Importance of FOV Integration for ACE

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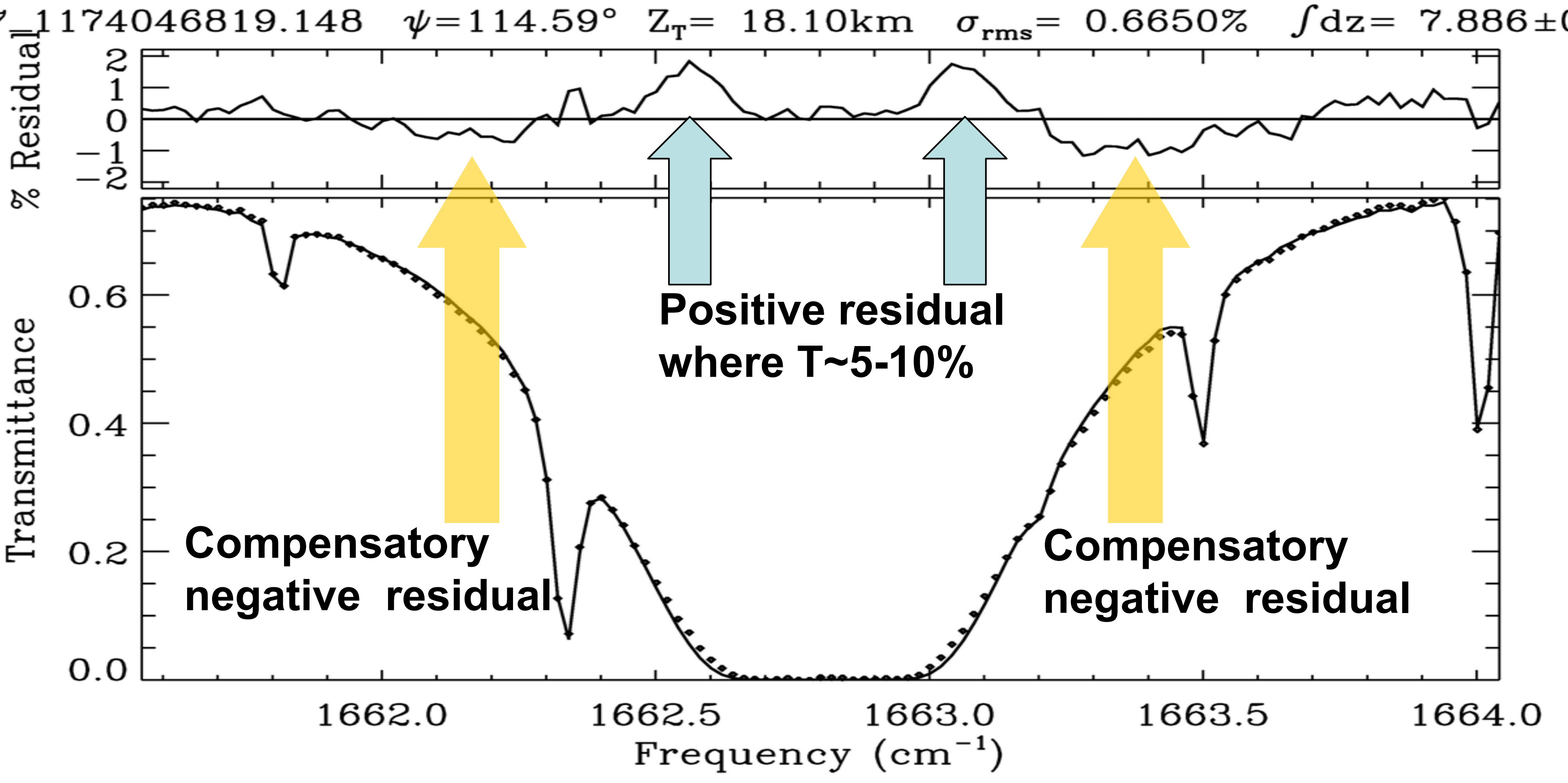
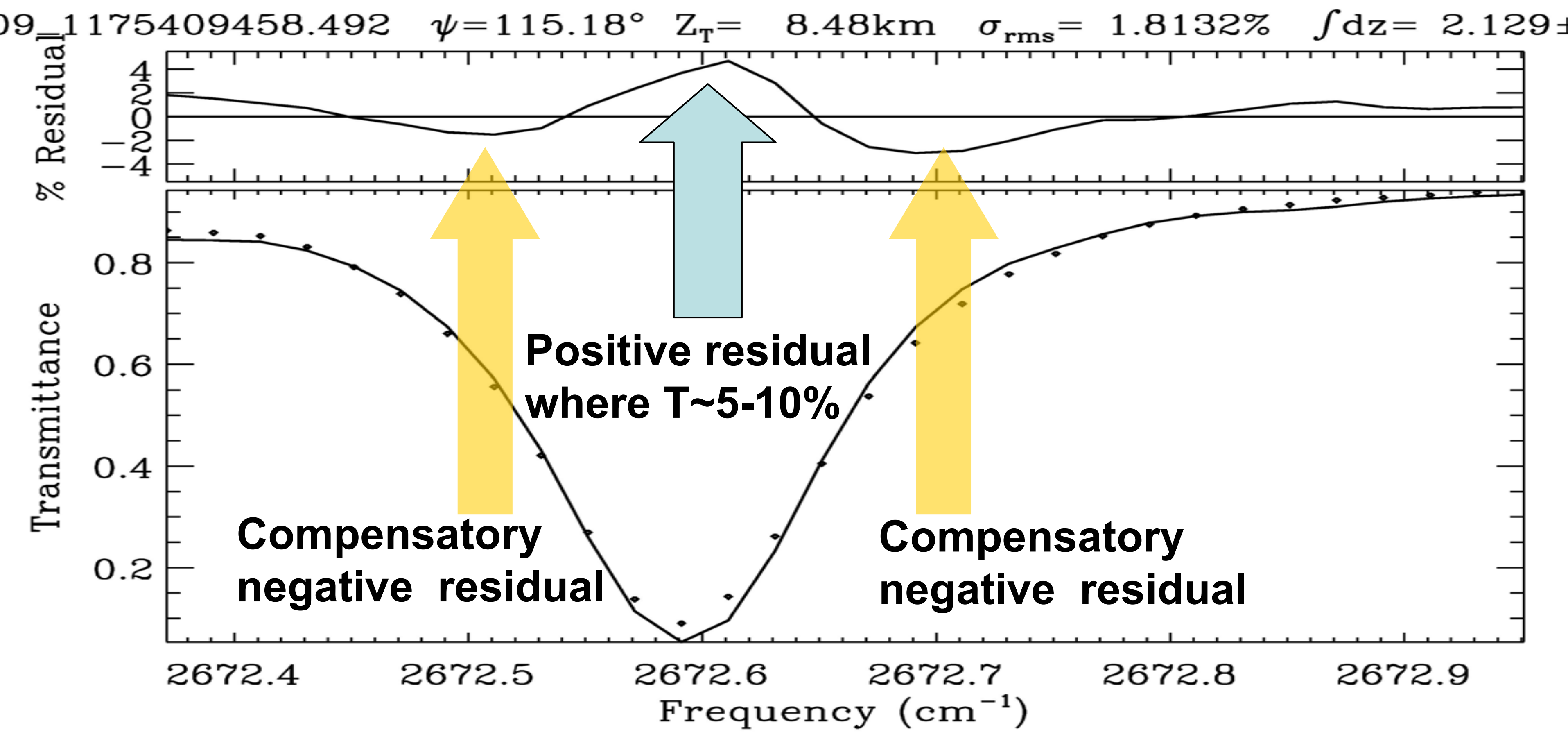
Background
While studying HDO/H_2O fractionation in tropical ACE spectra, using the JPL GFIT algorithm, we encountered two problems:
1. The retrieved H_2O & HDO profiles were dryer than expected in the tropical troposphere (a factor 2 at 10 km, worse lower), a problem also reported by Wayne Evans at last ACE meeting
2. Spectral fits to H_2O and HDO lines exhibited abnormal systematic residuals

Could these two problems have a common origin ?

Example of abnormal spectral residual: strong H_2O line at 18 km altitude

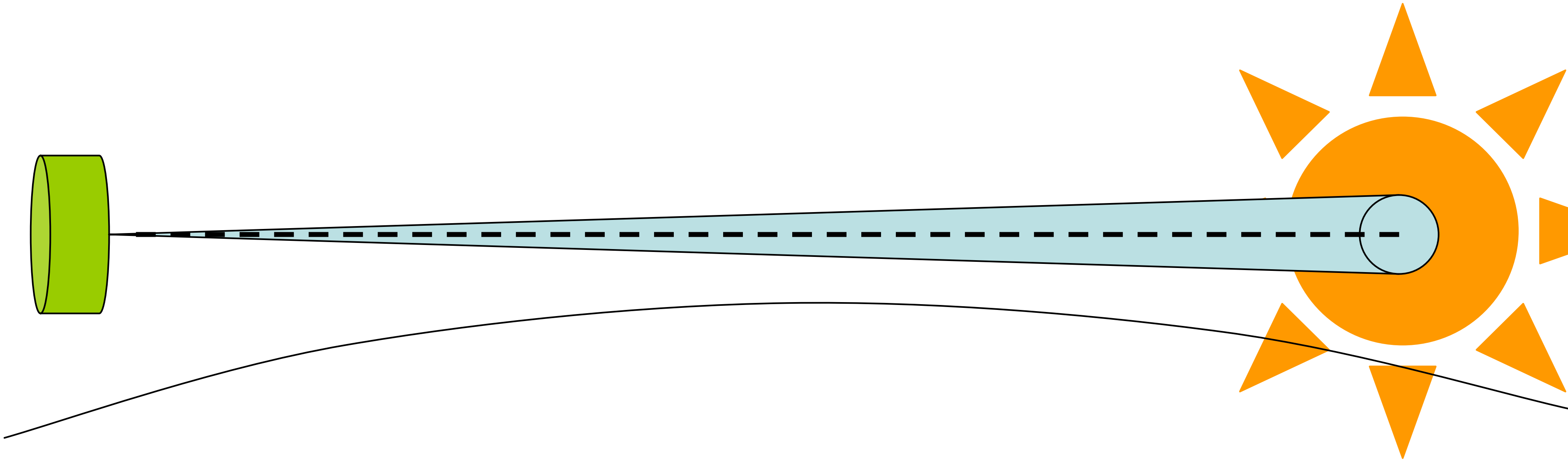


Example of abnormal spectral residual: weak HDO line at 8.5 km altitude



Why is FOV Integration necessary?

Due to the 1.25 mrad diameter of the ACE external field of view (FOV), the radiation entering the instrument from the upper and lower parts of the FOV has traversed the atmosphere at different altitudes and has different radiance spectra.



Comparison of external FOV's for solar occultation FTS

	FOV (mrad)	Altitude (km)	Distance to TP (km)	Z_{FOV} (km)
ATMOS	1.0 1.4 2.0	300	2000	2.0 2.8 4.0
MkIV	3.6	36	450	1.62
ACE	1.25	650	3000	3.75

Due to its higher altitude orbit, the ACE field of view subtends a larger range of altitudes (Z_{FOV}) at the limb than ATMOS or MkIV.

So although ATMOS and MkIV may neglect the FOV integration, ACE may not.

FOV Center Approximation

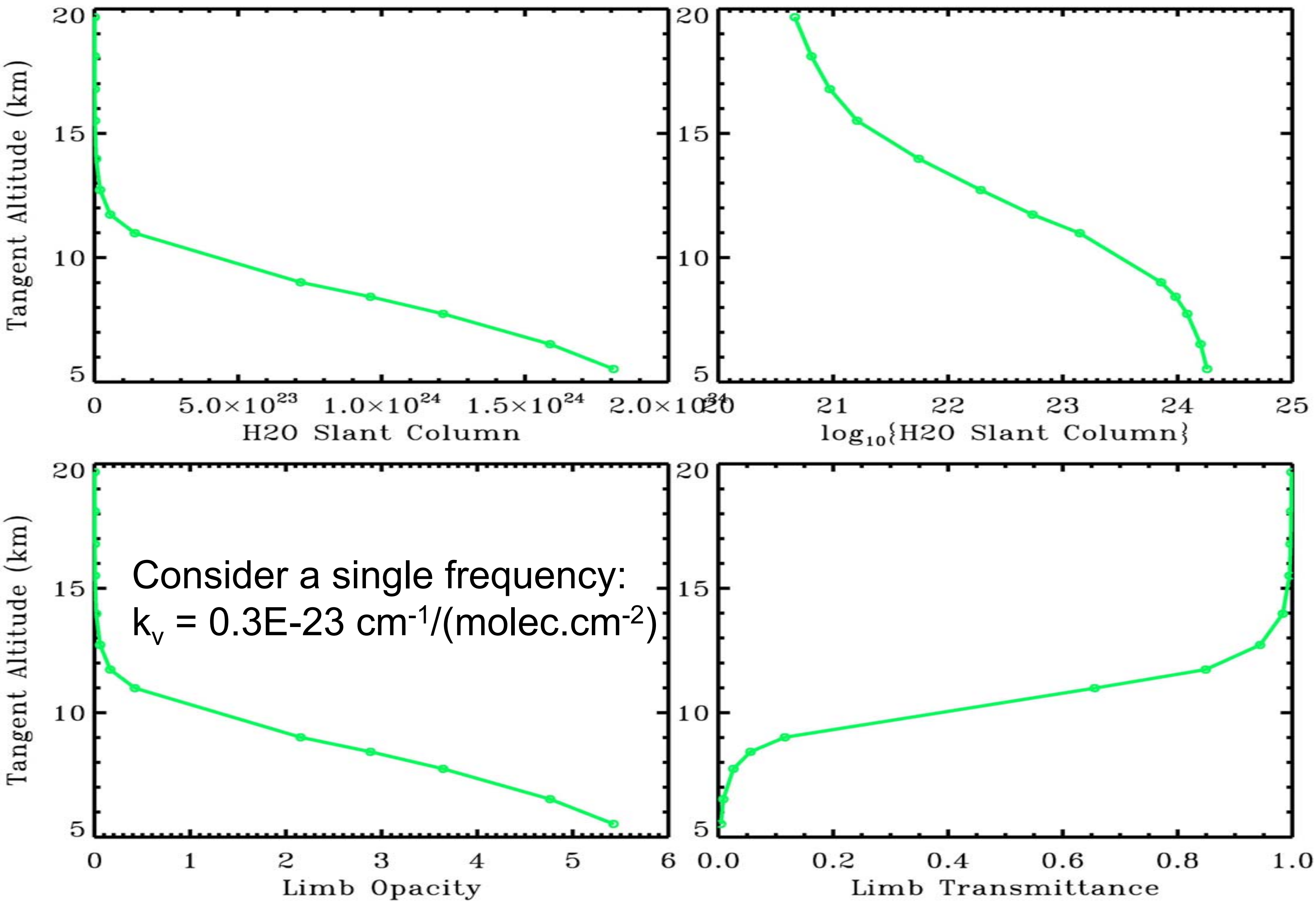
Many remote sensing retrieval algorithms have forward models that implicitly assume a linear variation of incident radiance with zenith angle, so that the FOV-center radiance provides a good approximation to the average FOV-integrated radiance.

Under this assumption, only the FOV-center ray need be considered, avoiding the computational cost/complexity of a proper integration of the incident radiance over the FOV.

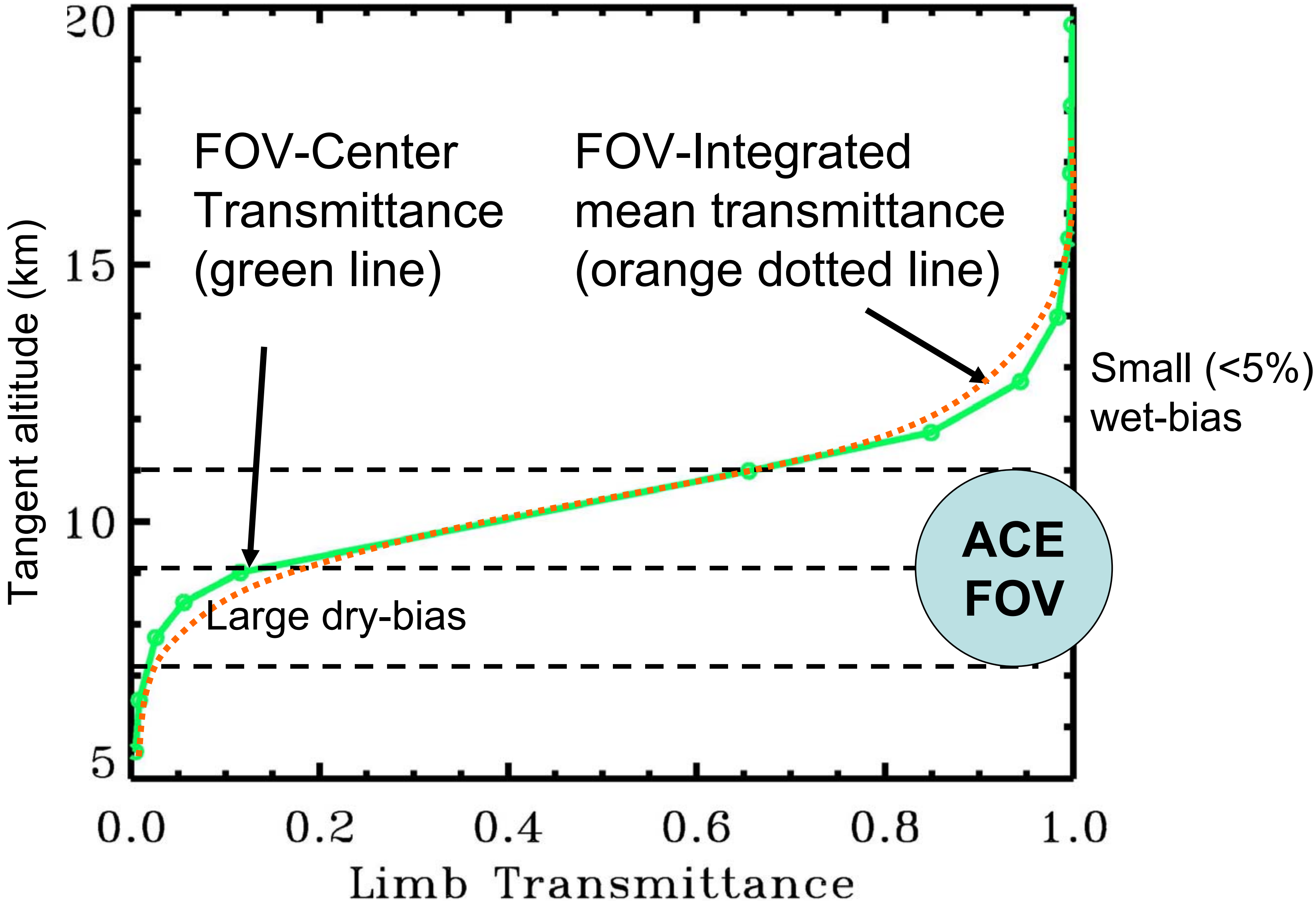
This FOV-center approximation is usually very good, except for:

- saturated absorption lines
- cases where the vertical extent of the FOV at the tangent point exceeds the scale height of the predominant absorbing gases

H_2O Limb Transmittance SS10677



How the FOV integration smoothes the limb transmittance



Worst-Case Scenario – Tropical H_2O

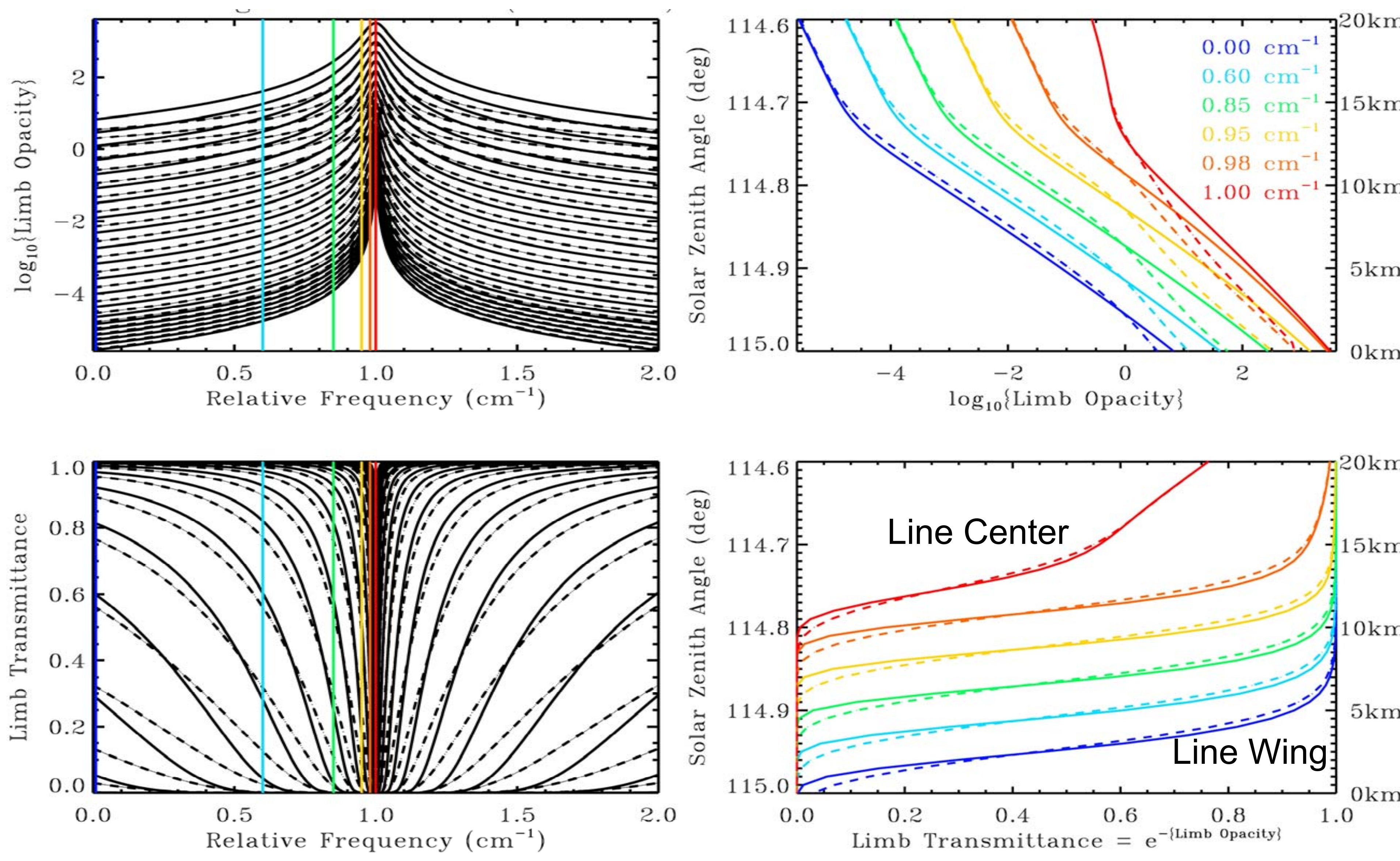
H_2O vmr = 2% near the surface; 3 ppm at 16 km (tropopause)
Additionally, pressure falls by an order of magnitude,
$[H_2O]$ decreases by 5 orders-of-magnitude (H_{H2O}=1.25 km)

At tangent altitudes below 15 km, the H_2O limb opacity will change by a factor $e^{-(3.75/1.25)}$=20 across the ACE FOV.

Limb transmittance will change even more due to Beer's Law: A spectral frequency that has a 65% transmittance at the top of the FOV will have a transmittance of 11% in the center of the FOV and 2% at the bottom -- a factor 30 change in radiance.

Thus the FOV-averaged transmittance (~18%) exceeds the FOV-center transmittance by a factor ~1.5. Neglect of the finite FOV should cause a factor ~1.5 under-estimate in H_2O.

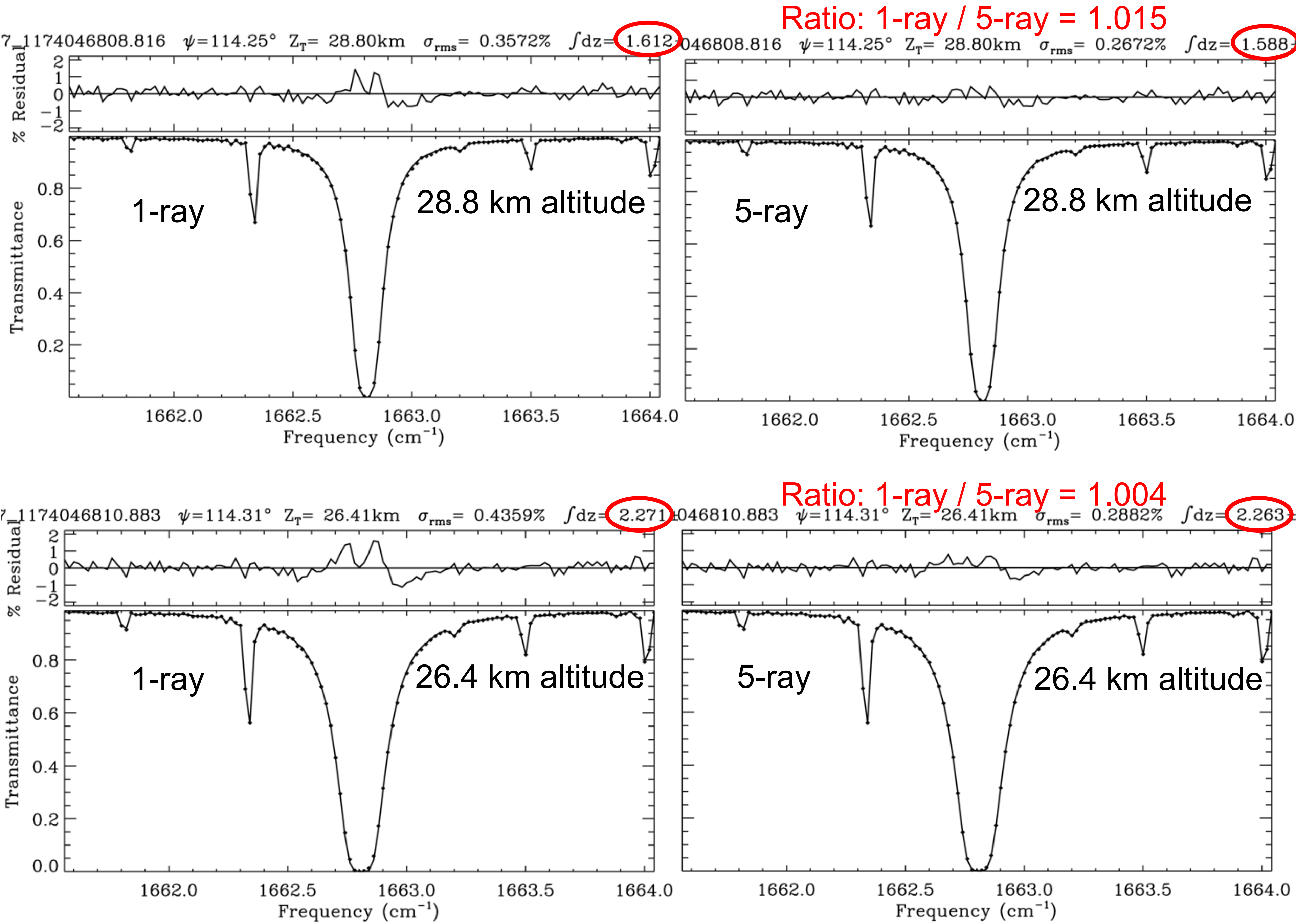
Considering Multiple Frequencies



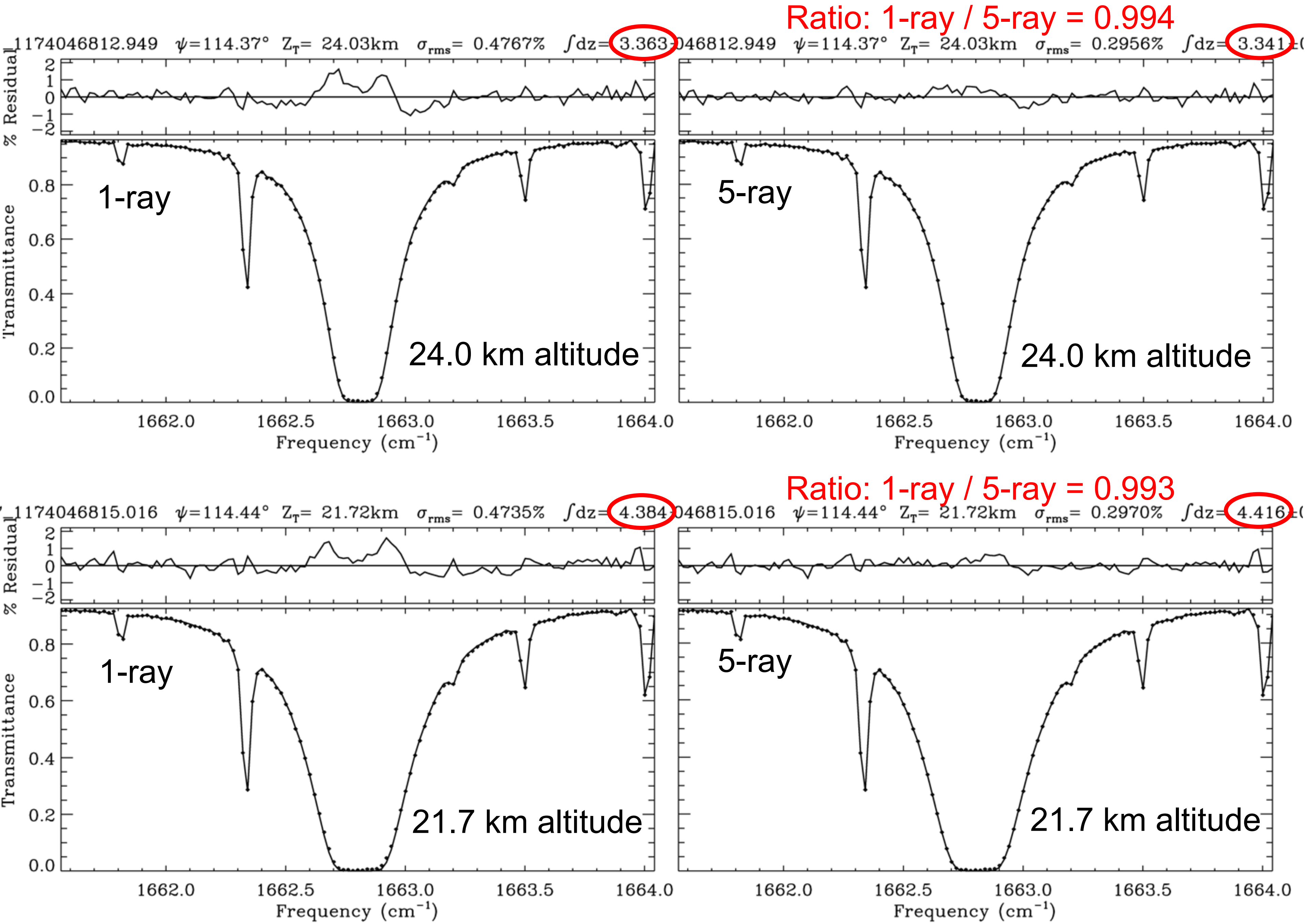
Examples of spectral residual resulting from neglect of FOV integration

In the following slides, the left-hand panels show spectral fits that results when the FOV integration is neglected

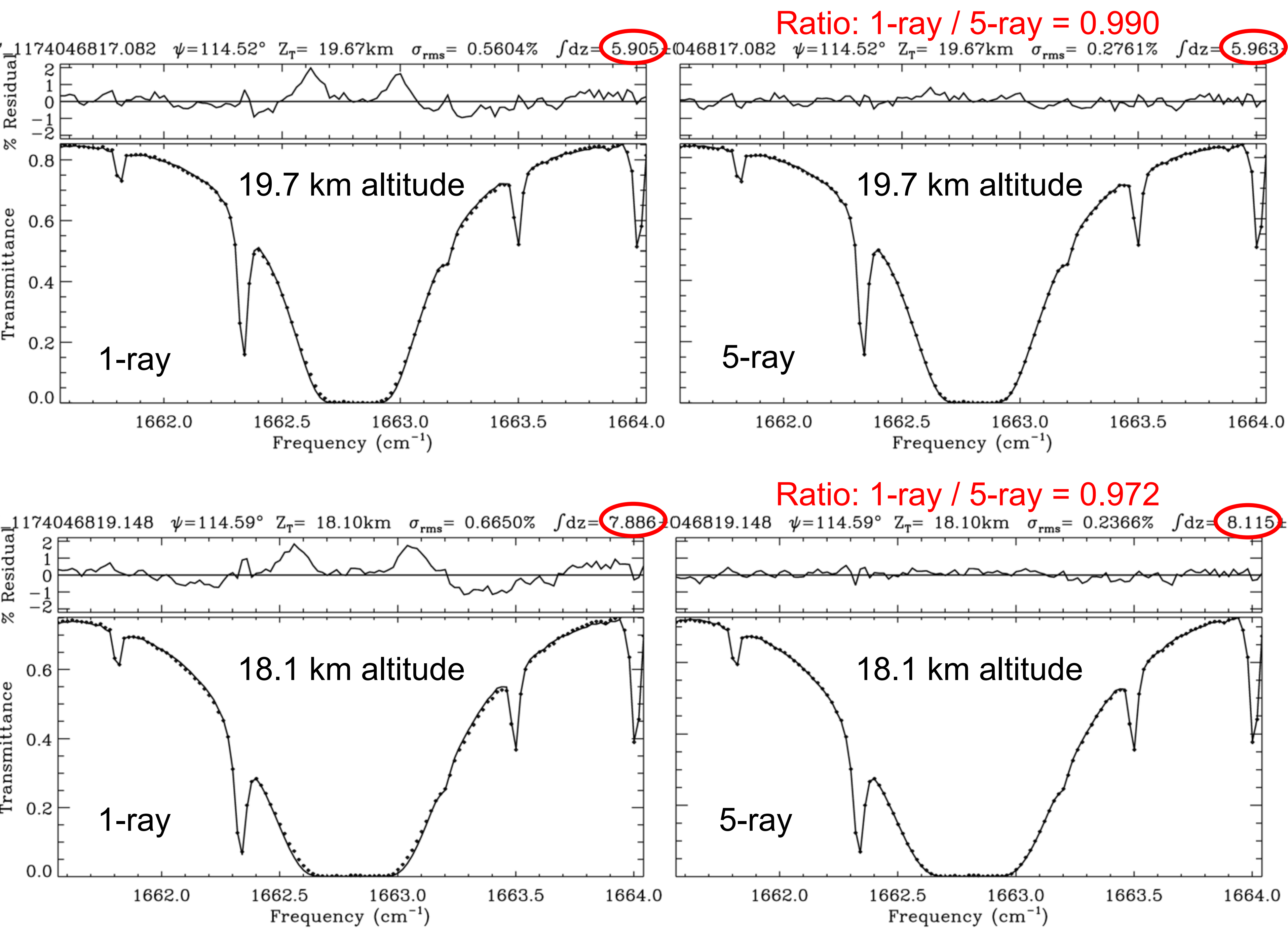
The right-hand panels show the improvement resulting from a numerical FOV integration

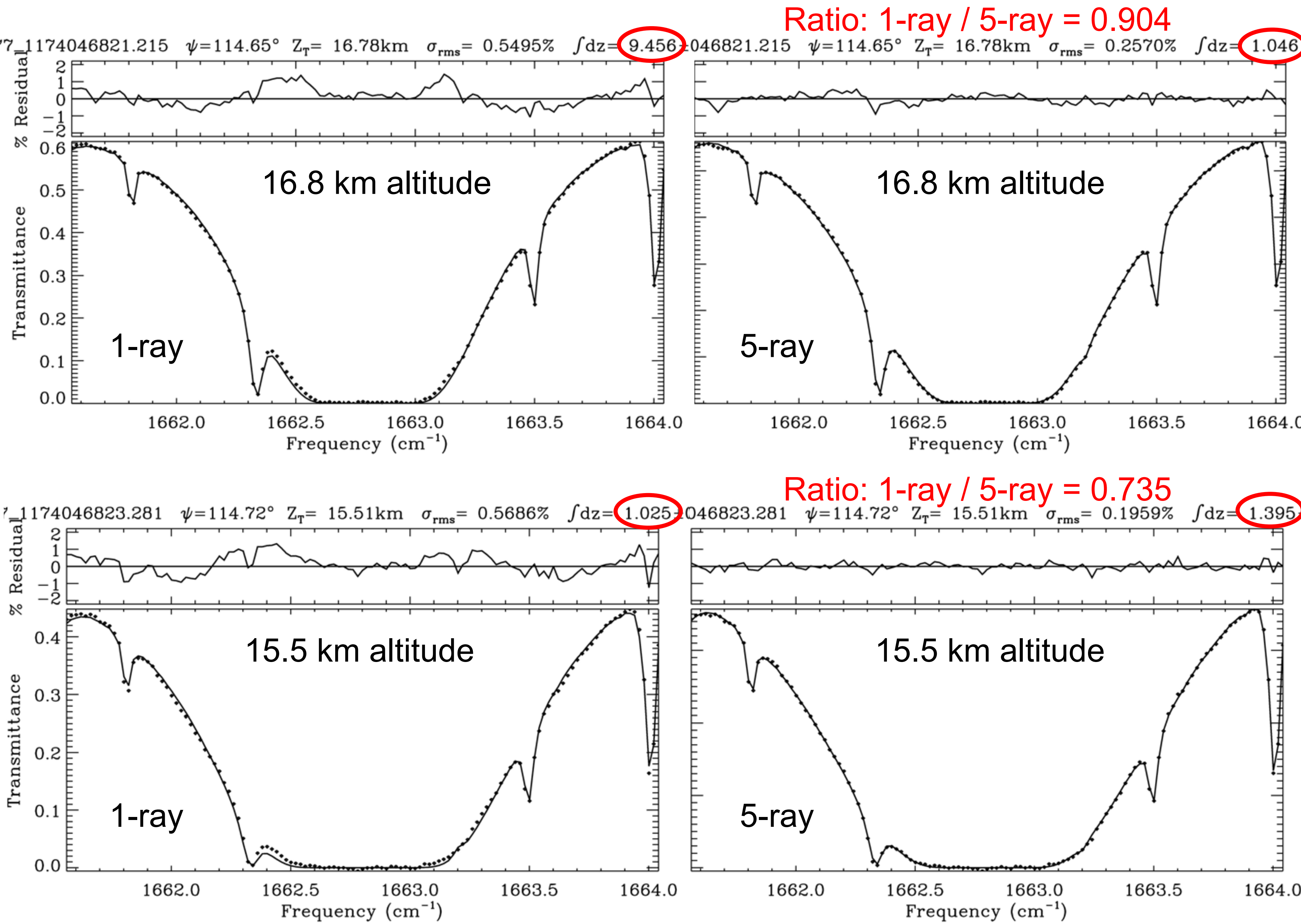


Ratio: 1-ray / 5-ray = 1.015
7_1174046808.816 ψ=114.25° Z_T= 28.80km σ_rms= 0.3572% ∫dz= 1.612
046808.816 ψ=114.25° Z_T= 28.80km σ_rms= 0.2672% ∫dz= 1.588
% Residual
Transmittance
1-ray
28.8 km altitude
5-ray
28.8 km altitude
Frequency (cm⁻¹)
Ratio: 1-ray / 5-ray = 1.004
7_1174046810.883 ψ=114.31° Z_T= 26.41km σ_rms= 0.4359% ∫dz= 2.271
046810.883 ψ=114.31° Z_T= 26.41km σ_rms= 0.2882% ∫dz= 2.263
1-ray
26.4 km altitude
5-ray
26.4 km altitude
Frequency (cm⁻¹)



Ratio: 1-ray / 5-ray = 0.994
1174046812.949 ψ=114.37° Z_T= 24.03km σ_rms= 0.4767% ∫dz= 3.363
046812.949 ψ=114.37° Z_T= 24.03km σ_rms= 0.2956% ∫dz= 3.341
1-ray
5-ray
24.0 km altitude
24.0 km altitude
Ratio: 1-ray / 5-ray = 0.993
1174046815.016 ψ=114.44° Z_T= 21.72km σ_rms= 0.4735% ∫dz= 4.384
046815.016 ψ=114.44° Z_T= 21.72km σ_rms= 0.2970% ∫dz= 4.416
1-ray
5-ray
21.7 km altitude
21.7 km altitude
% Residual
Transmittance
Frequency (cm⁻¹)


Ratio: 1-ray / 5-ray = 0.990
1174046817.082 ψ=114.52° Z_T= 19.67km σ_rms= 0.5604% ∫dz= 5.905
046817.082 ψ=114.52° Z_T= 19.67km σ_rms= 0.2761% ∫dz= 5.963
19.7 km altitude
1-ray
5-ray
% Residual
Transmittance
Frequency (cm⁻¹)
Ratio: 1-ray / 5-ray = 0.972
1174046819.148 ψ=114.59° Z_T= 18.10km σ_rms= 0.6650% ∫dz= 7.886
046819.148 ψ=114.59° Z_T= 18.10km σ_rms= 0.2366% ∫dz= 8.115
18.1 km altitude
1-ray
5-ray

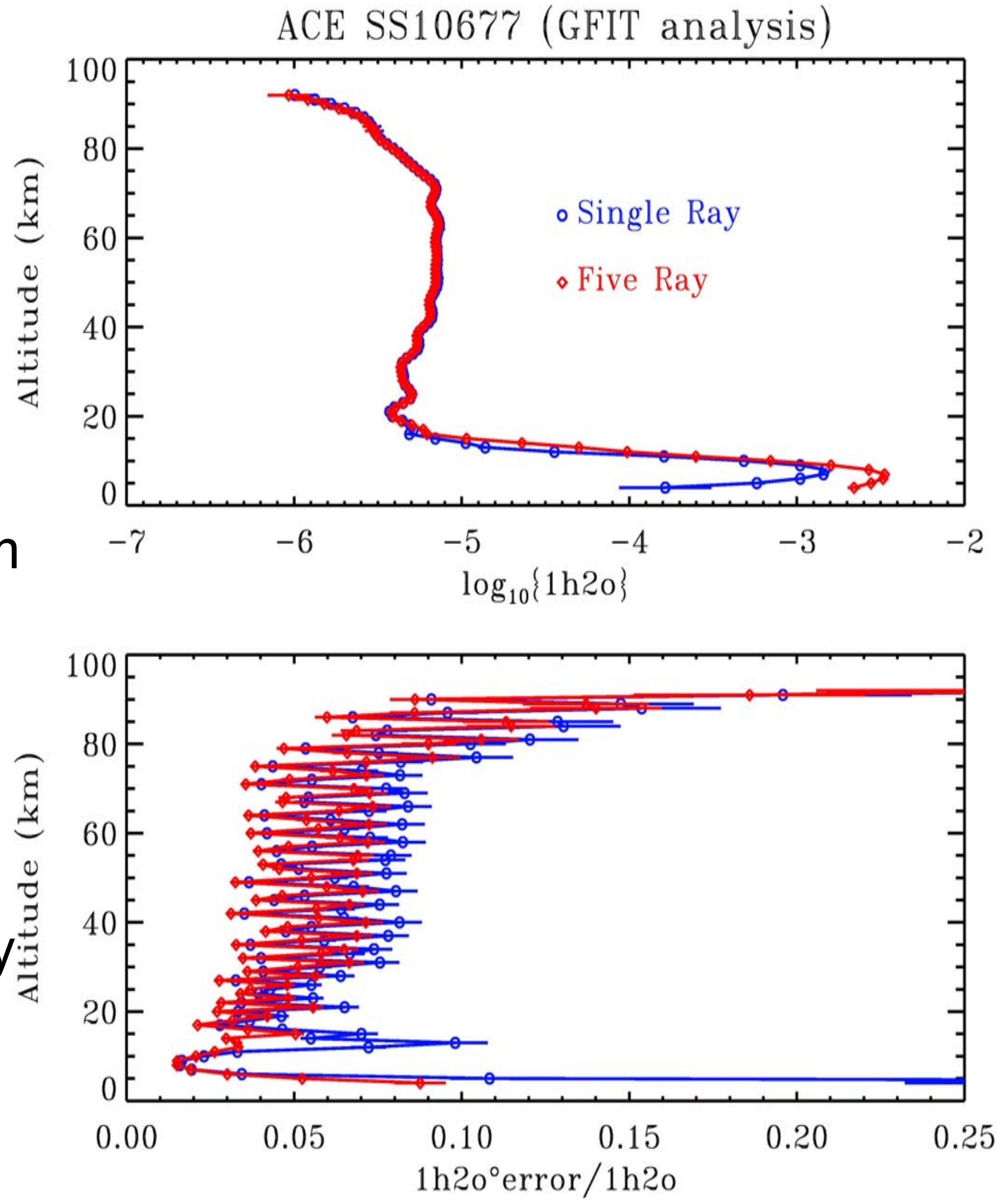


Ratio: 1-ray / 5-ray = 0.904
7_1174046821.215 ψ=114.65° Z_T= 16.78km σ_rms= 0.5495% ∫dz= 9.456
046821.215 ψ=114.65° Z_T= 16.78km σ_rms= 0.2570% ∫dz= 1.046
% Residual
Transmittance
16.8 km altitude
1-ray
16.8 km altitude
5-ray
Frequency (cm⁻¹)
Ratio: 1-ray / 5-ray = 0.735
7_1174046823.281 ψ=114.72° Z_T= 15.51km σ_rms= 0.5686% ∫dz= 1.025
046823.281 ψ=114.72° Z_T= 15.51km σ_rms= 0.1959% ∫dz= 1.395
15.5 km altitude
1-ray
15.5 km altitude
5-ray
Frequency (cm⁻¹)

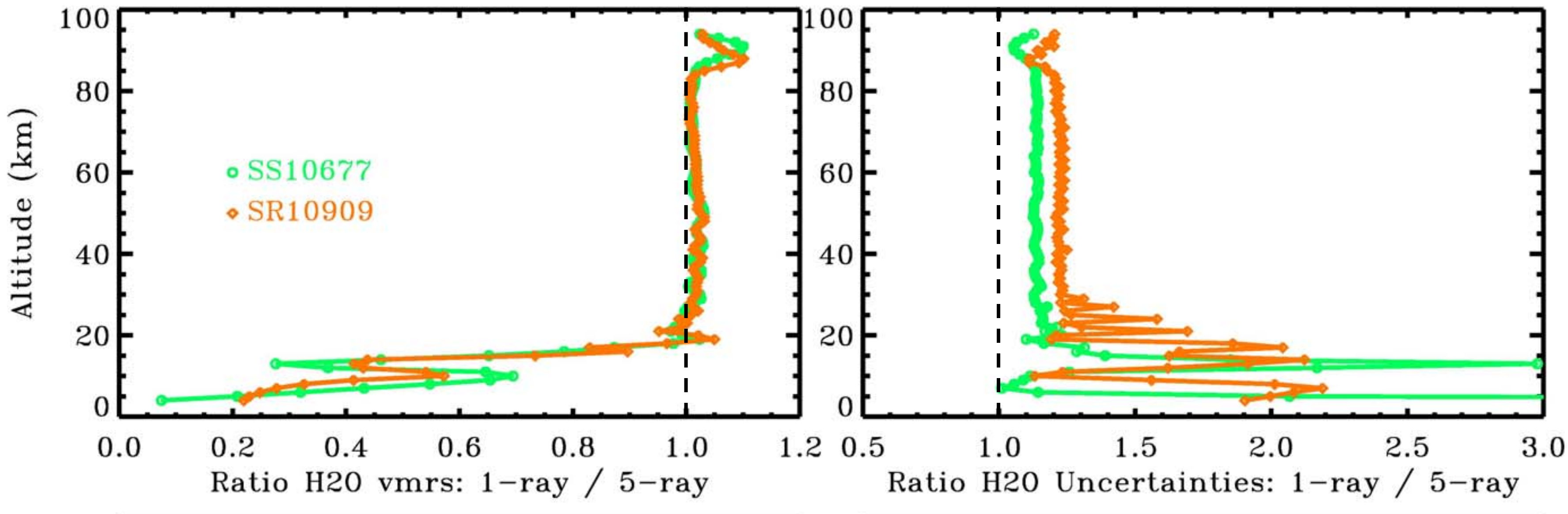
Retrieved H_2O profiles with (red) and without (blue) FOV integration

Upper Panel:
5-ray FOV integration produces slightly drier H_2O profiles above 20 km but much wetter below

Lower Panel:
Retrieval error (from rms spectral fits) is better at all altitudes with the 5-ray FOV integration



Ratio: 1-ray / 5-ray vmr profiles



Neglecting FOV integration causes:

- Small overestimate of H_2O in stratosphere
- Large under-estimate of H_2O in the troposphere
- Worse retrieval uncertainties at all altitudes

Important Clarification

I'm not saying that the archived ACE H_2O profiles are wrong by a factor 2 in the tropopause

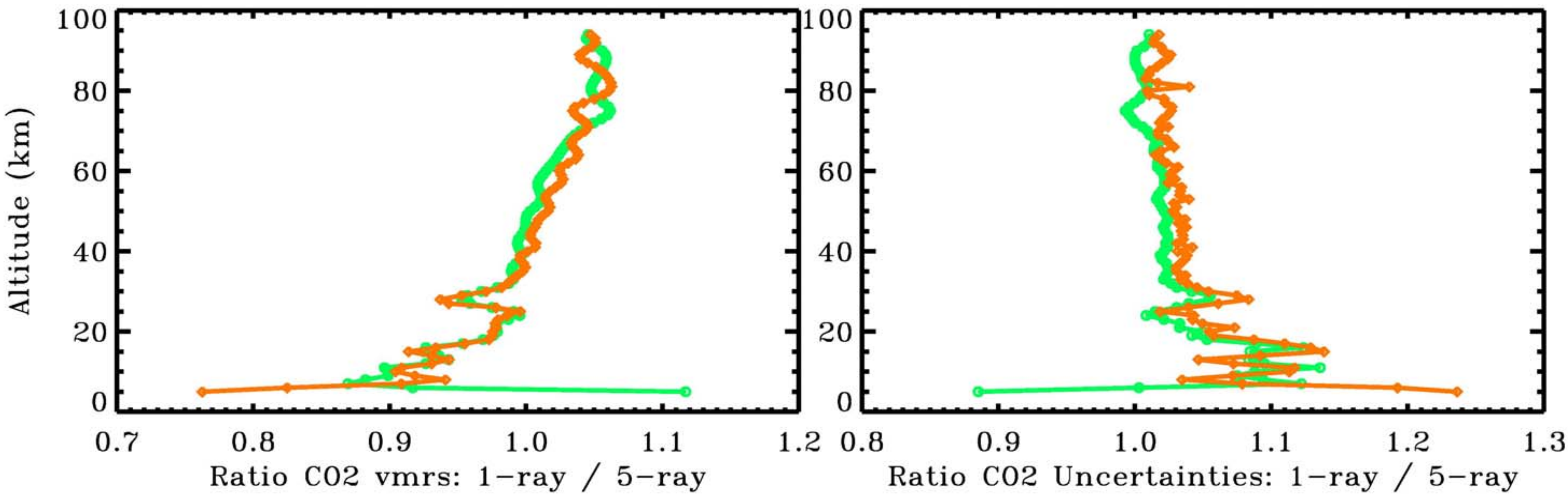
The magnitude of the tropospheric dry bias depends on the degree of saturation of the selected H_2O lines.

The ensemble of H_2O lines that **I** used, produced a factor 2 error due to neglecting the FOV integration.

The ACE H_2O lines are weaker than the ones that I chose, in which case the tropospheric dry bias will be smaller.

But, the best (i.e., T-insensitive, parent isotopolog) H_2O lines do become highly saturated in the troposphere

Impact on other gases (CO_2)



Impact of FOV integration (or neglect thereof) on CO_2 is much less than on H_2O, especially in the troposphere.

Skews retrieved CO_2 profiles, relative to single-ray approach, but improves uncertainties.

Like H_2O, magnitude of impact likely depends on how strong are the selected CO_2 lines.

Conclusions (1)

FOV integration is necessary whenever there is a non-linear variation of radiance vertically across the FOV such that the spectrum at the center of the FOV is not a good representation of the FOV-averaged spectrum. This can be caused by:

- Weak absorbers whose vmr varies exponentially with altitude
- Strong, uniformly-mixed absorbers (due to Beer's law $e^{-k.x}$)

This effect is quadratic in the width of the FOV, so the impact on ACE data will be (3.75/1.62)2 = 5x worse than on MkIV

Conclusions (2)

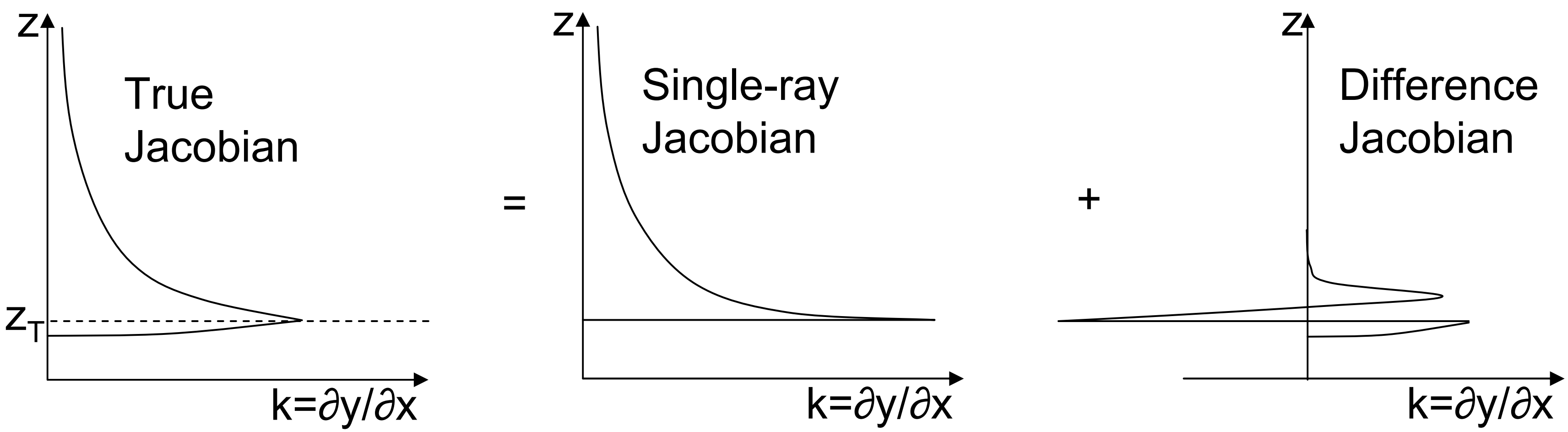
The finite FOV width causes also distortion of the spectral line shapes because:

- At frequencies where the limb path is nearly opaque, photons come exclusively from the upper part of the FOV
- At frequencies where the limb path is fairly transparent, photons come more equally from the all parts of the FOV

Thus, in the vicinity of a strong line, the effective tangent altitude will be higher in the line center than in the line wings. For H_2O, with a tropospheric scale height of only 1¼ km, this altitude ambiguity can cause a large retrieval error.

Although strong H_2O lines can be ignored for the purposes of doing H_2O retrievals, their large residuals nevertheless upset retrievals of other gases whose absorption lines in the vicinity

Side-Effect: Neglecting FOV integration smoothes the retrieved vmr profiles



Difference Jacobian has zero area (hence no bias in retrieved vmr) and strong anti-correlation between tangent level and adjacent levels

Difference Jacobian resembles (2'nd difference) smoothing constraint. Hence, use of single-ray Jacobians smoothes the retrieved vmr profile

When Chris Boone switched from single-ray to 11-ray forward model, this implicit smoothing constraint disappeared, resulting in increased noise sensitivity when retrieval grid Δz = tangent altitude Δz < 3.75 km

Summary – Impact of neglecting FOV Integration

Under-estimates tropospheric H_2O, esp. for saturated lines
- Avoiding saturated lines minimizes impact, but this is difficult (e.g. within ACE bandpass, lower tropospheric H_2O lines are either saturated, isotopologs, or T-sensitive)

Over-estimates unsaturated lines (e.g. stratospheric H_2O)

Systematically distorts spectral line shapes (and hence residuals) for strong lines.

These systematic residuals indirectly affect other species whose absorption lines are blended with strong H_2O lines.

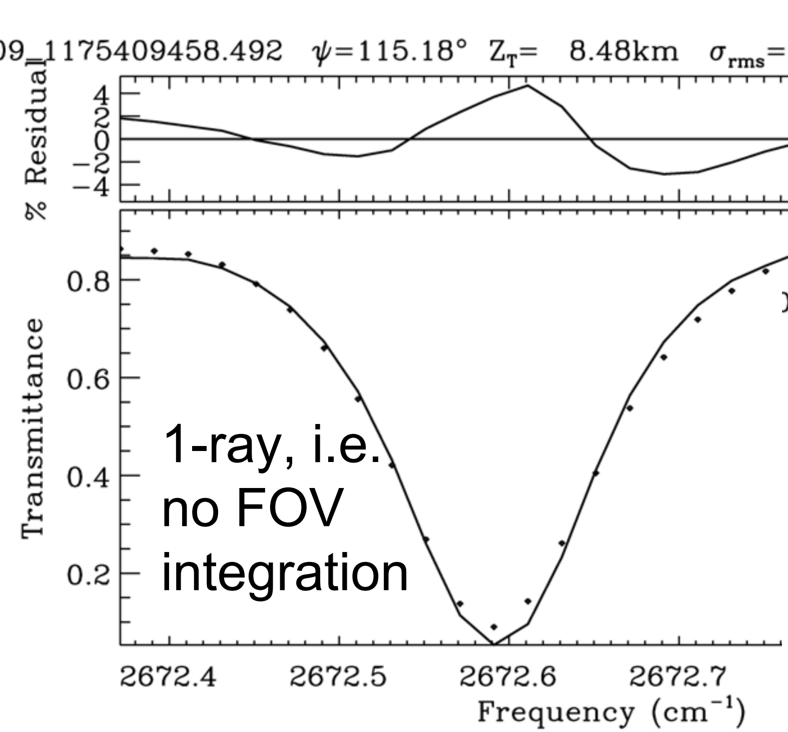
Small effect on uniformly mixed gases, e.g. CO_2

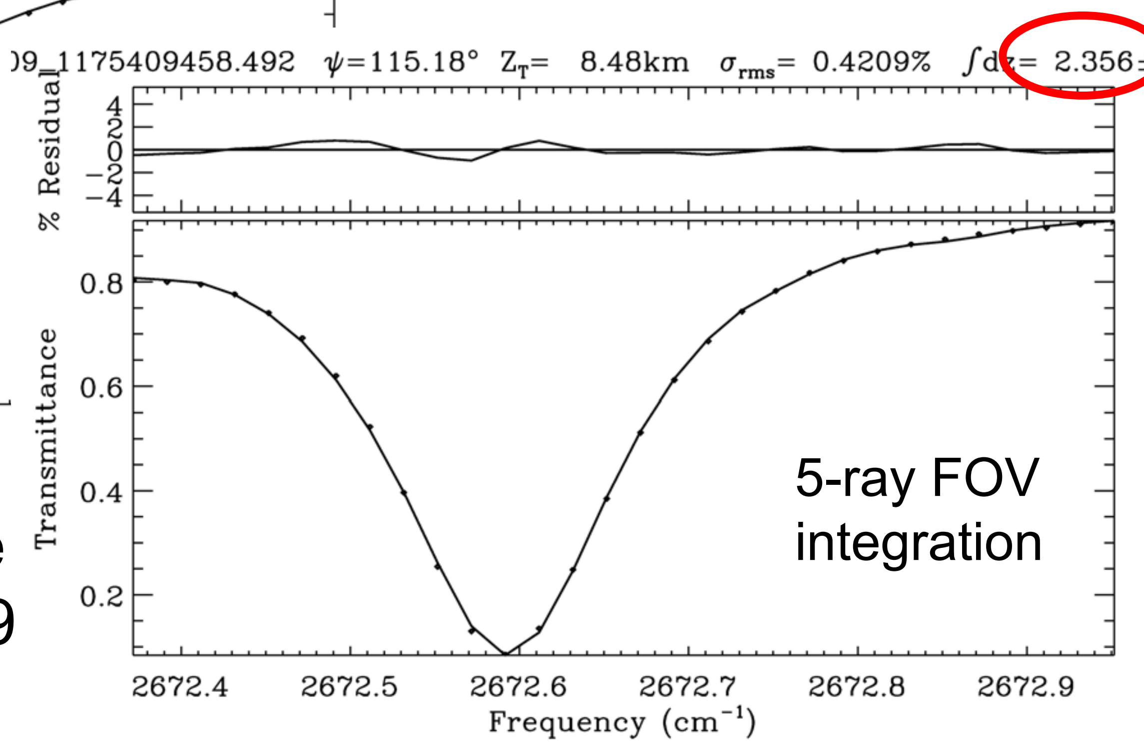
Provides implicit smoothing constraint

Additional Material

Spectral fits to the HDO line used in figure 3 of Boone et al. [2007], with and without the FOV integration.

11% HDO increase using 5-ray FOV ∫





8.5 km tangent altitude spectrum from sr10909