



Rehearsal of the gaseous transmission functions

J. Mašek, T. Král, R. Brožková

Motto

Student: Gaseous transmission? Just the sum of decaying exponentials! So where is the problem?!

Guru: Compute it myriad of times and you will see.

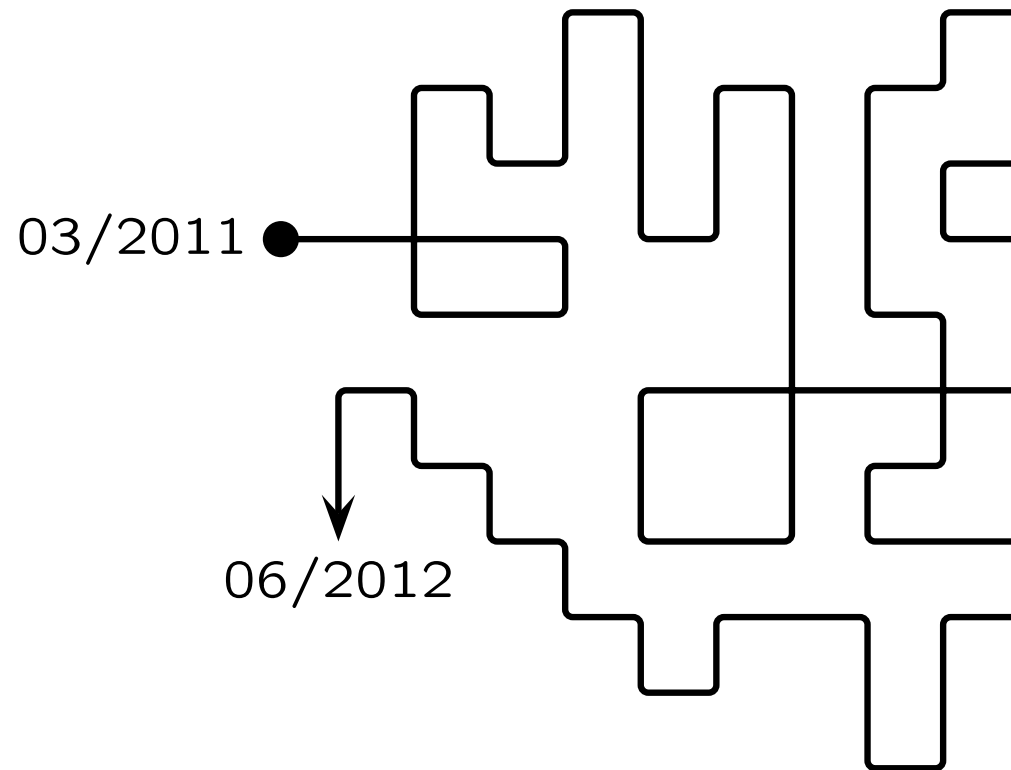
Introduction

- radiative transfer is one of the key processes determining Earth's weather and climate
- solution of radiative transfer equation is complicated (among the other things) by strong spectral dependence of optical coefficients
- two extreme approaches exist in addressing it:
 1. computation in big number of narrow spectral intervals combined with k -distribution method (RRTM, 140 thermal bands)
 2. computation in small number of broad spectral intervals using modified band model approach (ACRANEBS, 1 thermal band)
- both approaches have their pluses and minuses, first one being accurate and expensive, second being cheaper but less accurate
- question is whether second approach (i.e. ACRANEBS scheme) can be improved at moderate cost

Goals of the work

- improve ACRANEB gaseous transmissions (especially problematic Pade fits) since it was felt that they are the weakest part of the scheme
- introduce two sets of thermal weights (Planck weights $B_\nu(T)$ for cooling to space term; dB_ν/dT for remaining exchanges) to get more accurate thermal exchanges
- retune NER statistical model
- enable intermittent update of thermal gaseous transmissions in order to reduce CPU cost
- update atmospheric composition to reflect change in concentration of greenhouse gases (current ACRANEB tunings are 20 years old)
- implement possibility of more than two spectral bands in ACRANEB

Roadmap (simplified)



Starting bricks (March 2011)

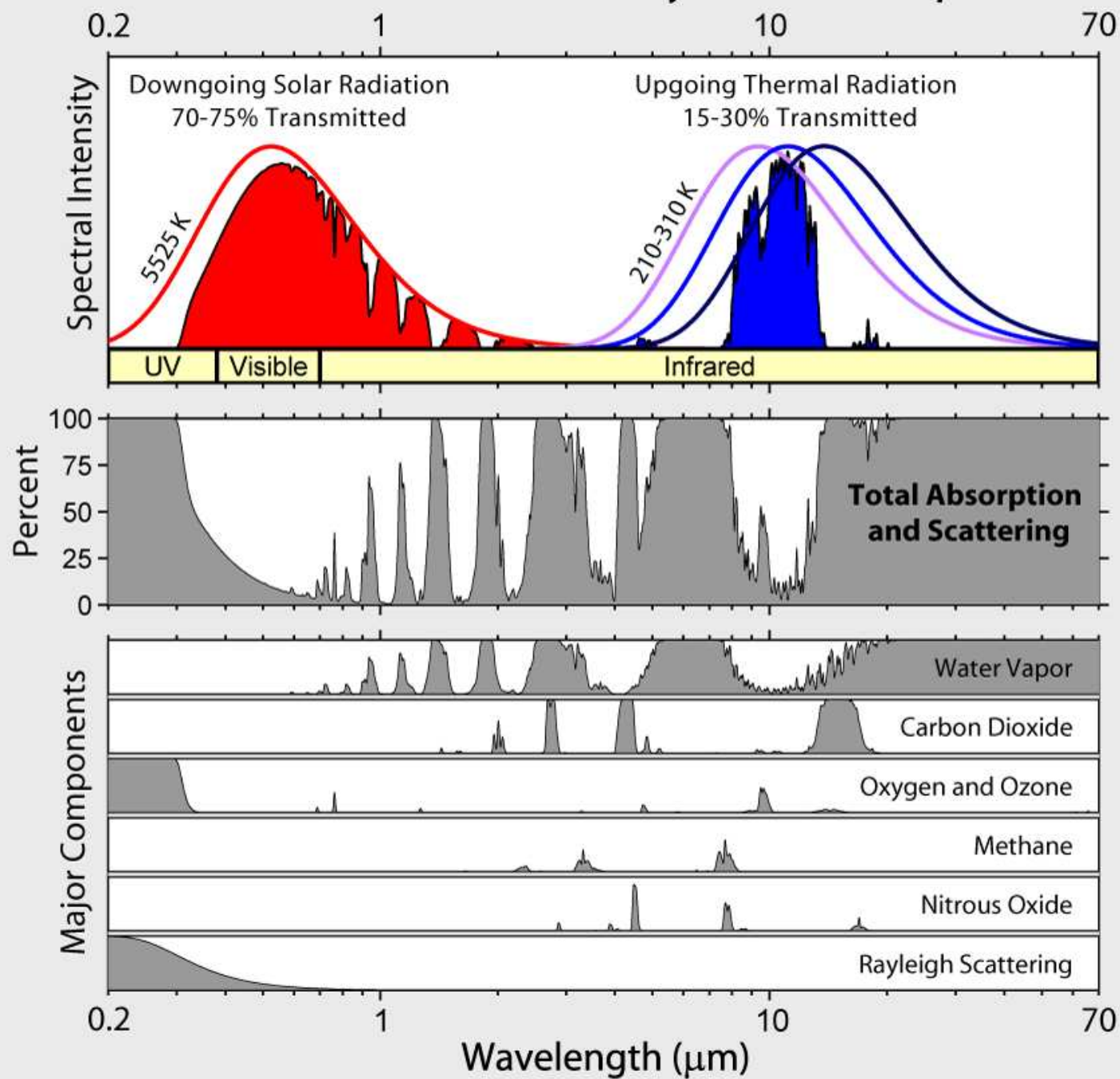
- modularized version of ACRANEB (T. Král), phased to cycle 36t1 and extended by possibility of intermittent thermal gaseous computations (R. Brožková)
- narrowband Malkmus coefficients for H_2O , CO_2 and O_3 tabulated for 5 temperatures and 840 spectral intervals (computed in early 1990s by B. Ritter and J.-F. Geleyn employing their own line by line model using AFGL spectroscopic data)
- SPLIDACO tool performing spectral averaging of narrowband transmissions, providing reference solar/thermal transmissions for homogeneous case (B. Ritter, J.-F. Geleyn)
- externalized RRTM scheme for single homogeneous layer (T. Král)

Radiative transfer (1)

- fundamental principles are well known (*)
- in Earth's atmosphere it can be treated separately for solar band (UV, visible and near infrared) and thermal band (far infrared)
- contributing species are gases, aerosols, cloud particles and Earth's surface
- absorbing gases treated in ACRANEB are H_2O , CO_2+ (composite of CO_2 , N_2O , CO , CH_4 and O_2 , i.e. gases with constant volume ratios) and O_3

(*) Biggest uncertainties concern spectroscopic measurements and proper shape of line wings.

Radiation Transmitted by the Atmosphere



Radiative transfer (2)

- radiative transfer must account for:
 - absorption
 - emission (thermal band only)
 - scattering (in clearsky case solar band only)
 - strong spectral dependence of absorption coefficient $k(\nu)$, resulting in saturation effect
- direct solution of unapproximated radiative transfer equation is not feasible in NWP conditions, since it contains 4 integrations (2 spatial, angular and spectral)

Approximations used in ACRANEB

- plane parallel atmosphere \Rightarrow 1D rather than 3D radiative transfer
- hemispheric constant intensities of diffuse fluxes plus simplified shape of scattering phase function with forward δ -peak to approximate Lorentz-Mie scattering by clouds/aerosols \Rightarrow δ -two stream system for upward/downward fluxes
- gaseous saturation based on Malkmus band model (assumes Lorentz line shape but can be adjusted for Voigt line shape), corrected by empirical fit to account for broadband effects
- method of idealized optical paths to account for scattering effect on gaseous saturation (involves diffusivity factor)
- non-homogeneous optical paths treated by Curtis-Godson approximation

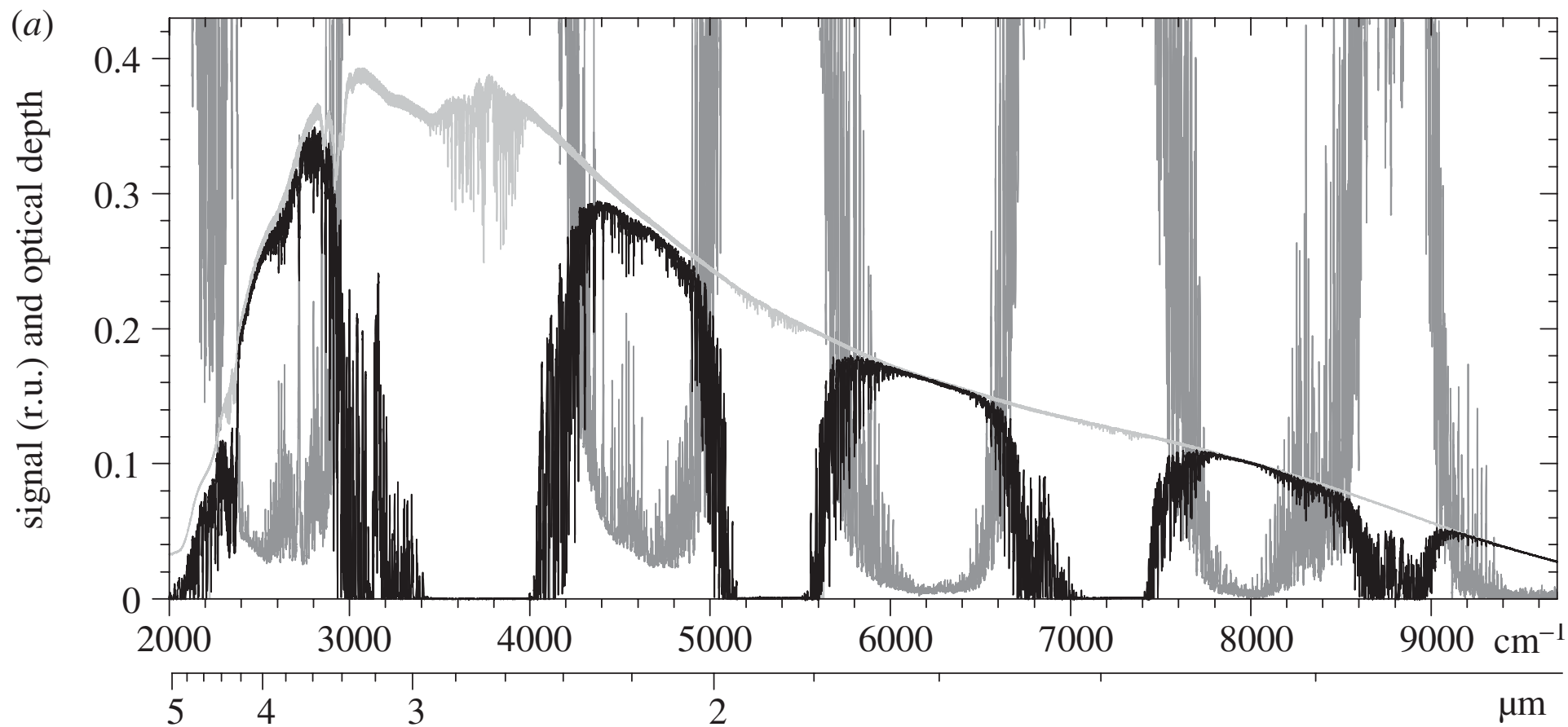
Gaseous absorption (1)

- gases have line absorption spectra resulting from quantized energy states of their molecules (due to molecule rotation, vibration and excitation of electrons)
- transition between two quantum states obeying selection rules creates spectral line centered at wavenumber $\nu_0 = (E_2 - E_1)/hc$
- spectral line is broadened by 3 processes:
 - **natural** broadening due to finite lifetime of excited state (Lorentz line shape)
 - **collisional** broadening (for instantaneous collisions leads to Lorentz line shape)
 - **Doppler** broadening due to thermal motion of air molecules (Gaussian line shape)

Gaseous absorption (2)

- natural broadening is negligible in atmosphere
- collisional broadening is dominant in troposphere
- contribution from Doppler broadening becomes important in high atmosphere ($\alpha_D/\alpha_L \propto 1/\rho_{\text{air}}$)
- both broadening mechanisms can be combined, giving Voigt line shape
- absorption lines are not distributed randomly, but rather grouped into **absorption bands** (regions containing many strong lines) separated by **windows** (regions with weak or no lines absorbing mostly via line wings of strong lines centered outside)
- window absorption is referred also as **continuum**

Measured H₂O near infrared spectrum
(taken from Ptashnik et al. 2012)



Lorentz line shape

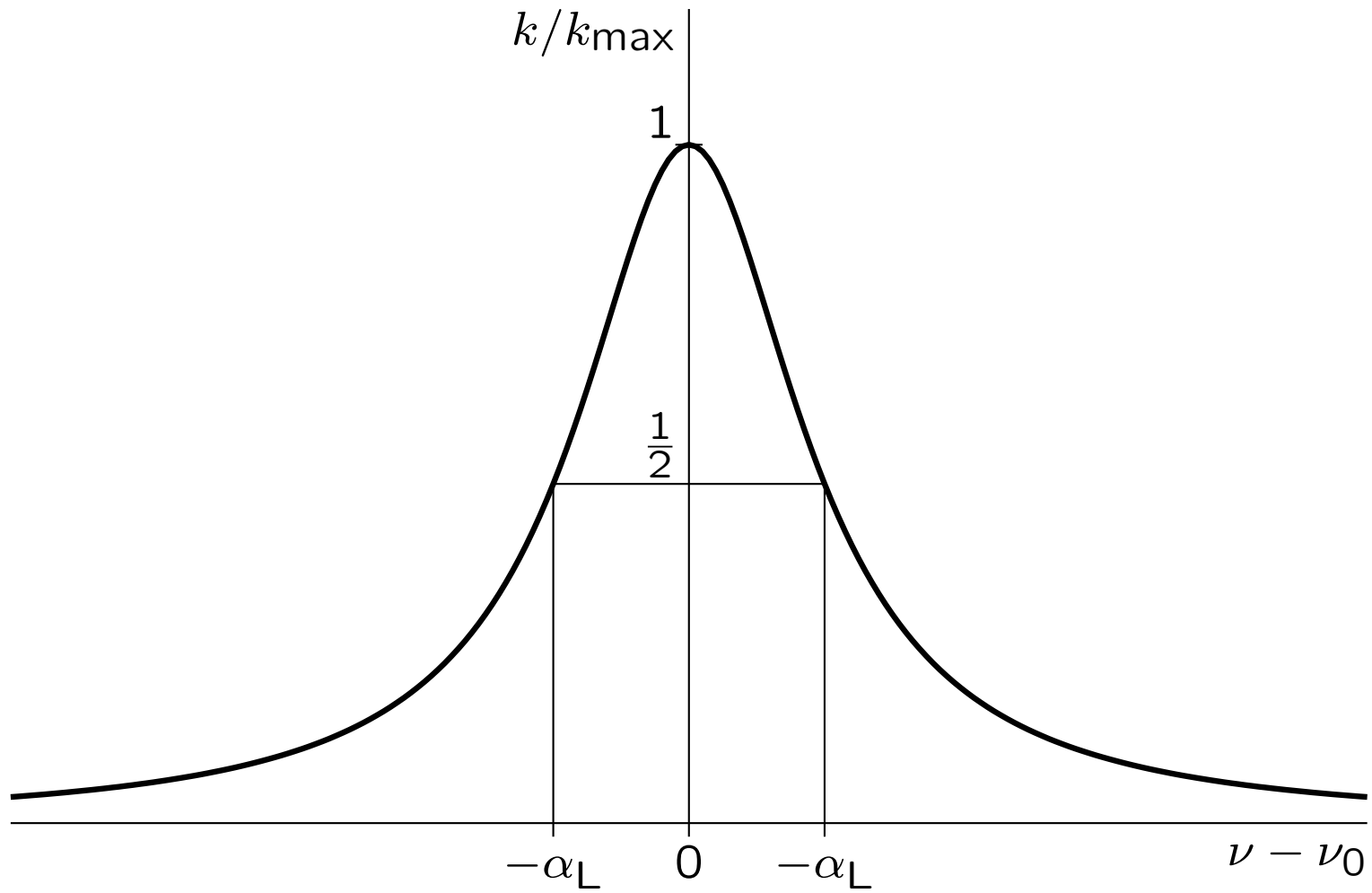
- Lorentz line shape is given by simple function:

$$k(\nu) = \frac{S}{\pi} \cdot \frac{\alpha_L}{(\nu - \nu_0)^2 + \alpha_L^2} \quad \int_{-\infty}^{+\infty} k(\nu) d\nu = S$$

k – absorption coefficient, S – line strength, α_L – line half width, ν – wavenumber, ν_0 – position of line center

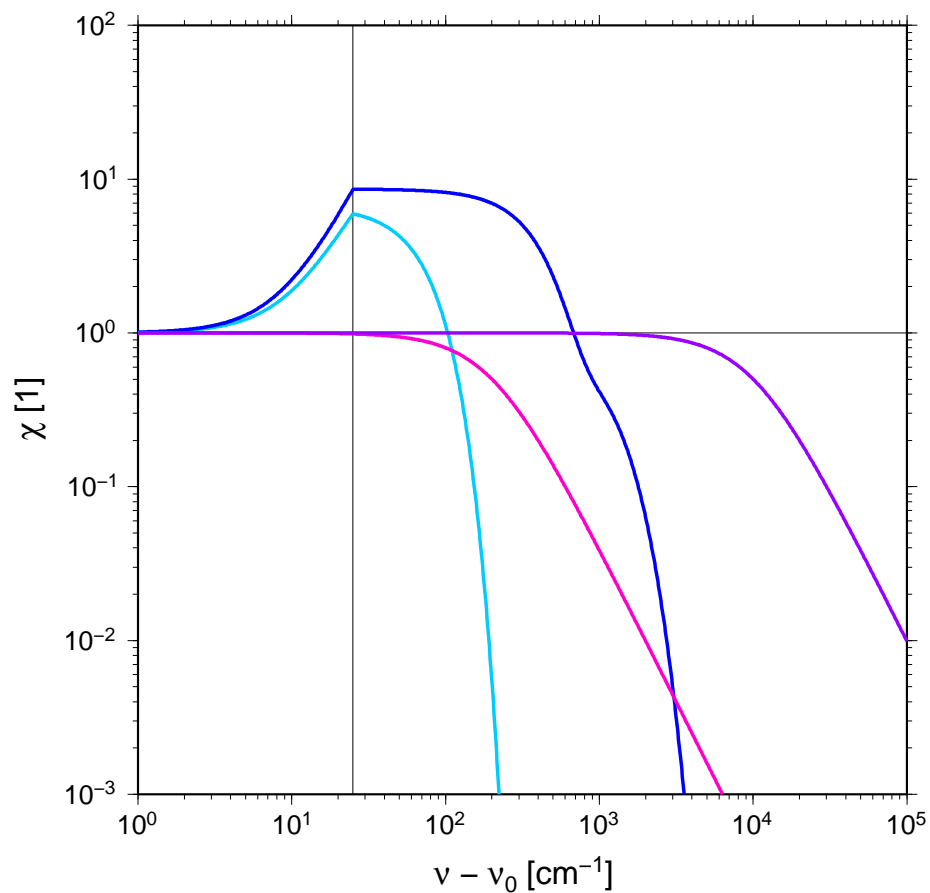
- it is known that collisions of finite duration create line shape with faster than Lorentzian decay of line wings
- this must be taken into account in line by line models in order to get correct continuum absorption

Shape of Lorentz line

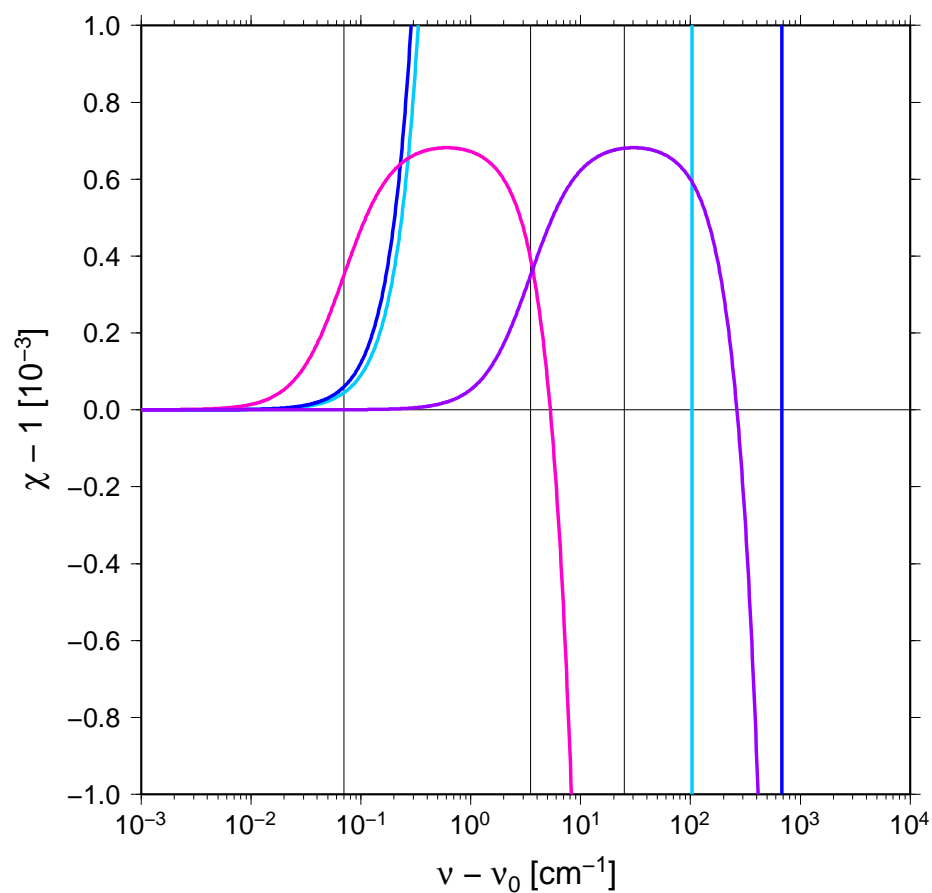


(α_L is typically $0.01 - 0.1 \text{ cm}^{-1}$)

χ -factor modifying Lorentz line shape for H₂O



- CKD1989, H₂O foreign broadening at 296K
- CKD1989, H₂O self broadening at 296K
- RG1992, $b = 200\text{cm}^{-1}$, $\alpha_m = 0.07\text{cm}^{-1}$, $\alpha = 0.07\text{cm}^{-1}$
- RG1992, $b = 200\text{cm}^{-1}$, $\alpha_m = 0.07\text{cm}^{-1}$, $\alpha = 3.5\text{cm}^{-1}$



- CKD1989, H₂O foreign broadening at 296K
- CKD1989, H₂O self broadening at 296K
- RG1992, $b = 200\text{cm}^{-1}$, $\alpha_m = 0.07\text{cm}^{-1}$, $\alpha = 0.07\text{cm}^{-1}$
- RG1992, $b = 200\text{cm}^{-1}$, $\alpha_m = 0.07\text{cm}^{-1}$, $\alpha = 3.5\text{cm}^{-1}$

Pressure and temperature dependency

- line positions ν_0 are pressure and temperature independent
- line strengths S are influenced by population of molecular energetic states, which is temperature dependent $\Rightarrow S = S(T)$
- Lorentzian line half widths α_L should be proportional to collision frequency and thus $\rho_{\text{air}}v \propto \frac{p}{T}\sqrt{T} = \frac{p}{\sqrt{T}}$
- experiments however show that $\alpha_L(p, T) = (\alpha_L)_0 \frac{p}{p_0} \left(\frac{T_0}{T}\right)^n$, where n ranges between $\frac{1}{2}$ (classical value) and 1

Monochromatic versus band absorption

- monochromatic absorption obeys Lambert-Beer law:

$$I_\nu = I_{0\nu} \exp[-k(\nu)u] \equiv I_{0\nu} \exp[-\delta_\nu(u)] \quad u = \rho_{\text{abs}}\Delta l$$

I_ν – intensity (radiance) of transmitted radiation,

$I_{0\nu}$ – intensity of incident radiation, u – absorber amount,

δ_ν – optical depth, ρ_{abs} – absorber density, Δl – geometrical path

- band absorption in spectral interval $[\nu_1, \nu_2]$ is given by integral:

$$I = \frac{1}{\nu_2 - \nu_1} \int_{\nu_1}^{\nu_2} I_\nu d\nu = \frac{1}{\nu_2 - \nu_1} \int_{\nu_1}^{\nu_2} I_{0\nu} \exp[-k(\nu)u] d\nu$$

- it implies band transmission $\tau(u)$ to be:

$$\tau(u) \equiv \frac{I}{I_0} = \int_{\nu_1}^{\nu_2} w_\nu \exp[-k(\nu)u] d\nu \quad \int_{\nu_1}^{\nu_2} w_\nu d\nu = 1$$

- spectral weights w_ν are proportional to intensity of incident radiation $I_{0\nu}$

Optical saturation

- defining band optical depth $\delta(u)$ by relation $\tau(u) = \exp[-\delta(u)]$ implies:

$$\delta(u) = -\ln \left[\int_{\nu_1}^{\nu_2} w_\nu \exp[-k(\nu)u] d\nu \right]$$

- only in linear region (i.e. for $k(\nu)u \ll 1$) it follows that:

$$\delta(u) \approx \left[\int_{\nu_1}^{\nu_2} w_\nu k(\nu) d\nu \right] u \equiv \bar{k}u$$

- for bigger optical depths there is significant departure from above relation, since $\overline{\exp[-k(\nu)u]} \neq \exp(-\bar{k}u)$
- in regions of big $k(\nu)$ almost all radiation becomes absorbed for certain value of u ; any further increase of u results in $\delta(u)$ growth slower than $\bar{k}u$ since only regions with small $k(\nu)$ are contributing
 \Rightarrow **saturation effect**

Saturation for single Lorentz line (1)

- in this case band absorption can be computed analytically, assuming infinite spectral interval and constant intensity of incident radiation
- equivalent line width $W(u)$ is then given by:

$$W(u) \equiv \int_{-\infty}^{+\infty} \left(1 - \exp \left[-\frac{S\alpha_L u}{\pi(\alpha_L^2 + \nu^2)} \right] \right) d\nu = 2\pi\alpha_L L \left(\frac{Su}{2\pi\alpha_L} \right)$$

- L in above expression is Ladenburg-Reiche function, it can be expressed via modified Bessel functions and approximated as:

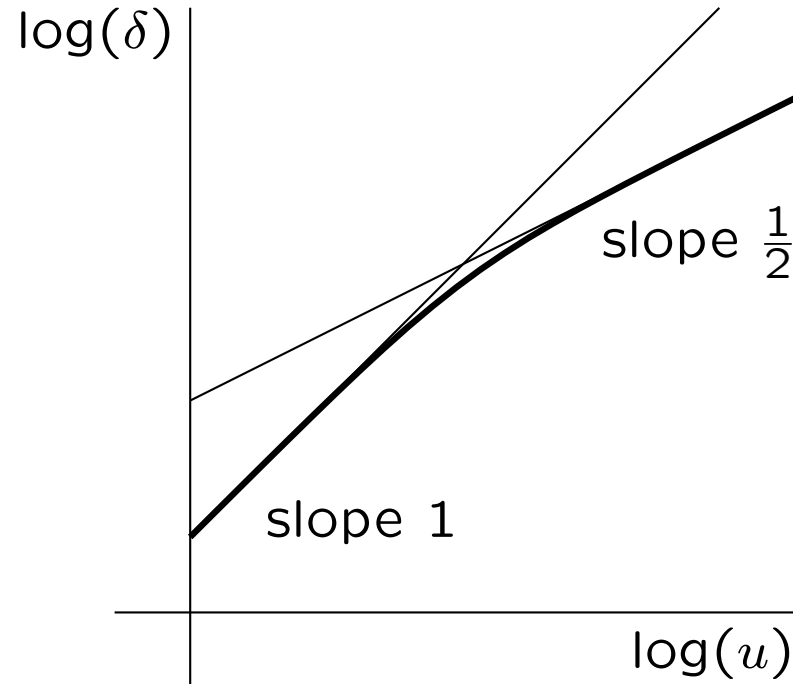
$$L(x) \approx x \left[1 + (\pi x/2)^{\frac{5}{4}} \right]^{-\frac{2}{5}}$$

- expression for $W(u)$ is valid also for interval of finite width $\Delta\nu$ provided $\Delta\nu \gg W(u)$, in such case there is:

$$\delta(u) \equiv -\ln \left[1 - \frac{W(u)}{\Delta\nu} \right] \approx \frac{W(u)}{\Delta\nu}$$

Saturation for single Lorentz line (2)

- for $x \ll 1$ there is $L(x) \approx x$ and thus $W(u) \approx Su$
 \Rightarrow **weak line limit**, independent on line shape, $\delta \propto u$
- for $x \gg 1$ there is $L(x) \approx \sqrt{2x/\pi}$ and thus $W(u) \approx 2\sqrt{\alpha_L Su}$
 \Rightarrow **strong line limit**, saturation depends on line shape, $\delta \propto u^{\frac{1}{2}}$



Band models

- when many spectral lines are present and their separation is not much bigger than line half width, band absorption beyond weak line limit is influenced by their overlaps $\Rightarrow \delta(u) \neq \sum_{i \in \text{lines}} \delta_i(u)$
- one solution is to compute transmission by numerical integration over wavenumbers, choosing such fine spectral division that individual lines are resolved \Rightarrow **line by line computation**, beyond scope of NWP
- another possibility is to suppose certain distribution of line strengths and positions and to develop corresponding **band model**, such as:

name	line strengths	line positions
Elsasser	constant	regular
Goody	$p(S) \propto \exp(-S/S_0)$	random
Malkmus	$p(S) \propto (1/S) \exp(-S/S_0)$	random

Malkmus band model

- Malkmus band model was derived assuming infinite spectral interval $\Delta\nu$ and constant intensity of incoming radiation
- together with assumption of random line positions and exponentially tailed S^{-1} distribution of line strengths it gives simple formula:

$$\delta(u) = \frac{\pi\bar{\alpha}_L}{2d} \left(\sqrt{1 + \frac{4\bar{S}u}{\pi\bar{\alpha}_L}} - 1 \right) = \frac{a}{2b} \left(\sqrt{1 + 4bu} - 1 \right)$$

\bar{S} - mean line strength, $\bar{\alpha}_L$ - mean line half width,

d - mean line spacing, $a(T) \equiv \frac{\bar{S}(T)}{d}$, $b(p, T) \equiv \frac{\bar{S}(T)}{\pi\bar{\alpha}_L(p, T)}$

- in practice its applicability is restricted to bands narrow enough so that random line positioning holds approximately and variation of Planck function can be neglected
- when used in narrow band, adjustment is needed to account for finite bounds in spectral integral

Use of Malkmus model in narrow band (1)

- SPLIDACO utility uses 840 spectral intervals (408 solar and 432 thermal), thermal intervals have widths $0.7\text{--}16\text{ cm}^{-1}$
- in each spectral interval it employs Malkmus band model extended by linear correction term cu related to continuum:

$$\delta(u) = \frac{a}{2b} \left(\sqrt{1 + 4bu} - 1 \right) + cu$$

- in each spectral interval coefficient $c = c(p, T)$ is computed as contribution of lines centered outside (due to part of their wings falling inside) **minus** absorption of line wings escaping outside (for lines centered inside)
- it can thus have both positive and negative sign and is valid only in linear (unsaturated) region

Use of Malkmus model in narrow band (2)

- for $c < 0$ further modification of Malkmus formula is needed in order to prevent unphysical negative absorption when u is big:

$$\frac{a}{2b} \left(\sqrt{1 + 4bu} - 1 \right) + cu \quad \mapsto \quad \frac{a}{2b} \left(\sqrt{1 + \frac{4bu}{1 - c/a}} - 1 \right)$$

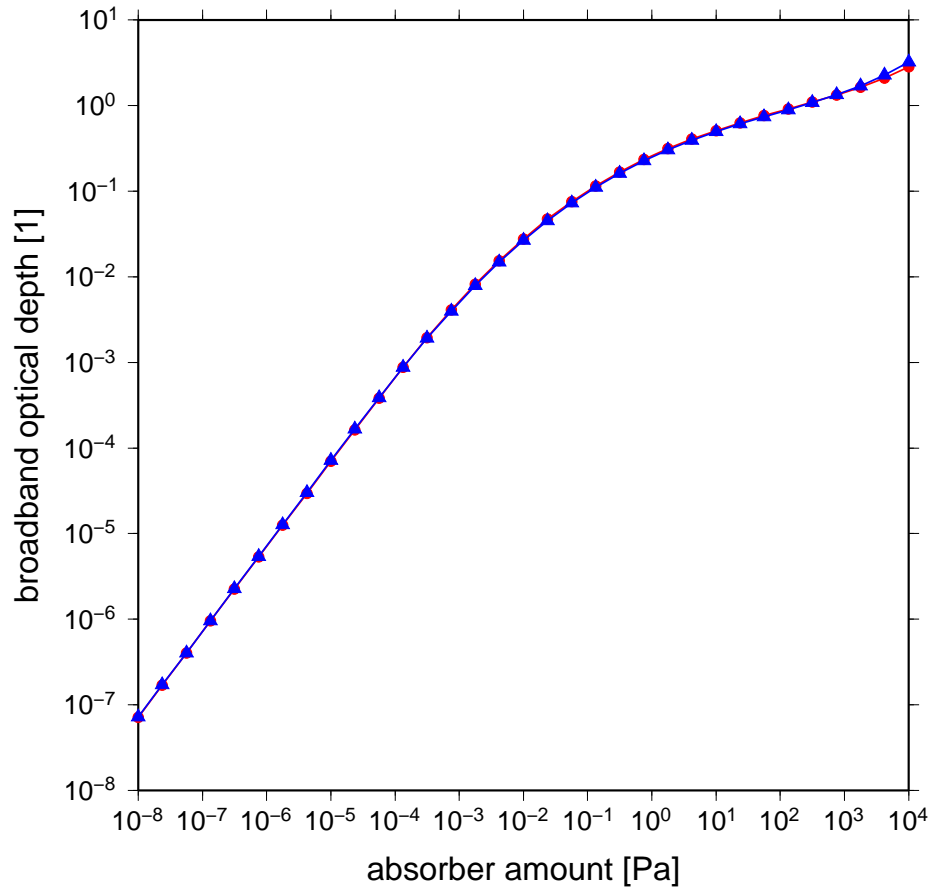
- both formulas have the same weak line limit $(a+c)u$, provided $|c| \ll a$ (this excludes use of too narrow spectral intervals)
- coefficient $c(p, T)$ is proportional to $\bar{S}(T)\bar{\alpha}_L(p, T) \propto p$, temperature dependence is more complicated
- inclusion of cu term in Malkmus formula makes broadband results independent on underlying narrowband spectral division (in the range $\bar{\alpha}_L \ll \Delta\nu \ll$ interval of significant w_ν variation)

SPLIDACO reference

- SPLIDACO utility computes narrowband transmissions based on extended Malkmus formula and averages them to get broadband transmissions (currently 1 solar and 1 thermal, but it was adapted to arbitrary spectral division)
- each computation is done for 3(4) gases (H_2O , CO_2 , O_3 and possibly H_4O_2), 15 pressures, 5 temperatures and 33 absorber amounts
- weights w_ν used in spectral averaging are proportional to Planck function $B_\nu(T)$ (respectively dB_ν/dT) in thermal band and to incoming solar radiation at top of atmosphere in solar band
- results are used as reference for fitting broadband gaseous optical depths $\delta(u, p, T)$

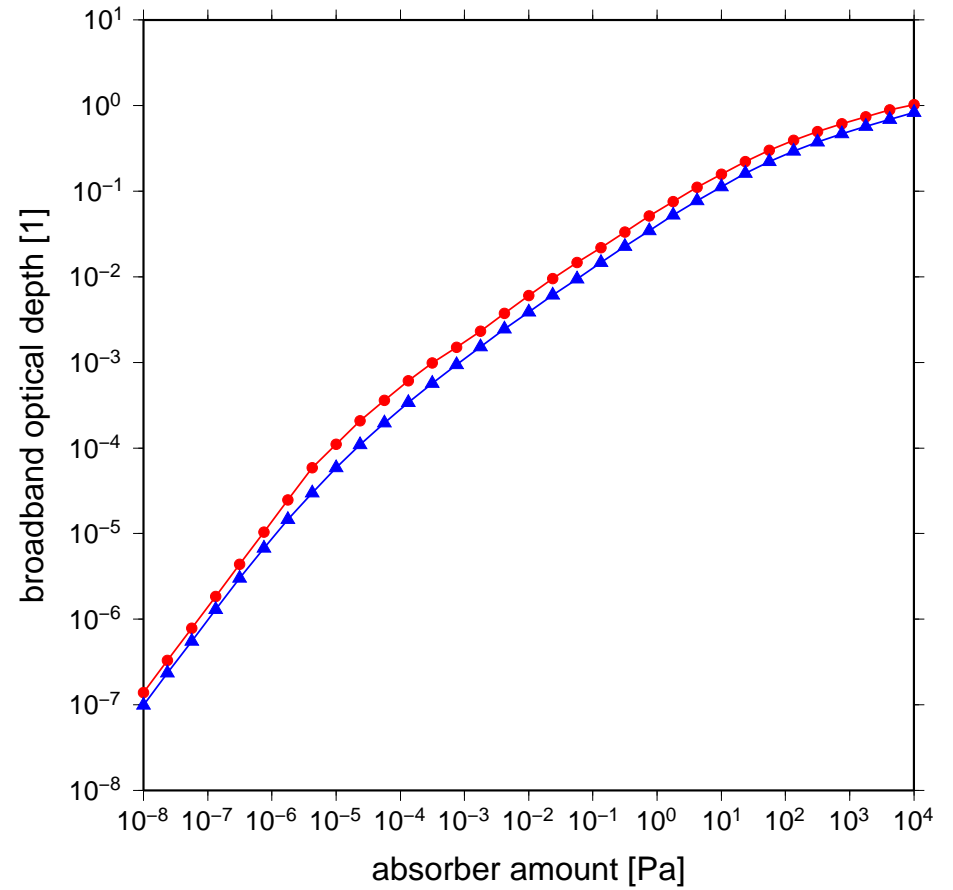
SPLIDACO versus RRTM H₂O optical depths, thermal band

$p = 1000 \text{ hPa}, T = 307.6 \text{ K}$



● RRTM
▲ SPLIDACO

$p = 5 \text{ hPa}, T = 204.0 \text{ K}$



● RRTM
▲ SPLIDACO

Secondary saturation

- narrowband Malkmus formula accounts for **primary saturation**
- spectral averaging of narrowband transmissions to get broadband value causes **secondary saturation**
- it results in smaller than $u^{\frac{1}{2}}$ growth of broadband $\delta(u)$ in strong line limit \Rightarrow Malkmus formula cannot be used in broadband case
- correct asymptotic behaviour can be restored by simple 2-parametric rescaling with tuning parameters α and δ_0 (instead of original 10-parametric Pade fit which was not able to modify strong line limit growth):

$$\delta(u) = \frac{\delta_0}{\alpha} \left[\left(1 + \frac{\delta_{\text{malkmus}}(u)}{\delta_0} \right)^\alpha - 1 \right]$$

- rescaling does not touch weak line limit and modifies strong line limit to $\delta(u) \propto u^{\frac{\alpha}{2}}$

Homogeneous fits (1)

- last missing element for broadband $\delta(u)$ fits is pressure and temperature dependency of Malkmus coefficients $a(T)$, $b(p, T)$ and $c(p, T)$ (parameters α and δ_0 can be kept pressure and temperature independent)
- there is theoretical argument for keeping broadband pressure dependency to be $b \propto 1/p$ and $c \propto p$
- temperature dependency is assumed to have power form, so that we have:

$$a = a_0 \left(\frac{T}{T_0} \right)^{\alpha_a} \quad b = b_0 \frac{p_0}{p} \left(\frac{T}{T_0} \right)^{\alpha_b} \quad c = c_0 \frac{p}{p_0} \left(\frac{T}{T_0} \right)^{\alpha_c}$$

- it means that for each gas, spectral band and weight function we have 8 fitting parameters a_0 , b_0 , c_0 , α_a , α_b , α_c , α and δ_0

Homogeneous fits (2)

- fitting parameters can be computed in one go, using least square method based on error function:

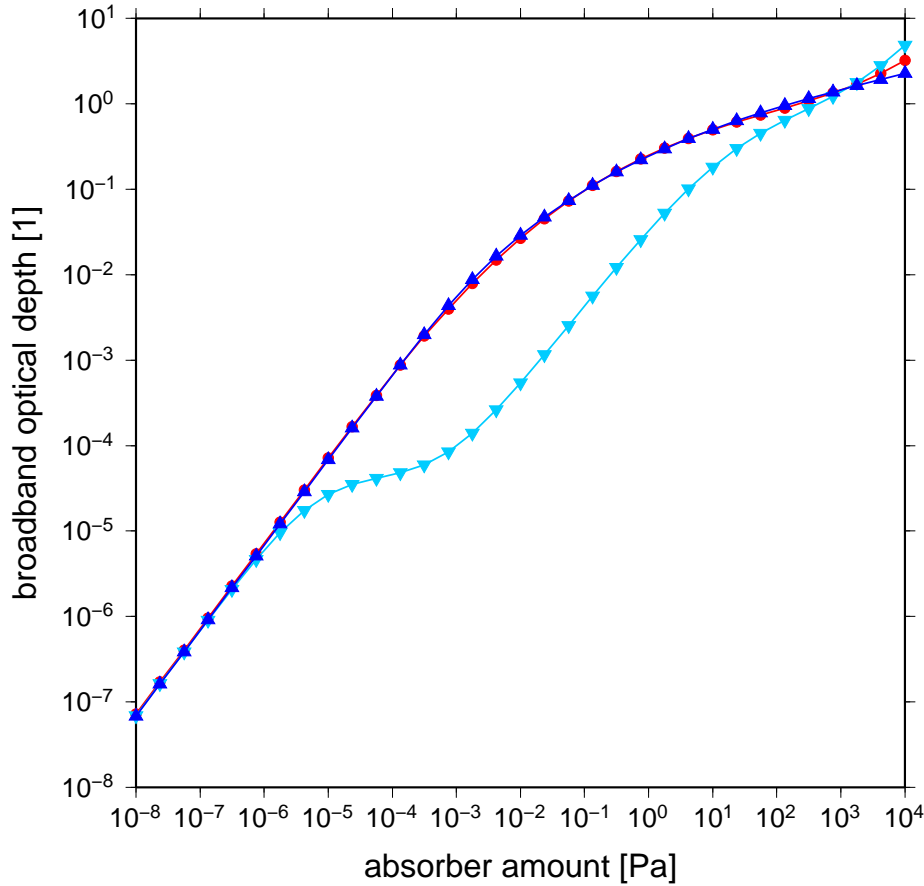
$$\varepsilon^2 = \frac{1}{N} \sum_{i=1}^N \log^2 \left[\frac{\delta_i}{(\delta_{\text{ref}})_i} \right]$$

(summation goes over pressures, temperatures and absorber amounts)

- error function is minimized numerically, using incremental approach
- global minimization removes the risk of unstable fits, encountered when splitted procedure was used

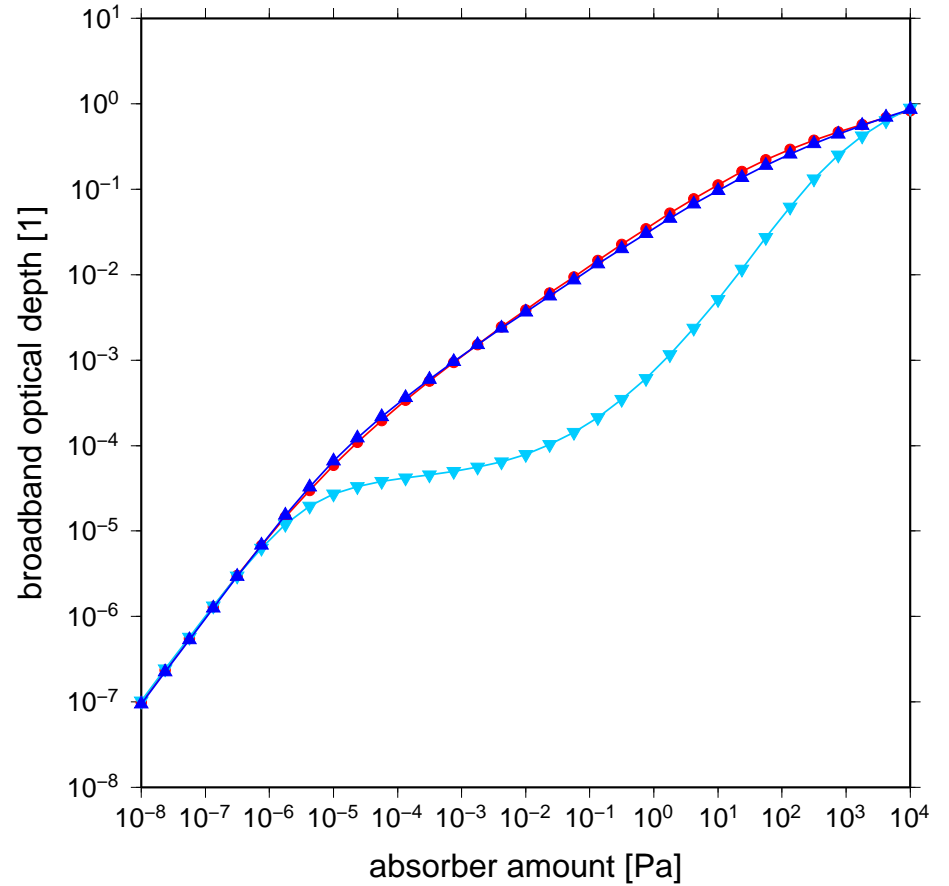
Fitted versus reference H₂O optical depths, thermal band

$p = 1000 \text{ hPa}, T = 307.6 \text{ K}$



- SPLIDACO reference
- ▼ Malkmus + Pade fit of SPLIDACO (current ACRANEB)
- ▲ rescaled Malkmus fit of SPLIDACO (new ACRANEB)

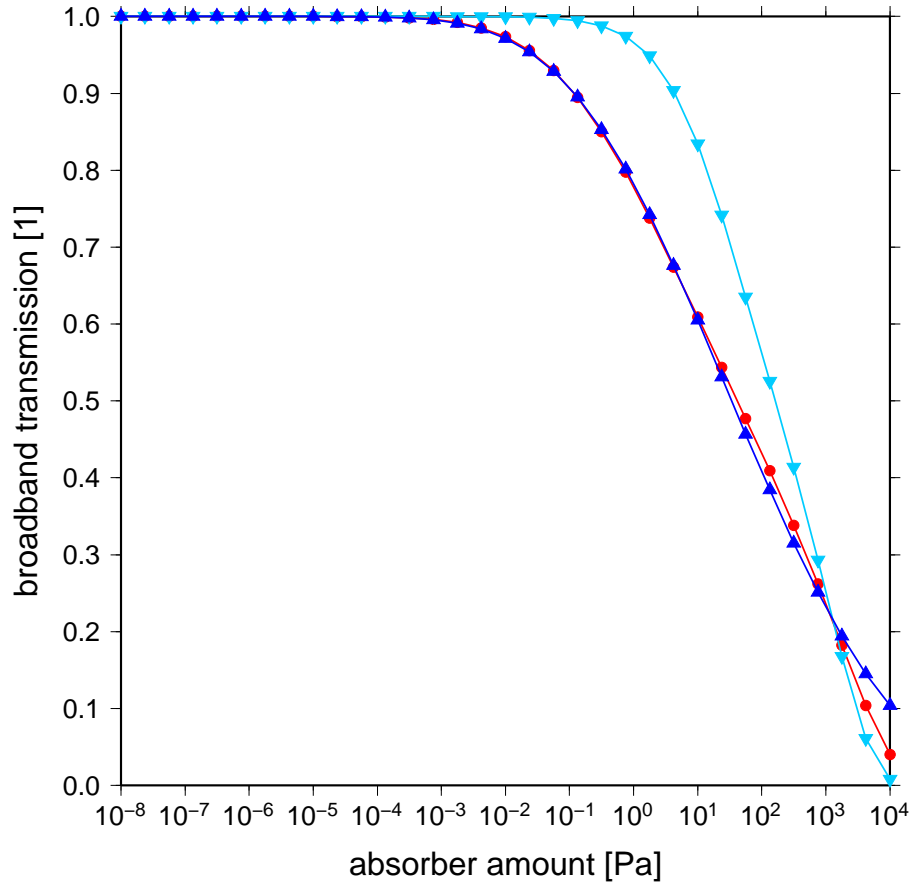
$p = 5 \text{ hPa}, T = 204.0 \text{ K}$



- SPLIDACO reference
- ▼ Malkmus + Pade fit of SPLIDACO (current ACRANEB)
- ▲ rescaled Malkmus fit of SPLIDACO (new ACRANEB)

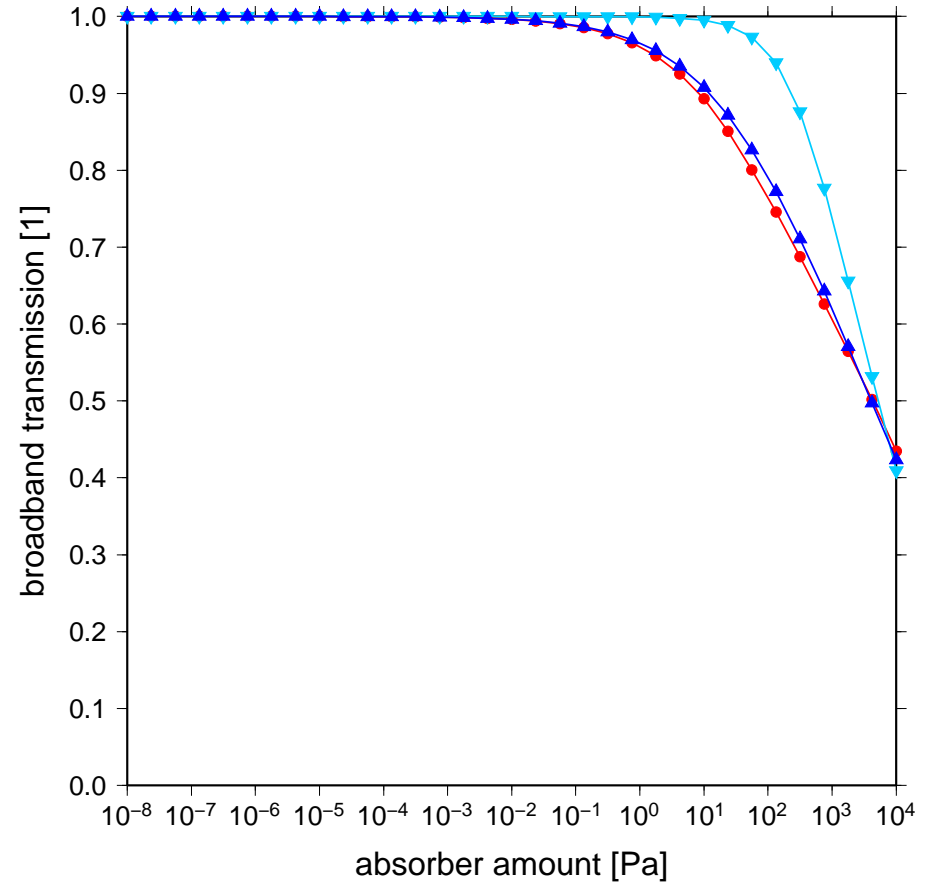
Fitted versus reference H₂O transmissions, thermal band

$p = 1000 \text{ hPa}, T = 307.6 \text{ K}$



- SPLIDACO reference
- ▼▼▼ Malkmus + Pade fit of SPLIDACO (current ACRANEB)
- ▲▲▲ rescaled Malkmus fit of SPLIDACO (new ACRANEB)

$p = 5 \text{ hPa}, T = 204.0 \text{ K}$



- SPLIDACO reference
- ▼▼▼ Malkmus + Pade fit of SPLIDACO (current ACRANEB)
- ▲▲▲ rescaled Malkmus fit of SPLIDACO (new ACRANEB)

Problem with H₂O self continuum (1)

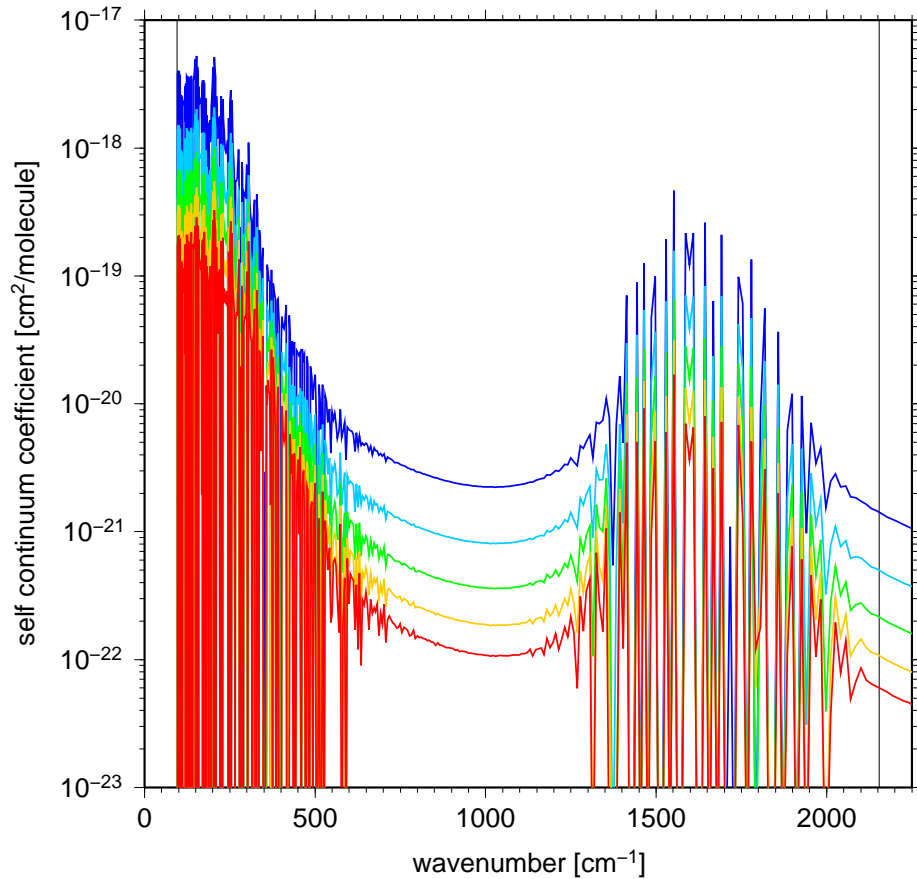
- water vapor absorption has one specificity - significant part of continuum absorption is not proportional to absorber amount $u = q_v \rho_{\text{air}} \Delta l$ (**classical** or **foreign continuum**), but rather to $q_{vu} = q_v^2 \rho_{\text{air}} \Delta l$ (**self** or **e-type continuum**)
- for several decades there is no consensus on origin of H₂O self continuum, two competing theories explain it either as a result of transitions induced by collisions between two H₂O molecules or as a consequence of H₂O-H₂O dimer formation (we will denote it H₄O₂)
- SPLIDACO reference uses empirical approach to H₂O self continuum, computing it analogically as narrowband correction term cu , but using 50 times broader line shape
- such approach gives both positive and negative values for self continuum, negative values have to be truncated

Problem with H₂O self continuum (2)

- extra factor 50 for line broadening was tuned against continuum measurements done at laboratory temperature
- 3D experiments indicated problem with H₂O self continuum, which was found to be due to its exaggerated temperature dependence
- solution was to import H₂O self continuum from MT_CKD model, the best validated reference available
- this can be done without risk since self continuum is defined uniquely thanks to its q_V^2 dependence (definition of foreign continuum depends on assumed line shape and line cut-off procedure)

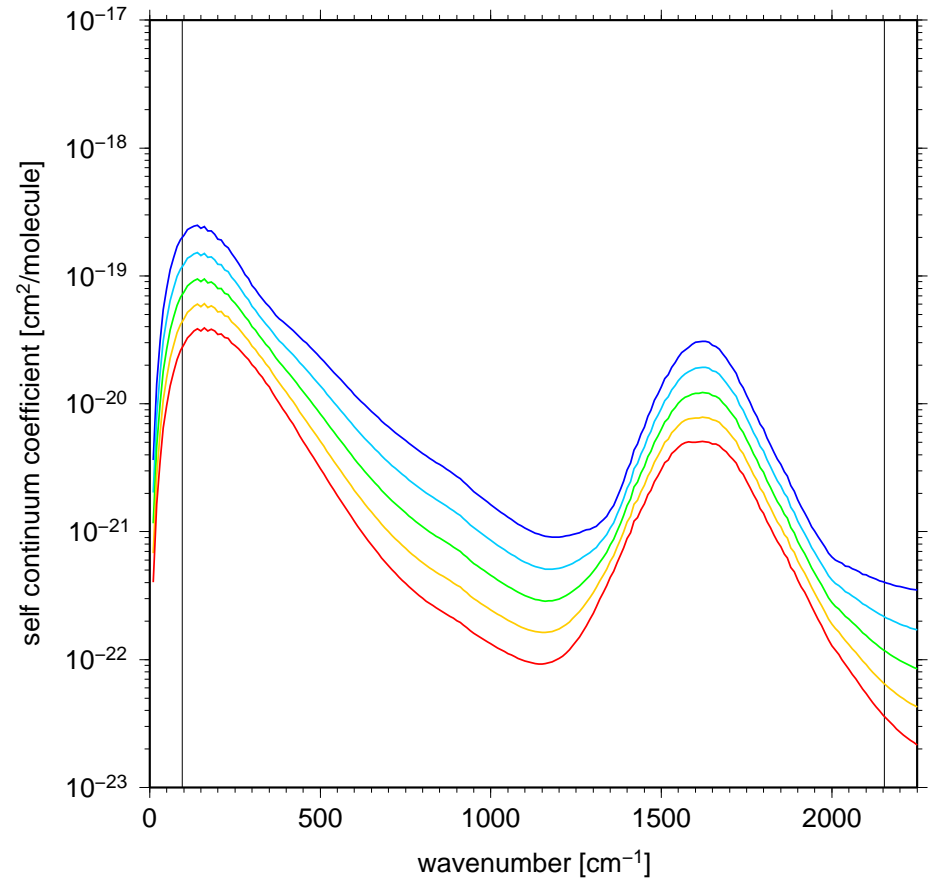
H₂O self continuum in thermal band

SPLIDACO (all values, unsmoothed)



- T = 204.00K
- T = 229.90K
- T = 255.80K
- T = 281.70K
- T = 307.60K

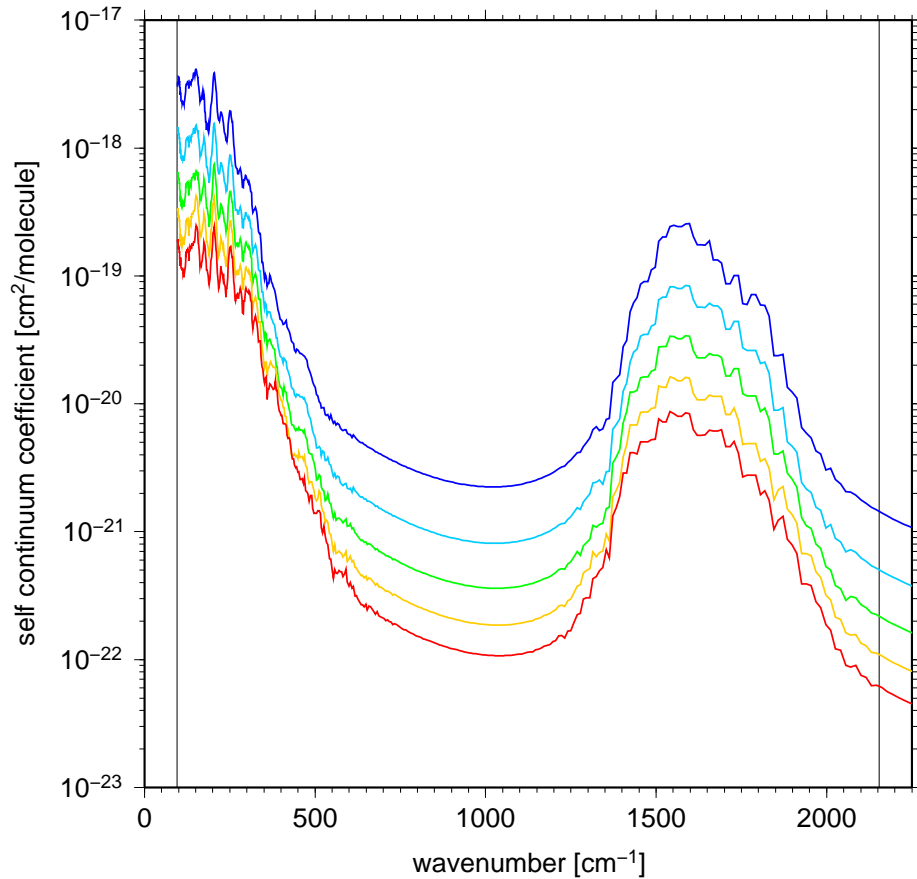
MT_CKD_2.5.2



- T = 204.0K
- T = 229.9K
- T = 255.8K
- T = 281.7K
- T = 307.6K

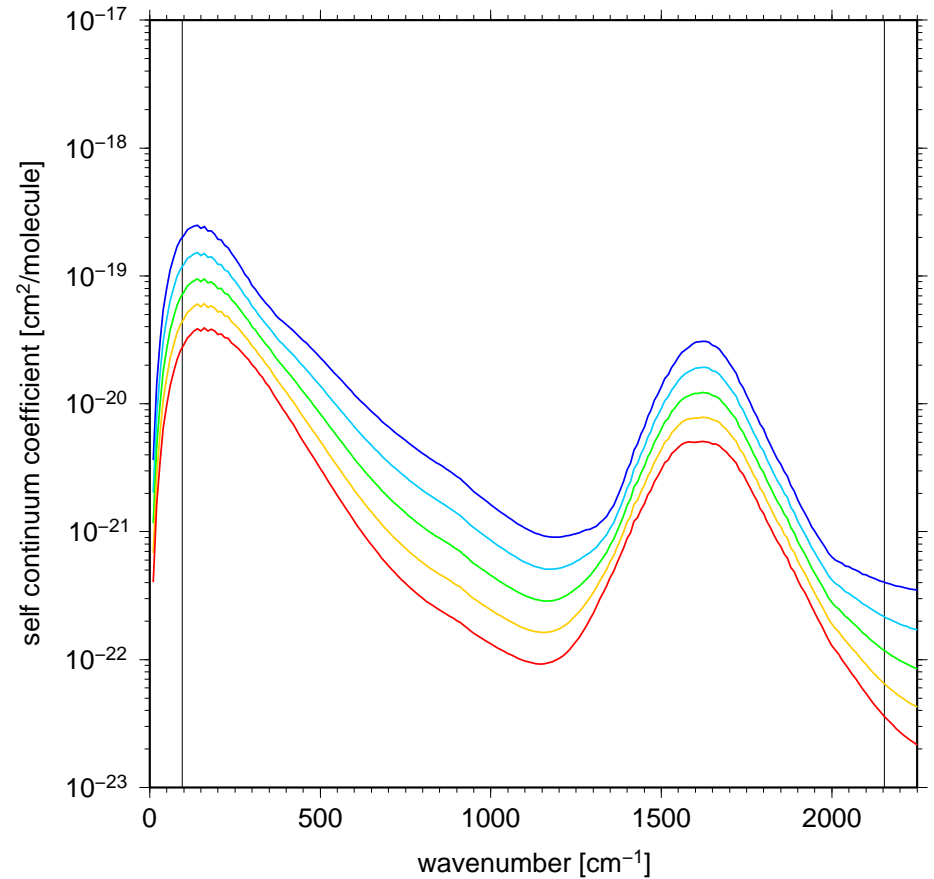
H₂O self continuum in thermal band

SPLIDACO (positive values, smoothed)



- T = 204.00K
- T = 229.90K
- T = 255.80K
- T = 281.70K
- T = 307.60K

MT_CKD_2.5.2



- T = 204.0K
- T = 229.9K
- T = 255.8K
- T = 281.7K
- T = 307.6K

New treatment of H₂O self continuum in ACRANEB

- in order to enable consistent treatment of nonhomogeneous optical paths, H₂O self continuum is introduced as separate pseudo-gas H₄O₂, postulating its absorber amount to be $u(\text{H}_4\text{O}_2) = q_v u(\text{H}_2\text{O})$
- having just linear narrowband part, H₄O₂ feels only secondary saturation when going to broadband:

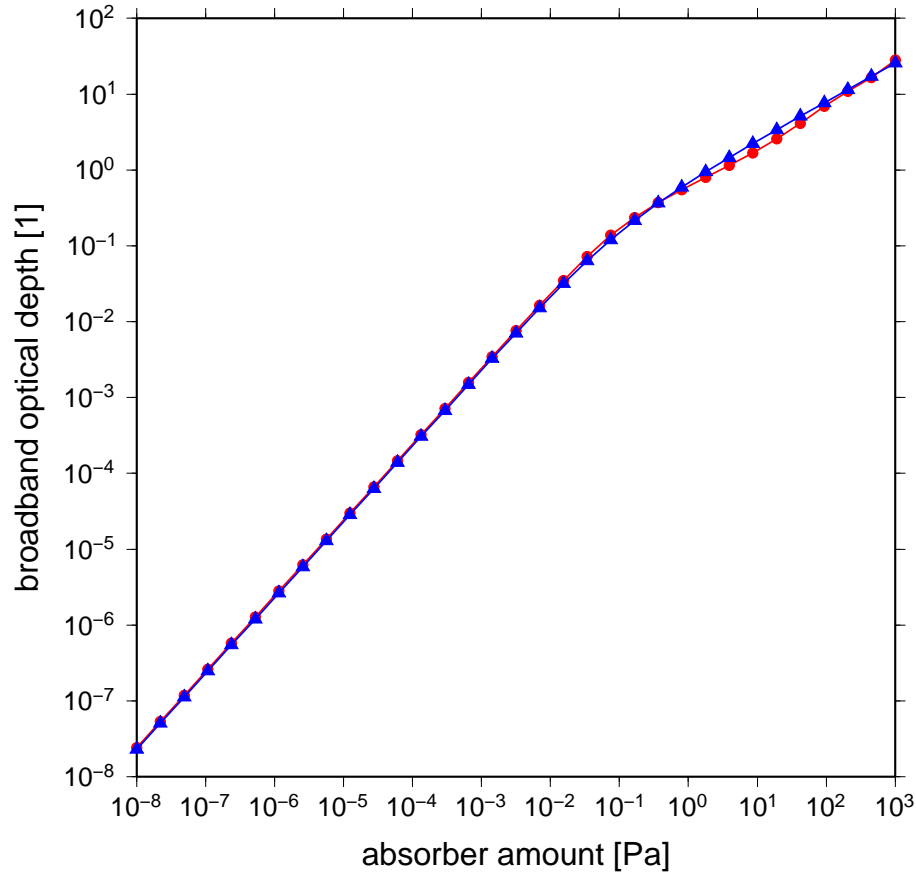
$$\delta(u) = \frac{\delta_0}{\alpha} \left[\left(1 + \frac{eq_v u}{\delta_0} \right)^\alpha - 1 \right]$$

$e = e(p, T)$ – self continuum coefficient, q_v – specific humidity,
 u – H₂O absorber amount

- such approach however requires treatment of (H₂O, H₄O₂) broadband overlaps, since their transmissions are strongly correlated and thus $\bar{\tau}(u_1, u_2) \neq \bar{\tau}_1(u_1)\bar{\tau}_2(u_2)$ alias $\delta(u_1, u_2) \neq \delta_1(u_1) + \delta_2(u_2)$

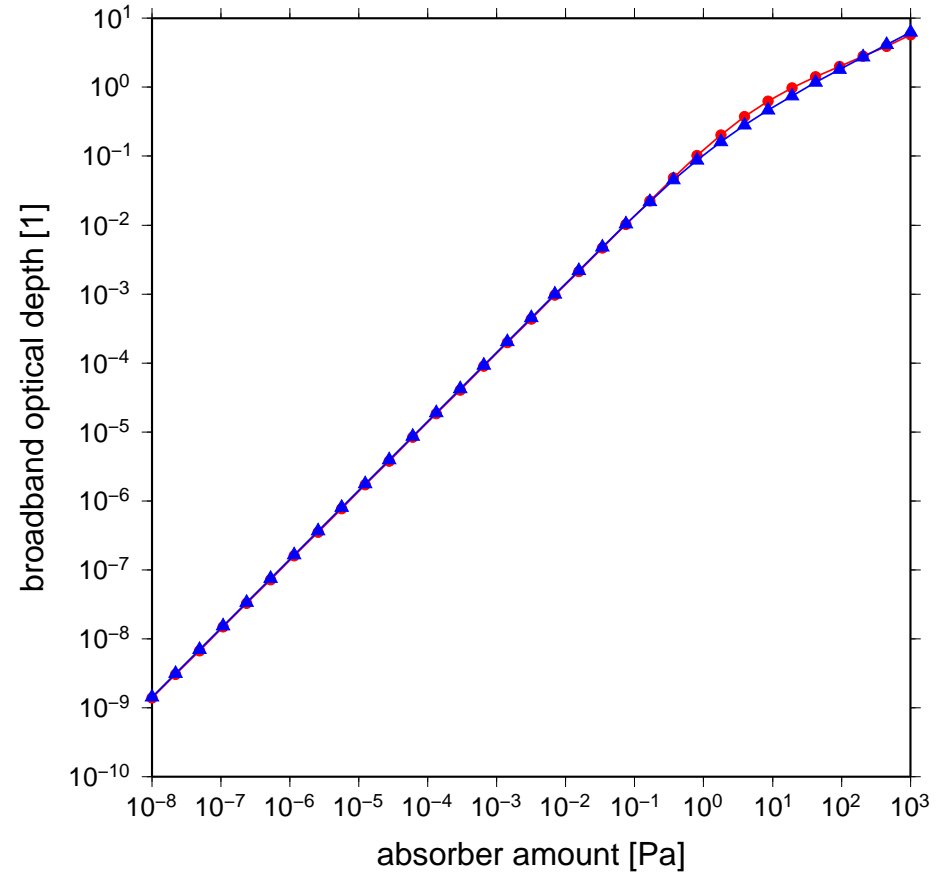
Fitted versus reference H₄O₂ optical depths, thermal band

$p = 1000 \text{ hPa}, T = 307.6 \text{ K}$



●●● SPLIDACO reference
▲▲▲ rescaled Malkmus + fitted (p, T) dependency

$p = 5 \text{ hPa}, T = 204.0 \text{ K}$



●●● SPLIDACO reference
▲▲▲ rescaled Malkmus + fitted (p, T) dependency

Gaseous overlaps (1)

- optical depths of different gases can be assumed roughly additive in narrow spectral bands, but not in broad ones (this is due to large scale spectral structure, i.e. existence of absorption bands and windows which may have other than random overlaps for various gases)
- assuming narrowband additivity, SPLIDACO can provide reference broadband optical depths for mixture of gases
- it was seen that dominant contribution to overlap effect comes from gaseous pairs, which makes its parameterization feasible
- sought dependency for pair overlaps $\Delta\delta_{12}(u_1, u_2, p, T)$ is still 4D, but explicit occurrence of pressure and temperature can be suppressed when it is reformulated as $\Delta\delta_{12}(\delta_1, \delta_2)$

Gaseous overlaps (2)

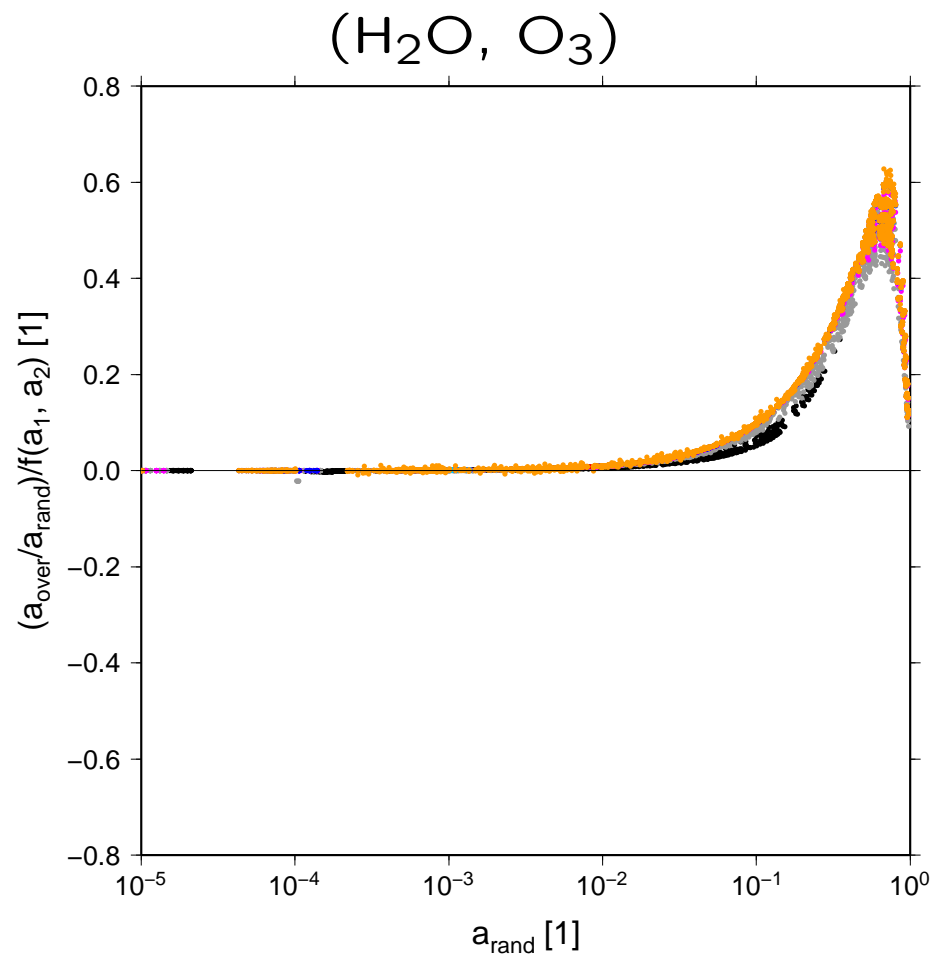
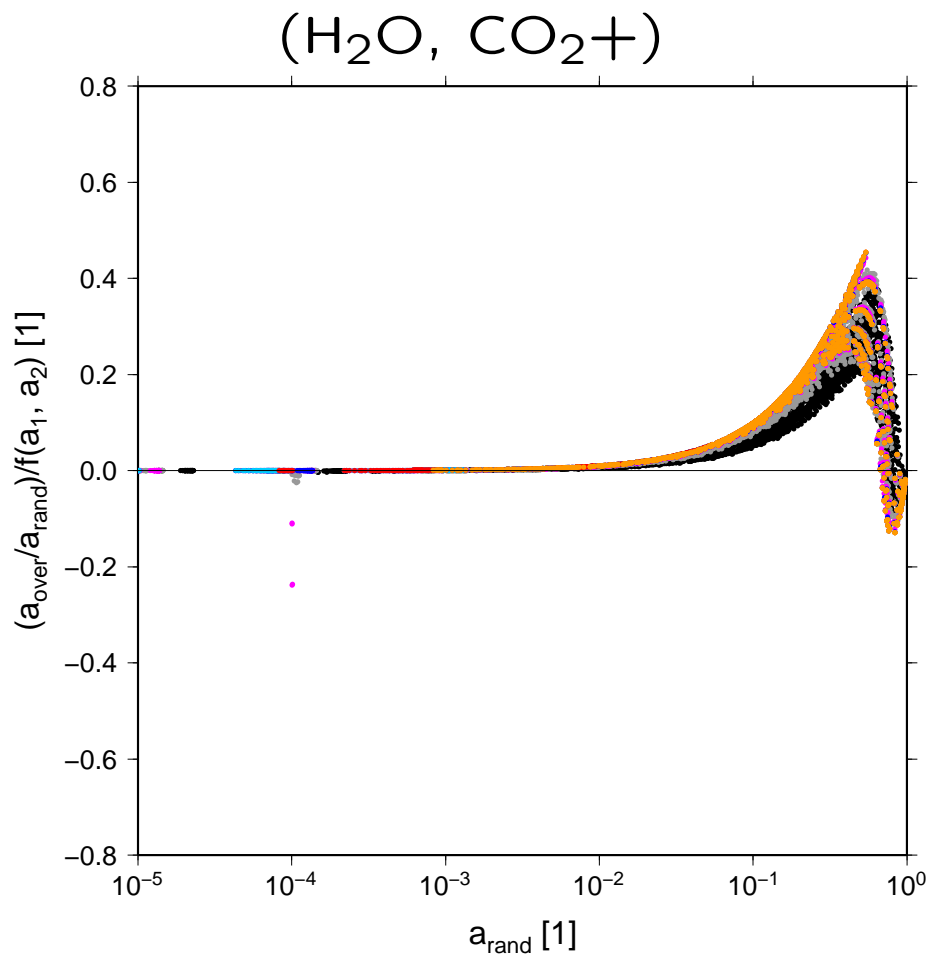
- still better approach is to express pair overlap contribution in space of absorptivities $a \equiv 1 - \tau = 1 - \exp(-\delta)$
- here it is possible to reduce 2D dependence to 1D by introducing variable $a_{\text{rand}} = a_1 + a_2 - a_1a_2$ and modulation factor $f(a_1, a_2) = 1/(a_1/a_2 + a_2/a_1)$ taking into account that overlap effect becomes negligible when absorptivities a_1 and a_2 are very different
- absorptivity of mixture of gases 1 and 2 is then given by:

$$a_{12} = a_{\text{rand}} + f(a_1, a_2) \cdot g(a_{\text{rand}})$$

- function g can be expressed by 3-parametric fit:

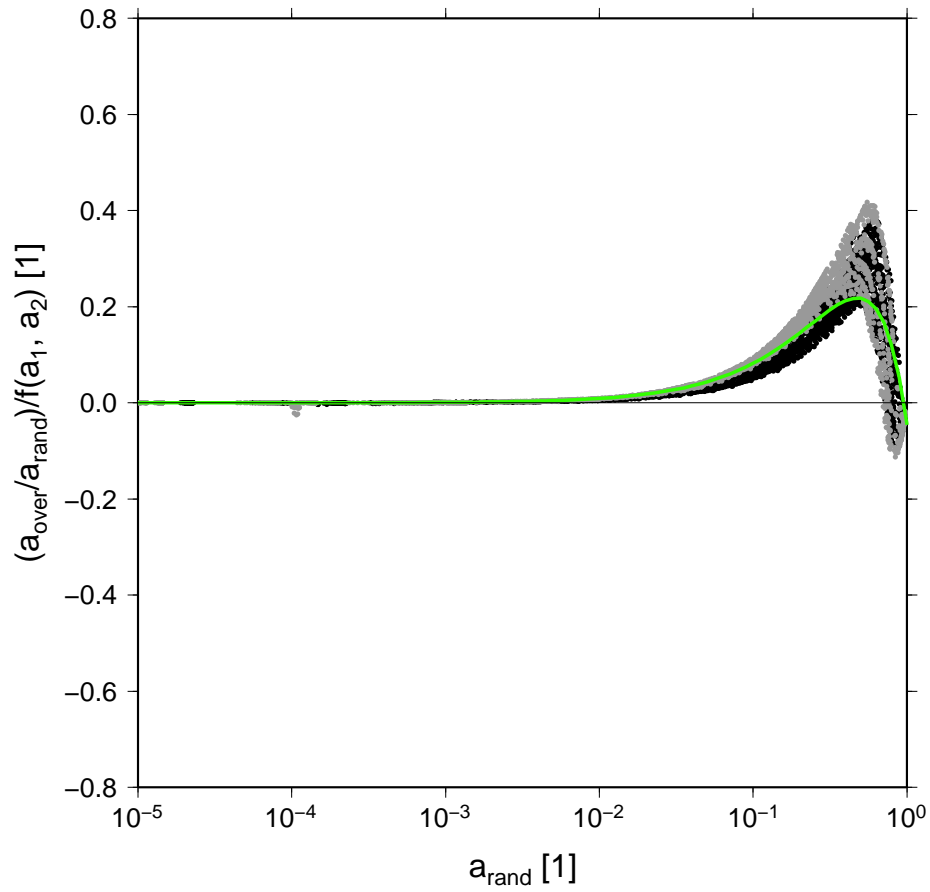
$$g(x) = \begin{cases} Ax^{C+1}/(1 + Bx^{2C}); & \text{solar band} \\ Ax^C(1 - Bx) & ; \text{thermal band} \end{cases}$$

Pair gaseous overlaps, thermal band (all p , T , u_1 and u_2 shown)

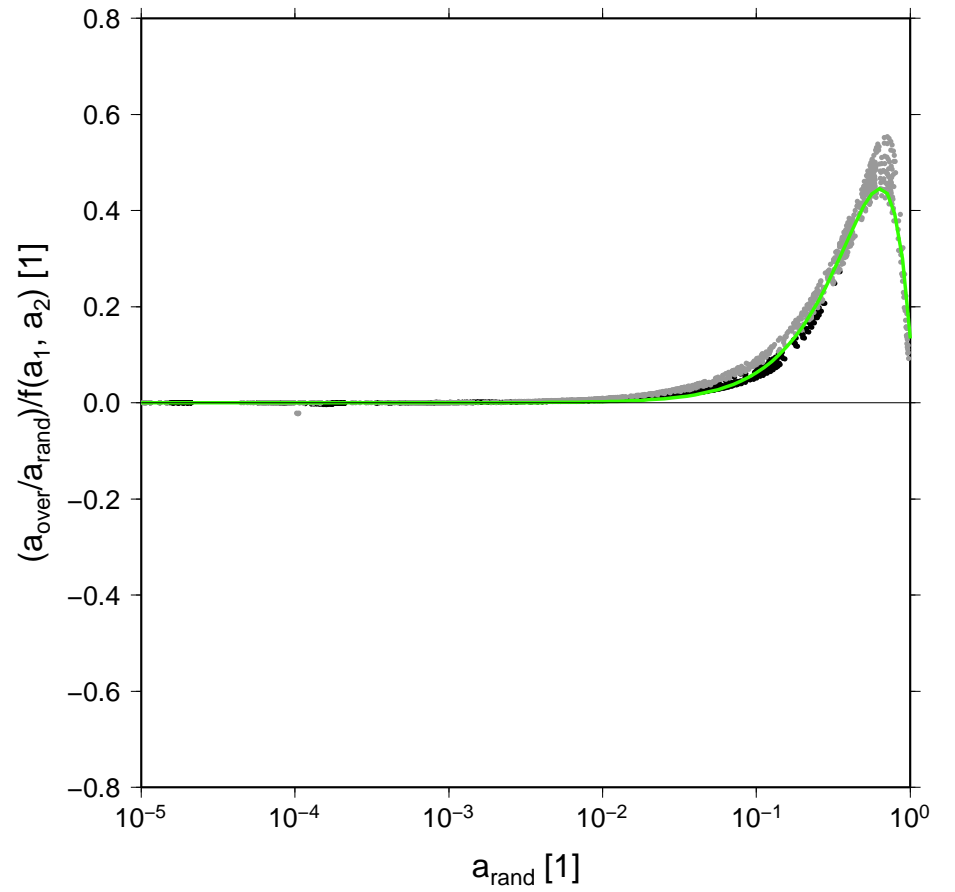


Fits of pair gaseous overlaps, thermal band

(H₂O, CO₂†)

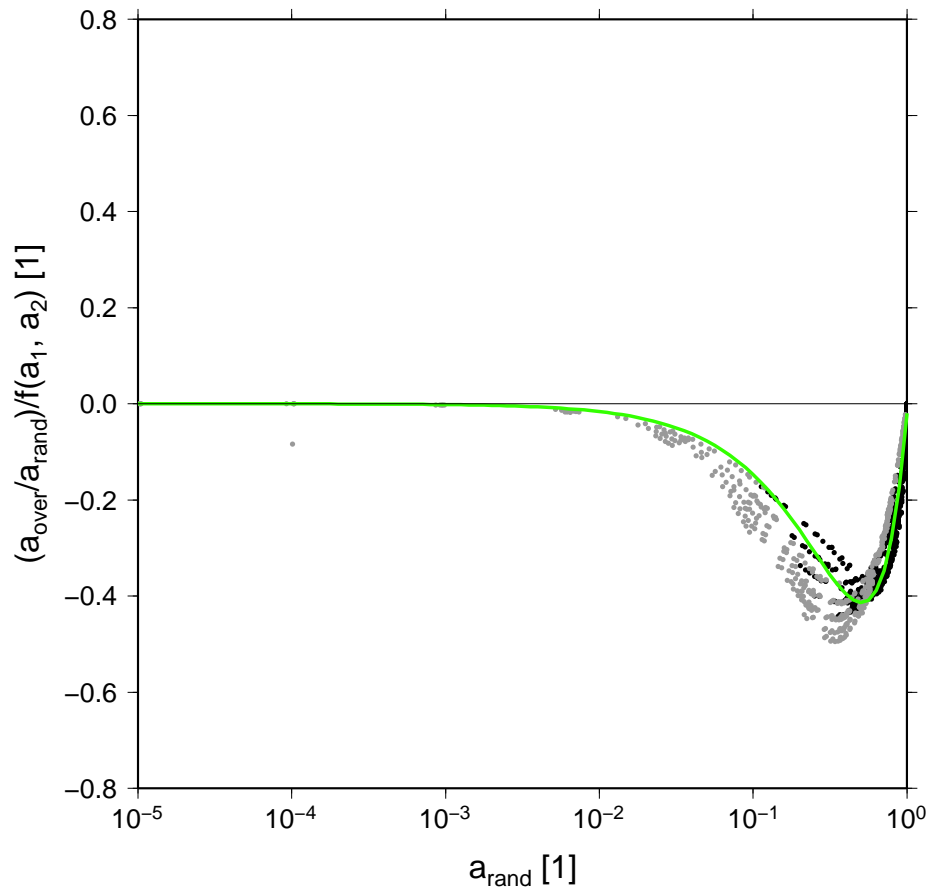


(H₂O, O₃)

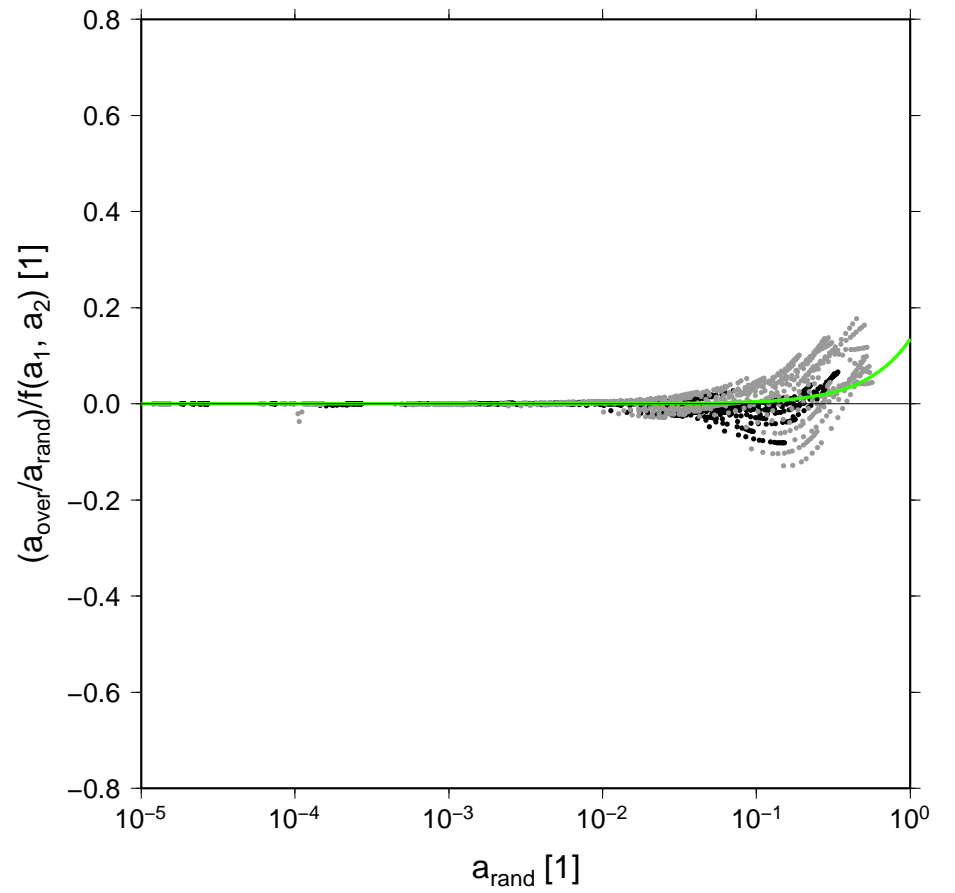


Fits of pair gaseous overlaps, thermal band

(H₂O, H₄O₂)

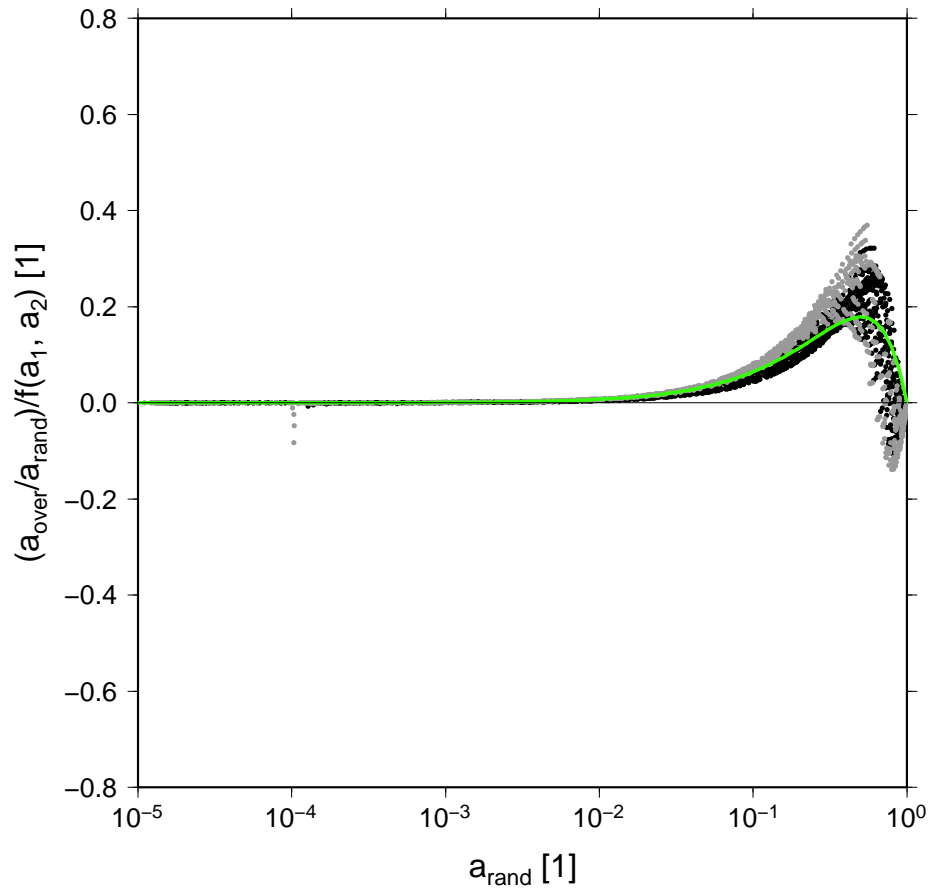


(CO₂+, O₃)

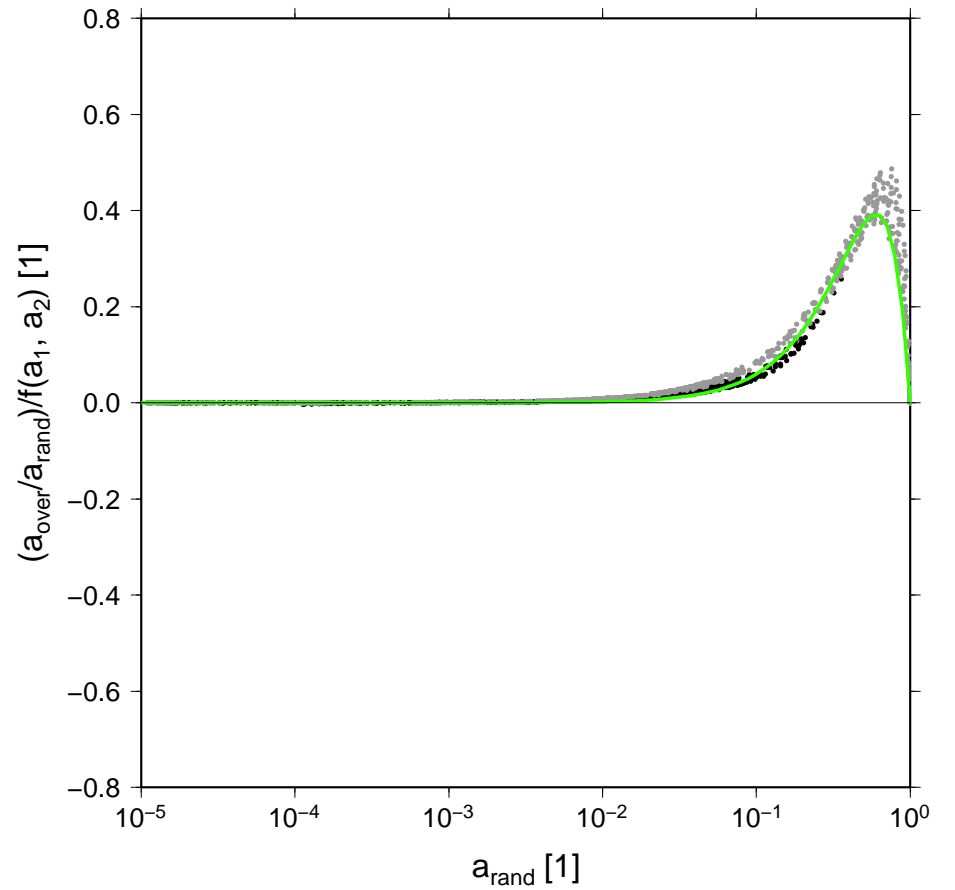


Fits of pair gaseous overlaps, thermal band

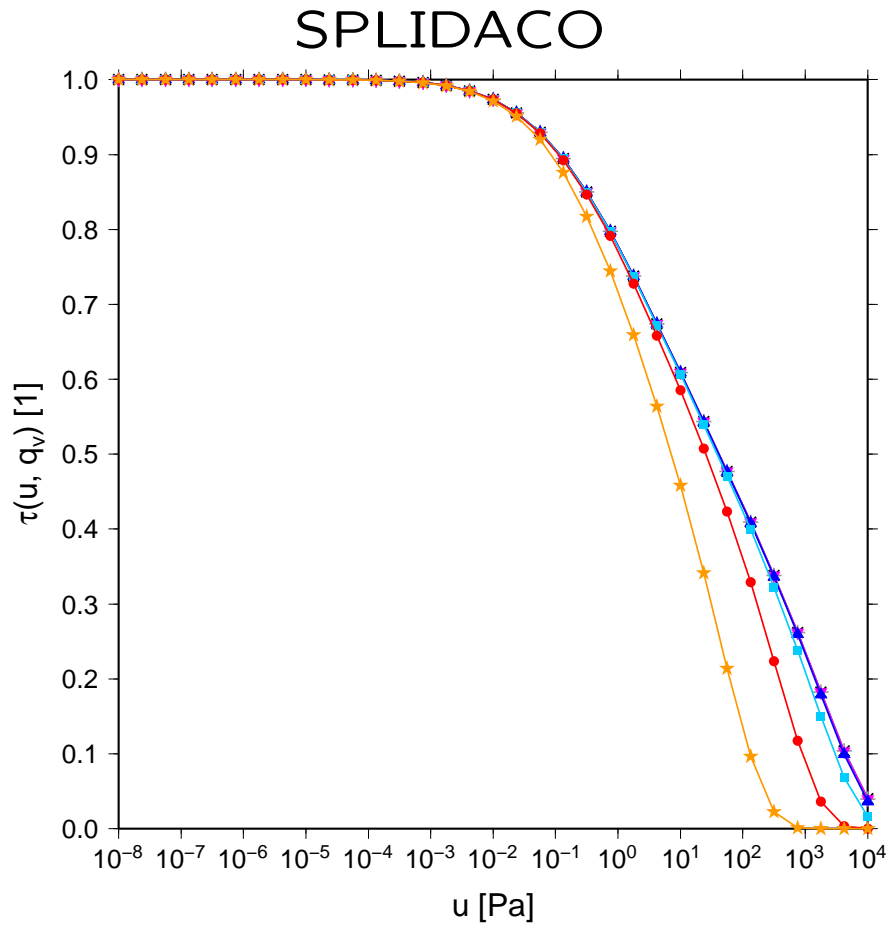
(CO₂+, H₄O₂)



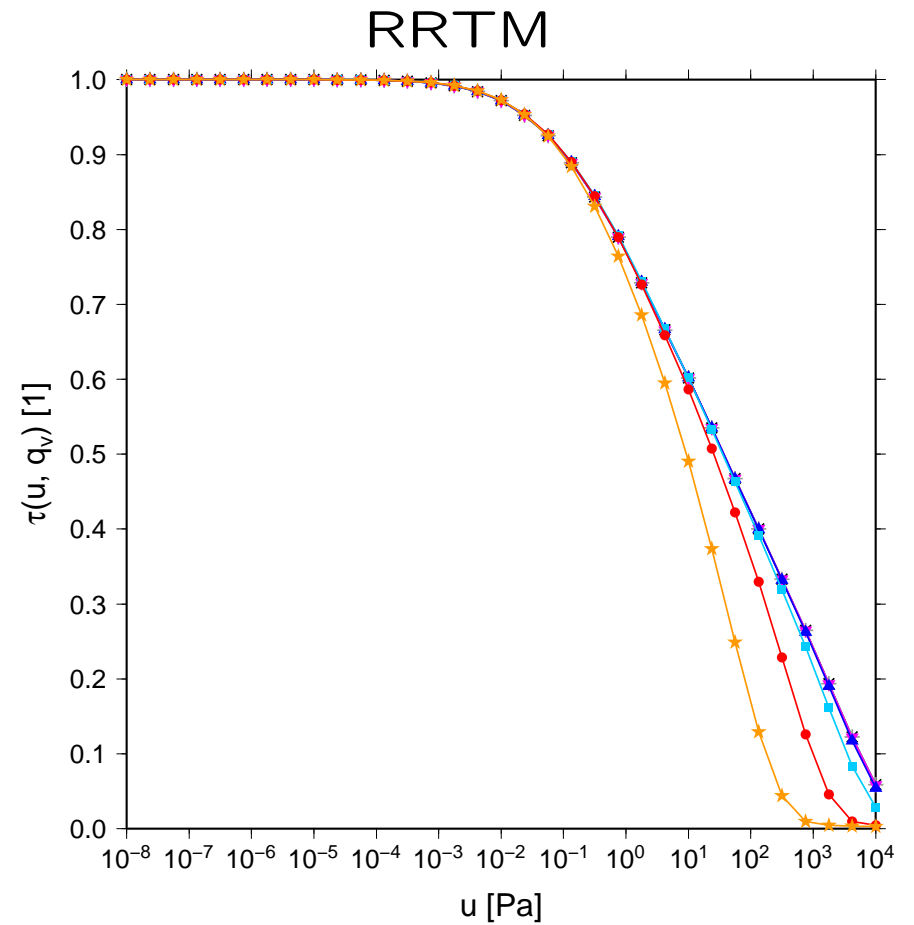
(O₃, H₄O₂)



H₂O transmissions including self continuum (thermal band, $p = 1000$ hPa, $T = 307.6$ K)

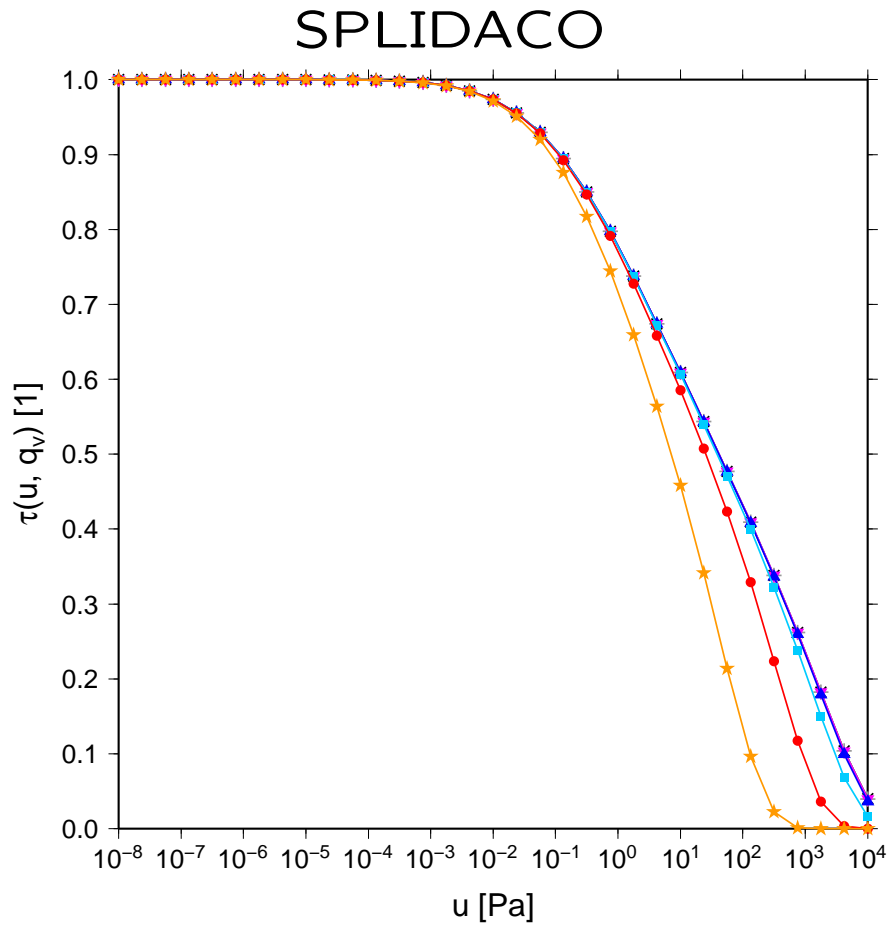


- ×—×—× $q_v = 1.0e-07$
- +—+—+ $q_v = 1.0e-06$
- ▼—▼—▼ $q_v = 1.0e-05$
- ▲—▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★—★ $q_v = 1.0e-01$

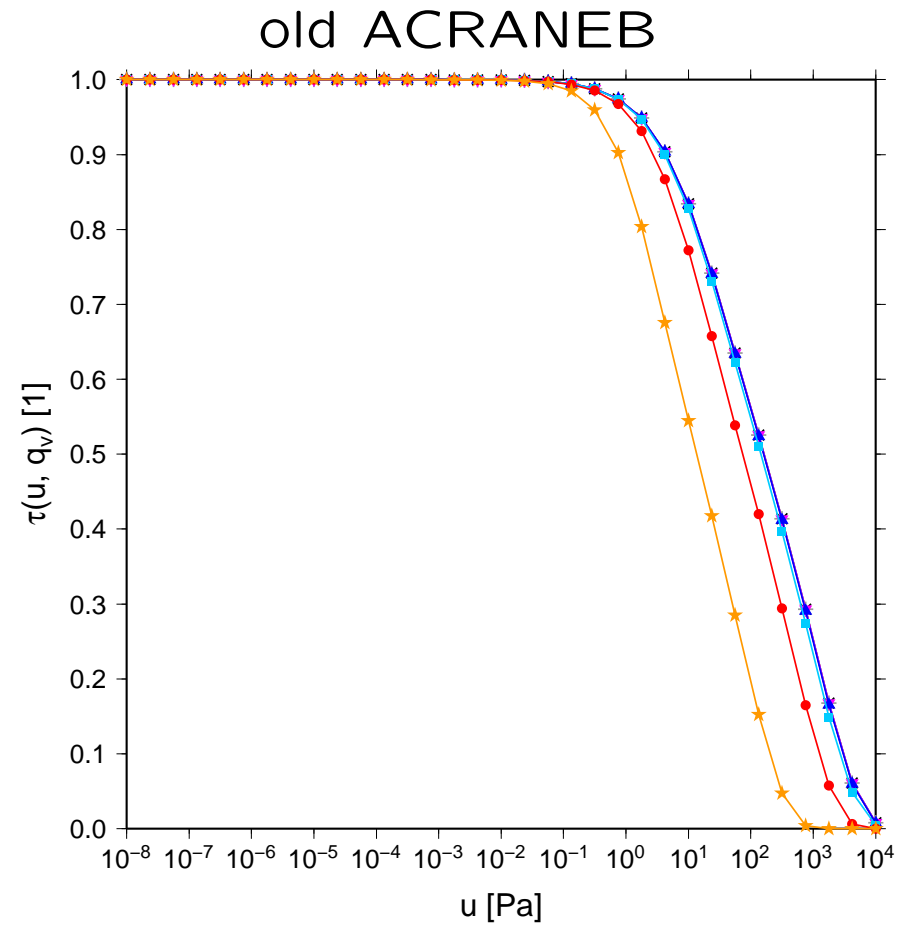


- ×—×—× $q_v = 1.0e-07$
- +—+—+ $q_v = 1.0e-06$
- ▼—▼—▼ $q_v = 1.0e-05$
- ▲—▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★—★ $q_v = 1.0e-01$

H₂O transmissions including self continuum (thermal band, $p = 1000$ hPa, $T = 307.6$ K)



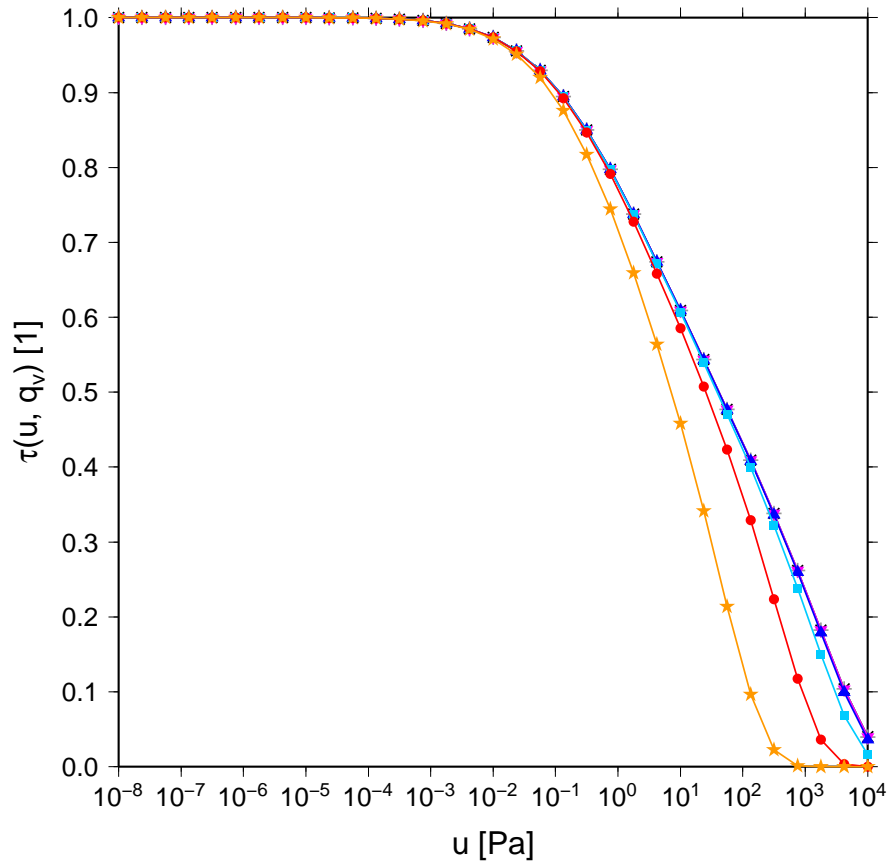
- ×—×—× $q_v = 1.0e-07$
- +—+—+ $q_v = 1.0e-06$
- ▼—▼—▼ $q_v = 1.0e-05$
- ▲—▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★—★ $q_v = 1.0e-01$



- ×—×—× $q_v = 1.0e-07$
- +—+—+ $q_v = 1.0e-06$
- ▼—▼—▼ $q_v = 1.0e-05$
- ▲—▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★—★ $q_v = 1.0e-01$

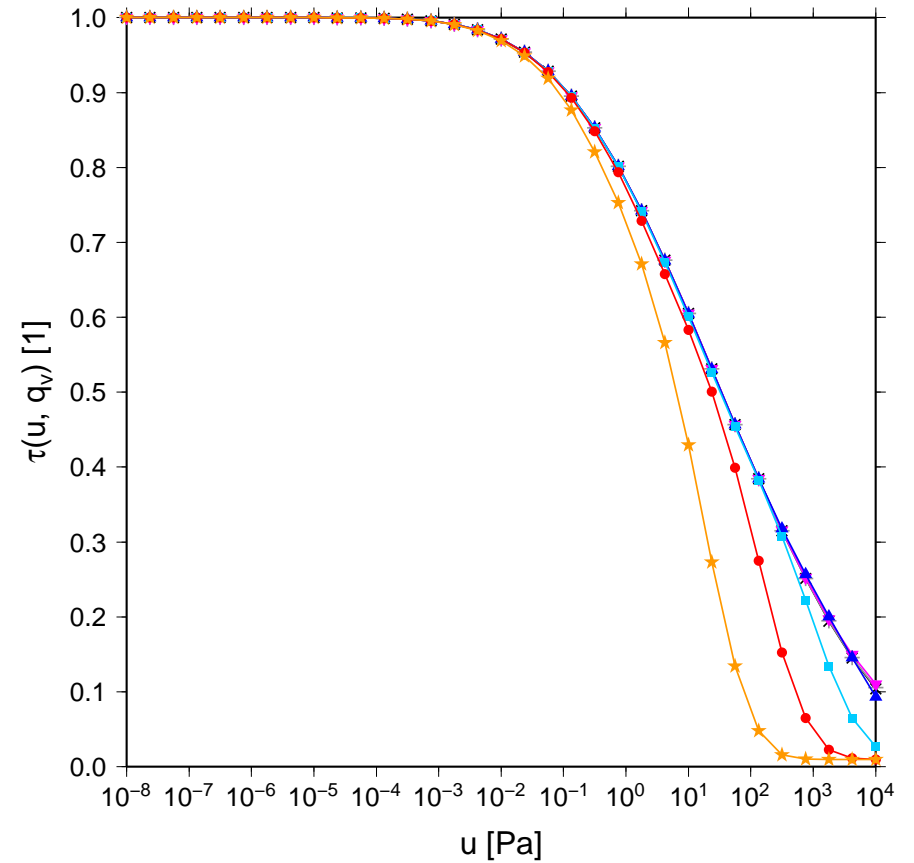
H₂O transmissions including self continuum (thermal band, $p = 1000$ hPa, $T = 307.6$ K)

SPLIDACO



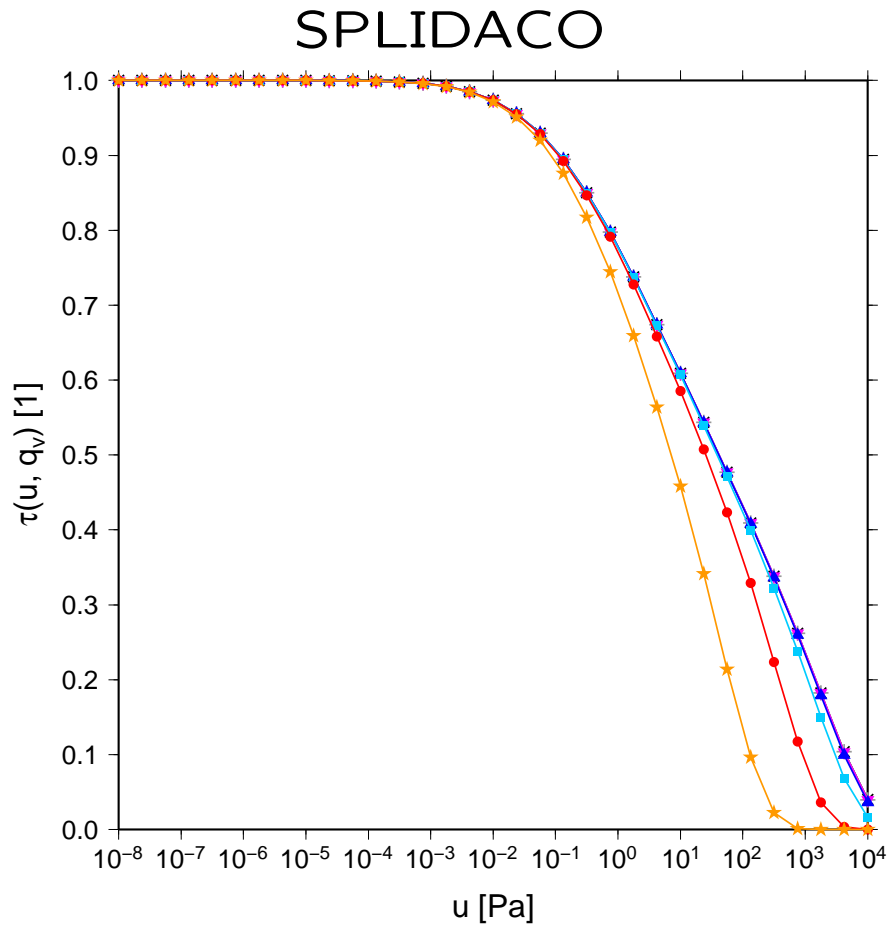
- ×—× $q_v = 1.0e-07$
- +—+ $q_v = 1.0e-06$
- ▼—▼ $q_v = 1.0e-05$
- ▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★ $q_v = 1.0e-01$

new ACRANEB

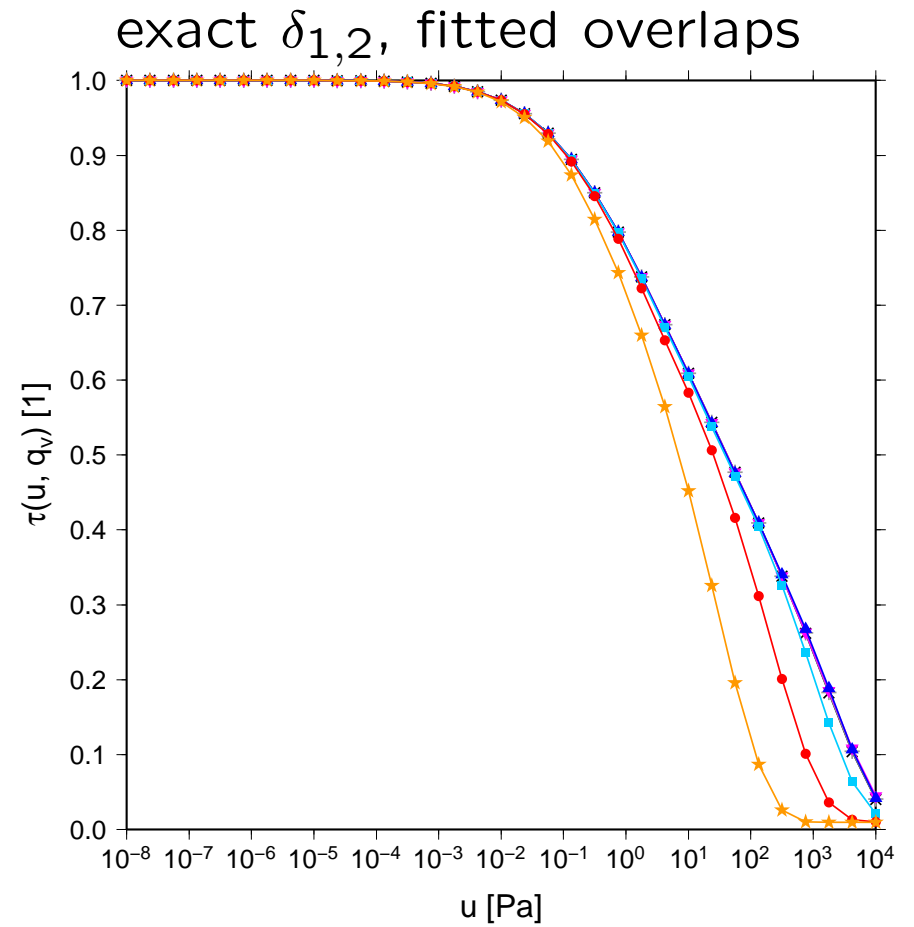


- ×—× $q_v = 1.0e-07$
- +—+ $q_v = 1.0e-06$
- ▼—▼ $q_v = 1.0e-05$
- ▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★ $q_v = 1.0e-01$

H₂O transmissions including self continuum (thermal band, $p = 1000$ hPa, $T = 307.6$ K)

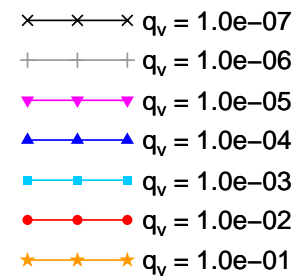
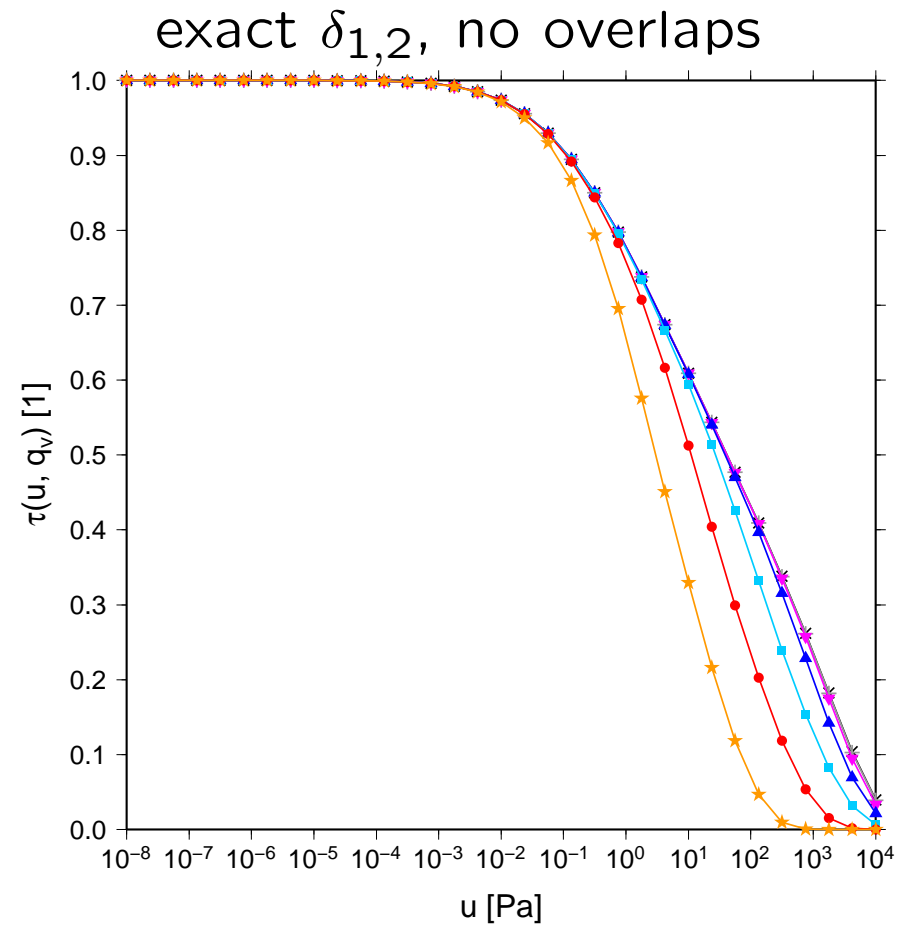
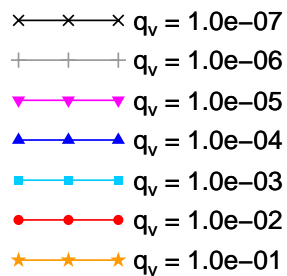
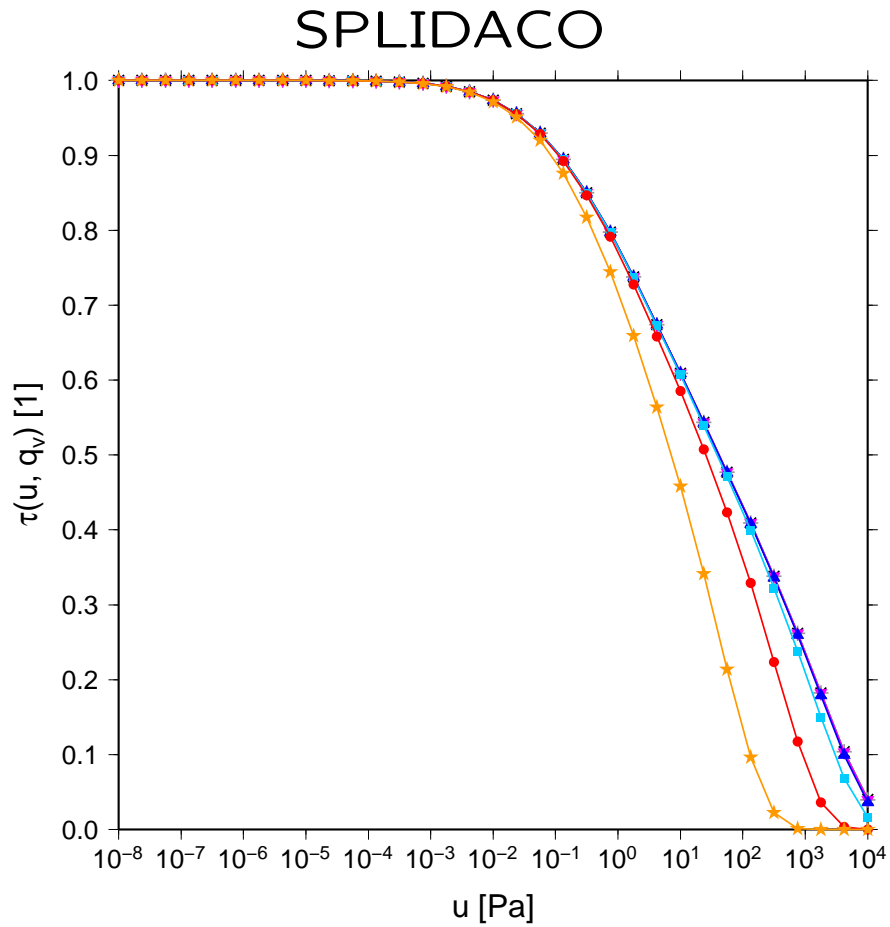


- ×—× $q_v = 1.0e-07$
- +—+ $q_v = 1.0e-06$
- ▼—▼ $q_v = 1.0e-05$
- ▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★ $q_v = 1.0e-01$



- ×—× $q_v = 1.0e-07$
- +—+ $q_v = 1.0e-06$
- ▼—▼ $q_v = 1.0e-05$
- ▲—▲ $q_v = 1.0e-04$
- $q_v = 1.0e-03$
- $q_v = 1.0e-02$
- ★—★ $q_v = 1.0e-01$

H₂O transmissions including self continuum
(thermal band, $p = 1000$ hPa, $T = 307.6$ K)



Curtis-Godson approximation (1)

- so far all developments were done assuming homogeneous optical path, i.e. constant (p, T) along the ray
- this is not the case in atmosphere where pressure variation reaches many orders of magnitude and temperature change also cannot be neglected
- for single Lorentz line problem can be solved by Curtis-Godson approximation, i.e. by finding equivalent homogeneous path which will give the same weak and strong line limits as exact integration along nonhomogeneous path:

$$\bar{S} = \frac{1}{u} \int_0^u S(u') du' \quad \bar{\alpha}_L = \frac{1}{\bar{S}u} \int_0^u S(u') \alpha_L(u') du'$$

(absorber amount u' plays the role of spatial coordinate)

- average quantities \bar{S} , $\bar{\alpha}_L$ can be applied to band model \Rightarrow this is another level of approximation since they were obtained assuming isolated line

Curtis-Godson approximation (2)

- application of Curtis-Godson approximation in Malkmus band model extended by continuum term cu gives:

$$\delta(u) = \frac{u_S}{2u_W} \left(\sqrt{1 + \frac{4u_W^2}{u_S}} - 1 \right) + u_C$$

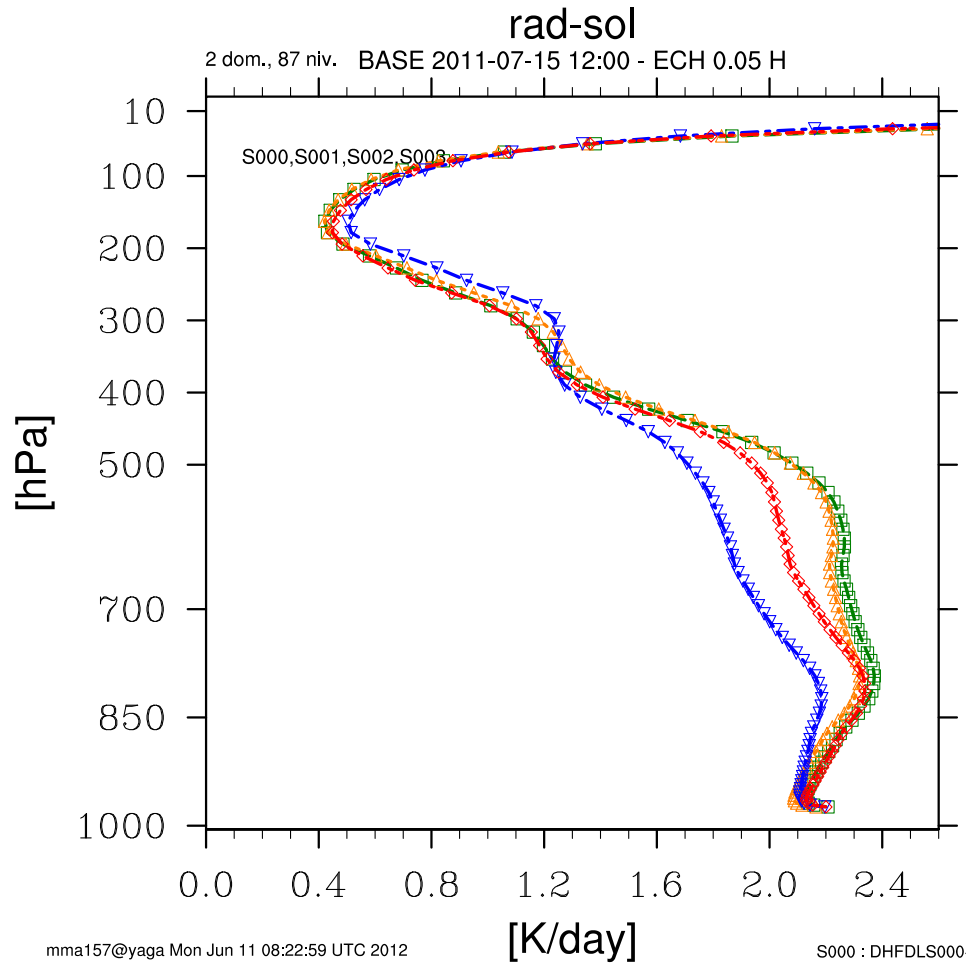
$$u_W(u) = \int_0^u a(u') du' \quad u_S(u) = \int_0^u \frac{a^2(u')}{b(u')} du' \quad u_C(u) = \int_0^u c(u') du'$$

- we assume that it does not interfere with secondary saturation and use it also in broadband case with additional rescaling of $\delta(u)$
- this is similar to assumption that line overlaps do not interfere with Curtis-Godson approximation derived for isolated Lorentz line

Tests in full model (1)

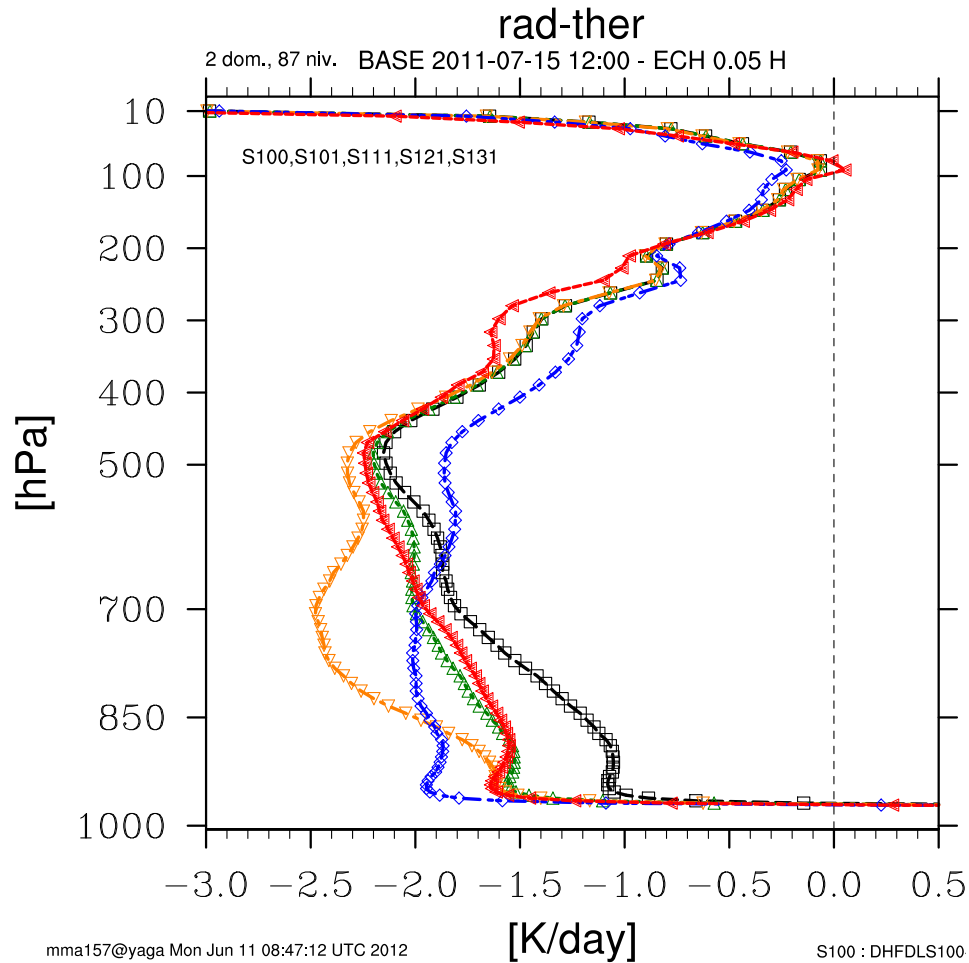
- first sets of experiments used single timestep integrations, in order to exclude feedbacks with other parameterizations
- to prevent possibly different surface emissivity treatment in various radiation schemes, blackbody surface was assumed
- to see pure gaseous effect, clouds and aerosols were off
- ALADIN/CHMI domain, $\Delta x = 4.7$ km, linear grid, 87 vertical levels
- profiles of solar/thermal radiative heating rates were plotted using DDH

DDH heating rates, solar band



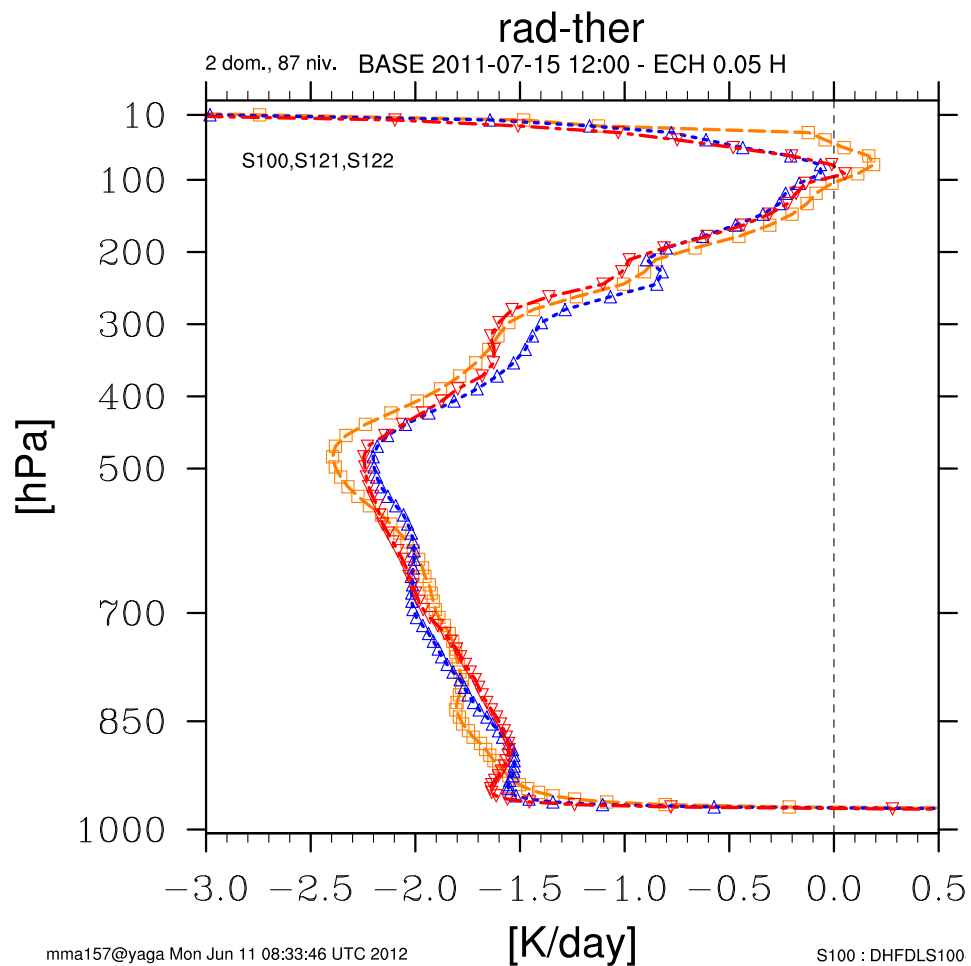
FMR (reference)
old ACRANEB
new ACRANEB
new ACRANEB, no overlaps

DDH heating rates, thermal band, exact exchanges



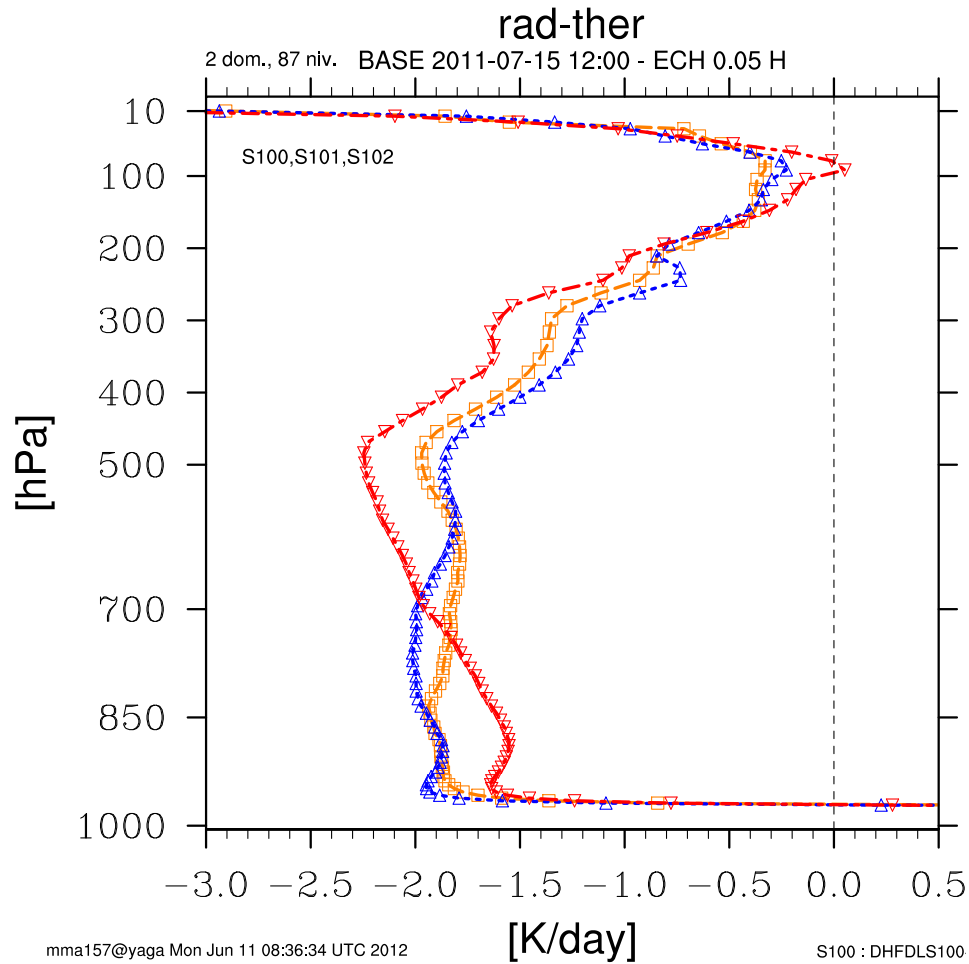
- RRTM (reference)
- old ACRANEB
- new ACRANEB, e-type
- new ACRANEB, e-type/4
- new ACRANEB, e-type off

DDH heating rates, thermal band, new ACRANEB with e-type/4



RRTM (reference)
ACRANEB, exact exchanges
ACRANEB, statistical model

DDH heating rates, thermal band, old ACRANEB

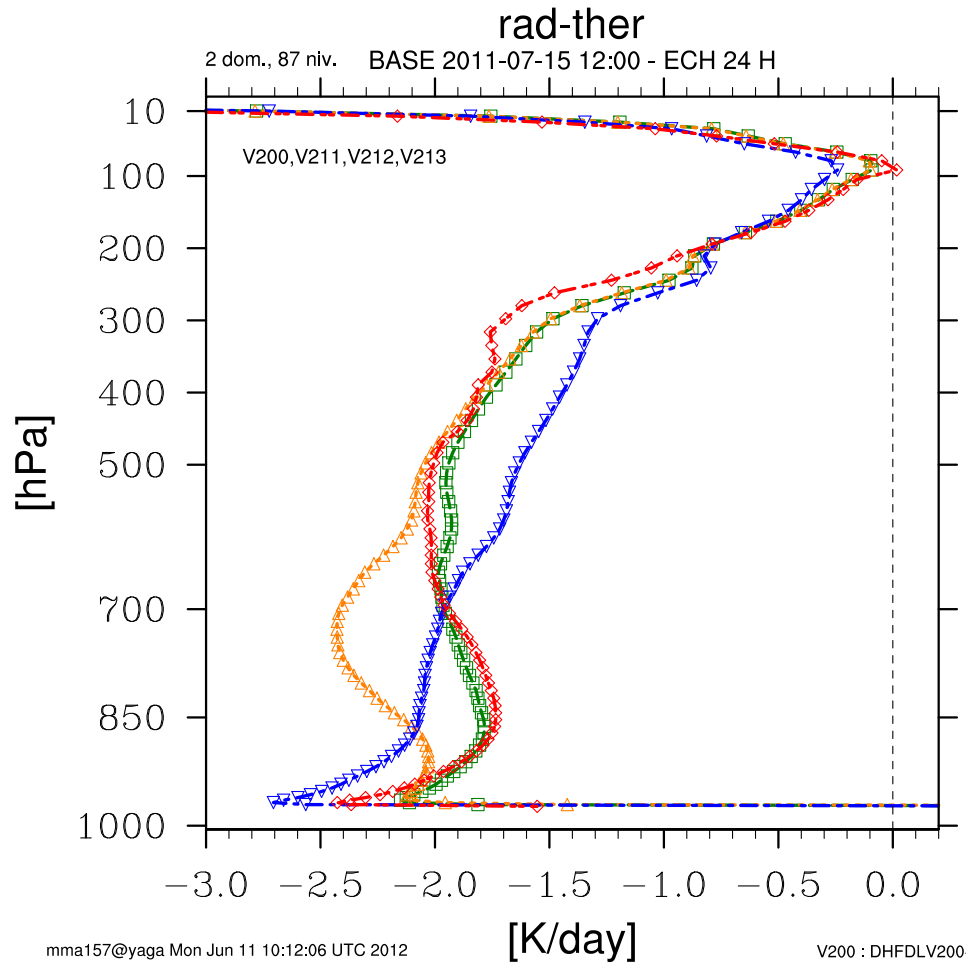


RRTM (reference)
ACRANEB, exact exchanges
ACRANEB, statistical model

Tests in full model (2)

- second set of experiments used 24-hour integrations with timestep $\Delta t = 180$ s
- model was run with full physics, but radiation scheme got no clouds, aerosols were off and surface emissivity was one
- thermal exchanges were computed exactly

DDH heating rates, thermal band, exact exchanges

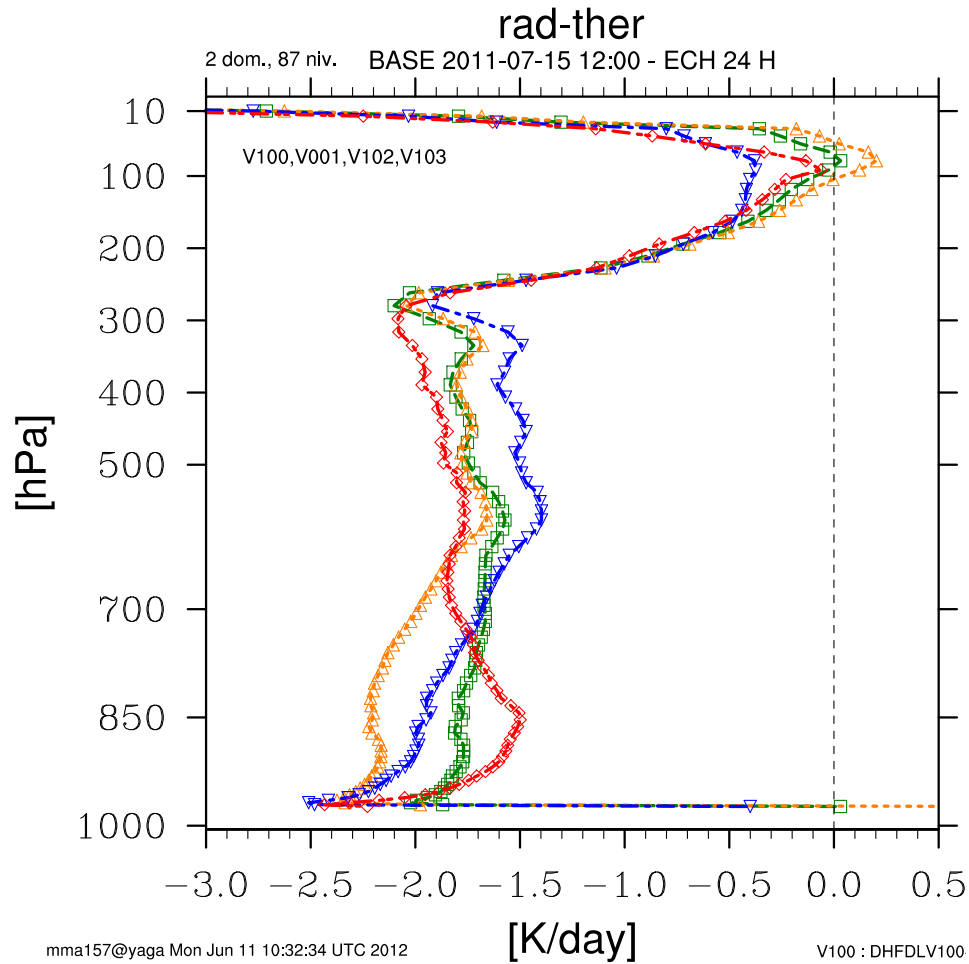


- RRTM (reference)
- old ACRANEB
- new ACRANEB, e-type
- new ACRANEB, e-type/4

Tests in full model (3)

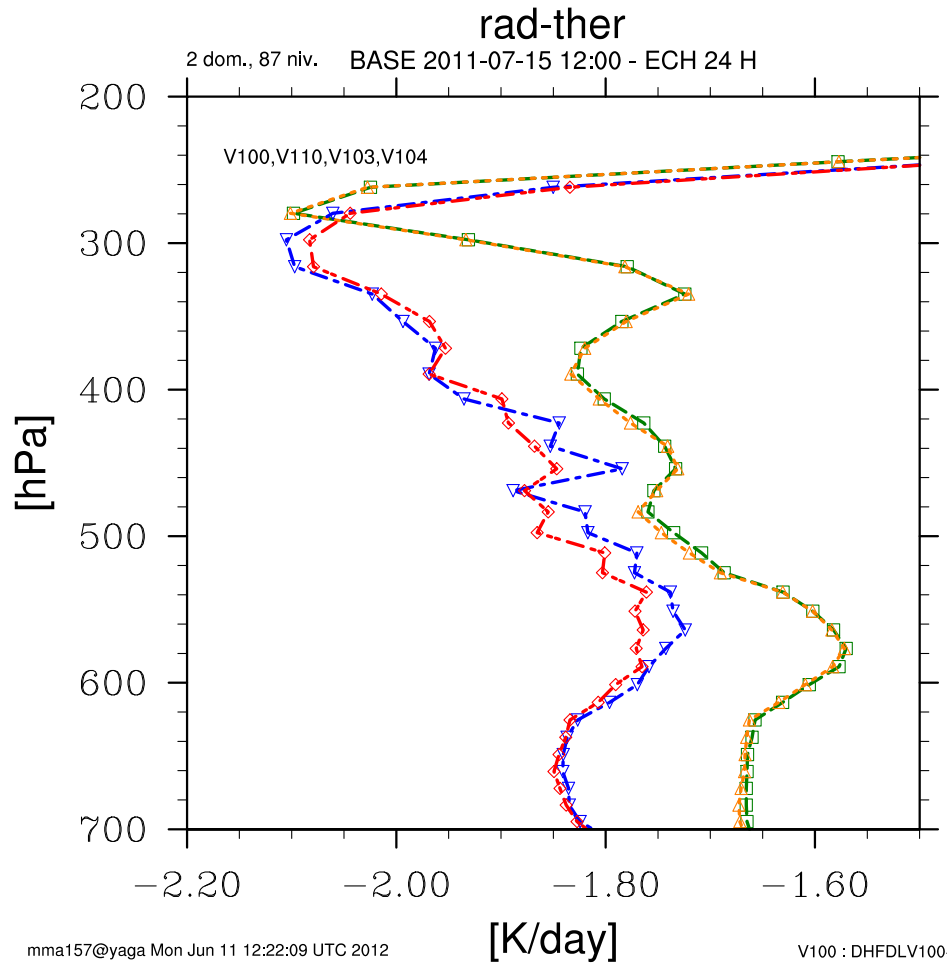
- third set of experiments used 24-hour integrations with timestep $\Delta t = 180$ s
- model was run with full physics, including radiation scheme
- thermal exchanges were computed using statistical model (so called bracketing technique)
- test is suitable to evaluate cost of various radiative schemes and configurations
- radiative feedback with cloudiness makes interpretation of results more difficult

DDH heating rates, thermal band, statistical model



RRTM (reference)
old ACRANEB,
new ACRANEB, e-type
new ACRANEB, e-type/4

DDH heating rates, thermal band, statistical model



- RRTM, every hour
- RRTM, every timestep
- new ACRANEB, every timestep
- new ACRANEB, every hour

CPU cost estimated from user time of 24-hour integration

scheme	update time [timestep]	relative CPU cost [1]
old ACranEB	1	reference, 1.00
RRTM	20	0.98
RRTM	1	2.46
new ACranEB	1	1.27
new ACranEB	20	1.05

Summary of current achievements (June 2012)

- new fits of gaseous transmission functions were developed, addressing following issues:
 1. broadband saturation via rescaling of Malkmus formula
 2. non-homogeneous optical paths via Curtis-Godson approximation
 3. incorporation of previously developed treatment of Voigt line shape, important in high atmosphere
 4. non-random broadband gaseous overlaps evaluated in absorptivity space
 5. H₂O self continuum as separate pseudo-gas H₄O₂ (thermal band)
 6. different spectral weights for cooling to space and remaining exchanges (thermal band)
- for points 1, 2 and 3 it is crucial that fitted broadband dependency is modification of Malkmus band model, which enables to keep approximate link with mean line parameters

Remaining work and problems

- H₂O thermal transmissions do not work well in lower troposphere, giving too much cooling
- it is not clear yet whether the problem is due to insufficient quality of the fits or some more fundamental reason (unreliable reference? reaching limits of broadband approach?)
- empirical reduction of self continuum by factor 4 is not justified, but it gives hope to broadband approach
- statistical model for NER method was not yet retuned for the new gaseous transmissions (no complications expected)
- update of reference line by line computations is needed, probably using LBLRTM code (our CO₂+ composition is valid for 1992 but not 2012!)

Conclusion

Update of radiative scheme is long term run,
failure would be to give up now.

