Water vapor continuum absorption over the terrestrial and solar infrared: Results from the Zugspitze radiative closure experiment

Ralf Sussmann, Andreas Reichert, and Markus Rettinger

I) About Zugspitze (→FIRMOS campaign)

II) Results from Zugspitze radiative closure experiment


IMK-IFU-Group “Atmospheric Variability and Trends“

Ralf Sussmann, Stefan Biggel, Petra Hausmann, Katharina Höveler, Andreas Ostler, Matthias Perfahl, Andreas Reichert, Markus Rettinger, Thomas Trickl, Hannes Vogelmann

- Variability & Trends, Transport, Sources & Sinks, …
- Verification of Montreal Protocol, Post-Kyoto Process
- Model Validation (ACTM, NIES TM, …)
- Satellite Validation (ENVISAT, GOSAT, OCO-II, …)
- Improving Radiation Codes (RRTM, …) in Climate Models (ECHAM, …)

Trace Gases
Aerosols
IR-Radiation

Zugspitze
Garmisch

NDACC
TCON
Total Carbon Column Observing Network
I) About Zugspitze (FIRMOS campaign)

(47.42 °N, 10.98 °E, 2964 m a.s.l.)
• many clear sky days
• very dry atmosphere
• very low aerosol load
• easy access
Standortvorteile am Schneefernerhaus

- Beginn des Messbereichs ab Gipfelhöhe Zugspitze
- Parallelmessungen mit FTIR am Gipfel möglich

2965m FTIR
2675m
Schneefernerhaus
Zugspitze summit station 2964 m a.s.l.
Zugspitze summit station:
solar FTIR (MIR & NIR), ER-AERI, L-HATPRO
Schneefernerhaus station 2675 m a.s.l.
Schneefernerhaus: Water vapor & temperature lidar (Raman)

Laser power: 180 W @ 308 nm
Telescope: 1.5 m diameter
Range (H<sub>2</sub>O): 4 – 20 km
Range (T): 4 – 60 km
Integration time: 1 h
Vertical resolution: 0.0025 – 1 km

![Graph showing water vapor density vs. altitude](image)
Garmisch site: 47.5 °N, 11.1 °E, 743 m a.s.l.
Garmisch site: solar FTIR (MIR & NIR), lidar (O3, aerosol)

125 HR, 2.50 m OPD
I) About Zugspitze: **instruments for radiance, water vapor, and temperature soundings**

**spectral radiance measurements**
- radiance FIR & MIR
- radiance NIR

**measurements of atmospheric state parameters**
- $\text{H}_2\text{O}$ column
- $\text{H}_2\text{O}$ profile, $\text{T}$-profile

**AERI**
**solar FTIR**
**microwave radiometer LHATPRO**
**Raman Lidar**
II) Results from the Zugspitze radiative closure experiment
(I) Quantitative knowledge of water vapor radiative processes: role in remote sensing and climate simulations

- H₂O is the atmospheric species which causes the strongest absorption/emission of radiation

- H₂O feedback approximately doubles the response of surface temperature to the imposition of an external forcing (e.g., CO₂ increase)

→ Water vapor radiative processes have to be simulated accurately by the radiation codes* forming the core of remote sensing methods and climate simulations

* e.g. Rapid Radiative Transfer Model (RRTM, AER., Inc.) is used to compute radiative fluxes and heating rates in GCM’s (e.g., ECHAM)
(II) What we know about water vapor radiative processes: line absorption, continuum, FIR, MIR, NIR

- $\lambda=2.5 \ \mu m$
- $\lambda=2.4 \ \mu m$
- $\lambda=5.1 \ \mu m$
What we know about water vapor radiative processes: relative importance line absorption vs. continuum: terrestrial IR

Reduction in **outgoing longwave radiation** due to water vapor:

Paynter and Ramaswamy, 2011

⇒ Continuum absorption contributes up to 100%
clear sky shortwave absorption due to water vapor with and without continuum:

Paynter and Ramaswamy, 2011

⇒ continuum causes additional absorption up to a factor of 10
(II) Difficulties in quantifying continuum absorption: lab measurements

- no laboratory measurements at atmospheric temperatures
- extrapolation of high-temperature laboratory measurements to low atmospheric temperatures hindered by unknown temperature dependency of self continuum
(III) Radiative closure: previous work and remaining gaps

- Much has been done to consolidate knowledge on line absorption
- Turner, Merrelli, Vimont, Mlawer, 2012 state: The far-infrared (wavelengths longer than 17 mm) has been shown to be extremely important for radiative processes in the earth’s atmosphere. The strength of the water vapor continuum absorption in this spectral region has largely been predicted using observations at other wavelengths that have been extrapolated
- Paynter & Ramaswamy, 2011 state: “…the continuum contributes notably to our lack of complete understanding of shortwave absorption. There is a need for improved measurements of the continuum in the shortwave (infrared) to help constrain these values better. Until this is done, there is a caution in performing shortwave radiative transfer calculations.“

⇒ We designed the Zugspitze experiment to include the FIR, MIR, and NIR.
(III) Radiative closure: principle (based on ARM and ECOWAR)

Atmospheric state measurements
- H₂O column, profile
- T profile
- further trace gas columns (CO₂, CH₄, O₃)
- aerosol optical density

Radiative transfer model (LBLRTM)

Spectral radiance measurements
- far-/mid-infrared thermal emission spectra
- near-infrared solar absorption spectra

Modeled radiance spectrum

Measured radiance spectrum

Difference spectrum (“residuals”)

iterative adjustment of water vapor absorption parameters
⇒ minimize spectral residuals

spectral radiance measurements:
- far-/mid-infrared thermal emission spectra
- near-infrared solar absorption spectra

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spectral radiance measurements:
- far-/mid-infrared thermal emission spectra
- near-infrared solar absorption spectra
(IV) Setup of the Zugspitze radiative closure experiment: requirements

- require **low water vapor column (FIR) & low AOD (NIR)**
- require **high-precision atmospheric state measurements** (key parameter: water vapor column)

Radiance uncertainties due to atmospheric state errors (from: Delamere et al., 2010)
(IV) Setup of the Zugspitze radiative closure experiment: Zugspitze benefits

IWV during the RHUBC measurement campaigns (Turner and Mlawer, 2010)

Zugspitze benefits

• high-altitude location: very low atmospheric water vapor column, & very low AOD: 0.0024–0.0032 at 7800 cm\(^{-1}\) at air mass 1
• long-term measurements: reduce statistical errors compared to short measurement campaigns

IWV from Zugspitze solar FTIR (Sussmann, Camy-Peyret et al., ACP, 2009)
(IV) Setup of the Zugspitze radiative closure experiment: instruments overview

**Instruments Overview**

- **O₃ column**
- **IWV first guess**
- **Brewer-Dobson**
- **MW, AERI, FTIR**
- **Zugspitze 2964 m a.s.l.**
- **SSARA**

**Spectral Radiance**
- (FIR & MIR), T profile, IWV
- spectral radiance (NIR)
- IWV, XCO₂, XCH₄, XN₂O
- AOD (NIR)
(IV) Setup of the Zugspitze radiative closure experiment: spectral radiance measurements in the FIR and MIR

- AERI: FIR & MIR downwelling thermal emission with ~0.5 cm\(^{-1}\) resolution
- calibration: hot (~ 310 K) and ambient blackbodies
(IV) Setup of Zugspitze closure experiment: combined Langley + blackbody calibration of solar FTIR for NIR closure

Beer-Lambert law: \( F_\nu = F_{\nu_0} \exp(-k_\nu m) \)

Langley plot: \( \ln(F_\nu) = \ln(F_{\nu_0}) - k_\nu m \)

- spectral shape between Langley calibration points determined with a high-temperature blackbody (1900 °C)

⇒ combined calibration uncertainty: ~ 1-1.7 %

Reichert, Rettinger, Sussmann, AMT, 2016
(V) Uncertainty analysis of radiance closure spectral residuals: FIR and MIR

- e.g. H2O column:
  - IWV precision 4.3 % (2 \( \sigma \)), IWV bias 4.4 %
  - multiplied by radiance derivative
(V) Uncertainty analysis of radiance closure spectral residuals: uncertainty from water vapor profile shape

In case of input profiles state error covariances were used:

E.g., uncertainty analysis of NCEP water vapor profile shape

derivative of surface downwelling radiance with respect to water vapor profile shape
(V) Uncertainty analysis of radiance closure spectral residuals: uncertainty from T-profile

uncertainty analysis of T profiles used in the closure experiment (composite of ER-AERI retrievals <3.5 km and NCEP above)

derivative of surface downwelling radiance with respect to the T profile
(V) Uncertainty analysis of radiance closure spectral residuals: FIR and MIR

- Blackbody radiance, 268K
- Mean downwelling radiance
- Total
- H₂O line parms
- AERI calibration
- H₂O column
- T profile
- Further species
- H₂O profile shape
- AERI noise

Radiance uncertainty [mW / (m² sr cm⁻¹)]

Wavenumber [cm⁻¹]

Radiance uncertainty [mW / (m² sr cm⁻¹)]

Wavenumber [cm⁻¹]
(V) Uncertainty analysis of radiance closure spectral residuals:
MIR and NIR

- Total
- $\text{H}_2\text{O}$ line parms
- Solar FTIR calibration
- $\text{H}_2\text{O}$ profile shape
- AOD
- Further species
- Solar FTIR noise
- $\text{H}_2\text{O}$ column
- T profile
- ESS
(V) Uncertainty analysis of radiance closure spectral residuals: findings summarized

- FIR: IWV & H2O profile shape uncertainty dominate, and partly H2O line parameters in the windows used for continuum retrieval
- MIR: T profile uncertainties dominate
- NIR bands/wings: H2O line parameters & profile shape uncertainties dominate
- NIR windows, low wavenumbers: solar FTIR calibration uncertainties dominate
- NIR windows, high wavenumbers: AOD uncertainties dominate
- NIR: exceptions are CH$_4$ & N$_2$O bands where line parameters uncertainties dominate

For details see: Sussmann, Reichert, Rettinger, ACP, 2016
(VI) Zugspitze results FIR continuum

Sussmann, Reichert, Rettinger, ACP, 2016
Constraints on the water vapor continuum can only be derived from spectral windows, where

i) residual uncertainty is sufficiently low, and

ii) continuum contributes significantly to measured radiance.

Window selection approach:

1. We calculated the continuum Jacobian, i.e., the derivative of continuum magnitude with respect to measured downwelling radiance, via the finite difference method using the MT_CKD 2.5.2 model as a priori.

2. We estimated the continuum uncertainty achievable in the closure experiment by multiplying our residual uncertainty estimate with the continuum Jacobian.

3. We selected windows for which the continuum uncertainty is less than 100% above the minimum uncertainty in 10 cm\(^{-1}\) wide bins.
(VI) Zugspitze results FIR continuum

MT_CKD 2.5.2
Liuzzi et al., 2014
Sussmann et al., 2016

Water vapor continuum: Zugspitze radiative closure, Ralf Sussmann et al.
(VI) Zugspitze results MIR & NIR continuum

Zugspitze closure
MT_CKD 2.5.2 (self & foreign)
MT-CKD 2.5.2 (foreign)
CRDS, Mondelaine 2015
Calorimetric, Bicknell 2006
Lab FTIR, Ptashnik 2013

$\bar{k}_{\text{cont}}$ [cm$^2$/molecule] vs Wavenumber [cm$^{-1}$]

P2
P3
P4

35 | Water vapor continuum: Zugspitze radiative closure, Ralf Sussmann et al.
Summary

• setup of Zugspitze long-term radiative closure study:
  • very low IWV & AOD, permanent setup
  • FIR, MIR & NIR

• systematic spectral radiance residual uncertainty analysis:
  • FIR: IWV uncertainties dominate
  • MIR: T profile uncertainties dominate
  • NIR bands/wings: H₂O line parameters dominate
  • NIR windows, low wavenumbers: solar FTIR calibration uncertainties dominate
  • NIR windows, high wavenumbers: AOD uncertainties dominate

• continuum results
  • FIR continuum ok in MT_CKD 2.5.2
  • continuum absorption in NIR windows too low in MT_CKD 2.5.2
Outlook
• Contribute to FIRMOS 2019 campaign at Zugspitze
• Offer long-term support to FORUM

Acknowledgments
• Helmholtz funding of the instruments (ER-AERI and L-HATPRO)
• Deutsche Bundesstiftung Umwelt DBU (PhD grant)
• Bavarian State Ministry of the Environment and Consumer Protection via grants TLK01U-49581 and VAO-II TPI/01.
Supplementary viewgraphs
Table 1. Instruments and geophysical parameters measured at the Zugspitze radiative closure experiment. Uncertainties are given for 2σ confidence.

<table>
<thead>
<tr>
<th>Geophys. parameter</th>
<th>Instrument</th>
<th>Repeat cycle</th>
<th>Uncertainty/specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIR &amp; MIR spectral radiance</td>
<td>ER-AERI</td>
<td>10 min</td>
<td>*resolution 0.5 cm(^{-1})</td>
</tr>
<tr>
<td>(400–3000 cm(^{-1}))</td>
<td></td>
<td></td>
<td>calibration bias &lt; 0.66 % of ambient BB radiance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>calibration precision &lt; 0.13 % of ambient BB</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>radiance</td>
</tr>
<tr>
<td>NIR spectral radiance</td>
<td>solar FTIR</td>
<td>75–150 s</td>
<td>*resolution 0.011 cm(^{-1})</td>
</tr>
<tr>
<td>(2500–7800 cm(^{-1}))</td>
<td></td>
<td></td>
<td>calibration accuracy 0.6–1.7 % of measured</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>radiance</td>
</tr>
<tr>
<td>IWV (ER-AERI)</td>
<td>retrieval from ER-AERI spectra</td>
<td>10 min</td>
<td>bias 2.5 %</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>precision 1.9 %</td>
</tr>
<tr>
<td>IWV (solar FTIR)</td>
<td>retrieval from solar FTIR spectra</td>
<td>75–150 s</td>
<td>bias 1.1 %</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>precision 0.8 %</td>
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<tr>
<td>Water vapor profile shape</td>
<td>NCEP</td>
<td>6 h</td>
<td>bias 1.7 %</td>
</tr>
<tr>
<td>Temperature profile</td>
<td>ER-AERI &amp; NCEP</td>
<td>10 min</td>
<td>precision 9.4 %</td>
</tr>
<tr>
<td>O(_3) column</td>
<td>Brewer–Dobson</td>
<td>~ 30 min</td>
<td>accuracy &lt; 1 K</td>
</tr>
<tr>
<td>XCO(_2)</td>
<td>TCCON</td>
<td>100 s</td>
<td>accuracy &lt; 1 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bias &lt; 0.07 %</td>
</tr>
<tr>
<td>XCH(_4)</td>
<td>TCCON</td>
<td>100 s</td>
<td>precision &lt; 0.25 %</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>bias &lt; 1.04 %</td>
</tr>
<tr>
<td>XN(_2)O</td>
<td>TCCON</td>
<td>100 s</td>
<td>precision &lt; 0.3 %</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>bias &lt; 1.85 %</td>
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<tr>
<td>NIR AOD</td>
<td>SSARA</td>
<td>1 s</td>
<td>precision &lt; 0.5 %</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>accuracy at air mass 1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.0015 (at 2500 cm(^{-1}))</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.0025 (at 7800 cm(^{-1}))</td>
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</table>
source. The calibration uncertainty achieved with this novel method is 1–1.7% (2σ) throughout the spectral range considered. Synthetic radiance spectra are generated using the LBLRTM. Figure 1 shows the mean measured and synthetic radiance spectra for the closure data set that will be presented in Sect. 3.3. The atmospheric state used as input to the calculations was set based on the measurements described in Sect. 2. Given the calibrated spectral radiance measurements and the synthetic spectra, radiance residuals \( \Delta I \) can then be calculated for a set of spectra selected according to the criteria that will be presented in Sect. 3.3:

\[
\Delta I = I_{\text{FTIR}} - I_{\text{LBLRTM, no continuum}} \cdot e^{-\text{AOD}},
\]

(2)

where \( I_{\text{FTIR}} \) designates the radiometrically calibrated solar FTIR spectra, \( I_{\text{LBLRTM, no continuum}} \) the synthetic LBLRTM spectra not including continuum absorption, and AOD the aerosol optical depth. Continuum optical depth \( \tau_{\text{cont}} \) is calculated from the spectral residuals as follows:

\[
\tau_{\text{cont}} = -\ln \left( \frac{\Delta I}{I_{\text{LBLRTM, no continuum}} \cdot e^{-\text{AOD}} + 1} \right). \tag{3}
\]

After the calculation of the continuum optical depth (OD), absorption coefficients were derived from these results. The continuum OD \( \tau_{\text{cont}} \) is linked to the continuum absorption coefficient \( k_{\text{cont}} \) as follows:

\[
\tau_{\text{cont}} = m \cdot \int_{h_{\text{obs}}}^{\infty} k_{\text{cont}}(T, n_{\text{wv}}, n_{\text{air}}) \cdot n_{\text{wv}} \, dh,
\]

(4)

where \( m \) designates the relative air mass, \( h_{\text{obs}} \) the altitude of the observing instrument, \( n_{\text{wv}} \) the water vapor number density, and \( n_{\text{air}} \) the dry-air number density.

\[
k_{\text{cont}} = c_s \cdot \frac{\rho_{\text{H}_2\text{O}}}{\rho_0} + c_f \cdot \frac{\rho_{\text{air}}}{\rho_0}, \tag{5}
\]

where \( c_s \) and \( c_f \) designate the self- and foreign-continuum coefficients and \( \rho_{\text{H}_2\text{O}}, \rho_{\text{air}}, \) and \( \rho_0 \) are the densities of water vapor, dry air, and a reference density, respectively. Specifically, \( \rho_0 = P_0/(k_b T_0) \), where \( P_0 = 1013 \, \text{mbar} \), \( k_b \) is the Boltzmann constant, and \( T_0 = 296 \, \text{K} \). In addition to their different dependence on water vapor density according to Eq. (5), self- and foreign-broadened continua are characterized by their distinct temperature dependence: while the self-continuum shows strong negative temperature dependence, the foreign continuum is assumed to have no or only weak temperature dependence.

The separation of \( k_{\text{cont}} \) into self- and foreign-continuum contributions from atmospheric measurements is challenging. In principle, an assignment to self- and foreign continuum is possible using a large set of measurements covering a wide range of atmospheric conditions, i.e., IWV and temperature. However, the available data do not permit such an assignment given the sensitivity of our setup as discussed in Sect. 4. Therefore, in the following, we characterize continuum strength using the mean continuum absorption coefficient \( \bar{k}_{\text{cont}} \), defined as follows:

\[
\bar{k}_{\text{cont}} = \frac{\int_{h_{\text{obs}}}^{\infty} k_{\text{cont}}(T, n_{\text{wv}}, n_{\text{air}}) \cdot n_{\text{wv}} \, dh}{\int_{h_{\text{obs}}}^{\infty} n_{\text{wv}} \, dh} = \frac{\tau_{\text{cont}}}{m \cdot \text{IWV}}. \tag{6}
\]

Low-uncertainty constraints on \( \bar{k}_{\text{cont}} \) can only be placed in a number of spectral windows. The selection of such suitable windows is outlined in Sect. 3.4. The continuum results
(IV) Setup of Zugspitze closure experiment: combined Langley + blackbody calibration of solar FTIR for NIR closure

Reichert, Rettinger, Sussmann, AMT, 2016

Water vapor continuum: Zugspitze radiative closure, Ralf Sussmann et al.
(IV) Setup of the Zugspitze radiative closure experiment: 
$\text{H}_2\text{O}$ column & profile: LHA*PRO microwave radiometer

- water vapor column uncertainty: $\sim 0.02 \text{ mm (for iwv } < 1 \text{ mm)}$ 
  $\sim 0.5 \text{ mm (for iwv } > 6-8 \text{ mm)}$
Langley fit uncertainty
blackbody uncertainty
shape error uncertainty
air mass uncertainty
mispointing uncertainty
FOV uncertainty