement of the noise performance with 5–10 dB would be favorable to reach the more desirable precision in the UT of 1–3%. A noise improvement results further in that higher amounts of liquid clouds can be accepted.

[29] The upper retrieval limit for water vapor is not changed notably for the noise improvements considered here. A lower level of thermal noise is partly used to improve the vertical resolution. For example, with a thermal noise SNR of 37 dB, the vertical resolution is better than 1 km up to 20 km. If a main concern is to reach highest possible altitudes, the upper retrieval limit can be moved somewhat by tuning the inversion toward poorer vertical resolutions, for example by using a coarser retrieval grid, or setting the a priori uncertainty for water vapor to a higher value.

[30] The impact of gain instabilities was further investigated by modeling quadratic and sinusoidal gain variations. These gain variations were assumed to be superimposed on the linear gain drift of 0.025 dB. Quadratic gain drifts of 0.025 dB results in a gain retrieval error for water vapor at 15 km of about 10%. Inclusion of quadratic gain drifts among the considered observation uncertainties, as done for linear gain drifts, gave only a small decrease in retrieval error. However, tests indicated that quadratic gain drifts can be retrieved for lower levels of thermal noise, but further investigations were not performed in this direction. The sensitivity to sinusoidal gain variations varies strongly with the time period, where the shortest time periods have the largest errors, but the lowest likelihood of existence. Retrieval errors for a time period of 10 s are given in Figure 6. To maintain the gain retrieval error $\leq$10% for water vapor below 15 km, the tolerable level of sinusoidal gain

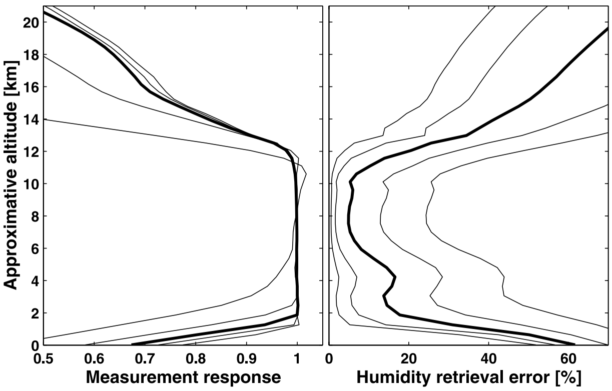


**Figure 5.** Measurement response and total retrieval error (including the smoothing error due to limited vertical resolution) for water vapor and different magnitudes of the thermal noise, in steps of 5 dB around the reference number of 27 dB. The thick lines correspond to the reference assumptions and the highest measurement response and the lowest total error are for a 10 dB lower noise. The linear gain drift was kept constant at 0.025 dB.

variations is about 0.01 and 0.001 dB for a time period of 50 and 10 s, respectively.

### 4.4. Spectroscopic Uncertainties

[31] The absorption parameterization of *Cruz Pol et al.* [1998] was selected as the reference for water vapor. The parameter values of this parameterization were compared to other relevant absorption models [*Liebe*, 1989; *Liebe et al.*, 1993; *Rosenkranz*, 1998] and the maximum deviation was selected as a conservative estimate on the uncertainty for the spectroscopic data. The line strength and the air broadening width of the 22 GHz line were found to be the most critical for the retrievals, with an uncertainty of 7% and 5%, respectively. These spectroscopic uncertainties mapped to retrieval errors are shown in Figure 7.

[32] Only two microwave absorption parameterizations for oxygen, *Rosenkranz* [1993] and *Liebe et al.* [1993], are widely used. The difference between these two parameterizations was used to estimate the uncertainty on the oxygen absorption, but as the two parameterizations are based on the same laboratory data, the true uncertainty is most likely larger. However, the retrieval error corresponding to the difference between the absorption models is here small (<2% for water vapor).

[33] There appears to exists higher uncertainties regarding microwave absorption than is generally believed. For example, it cannot today be decided which one of the water vapor absorption models that is most correct, this despite differences exceeding 5%, a number considerably higher than the expected accuracy of about 2%. The knowledge of microwave absorption is surprisingly poor and it should be possible to decrease the spectroscopic uncertainties significantly. The good absolute calibration of the WATS observations should make that data very interesting also for dedicated spectroscopic studies. It

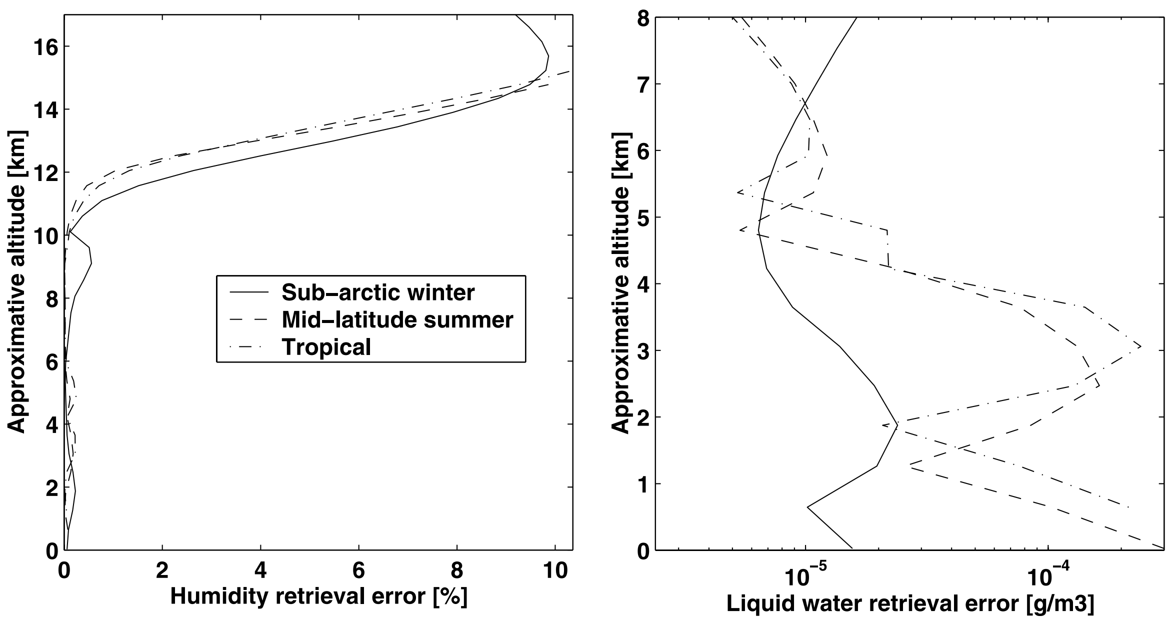


**Figure 6.** Retrieval error for (left) water vapor and (right) liquid water for sinusoidal gain variations with time period of 10 s and standard deviation of 0.001 dB.

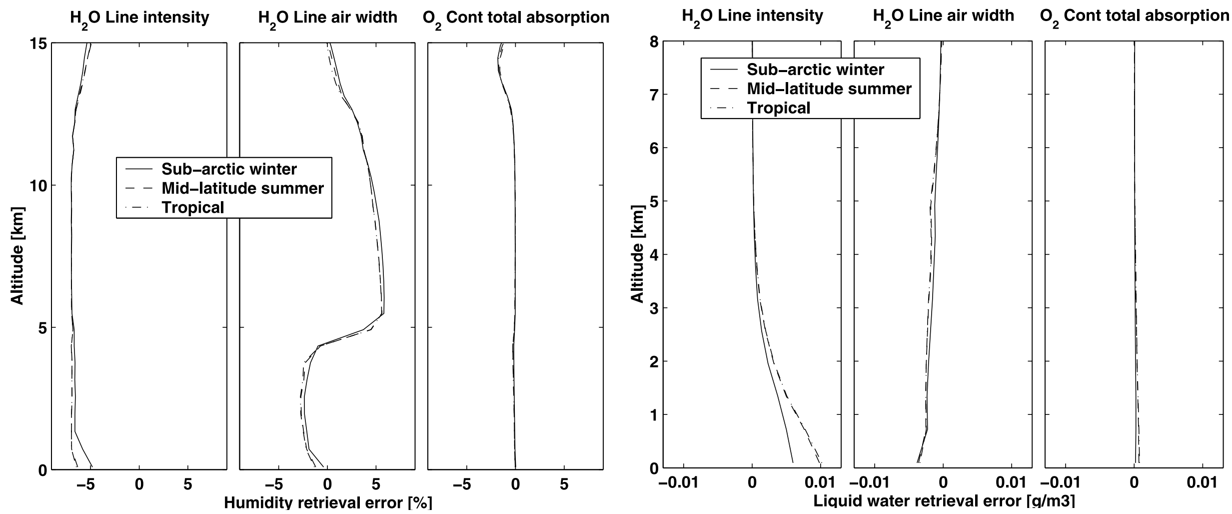


**Figure 7.** The impact of the main three spectroscopic uncertainties on the retrieval of (left) water vapor and (right) liquid clouds. Calculated for three atmospheric scenarios and a liquid water content of 0.01 g/m$^3$ up to 350 hPa.

should be noted that the measurements can be reevaluated if improved spectroscopic data are obtained.

## 5. Conclusions

[34] A first assessment of the retrieval potential of active transmission limb sounding in the range 10–35 GHz has been performed. The simulation setup followed the concept of WATS, proposed as an ESA Earth Explorer Core Mission. The capability of the measurements to determine the liquid water content of clouds, beside water vapor, was identified. Observations must be performed at a minimum of three frequencies. One observation frequency shall be placed as close as possible to the 22.2 GHz water transition, with respect to frequency protection considerations, to reach highest possible altitudes. To have some potential to measure water vapor in the presence of liquid clouds, two channels below ≈20 GHz are needed. Frequencies above 27 GHz were found to be less favorable due to higher atmospheric thicknesses and higher impact of scattering.

[35] A main advantage of the measurements is the low influence of scattering, which is normally the most critical point for other remote sensing techniques operating in the troposphere. As scattering calculations are not needed for the retrievals, a comparably direct way to measure water vapor in the presence of clouds is obtained.

[36] Observations can be performed through ice clouds and thin water clouds. The upper limit on liquid water depends on several factors, such as the altitude of the clouds and the magnitude of thermal noise. A shift of the channels at 10.3 and 17.2 GHz to lower frequencies would decrease the sensitivity to liquid clouds, but this option has not been studied. The lower retrieval limit for cloud-free conditions can be limited by problems with tracking the signal close to the ground.

[37] The water vapor measurement precision in the upper troposphere, for the assumed level of thermal noise, is 5–10%. A decrease of the thermal noise magnitude with 5–10 dB would be favorable to obtain a precision in the upper troposphere of 1–3% and to improve the cloud penetration capability. In fact, a 10 dB better SNR for thermal noise would result in a measurement performance that is hardly achieved by any other space based observation technique.

[38] A main consideration of the measurements is the stability of the system gain during an occultation. It was found that linear gain drifts can be partly retrieved. Approximative tolerable level of linear, quadratic and sinusoidal gain variations is in the order of 0.02, 0.02 and 0.001 dB, respectively.

[39] A detailed comparison of existing absorption parameterizations for water vapor and oxygen was performed, and surprisingly large uncertainties were found. For example, the line strength of the 22.235 GHz transition was found to differ with 7% between recent parameterizations. It should be possible to decrease these spectroscopic uncertainties significantly with dedicated laboratory studies.

[40] The main limitation of the performed study is the assumption of spherical symmetry of the atmosphere and further work is needed to develop inversion schemes to deal with atmospheric inhomogeneities. The influence of

scattering by raindrops and cirrus cloud ice particles should also be quantified.

[41] **Acknowledgments.** The work described here was carried out as part of the ESA lead study "Assessment of uncertainties in LEO-LEO transmission observations through the troposphere/stratosphere", ESTEC contract 15341/01/NL/SF.

## References

Bonnedal, M., R. Emardson, and J. Wettergren, Explorer core mission-WATS, Instrument description, technical report, Saab-Ericsson Space, Göteborg, Sweden, 2001.

Cruz Pol, S. L., C. S. Ruf, and S. J. Keihm, Improved 20- to 32-GHz atmospheric absorption model, *Radio Sci.*, *33*, 1319–1333, 1998.

Eriksson, P., Analysis and comparison of two linear regularization methods for passive atmospheric observations, *J. Geophys. Res.*, *105*(D14), 18,157–18,167, 2000.

Eriksson, P., S. Bühler, and A. von Engeln, ARTS—A modular public domain radiative transfer program, in *Atmospheric Millimeter and Sub-millimeter Wave Radiative Transfer Modeling II*, edited by P. Eriksson, and S. Bühler, pp. 57–114, Logos, Berlin, Germany, 2001.

Harries, J. E., The greenhouse Earth: A view from space, *Q. J. R. Meteorol. Soc.*, *122*, 799–818, 1996.

Harries, J. E., Atmospheric radiation and atmospheric humidity, *Q. J. R. Meteorol. Soc.*, *123*, 2173–2186, 1997.

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Scientific Basis*, Cambridge Univ. Press, New York, 2000.

Kley, D., and J. M. Russel, III, Plan for the SPARC water vapor assessment (WAVAS), *SPARC Newsl.*, *13*, 5–7, 1999.

Liebe, H. J., MPM—An atmospheric millimeter-wave propagation model, *Int. J. Infrared Millimeter Waves*, *10*, 631–650, 1989.

Liebe, H. J., G. A. Hufford, and M. G. Cotton, Propagation modeling of moist air and suspended water/ice particles at frequencies below 1000 GHz, paper presented at 52nd Specialists Meeting of the Electromagnetic Wave Propagation Panel, Advisory Group for Aerospace Res. and Dev., Palma de Mallorca, Spain, 1993.

Kursinski, E. R., G. A. Hajj, J. T. Schofield, R. P. Linfield, and K. R. Hardy, Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System, *J. Geophys. Res.*, *102*, 23,429–23,465, 1997.

Oltmans, S. J., and D. J. Hofmann, Increase in lower-stratospheric water vapor at a mid-latitude northern hemisphere site from 1981 to 1994, *Nature*, *374*, 146–149, 1995.

Palmer, P. I., and J. J. Barnett, Application of an optimal estimation method to GPS/MET bending angle observations, *J. Geophys. Res.*, *106*, 17,147–17,160, 2001.

Reburn, W. J., R. Siddans, B. J. Kerridge, S. Bühler, A. von Engeln, P. Eriksson, T. Kuhn-Sander, C. Verdes, and K. Künzi, Critical assessments in millimetre-wave atmospheric limb sounding, technical report, *ESTEC Contract 13348/98/NL/GD*, Eur. Space Res. and Technol. Cent., Noordwijk, Netherlands, 2000.

Rocken, C., et al., Analysis and validation of GPS/MET data in the neutral atmosphere, *J. Geophys. Res.*, *102*, 29,849–29,866, 1997.

Rodgers, C. D., *Inverse Methods for Atmospheric Sounding: Theory and Practise*, World Sci., River Edge, N. J., 2000.

Rosenkranz, P. W., Absorption of microwaves by atmospheric gases, in *Atmospheric Remote Sensing by Microwave Radiometry*, edited by M. A. Janssen, pp. 37–90, John Wiley, New York, 1993.

Rosenkranz, P. W., Water vapor microwave continuum absorption: A comparison of measurements and models, *Radio Sci.*, *33*, 919–928, 1998.

Stratospheric Processes and their Role in Climate (SPARC), Assessment of upper tropospheric and stratospheric water vapour, *WCRP 113, WMO/TD 1043, SPARC Rep. 2*, Geneva, 2000.

Waters, J. W., et al., The UARS and EOS Microwave Limb Sounder (MLS) experiments, *J. Atmos. Sci.*, *56*, 194–218, 1999.

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