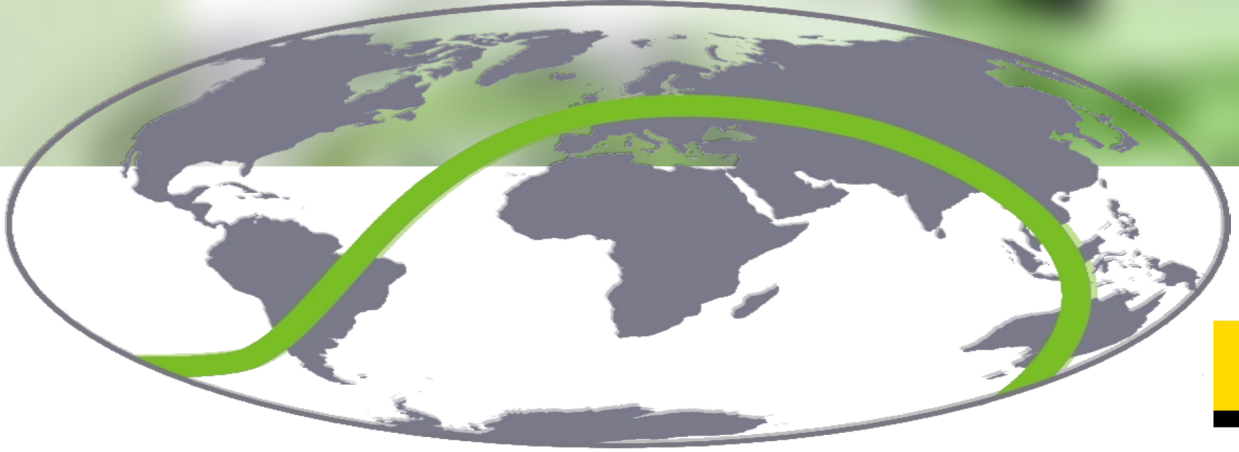

wege entstehen, indem wir sie gehen
paths emerge in that we walk them

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ACCURATE: Multi Species Retrieval (MSR) from Combined IR-Laser and Microwave Occultation Data

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1. Overview
   - LMIO-Scheme
   - Atmospheric Effects
2. Retrieval and Example Results
   - Scheme
   - Starting Parameter
   - Single-Line Trace Species Retrieval SSR
   - Multi-Line Trace Species Retrieval MSR
3. Summary and Conclusions

LEO-LEO Microwave and Laser Infrared Occultation LMIO

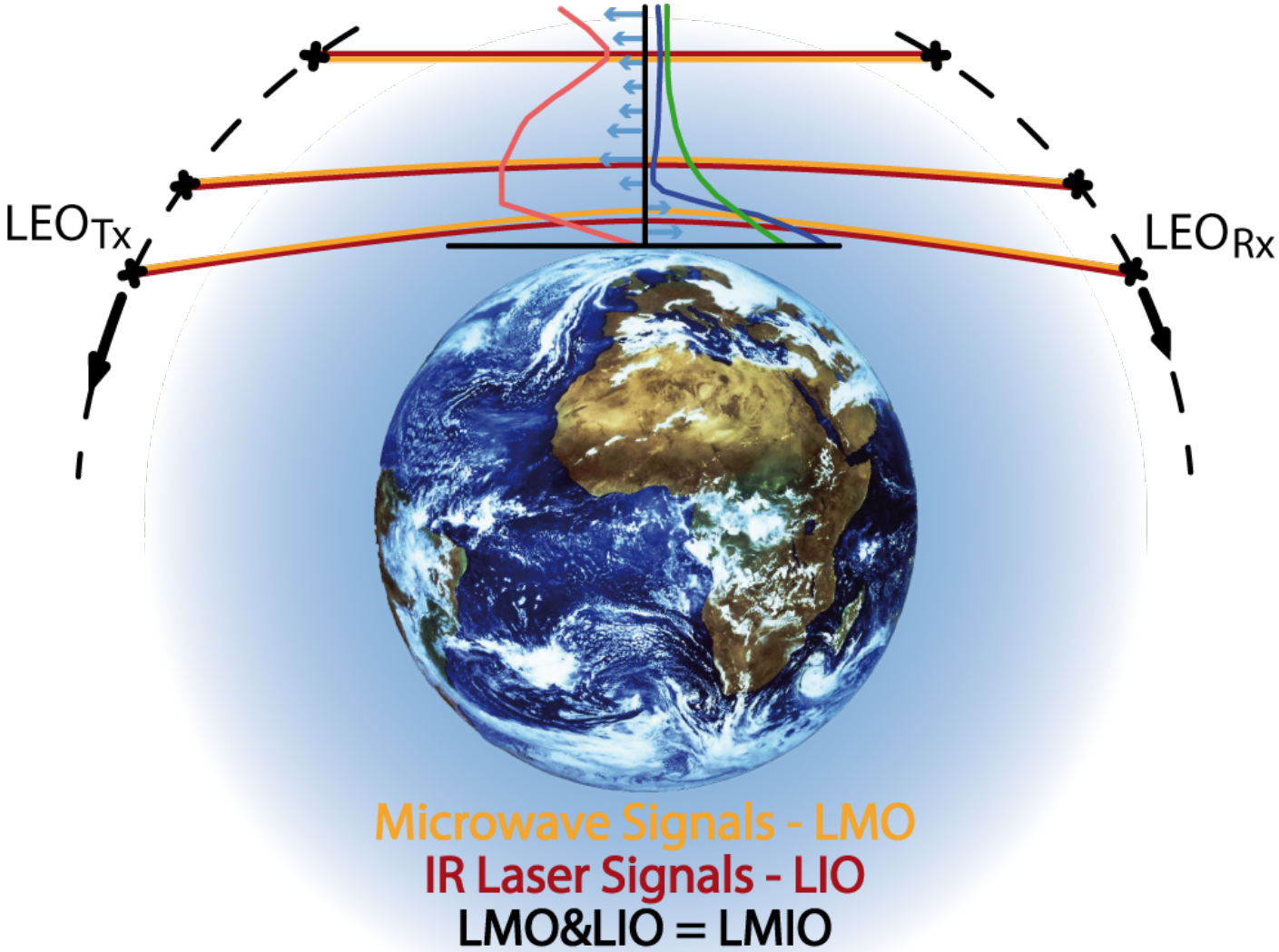


Figure: LMIO Scheme

LMO: 9-23 GHz, 175-200 GHz
LIO: 2-2.5 μm

- Refraction
- Rayleigh scattering
- Scintillation
- Solar scattering into the receiver
- Doppler shift on intensities due to wind
- Clouds, except very thin cirrus clouds, block the IR signals

Effect of interest:

- Absorption by molecules:
  - Greenhouse gases (GHGs) $\{H_2O, CO_2, CH_4, N_2O, O_3, CO\}$
  - Isotopes $\{^{13}CO_2, C^{18}OO, HDO, H_2^{18}O\}$

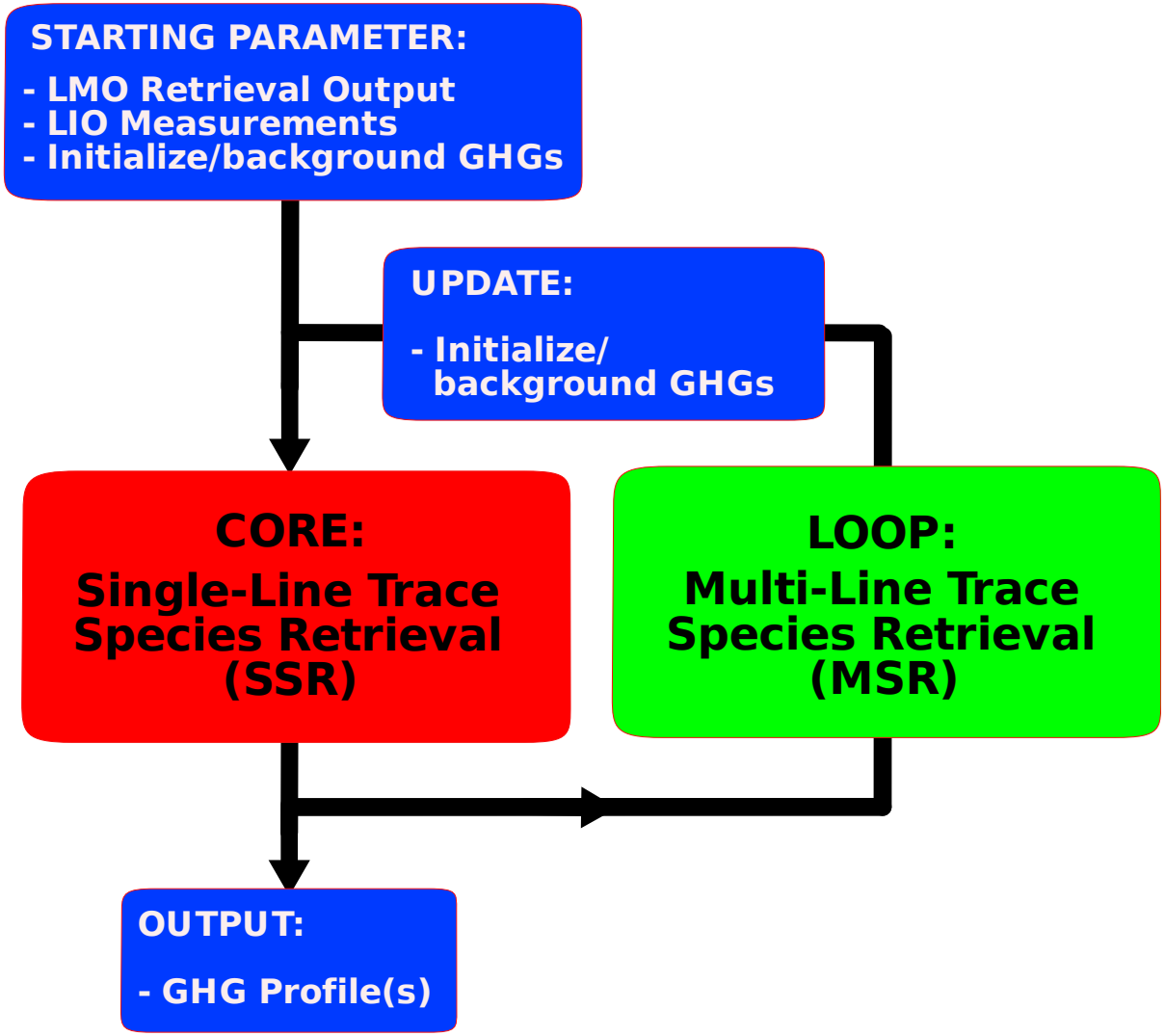


Figure: Retrieval Scheme

LMO:

- Tangent point height $\vec{z}_{\mathrm{mw}}(\vec{t})$
- Temperature $\vec{T}\,(\vec{z}_{\mathrm{mw}})$
- Pressure $\vec{p}\,(\vec{z}_{\mathrm{mw}})$
- Humidity $\vec{q}\,(\vec{z}_{\mathrm{mw}})$
- Positions $\vec{x}(\vec{t})$ of transmitter (T_x) and receiver (R_x)

LIO:

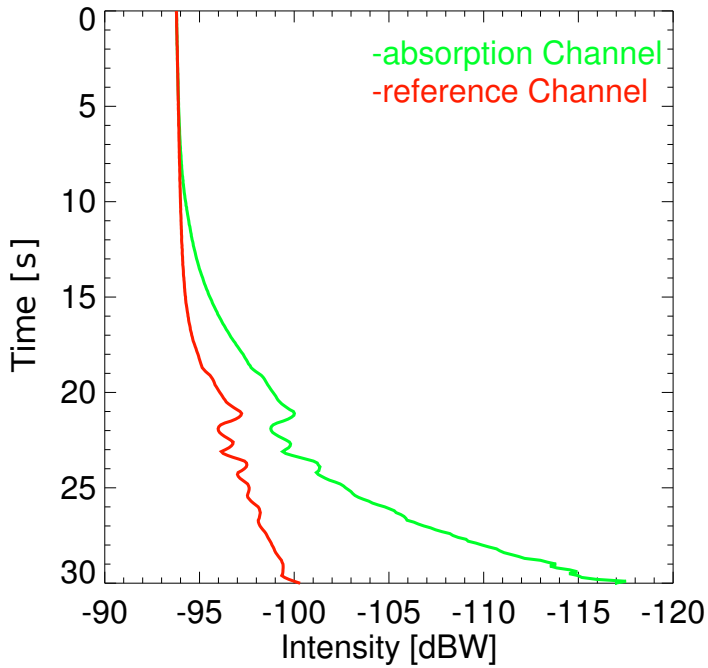


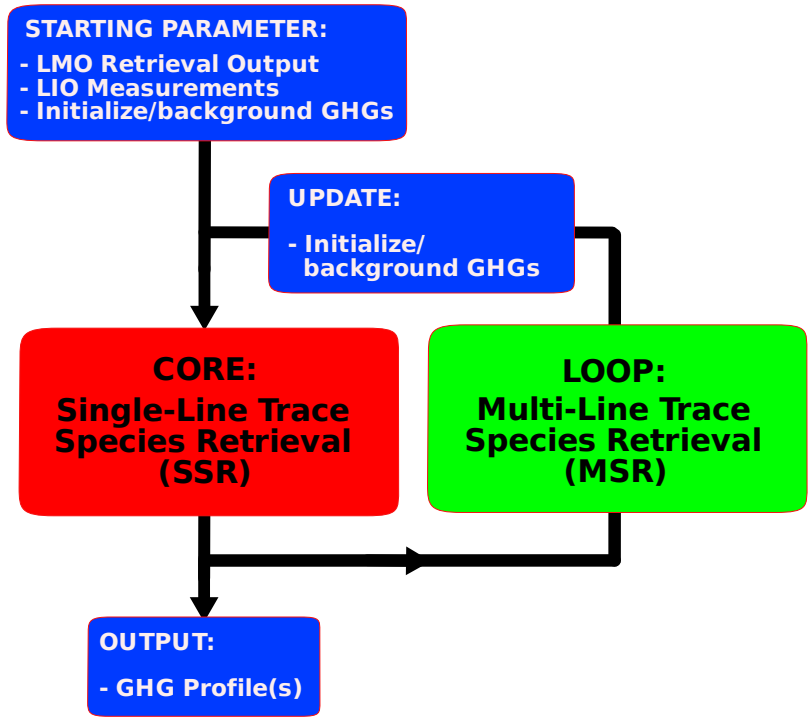
Figure: Intensity profile for the absorption and reference channel of $^{12}CO_2$

EXTERNAL:

- **Initialize/background GHG profile(s)**

Single-Line Trace Species Retrieval SSR Overview

1. Tangent point height calculation for the IR signal time series
2. Defocusing correction of the raw transmission
3. Target species transmission extraction:
   - **a)** Subtraction of reference- from absorption channel transmission
   - **b)** Foreign/background species absorption correction with background GHG profiles
4. Calculate the absorption coefficient from the GHG transmission
5. Calculate the volume mixing ratio of the GHG target species



1. Tangent point height of the IR signal ($z_{ir}(t)$) #1

Initializing parameter for the iteration process of $z_{\mathrm{ir}}(t)$:

- n_{ir} refractive index (*Edlen-type formula*) and a_{ir} impact parameter on $z_{\mathrm{mw}}(t)$-grid:

$$n_{\mathrm{ir}}(z_{\mathrm{mw}}) \propto a_{\mathrm{ir}}(z_{\mathrm{mw}}) \propto Const(\nu) \cdot \frac{p(z_{\mathrm{mw}})}{T(z_{\mathrm{mw}})} \tag{1}$$

- α_{ir} bending angle on $a_{\mathrm{ir}}(z_{\mathrm{mw}})$-grid:

$$\alpha_{\mathrm{ir}}(a_{\mathrm{ir}}) = 2 \cdot a_{\mathrm{ir}} \int_{r_{mw}}^{\infty} \frac{1}{\sqrt{r^2 n_{\mathrm{ir}}^2 - a_{\mathrm{ir}}^2}} \frac{\mathrm{d} \ln(n_{\mathrm{ir}})}{\mathrm{d}r} \mathrm{d}r \tag{2}$$

- α_{k} geometric bending angle relation as initialization profile at every grid level with $a_{k=0} = a_{\mathrm{ir}}$:

$$\alpha_k(a_k) = \theta - \arccos\left(\frac{a_k}{r_{R_x}}\right) - \arccos\left(\frac{a_k}{r_{T_x}}\right) \tag{3}$$

θ ... Opening angle between T_x and R_x
r_{mw} ... Distance from center of curvature to the tangent point height level
r_{Rx} ... Distance from center of curvature to the R_x
r_{Tx} ... Distance from center of curvature to the T_x

1. Tangent point height of the IR signal ($z_{ir}(t)$) #2

Iteration process of the tangent point height of the IR signal ($z_{\mathrm{ir}}(t)$):

- Newton iteration:

$$a_{k+1} = a_k + \frac{(\alpha_k - \alpha_{ir})}{\left(\frac{\mathrm{d}\alpha_k}{\mathrm{d}a_k}\right)} \tag{4}$$

- Interpolation of α_{ir} to the new a_{k+1}
- Calculation of the new $\alpha_{\mathrm{k+1}}$ with equation (3)
- Convergence of $\Delta a_{k+1} = (a_{k+1} - a_k) < 1\ m$
- Calculation of the tangent point height $z_{\mathrm{ir}}(t)$

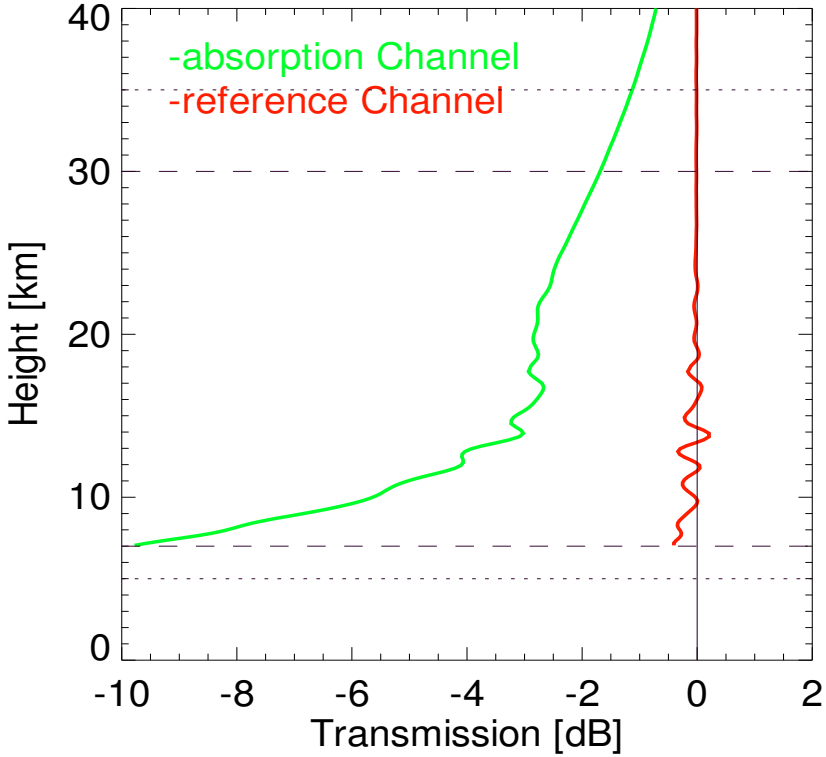
$$z_{\mathrm{ir}}(t) = \frac{a_{\mathrm{ir}}(t)}{n_{\mathrm{ir}}(t)} - R_C \tag{5}$$

R_C . . . Radius of curvature

After step 2. defocusing and spreading correction:

a) Subtraction of the reference- from the absorption channel transmission to cancel out broadband effects:

- Solar scattering into Rx
- Scintillation
- Aerosol extinction
- Very thin cirrus cloud extinction



$$\Delta Tr_{\text{abs,ref}}(z_{\text{ir}}) = Tr_{\text{abs}}(z_{\text{ir}}) - Tr_{\text{ref}}(z_{\text{ir}}) \quad (6)$$

Figure: Transmission profile for the absorption and reference channel of $^{12}CO_2$

$\Delta Tr_{abs,ref}$ ... Differential transmission
Tr_{abs} ... Transmission of the absorption channel
Tr_{ref} ... Transmission of the reference channel

b) Correction due to modeled foreign/background species transmission using the initialized/background GHG profile:

$$Tr_{\mathrm{GHG}}\left(z_{\mathrm{ir}}\right) = \Delta Tr_{\mathrm{abs,ref}}\left(z_{\mathrm{ir}}\right) - \left(Tr_{\mathrm{bgr,abs}}\left(z_{\mathrm{ir}}\right) - Tr_{\mathrm{bgr,ref}}\left(z_{\mathrm{ir}}\right)\right) \quad (7)$$

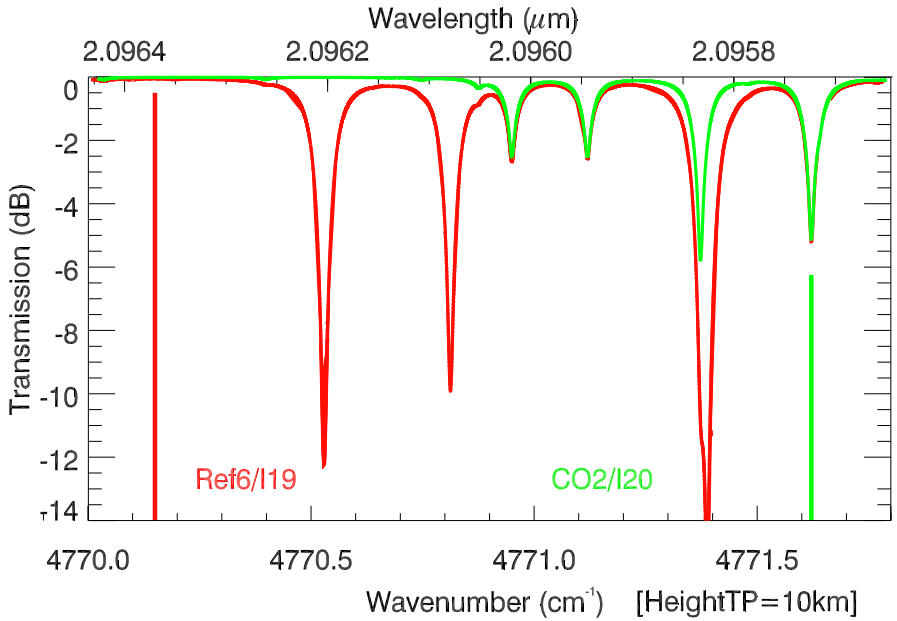


Figure: Transmission loss spectra (total, $^{12}CO_2$ only) and absorption- and reference channel

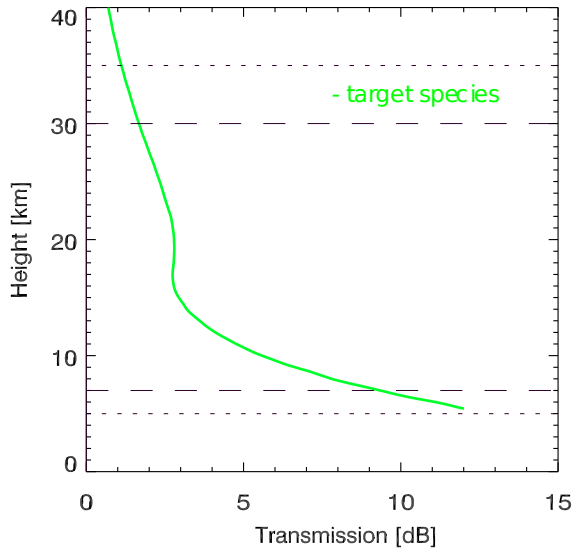


Figure: Transmission profile for the pure absorption by the target species $^{12}CO_2$

$Tr_{bgr,abs/ref}$ . . . Transmission of the foreign species of the absorption/reference channel calculated by model (RFM)
Tr_{GHG} . . . Transmission of the target greenhouse gas

Abel Transform of the transmission Tr_{GHG} into the absorption coefficient α_{ir}:

$$\kappa_{\mathrm{GHG}}\left(a_{\mathrm{ir,j}}\right) = \frac{1}{\pi}\frac{\mathrm{d}a_{\mathrm{ir}}}{\mathrm{d}r_{\mathrm{ir}}}\bigg|_{a_{ir}=a_{ir,j}} \int_{a_{ir,j}}^{\infty} \frac{1}{\sqrt{a_{\mathrm{ir}}^2 - a_{\mathrm{ir,j}}^2}} \frac{\mathrm{d}\ln\left(Tr_{\mathrm{GHG}}\left(a_{\mathrm{ir}}\right)\right)}{\mathrm{d}a_{\mathrm{ir}}} \mathrm{d}a_{\mathrm{ir}} \qquad (8)$$

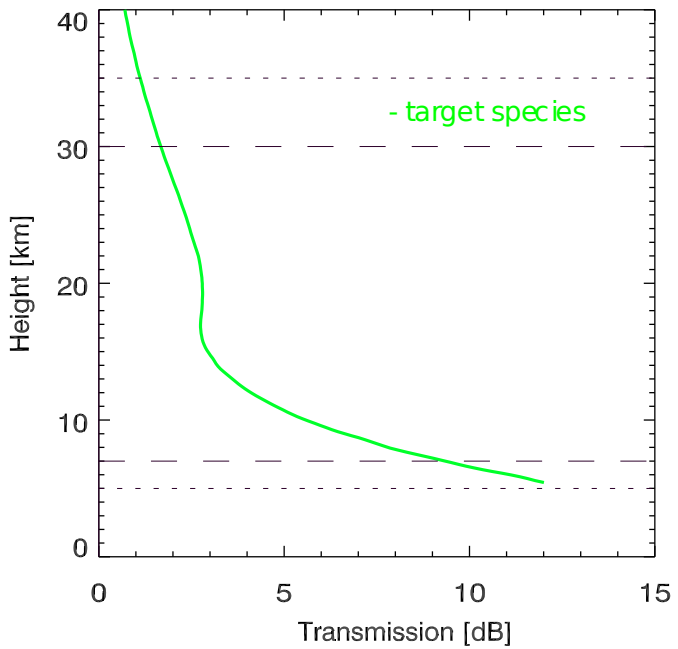


Figure: Transmission profile for $^{12}CO_2$

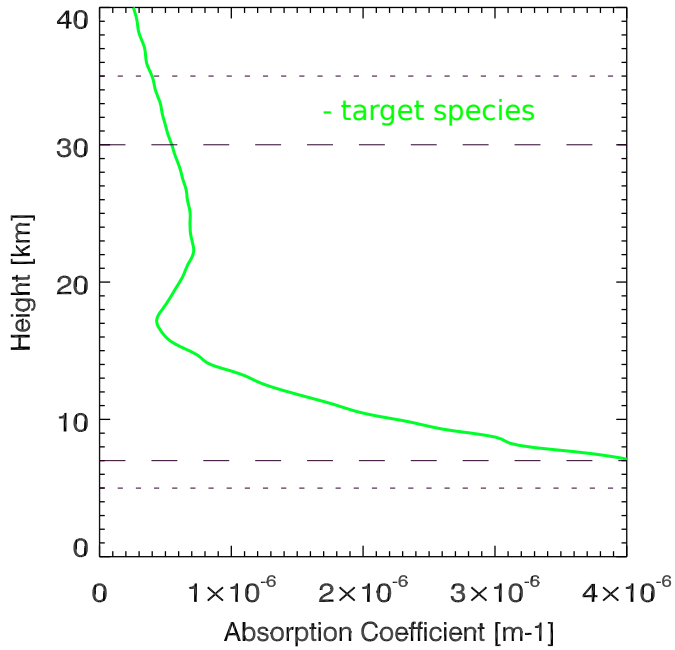


Figure: Abs. coeff. profile for $^{12}CO_2$

Conversion of the absorption coefficient $\kappa_{GHG}(z_{ir})$ into the volume mixing ratio $\chi_{GHG}(z_{ir})$ with the modeled species cross-section $\sigma_{GHG}(z_{ir})$

$$\chi_{GHG}\left(z_{ir,j}\right) \propto \frac{\kappa_{GHG}\left(a_{ir,j}\right)}{\sigma_{GHG}\left(a_{ir,j}\right)} \qquad (9)$$

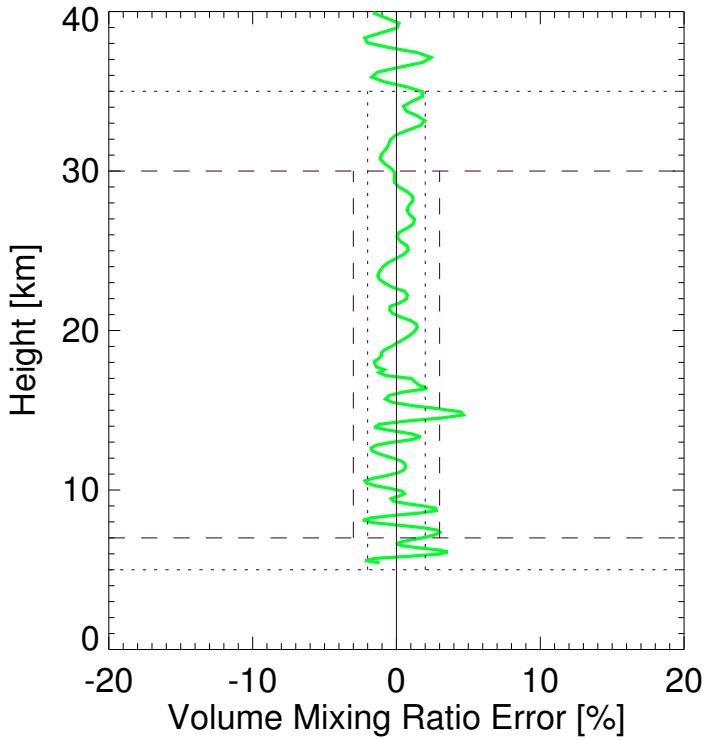
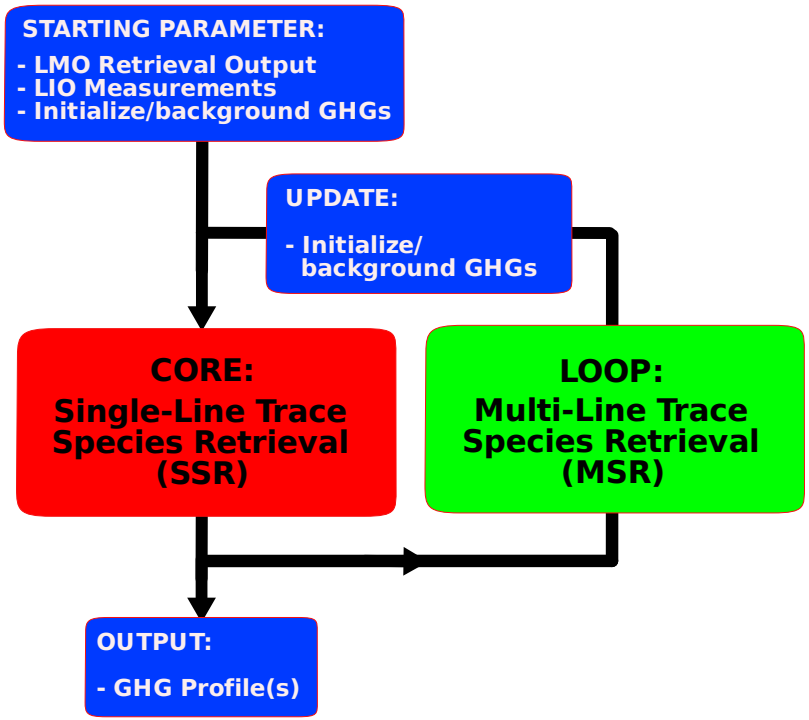


Figure: Relative volume mixing ratio error of $^{12}CO_2$ in %

κ . . . Absorption coefficient
σ . . . Cross section computed by RFM with HITRAN database using LMO T, p
χ . . . Volume mixing ratio

Multi-Line Trace Species Retrieval MSR Overview

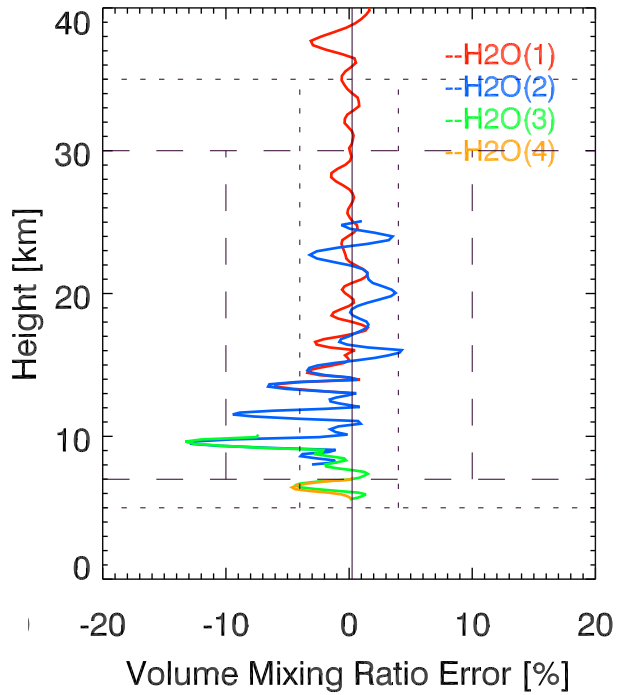


1. Loop over a defined order of trace species for sensible step-wise update of the initialize/background GHGs
2. Combination of $^{X}CO_2$ isotope profiles and H_2O(1-4) profiles
3. Iteration loop over the whole order of trace species sequence to guarantee convergence to the pure measurement-retrieved VMR profiles
4. Update of the initialize/background GHG profiles after every single GHG retrieval step

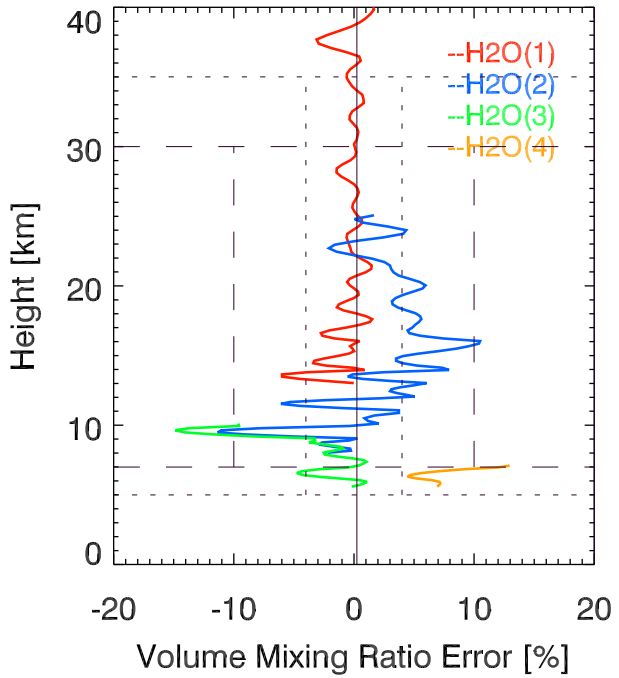
Consecutive order of retrieved single-line trace species:

$\{ {}^{14}N_2O,\ {}^{12}CH_4,\ {}^{13}CO_2,\ C^{18}OO,\ H_2O(1\text{-}4),\ {}^{12}CO_2,\ HDO,\ H_2{}^{18}O,\ {}^{12}CO,\ {}^{16}O_3 \}$

Correct CO_2 initialized/background GHG profile for H_2O ret.:

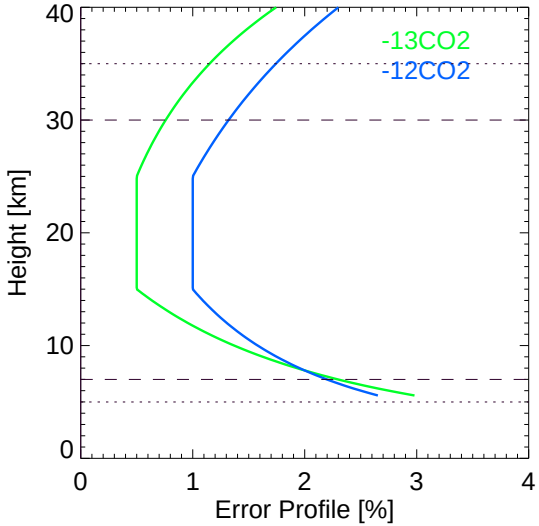


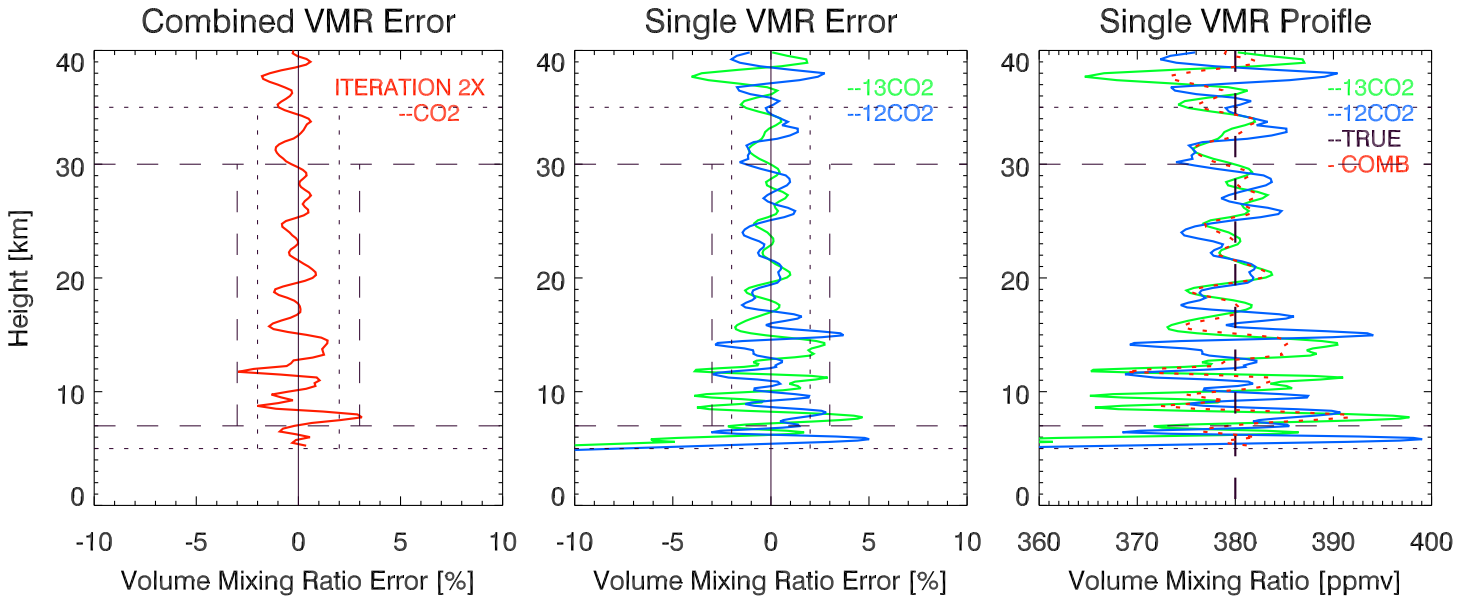
Zero CO_2 initialized/background GHG profile for H_2O ret.:



2. Combination of $^{X}CO_2$

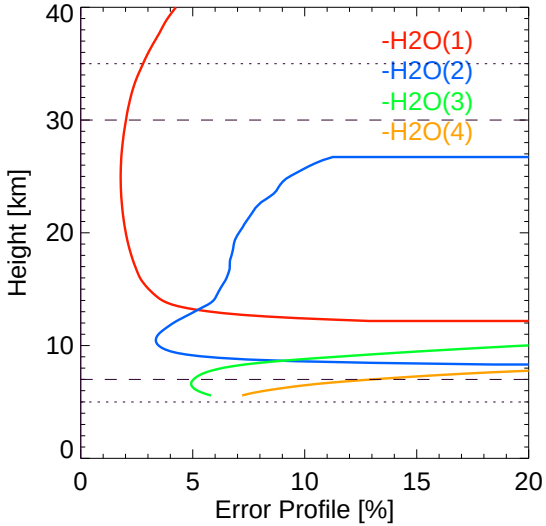
- $^{13}CO_2$ and $^{12}CO_2$ absorption lines
- each sensitive at all heights, but somewhat different
- combined with static inverse-variance weighting

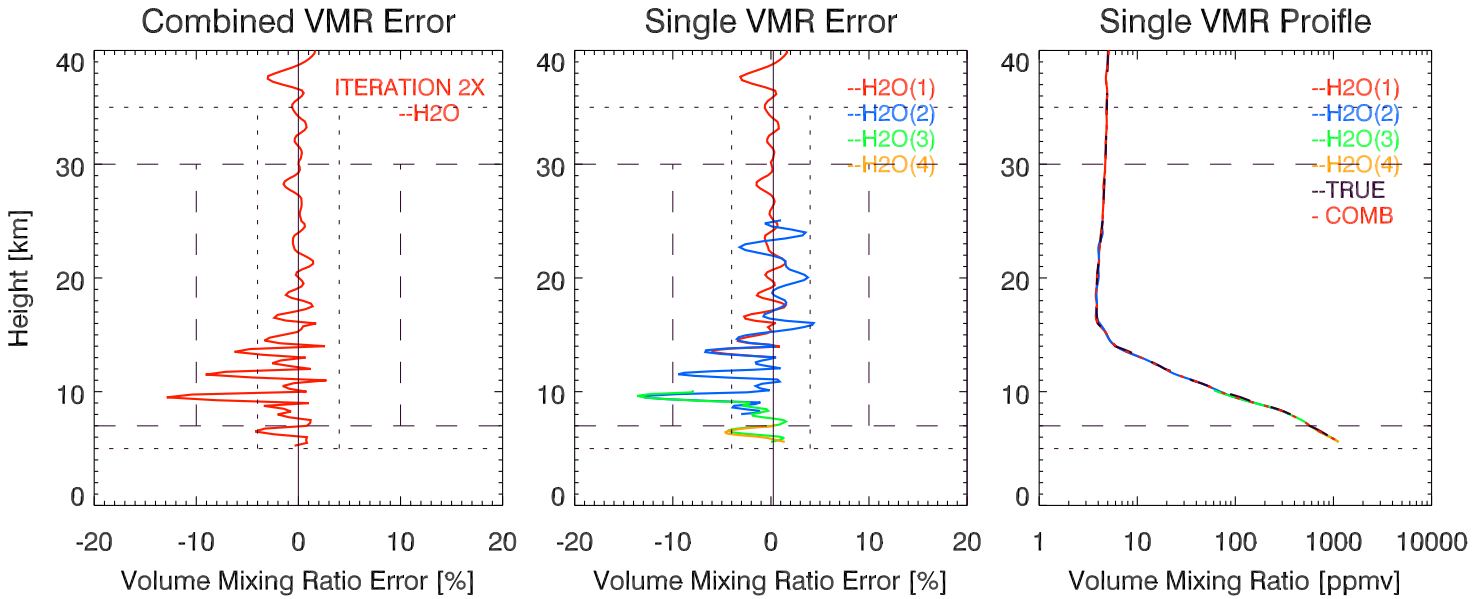




2. Combination of H_2O(1-4)

- 4 H_2O absorption lines
- sensitive to different height ranges
- combined by dynamic inverse-variance weighting





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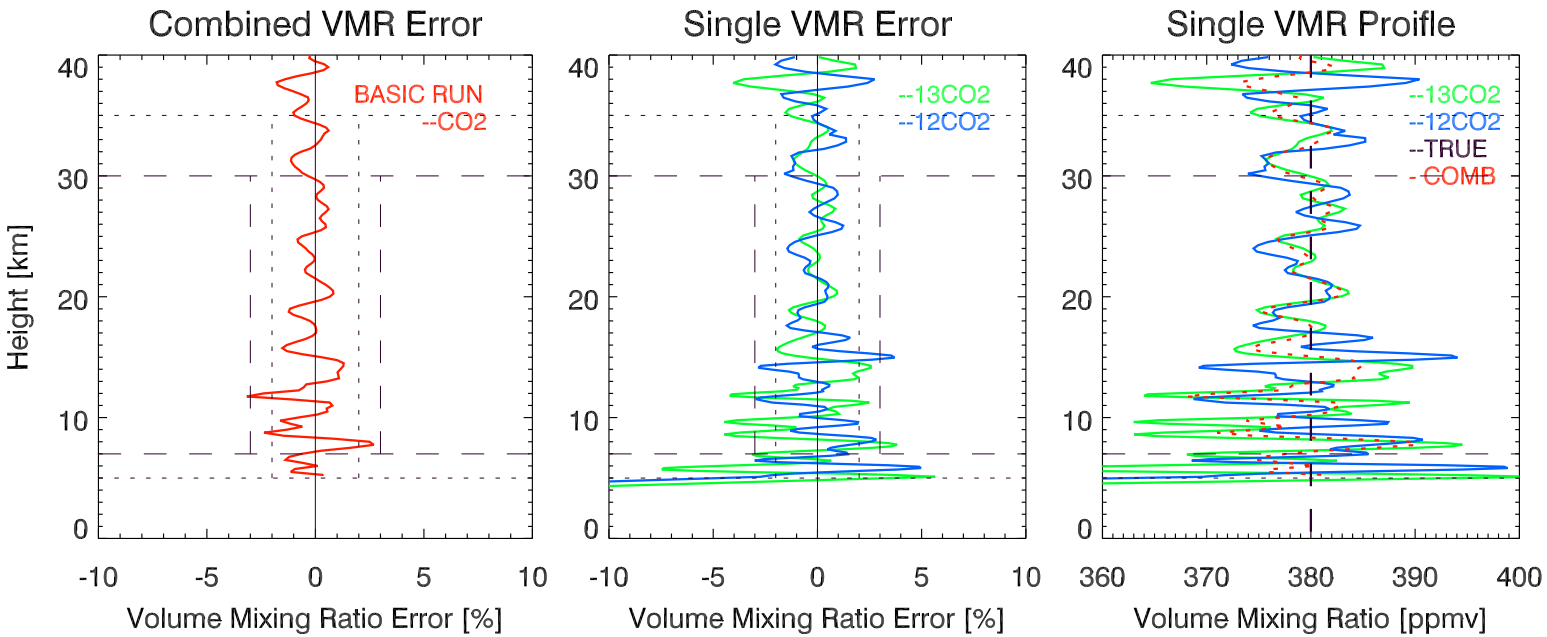
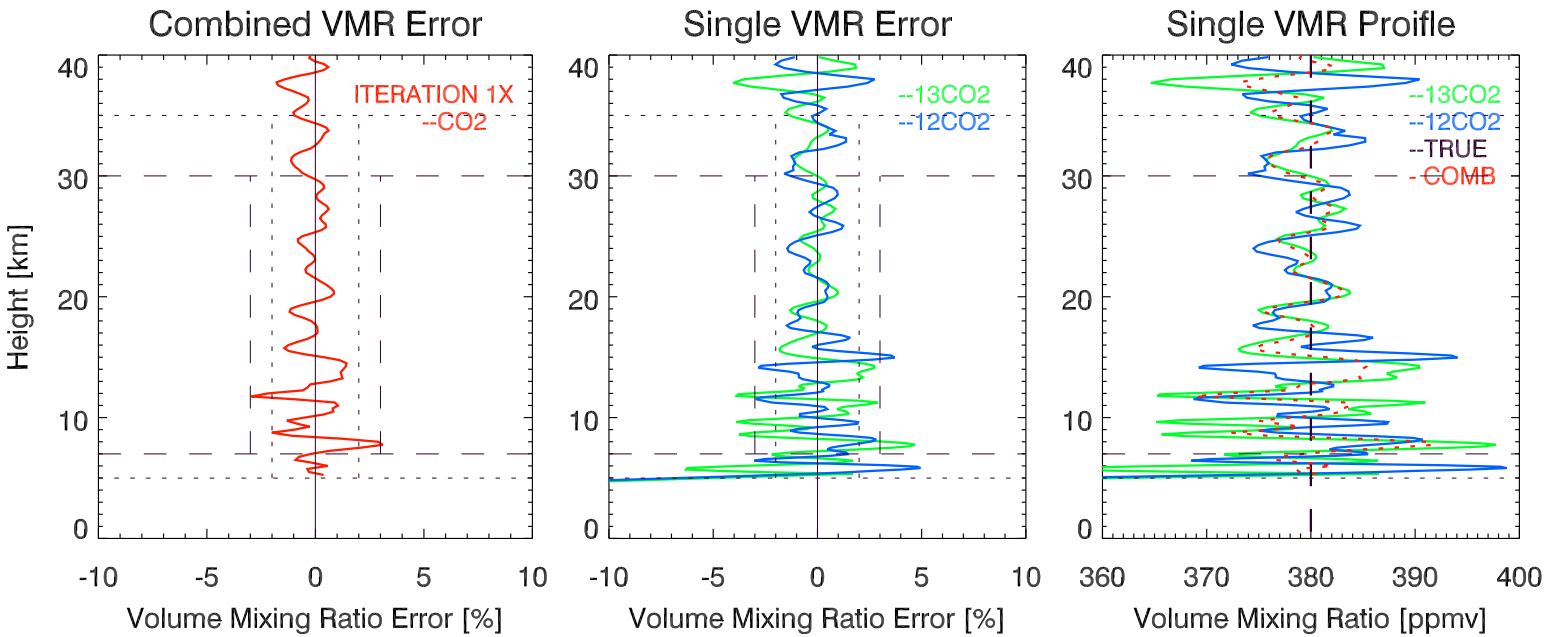
Modified values of initialized GHG profile:
$\{H_2O, CO_2, O_3\} = 0$ [ppmv]

1 Basic run



Modified values of initialized GHG profile:
$\{H_2O, CO_2, O_3\} = 0$ [ppmv]

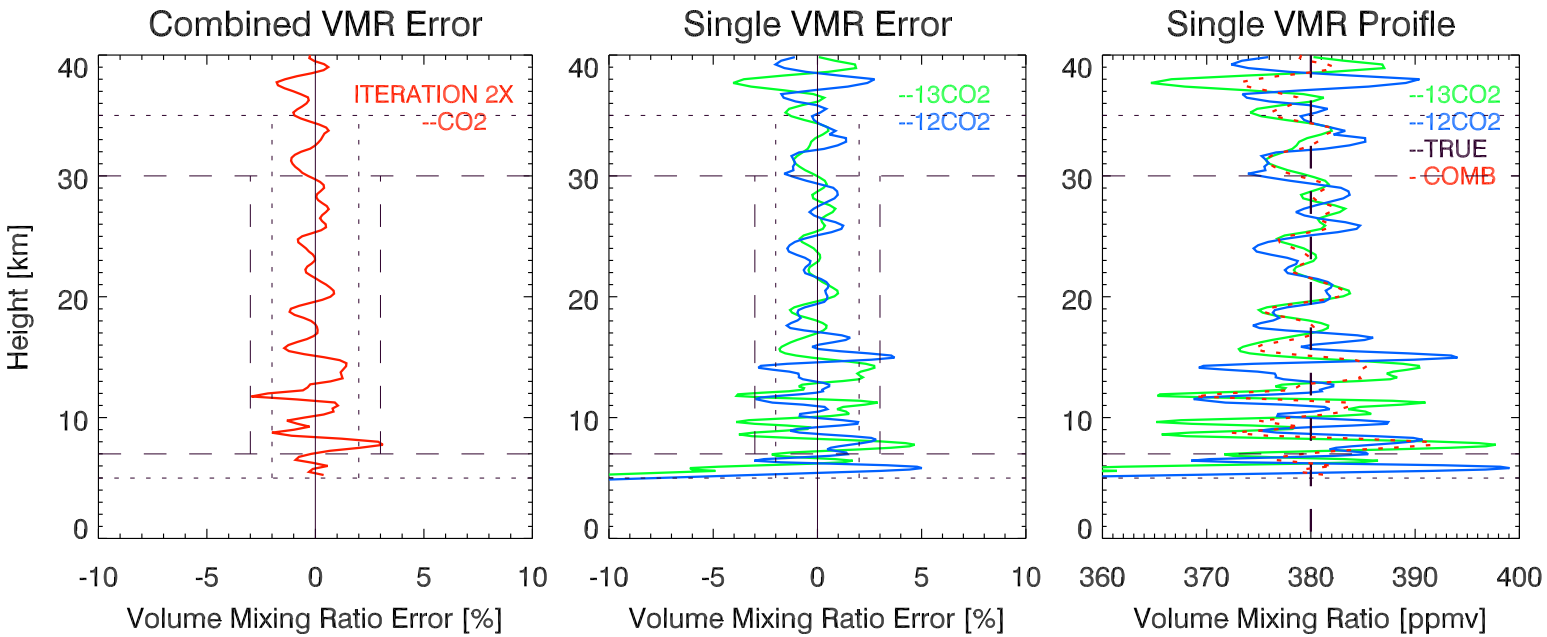
1. Basic run
2. First iteration run



3. CO_2 iteration loop

Modified values of initialized GHG profile:
$\{H_2O, CO_2, O_3\} = 0$ [ppmv]

1. Basic run
2. First iteration run
3. Second iteration run (Control run)



Summary and Conclusions

- Single Species Retrieval (SSR):
  - Core part of the whole retrieval process.
  - Reference obs system, since no external information dependence except the initialize/background GHG profiles
  - Algorithm of the GHG retrieval performs in a robust way and leads to accuracies of 1–4 % (monthly means expected < 0.15–0.5 %).
- Multi Species Retrieval (MSR):
  - Even with poor (zero) initial/background GHG profiles quick convergence to purely measurement-derived values; order of GHG sequence important as every next GHG already benefits from retrieval update of previous one.
  - Accurate retrieval possible in clear, aerosol-laden and turbulent air, also very thin cirrus clouds do not hinder a retrieval process (dedicated cloudy-air retrieval is next step).
  - Benefit due to combination of H_2O absorption and CO_2 isotope profiles; composite profiles.

Thank you for your attention!