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The new σ4Mars radiative transfer code for the analysis of the Martian atmosphere

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This work exists in the context of Earth-Moon-Mars project by ASI-CNR-INAF

11.06.2026

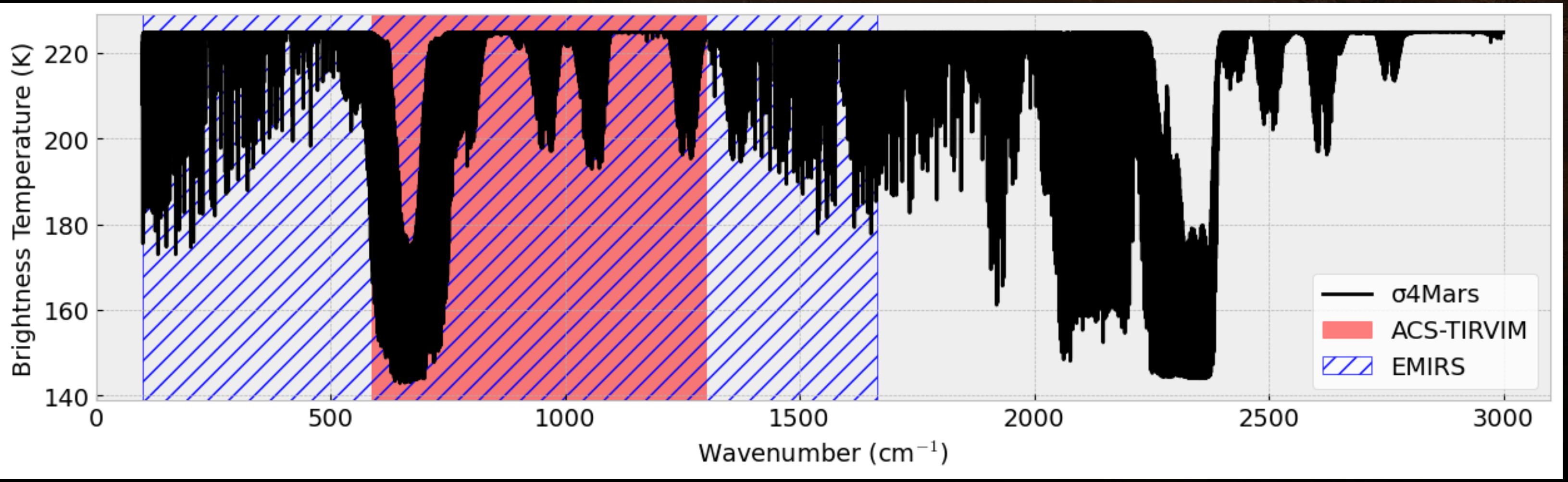
A Forward Model for Martian IR spectrum

State vector:

$P(z), T(z), VMR_g(z),$
$MMR_a(z), \mathrm{r_{eff}}(z), \mathrm{T_{surf}},$
$\varepsilon(\nu), \mu_o, \mu_{sun}$

FM →

Radiance $I(\nu)$



Martian IR instruments

Mars Express-PFS
2003
250 – 1750 cm-1

ExoMars–ACS-TIRVIM
2016
650-1300 cm-1

Hope–EMIRS
2020
100-1650 cm-1

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σ4Mars key points

- Speed: Can be used for fast retrieval analyzing large amount of data.
- Generality: Applicable to diverse atmospheric conditions and instruments.
- **Physically based: understanding of the physical process, analytical Jacobians for retrievals.**
- Proven Framework: The Martian implementation is based on a terrestrial radiative transfer code (σ-FORUM/ σ-IASI/F2N) extensively validated for terrestrial applications and mantained.

σ4Mars structure

σ4Mars features	
Geometry	Nadir looking
Spectral Range	100-3000 cm^{-1}
Resolution	10^{-2} cm^{-1}
Pressure layers	55 fixed layers
Gas	CO_2, H_2O, CO, O_3, HCl, HDO
Continuum Absorption	Self-CO_2 Collison Induced Absorption (CIA)
Scattering	Dust (Water Ice in the future)
Surface	Lambertian
Instrumental Response Function	Customizable, ACS-TIRVIM, EMIRS

INPUT

σ4Mars

$$I(\nu) = I_s(\nu) + I_a(\nu) + I_r(\nu) + I_i(\nu)$$

OUTPUT: Radiance

OUTPUT: Jacobians

Gas OD

Cloud/Aerosol properties

CIA coefficients

Precomputed

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Gas Optical Depth

The Gas OD of the Martian atmosphere are computed using a line-by-line radiative transfer code, the Planetary Spectrum Generator (PSG) by NASA.

OD4Mars

Computation of a mean Martian profile from atmospheric database (the Martian Climate Database)

↓

OD computation using PSG (for each gas, T, ν) and binning at σ4Mars resolution

↓

OD fitting as a cubic polynomial function of T

GitHub

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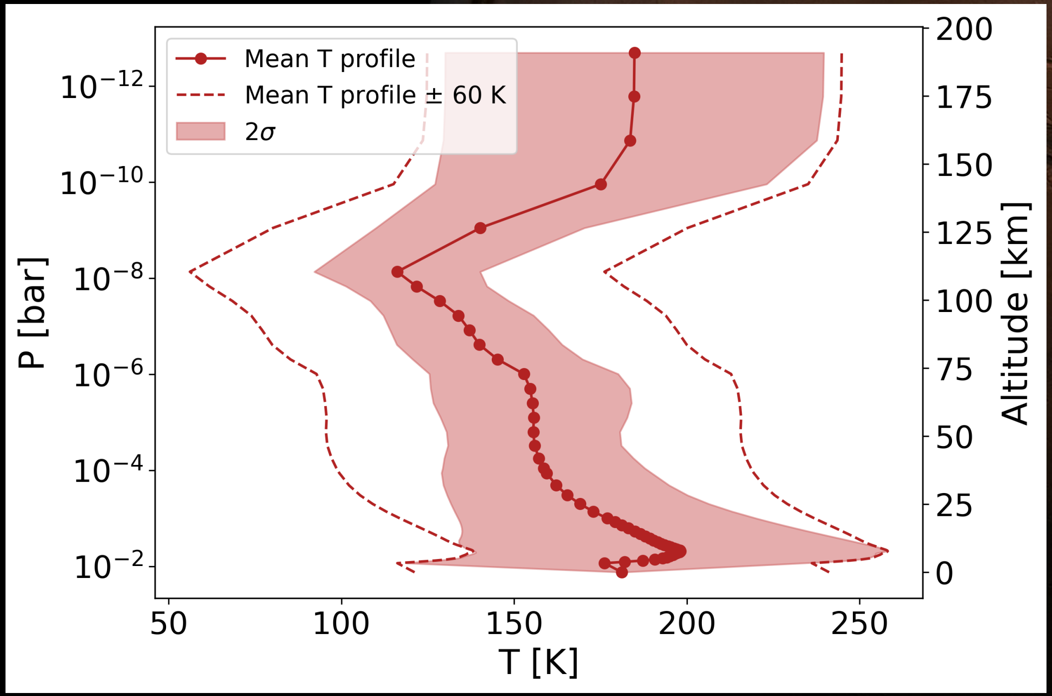
Gas Optical Depth

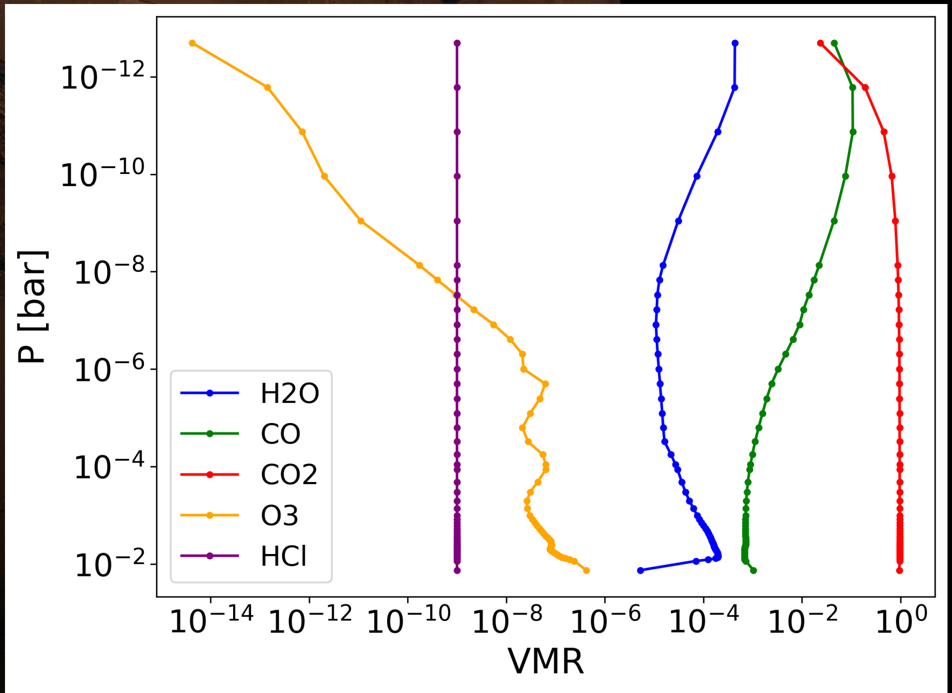
Computation of a mean Martian profile from atmospheric database (the Martian Climate Database)

Martian temperature and gas VMR profiles are retrieved for one Martian year (from 24-03-2019 to 08-02-2021) every ~5 degree in latitude and longitude (64×49).

Temperature profile



Gas Profiles



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Gas Optical Depth

OD computation using PSG (for each gas, T, ν and pressure layer) and binning at σ4Mars resolution

- Spectral database: HITRAN2020
- Spectral resolution: 10^{-4} cm^{-1}
- Pressure layer: fixed pressure layers of σ4Mars

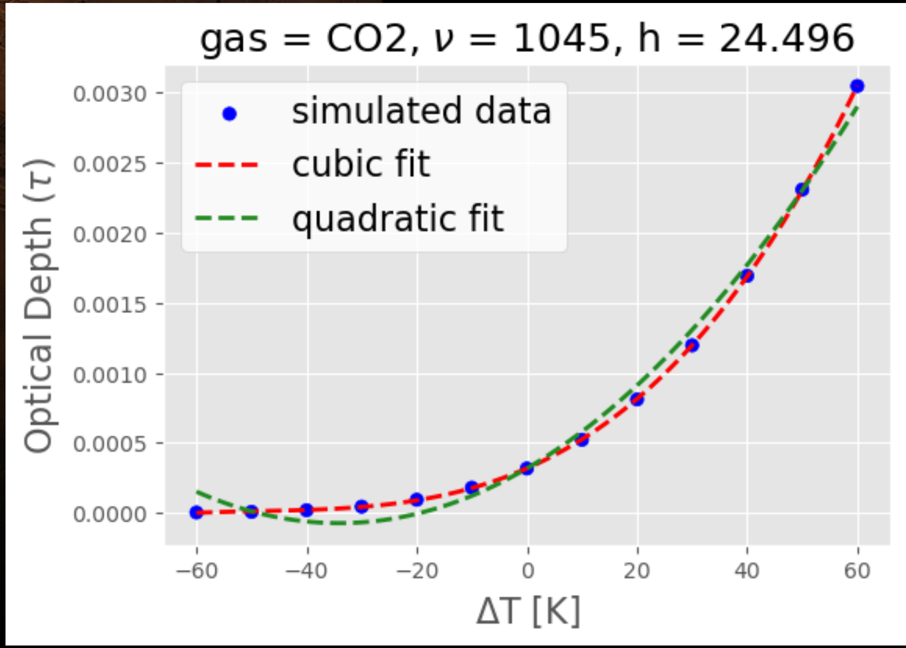
Gas Optical Depth

OD computation using PSG (for each gas, T, ν and pressure layer) and binning at σ4Mars resolution

- Spectral database: HITRAN2020
- Spectral resolution: 10^{-4} cm^{-1}
- Pressure layer: fixed pressure layers of σ4Mars

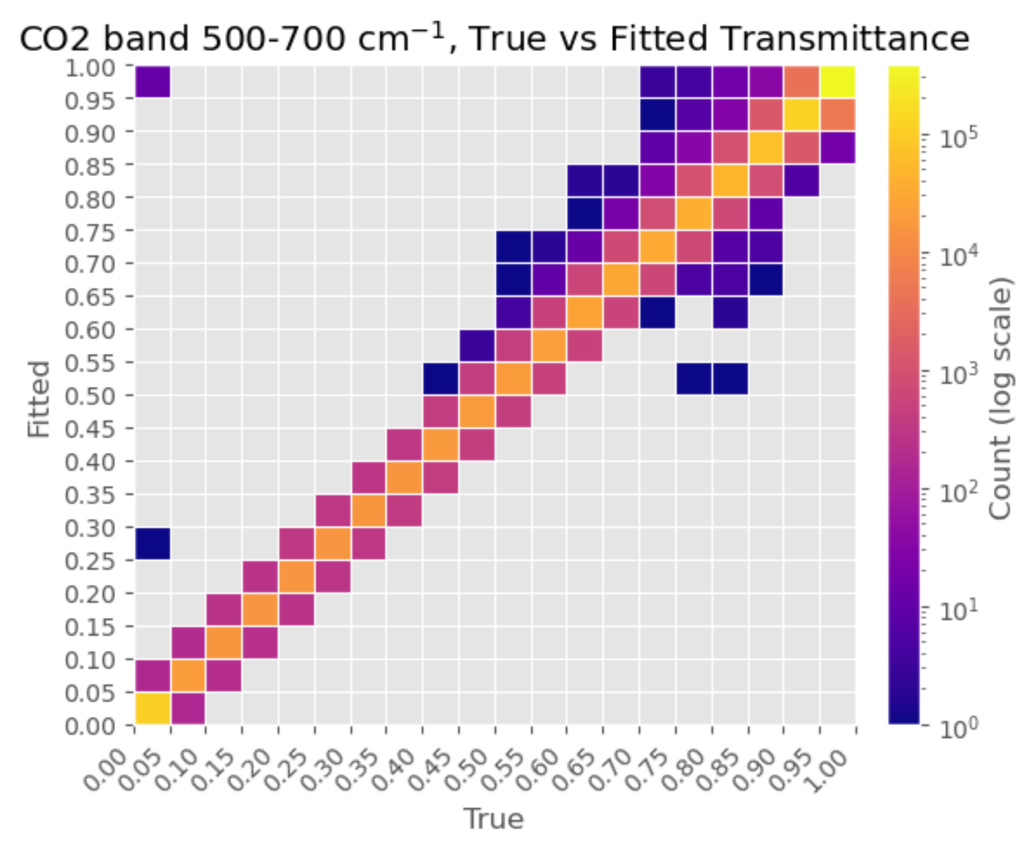
OD fitting as a cubic polynomial function of T

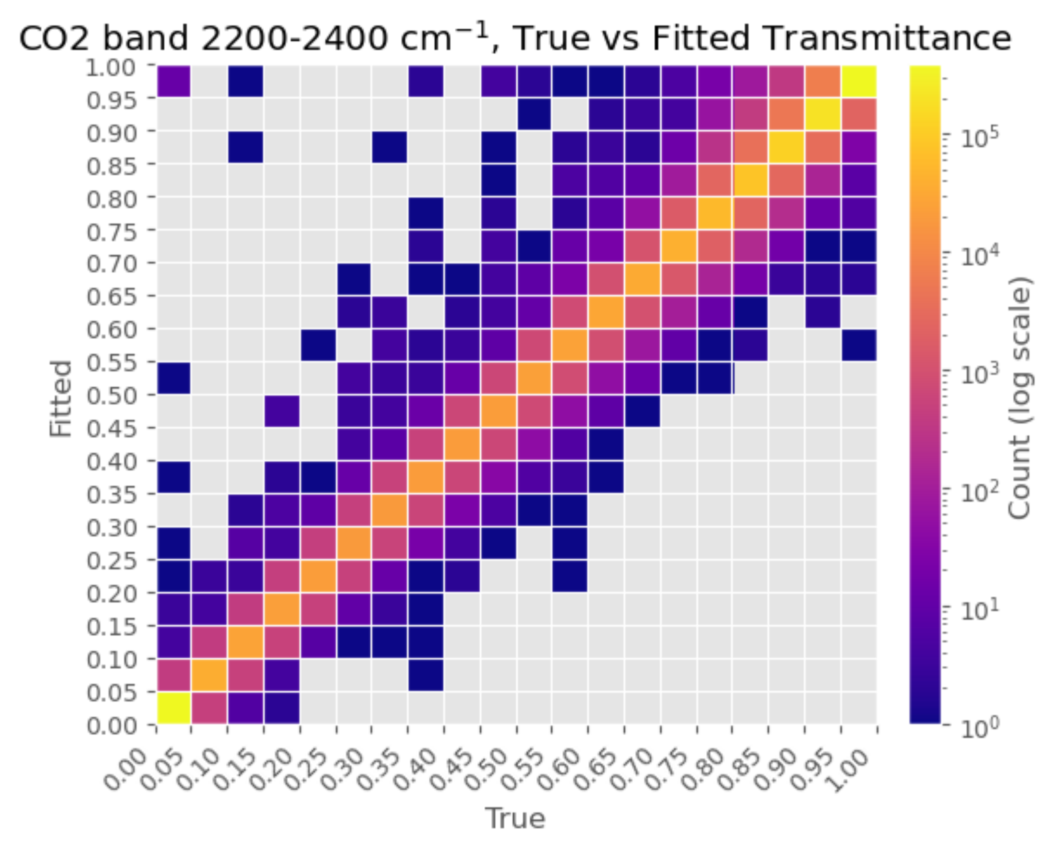
$$\tau_{l,g,\nu} = \frac{\rho_{l,g}}{\rho_{0,l,g}}\left(C_{l,g,\nu,0} + C_{l,g,\nu,1}\Delta T_l + C_{l,g,\nu,2}\Delta T_l^2 + C_{l,g,\nu,3}\Delta T_l^3\right)$$



Gas Optical Depth

Fit visualization: correlation





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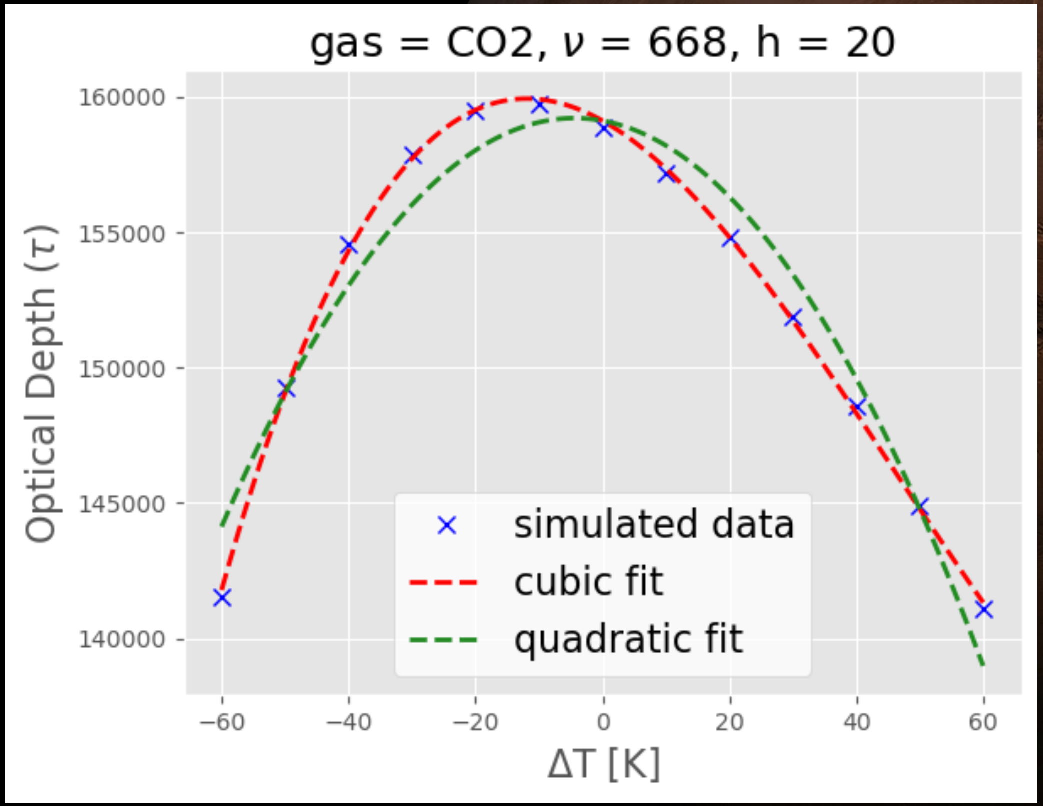
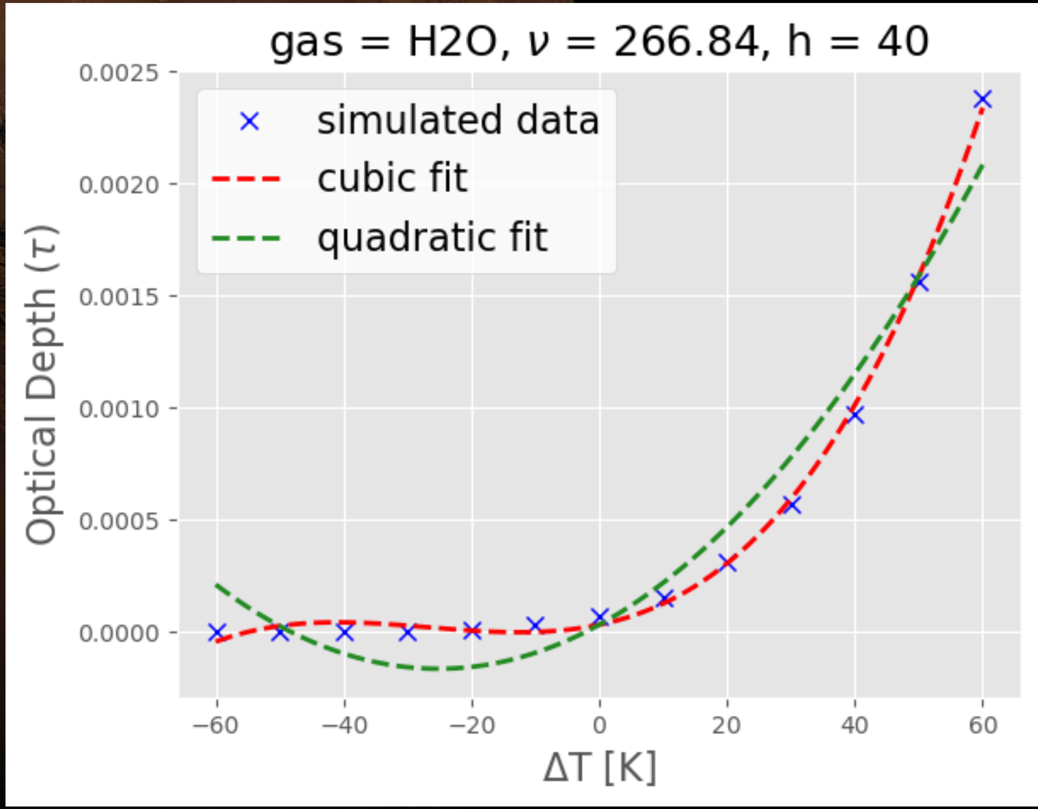
Gas Optical Depth

Fit visualization: quadratic vs cubic





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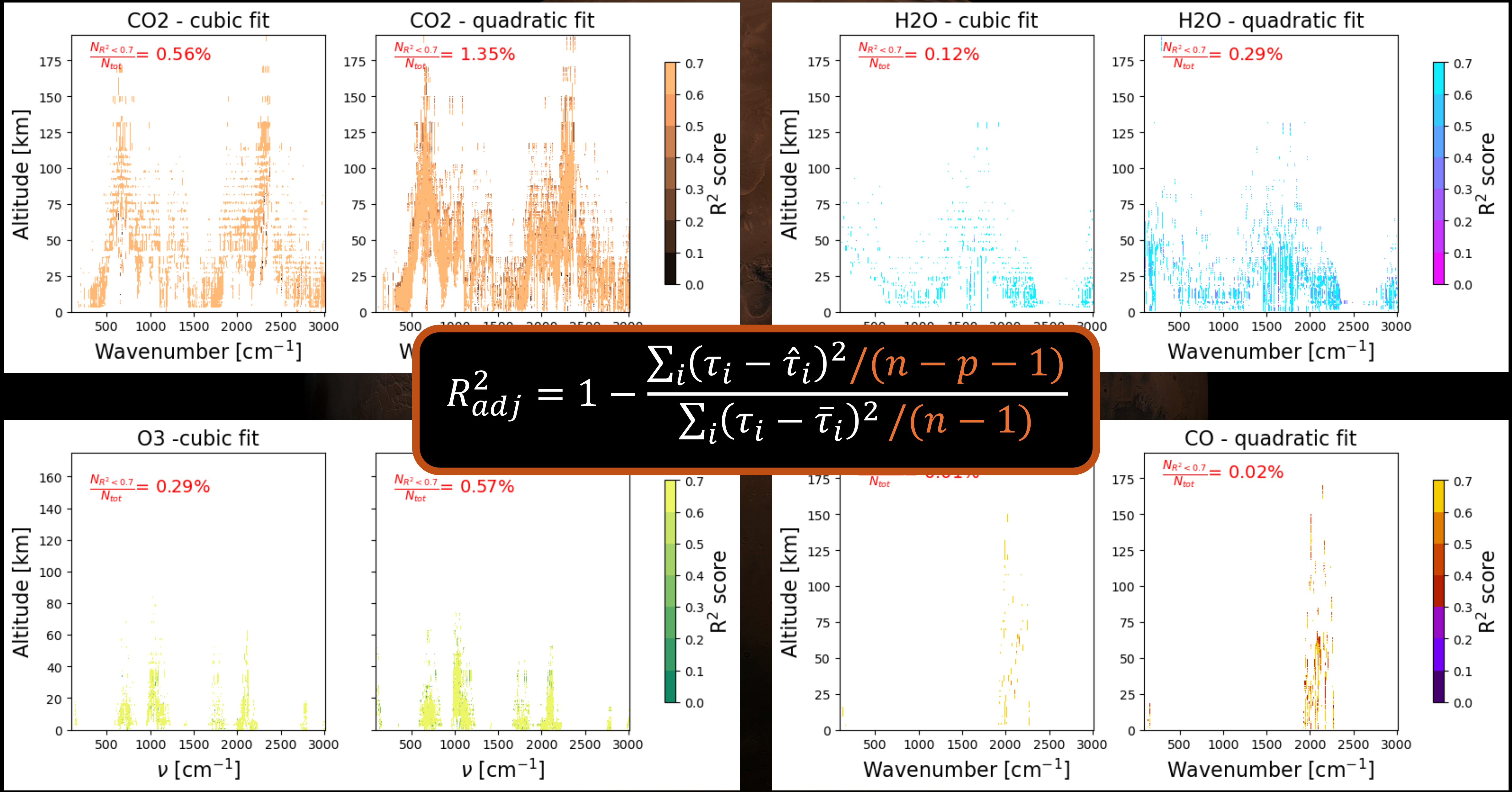
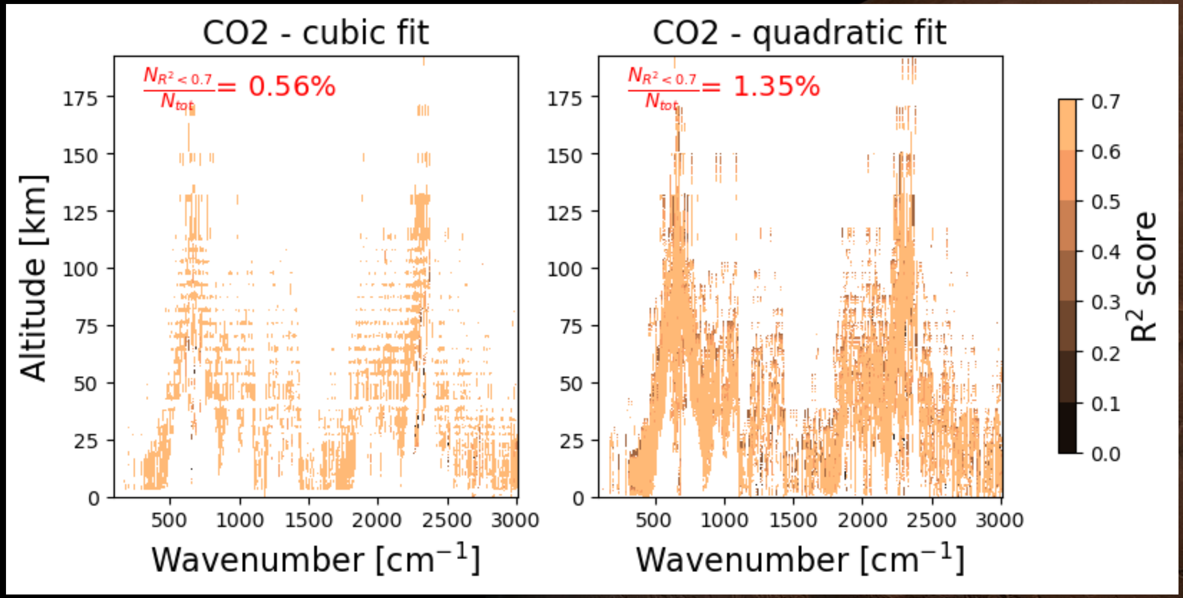
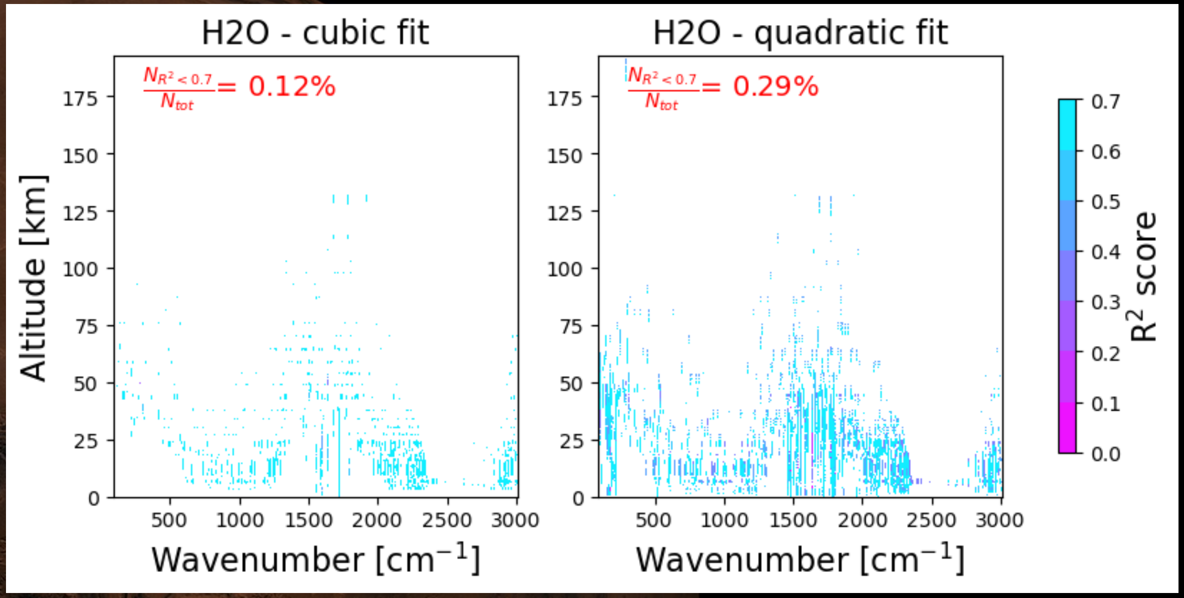
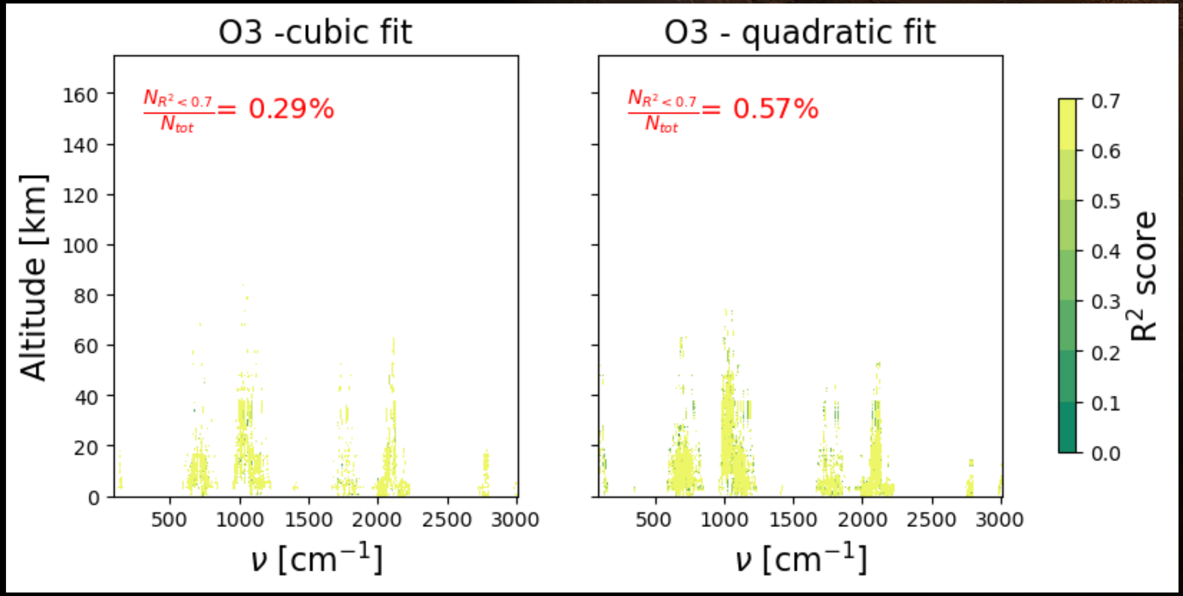
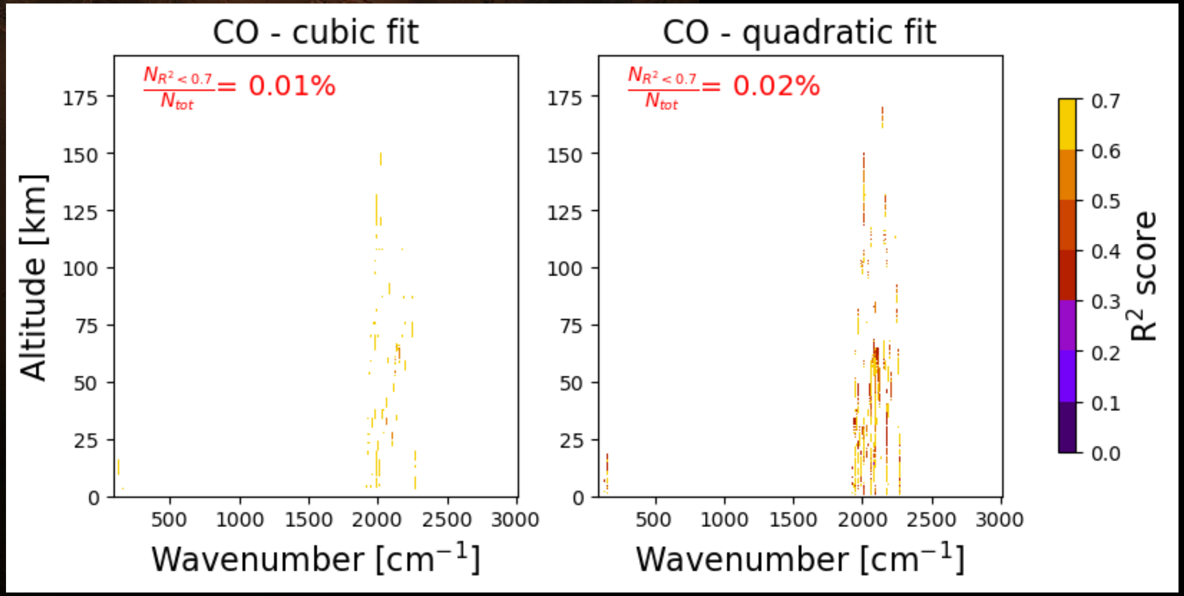


$$R^2_{adj} = 1 - \frac{\sum_i(\tau_i - \hat{\tau}_i)^2/(n-p-1)}{\sum_i(\tau_i - \bar{\tau}_i)^2\,/(n-1)}$$


CO2 - cubic fit
CO2 - quadratic fit
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 0.56%
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 1.35%
Altitude [km]
Wavenumber [cm^{-1}]
R^2 score


H2O - cubic fit
H2O - quadratic fit
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 0.12%
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 0.29%
Altitude [km]
Wavenumber [cm^{-1}]
R^2 score


O3 -cubic fit
O3 - quadratic fit
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 0.29%
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 0.57%
Altitude [km]
ν [cm^{-1}]
R^2 score


CO - cubic fit
CO - quadratic fit
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 0.01%
$\frac{N_{R^2<0.7}}{N_{tot}}$ = 0.02%
Altitude [km]
Wavenumber [cm^{-1}]
R^2 score

Scattering - Dust

Multiple scattering effects are included, treated using the Chou scaling approximation.

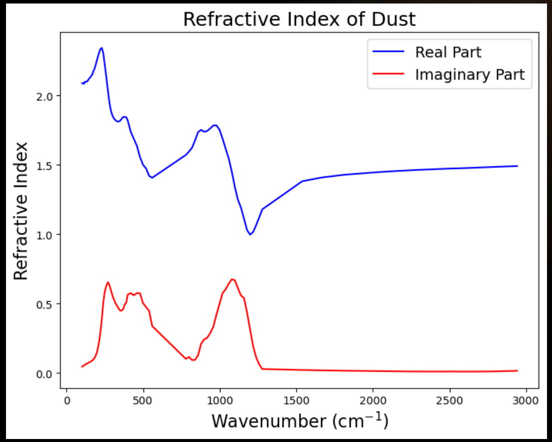
$$\frac{\tau_{dust}}{\Delta z} = \frac{3}{4}\frac{MMR_{dust}\,\rho_{air^*}}{r_{eff}\rho_{dust}} Q_{ext}((1-\omega_0)+\omega_0 b)$$

The scattering properties Q_{ext}, ω_0, b are reconstructed from LUT as 6-th degree polynomials of the effective radius, where P and t are function of the wavenumber:

$$Y = \sum_{i=0}^{6} P_{i,\nu} x^i \qquad x = 1/(r_{eff} + t_\nu)$$

Parameters are compute using SPHERICAL particles:

- <u>Refractive Index:</u>



- <u>Particle Size Distribution:</u>

Gamma distribution with r_{eff} between 0.1 and 10 µm and variance 0.3 µm

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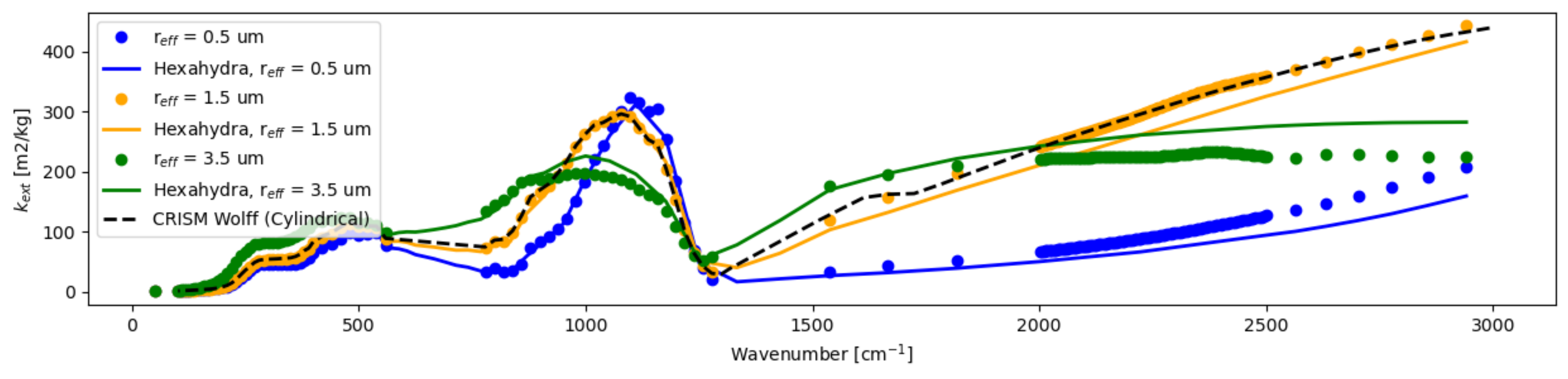
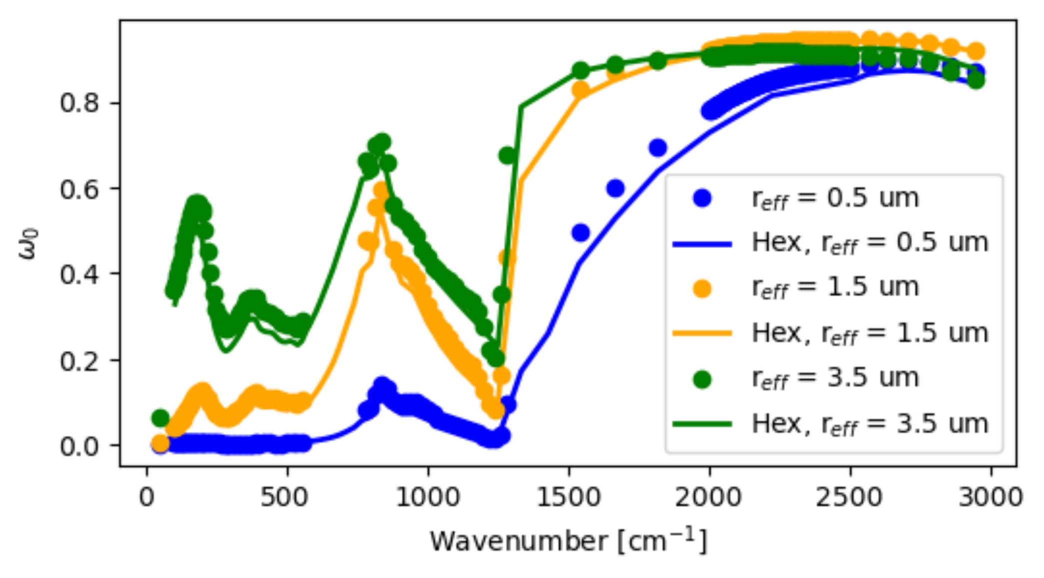
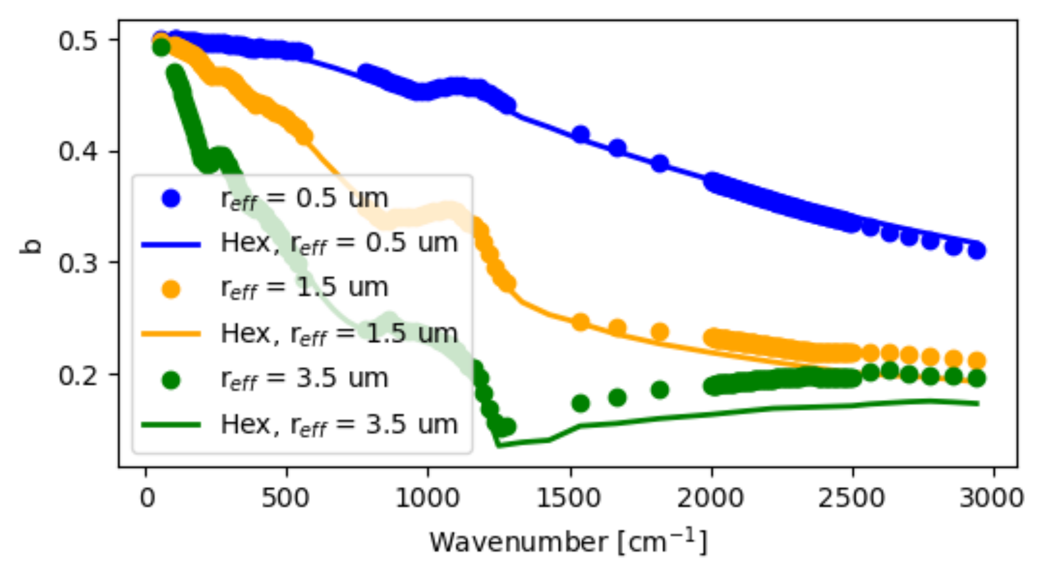
Scattering - Dust

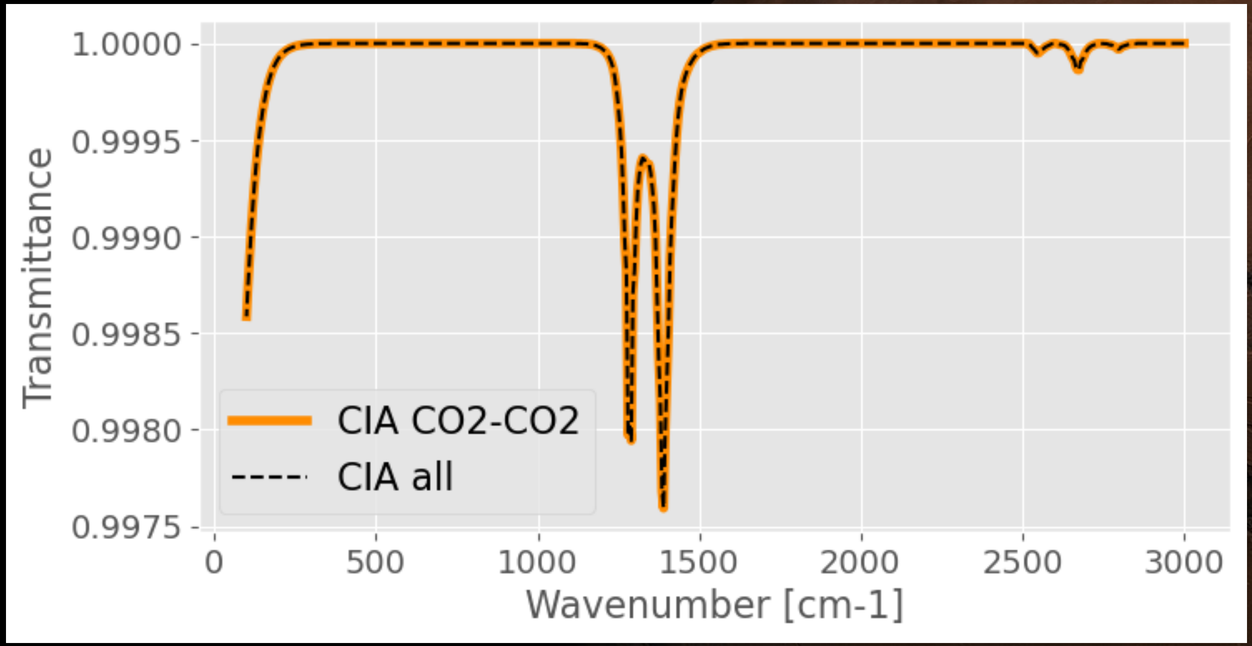
We can compare the Q_{ext}, ω_0, b of our spherical shape particles with the ones used by PSG





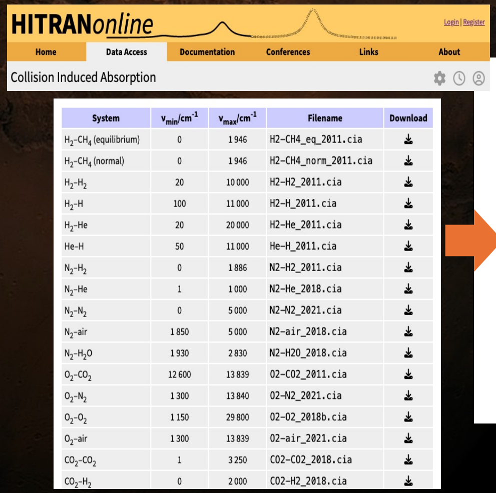


Continuum – Collision Induced Absorption



LUT of coefficients $k_{CO_2-CO_2}$ is computed from HITRAN [2][3] for T between 100 and 400 K and ν between 100 and 3000 cm^{-1}.

$$\tau(\nu,T) = \ell \cdot k_{CO_2-CO_2}(\nu,T)\rho^2_{CO_2}$$



System	ν_{min}/cm^{-1}	ν_{max}/cm^{-1}	Filename	Download
H_2-CH_4 (equilibrium)	0	1 946	H2-CH4_eq_2011.cia	
H_2-CH_4 (normal)	0	1 946	H2-CH4_norm_2011.cia	
H_2-H_2	20	10 000	H2-H2_2011.cia	
H_2-H	100	11 000	H2-H_2011.cia	
H_2-He	20	20 000	H2-He_2011.cia	
He-H	50	11 000	He-H_2011.cia	
N_2-H_2	0	1 886	N2-H2_2011.cia	
N_2-He	1	1 000	N2-He_2018.cia	
N_2-N_2	0	5 000	N2-N2_2021.cia	
N_2-air	1 850	5 000	N2-air_2018.cia	
N_2-H_2O	1 930	2 830	N2-H2O_2018.cia	
O_2-CO_2	12 600	13 839	O2-CO2_2011.cia	
O_2-N_2	1 300	13 840	O2-N2_2021.cia	
O_2-O_2	1 150	29 800	O2-O2_2018b.cia	
O_2-air	1 300	13 839	O2-air_2021.cia	
CO_2-CO_2	1	3 250	CO2-CO2_2018.cia	
CO_2-H_2	0	2 000	CO2-H2_2018.cia	

$$\begin{array}{c|cccc} & T_1 & T_2 & \cdots & T_M \\ \hline \nu_1 & k_{\nu_1,T_1} & k_{\nu_1,T_2} & \cdots & k_{\nu_1,T_M} \\ \nu_2 & k_{\nu_2,T_1} & k_{\nu_2,T_2} & \cdots & k_{\nu_2,T_1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \nu_N & k_{\nu_N,T_1} & k_{\nu_N,T_2} & \cdots & k_{\nu_N,T_M} \end{array}$$

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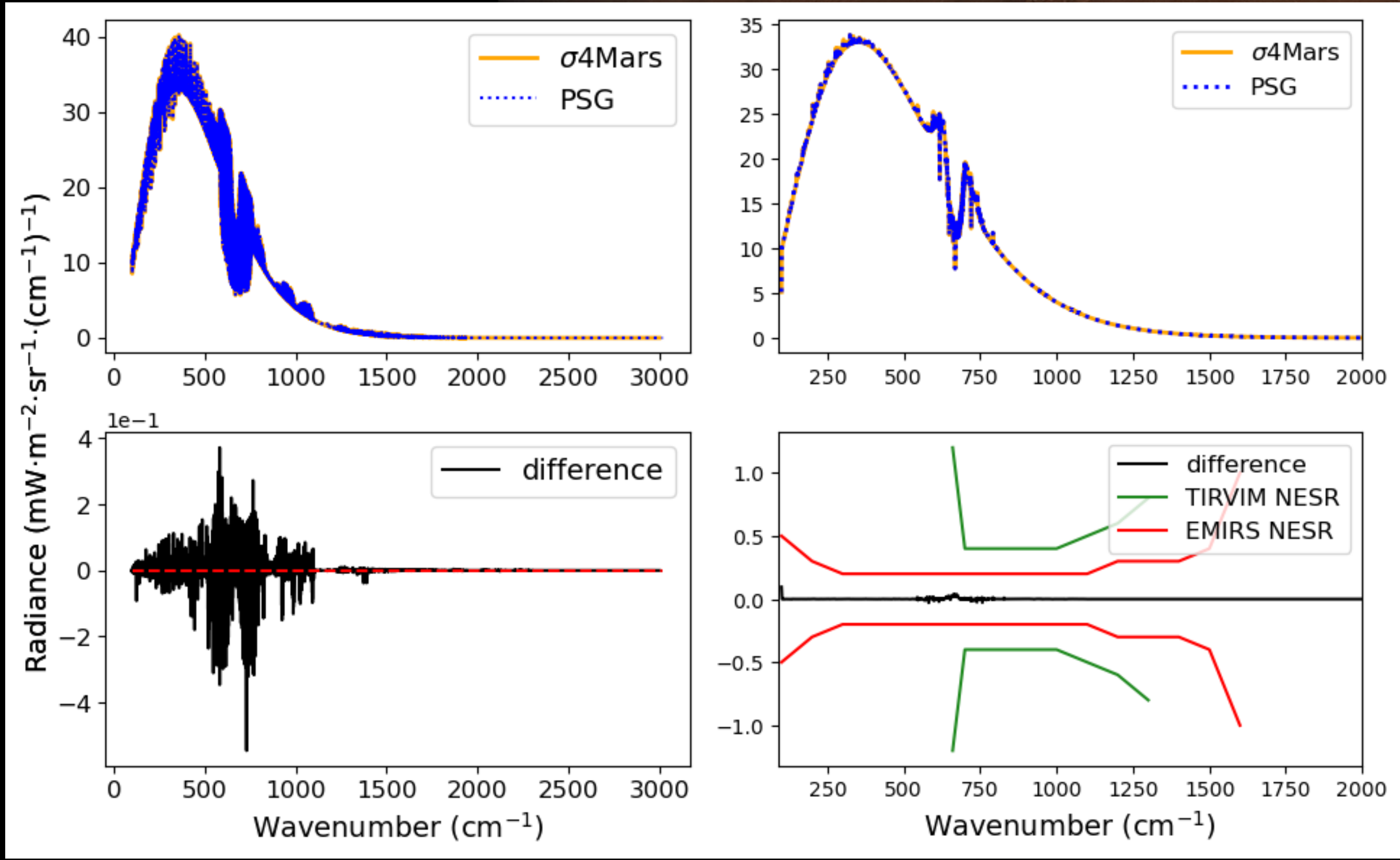
Results – Comparison with PSG

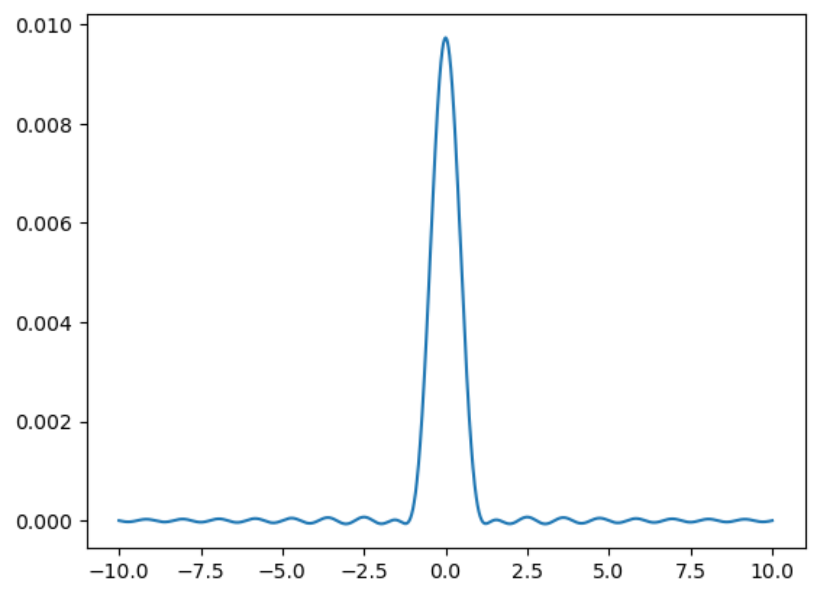
Standard profile

High resolution (10^{-2} cm^{-1})

Convolved with IRF (1 cm^{-1})



TIRVIM IRF



$$IRF(\nu) = 0.54\frac{\sin(\pi\nu L)}{\pi\nu L} + 0.23\left[\frac{\sin[\pi(\nu L-1)]}{\pi(\nu L-1)} + \frac{\sin[\pi(\nu L+1)]}{\pi(\nu L+1)}\right]$$

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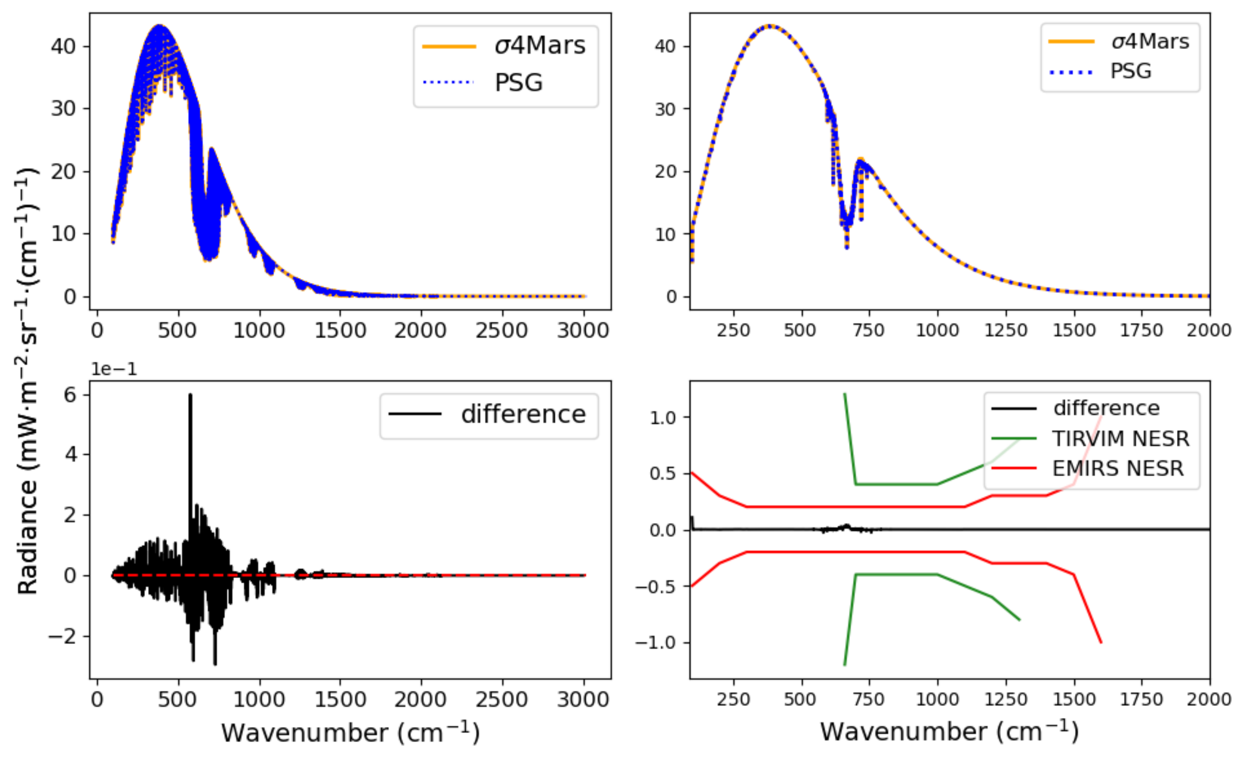
Results – Comparison with PSG

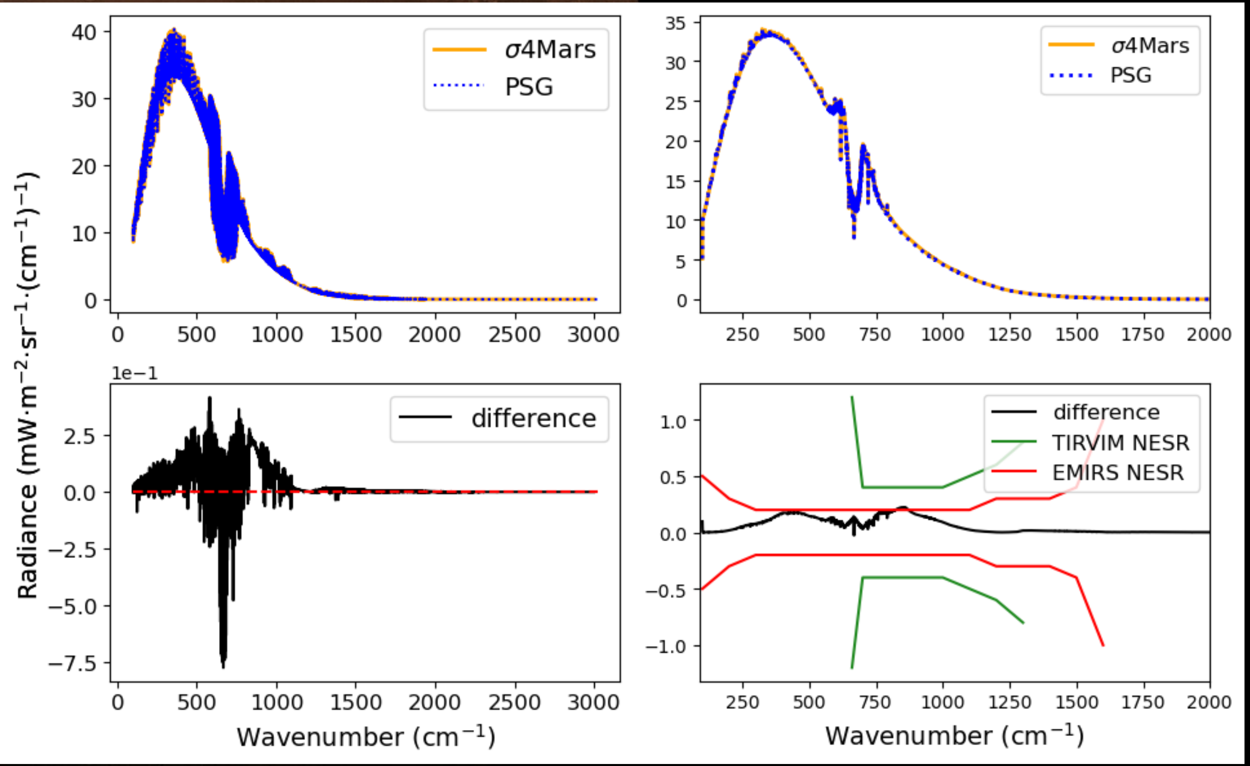
Clear Sky

High resolution (10^{-2} cm^{-1}) Convolved with IRF (1 cm^{-1})



Dusty Sky

High resolution (10^{-2} cm^{-1}) Convolved with IRF (1 cm^{-1})



σ4Mars computational time ∼ 5 s

PSG computational time ∼ 50 s

σ4Mars time ∼ 8 s

PSG time ∼ 3 min

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Conclusions

- We developed a fast and accurate new tool suited for the analysis of Martian atmosphere
- Martian OD are successfully computed and parametrized. Lookup tables are produced to be ingested into σ4Mars.
- CIA Continuum coefficients are preprocessed to be used by the code.
- Dust particles properties are parametrized to perform simulation in dusty scenarios
- The code has been tested using a reference code (the Planetary Spectrum Generator) with good results, expecially when comparing with errors of observing instrument.

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Next steps

- The code must be tested in different scenarios with high presence of dust and larger dust size grains (next months).
- The code must be compared to the TIRVIM (and EMIRS) measures to prove its capabilities of reproducing the observations (next months).
- A retrieval chain for the analysis of Martian data will be build using this code as Forward Model.

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Thank you for the kind attention

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