Regional mapping of the aerosol population and surface albedo of Titan by the massive inversion of the Cassini/VIMS dataset

Update on the Titan radiative transfer model

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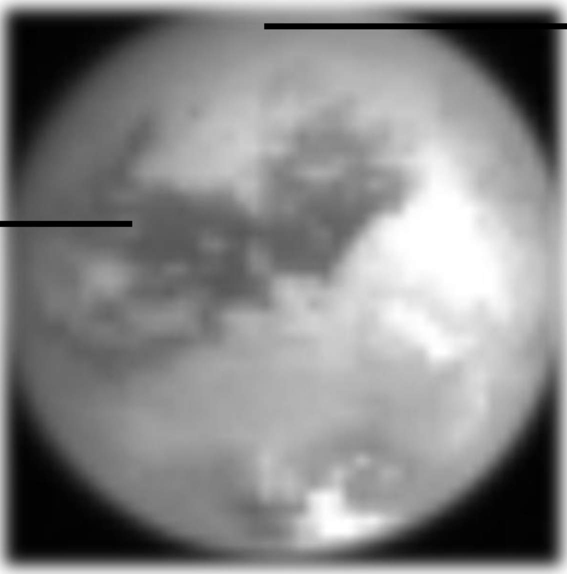
Titan’s surface geology

- **Varied geology** on Titan seen from Cassini: lakes, seas, rivers, dunes, craters, mountains, ...
- Erosion (mechanical, chemical?), resulting in production, transport and deposition of sediments.
- **Geological processes rely on the composition and the physical state of surface.**

Tropics: Dune fields

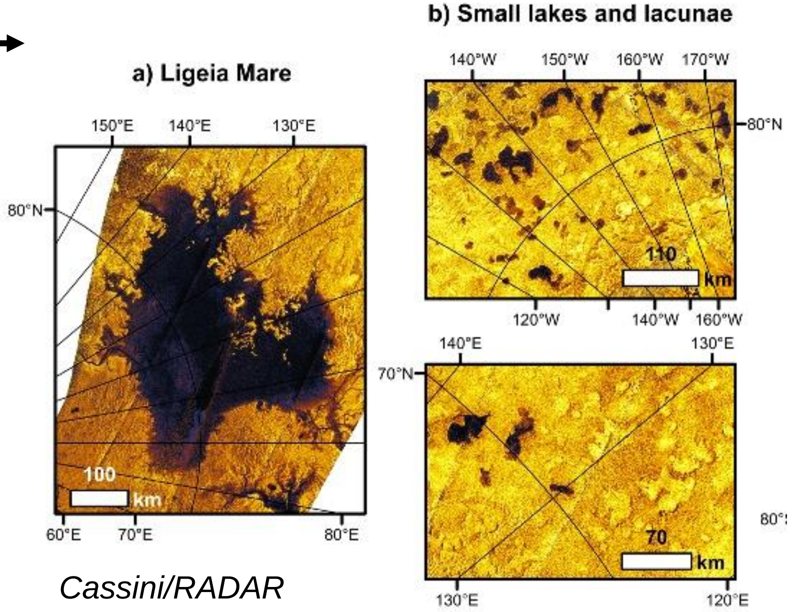
Cassini/RADAR

Radebaugh [2013]



Cassini/VIMS

Poles: lakes, seas, rivers, …



Cassini/RADAR

Cornet et al. [2015]

Titan’s surface composition maps

Titan’s surface composition maps

⇧

Titan’s surface albedo maps (in a large spectral range)

Titan’s surface composition maps

⇧

Titan’s surface albedo maps (in a large spectral range)

⇧

Reliable radiative transfer calculations

Titan's surface composition maps

⇧

Titan's surface albedo maps (in a large spectral range)

⇧

Reliable radiative transfer calculations

⇧

[New] Constraints on Titan's atmosphere (gases & haze)

Titan’s surface composition maps

⇧

Titan’s surface albedo maps (in a large spectral range)

⇧

Reliable radiative transfer calculations

⇧

[New] Constraints on Titan’s atmosphere (gases & haze)

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⇧

Titan’s surface albedo maps (in a large spectral range)

⇧

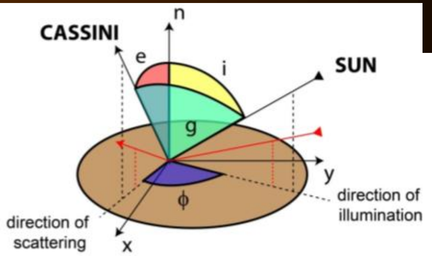
Reliable radiative transfer calculations

⇧

[New] Constraints on Titan’s atmosphere (gases & haze)

Extrapolations from DISR measurements

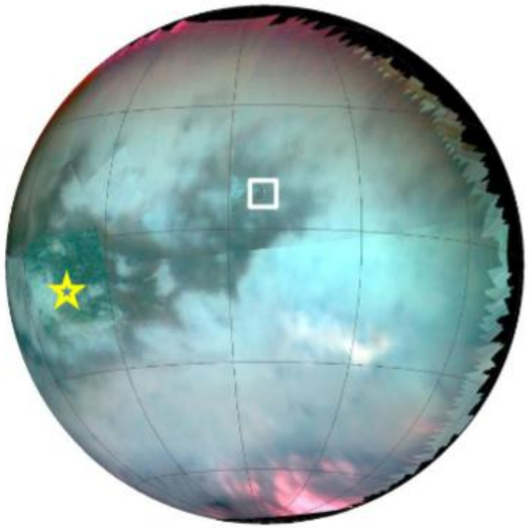
The T88 Emission-Phase Function (EPF)



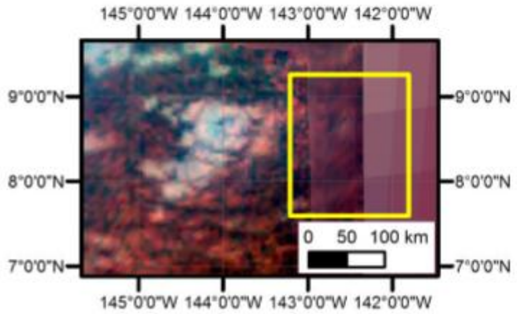
Cassini/VIMS-IR: 256 images acquired between 0.88 and 5.11 µm.

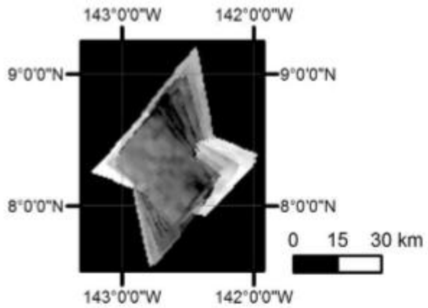
EPF ⇨ VIMS observation sequence made of 26 [12x12] cubes acquired 29 November 2012:
- over the same (small) area, rather uniform
- at a fixed incidence (~50°), varying emission between 47 and 63°, and phase between ~0° and 70°
- at a single date = **same haze population** for the 26 cubes

Huygens

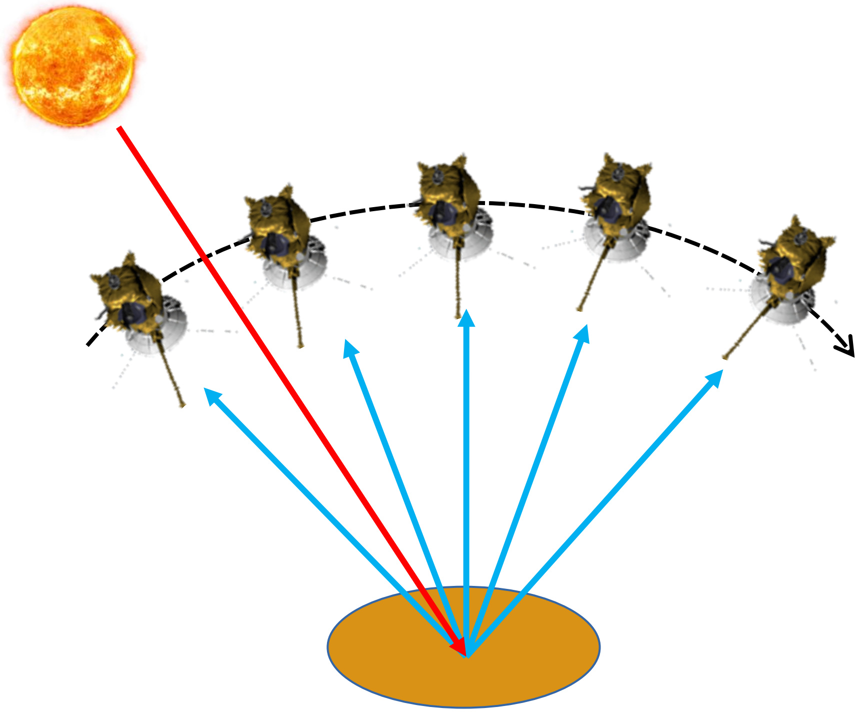


R: 5 ; G: 2.01 ; B: 1.59
(processed Le Mouélic et al. (2012))

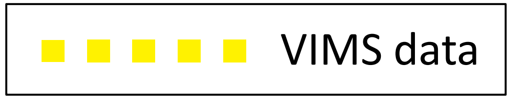


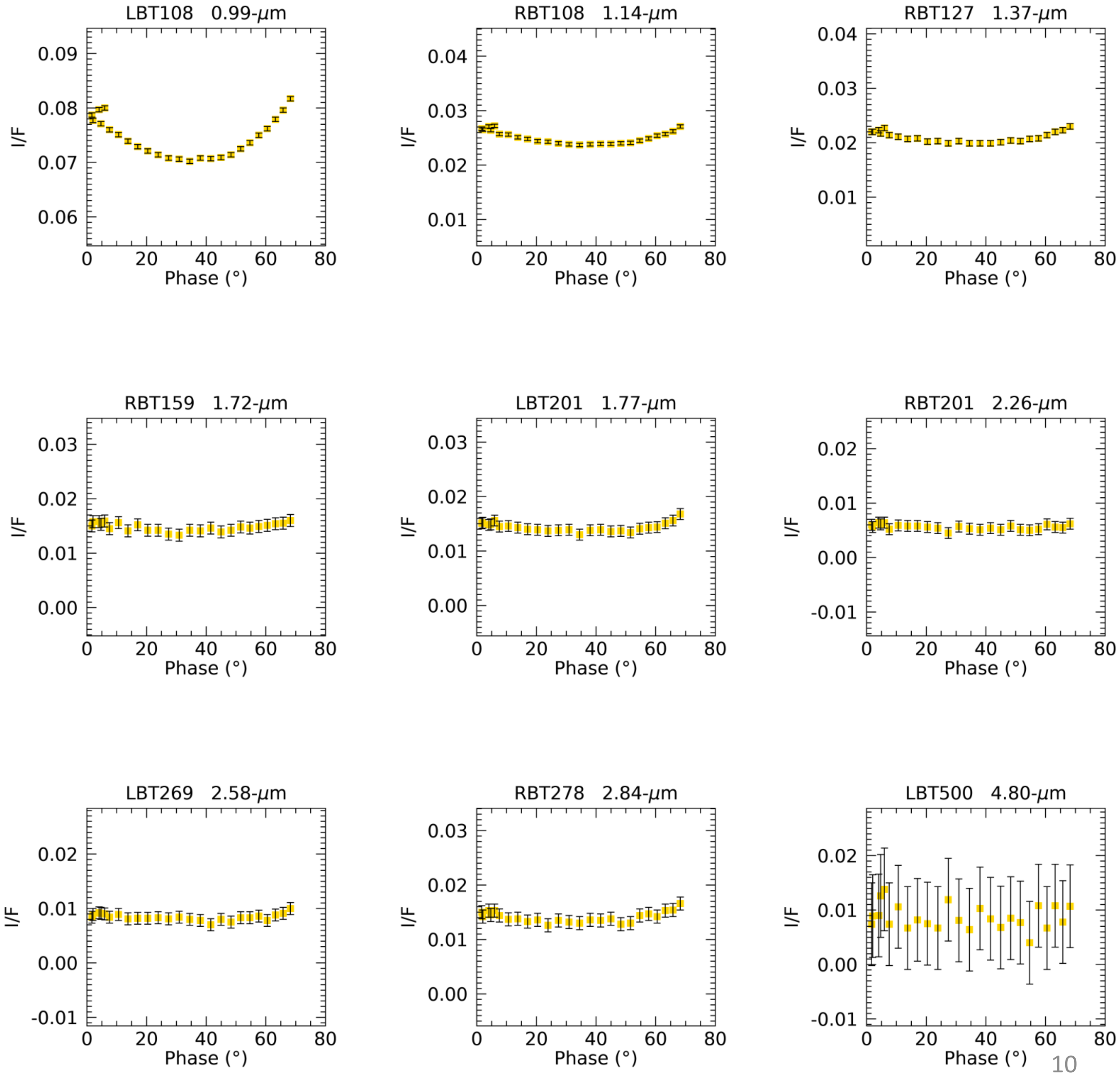


raw 2 microns

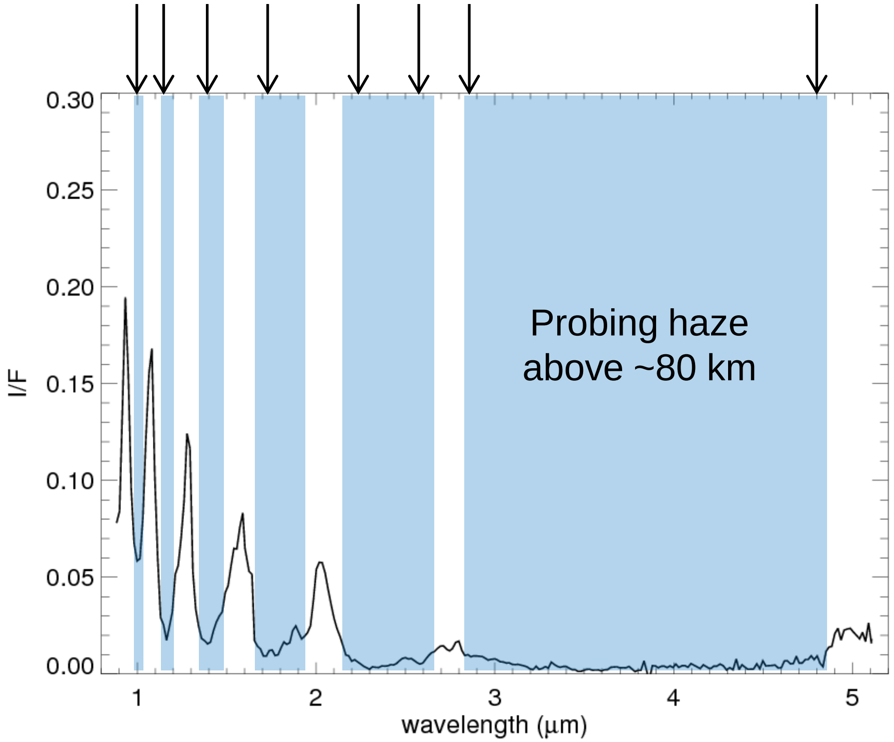


Excellent test case to bring constraints on the shape of the aerosols phase function!
But not only…





We build haze phase curves at 9 bands



Titan radiative transfer model

Last updates

700 km

70 layers

0 km

Atmospheric structure:

- P/T profiles from Huygens/HASI [Fulchignoni et al., 2005] and Cassini/CIRS [Vinatier et al., 2010]

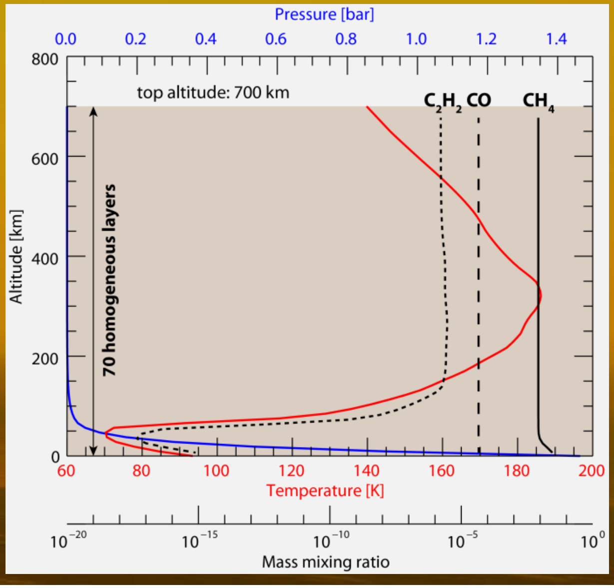
Gases:

- Abundance profiles: Huygens/GCMS for CH_4 [Niemann et al., 2010], Cassini/CIRS for CO [De Kok et al., 2007], C_2H_2 [Vinatier et al., 2010]
- Up-to-date molecular absorptions for $^{12}CH_4$, $^{13}CH_4$,$^{12}CH_3D$, CO, C_2H_2 + CIA for N_2-N_2 and N_2-H_2.
- Rayleigh scattering for CH_4, CO, C_2H_2, N_2.

Aerosols: Based on Huygens measurements

- Opacity (τ),
- single-scattering albedo (ω_0)
- phase function (P(g))

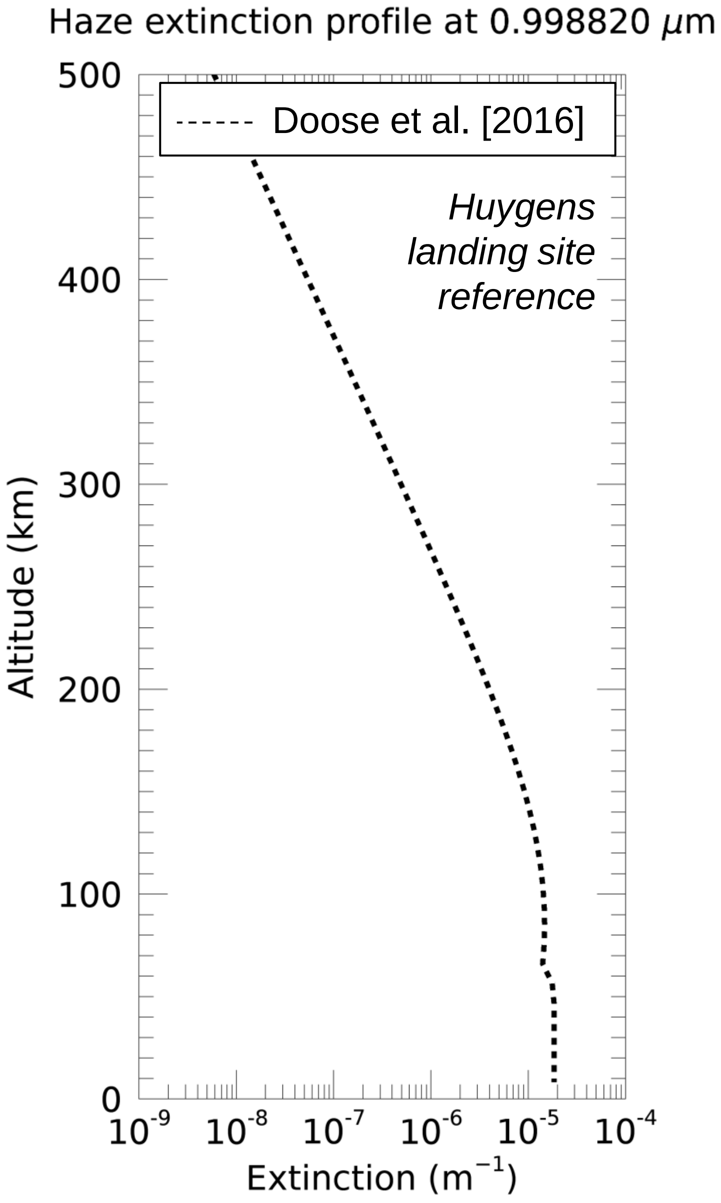
} Huygens/DISR [Tomasko et al., 2008; Doose et al., 2016] + Cassini/VIMS [Hirtzig et al., 2013]



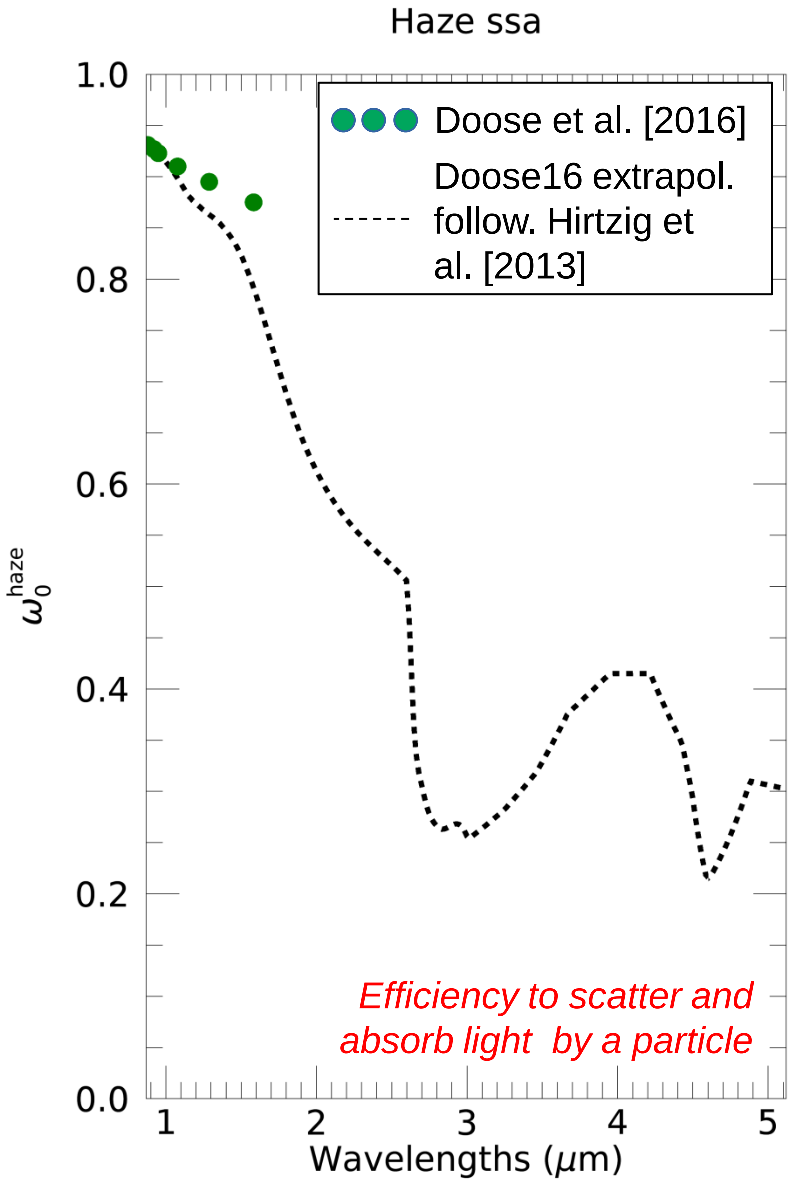
(Lambertian surface)

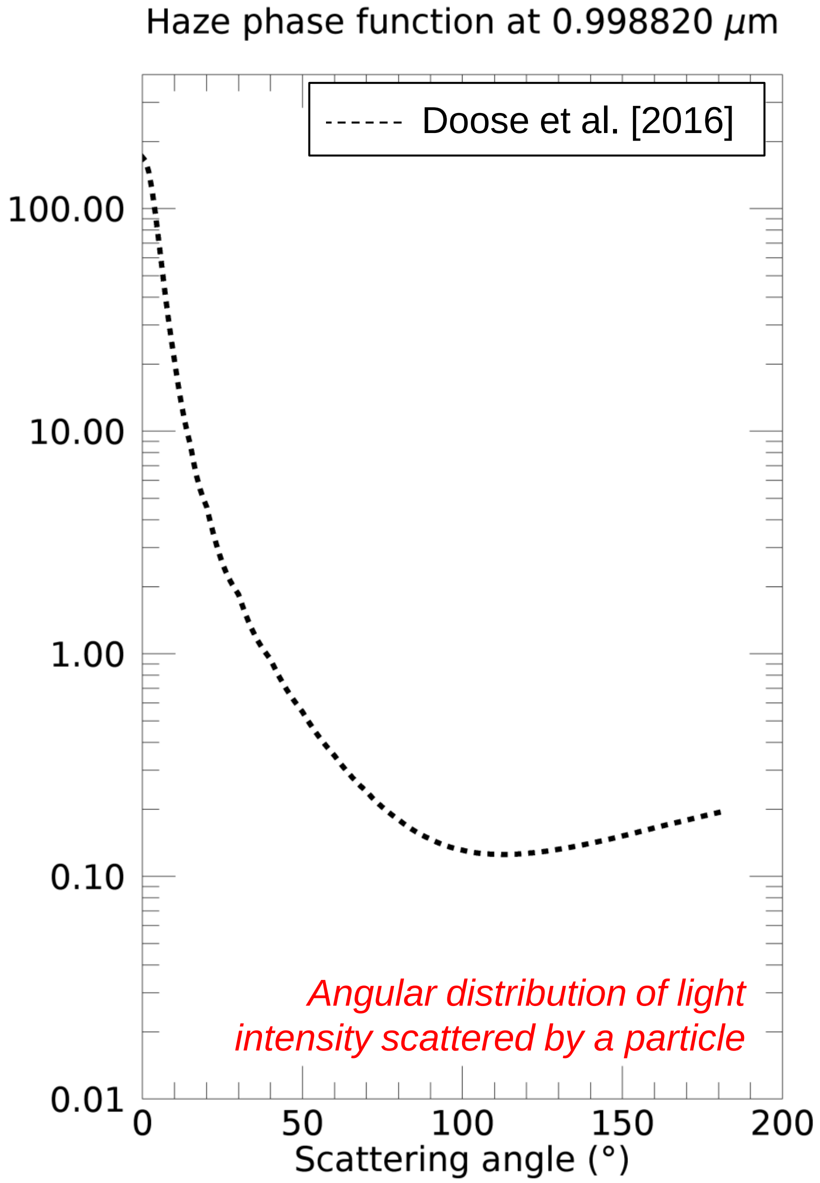
Based on Hirtzig et al. [2013], used in Solomonidou et al. [2014; 2016]

Haze population > 80 km



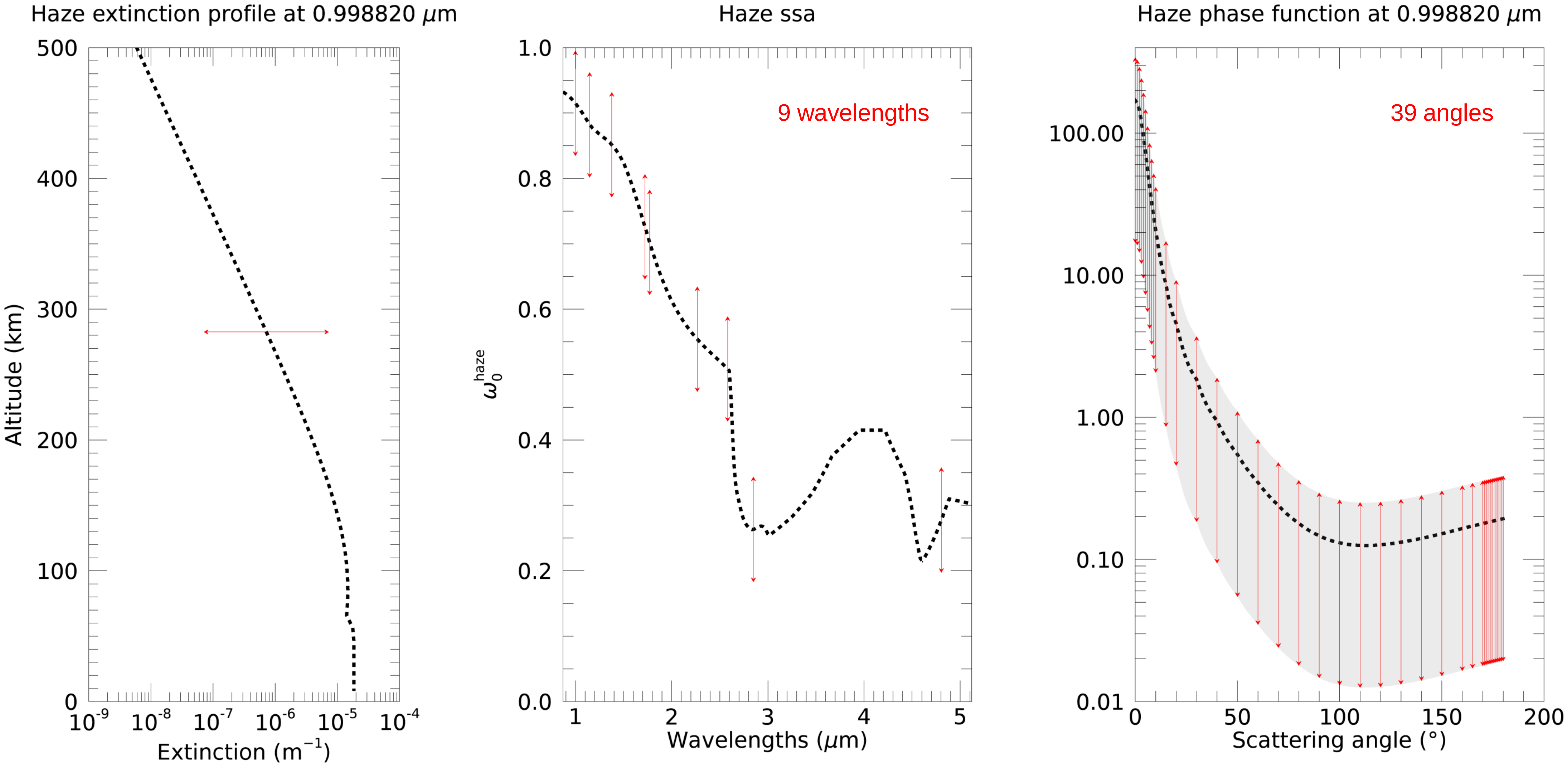
Haze particle average properties > 80 km





Haze population > 80 km

Haze particle average properties > 80 km



VIMS data

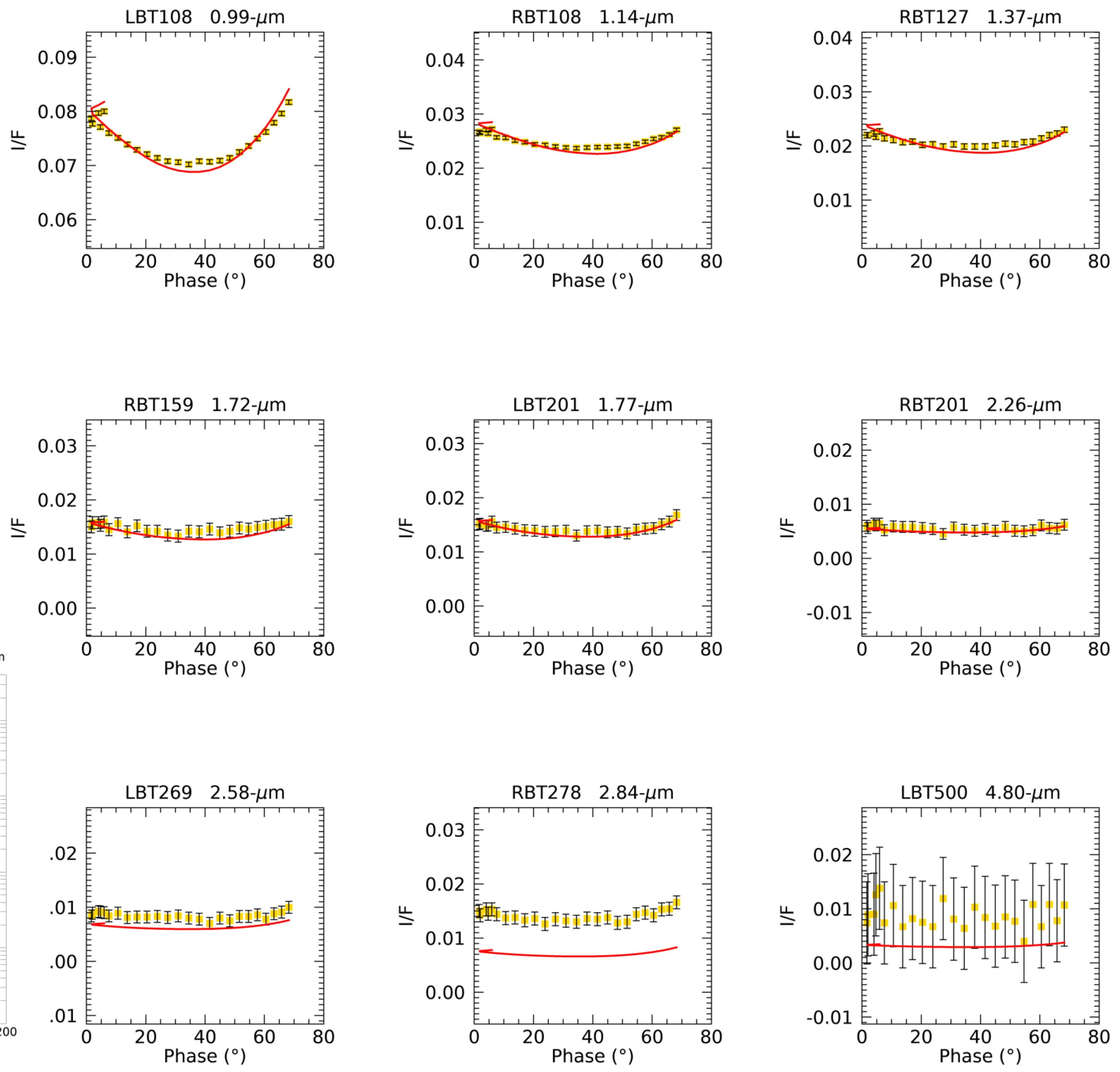
Model

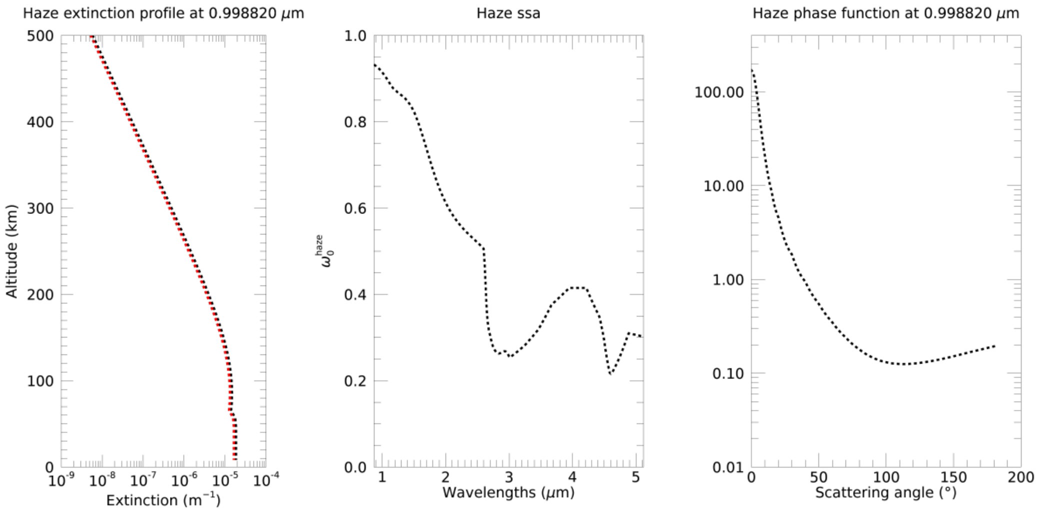
Free haze factor = 0.9

Hirtzig's ω_0

Doose phase function

$\chi^2 = 7.14$





VIMS data

Model

Free haze factor = 0.9

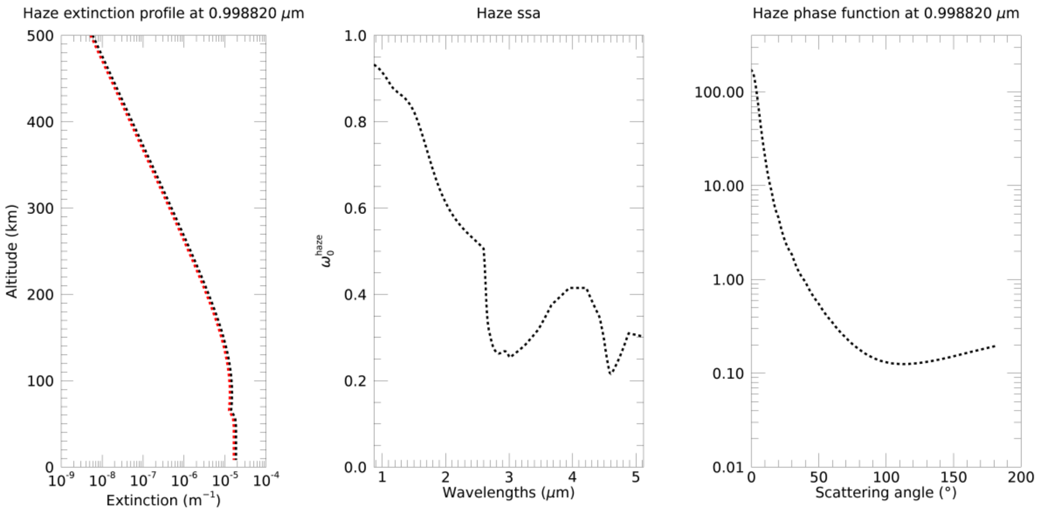
Hirtzig's ω_0

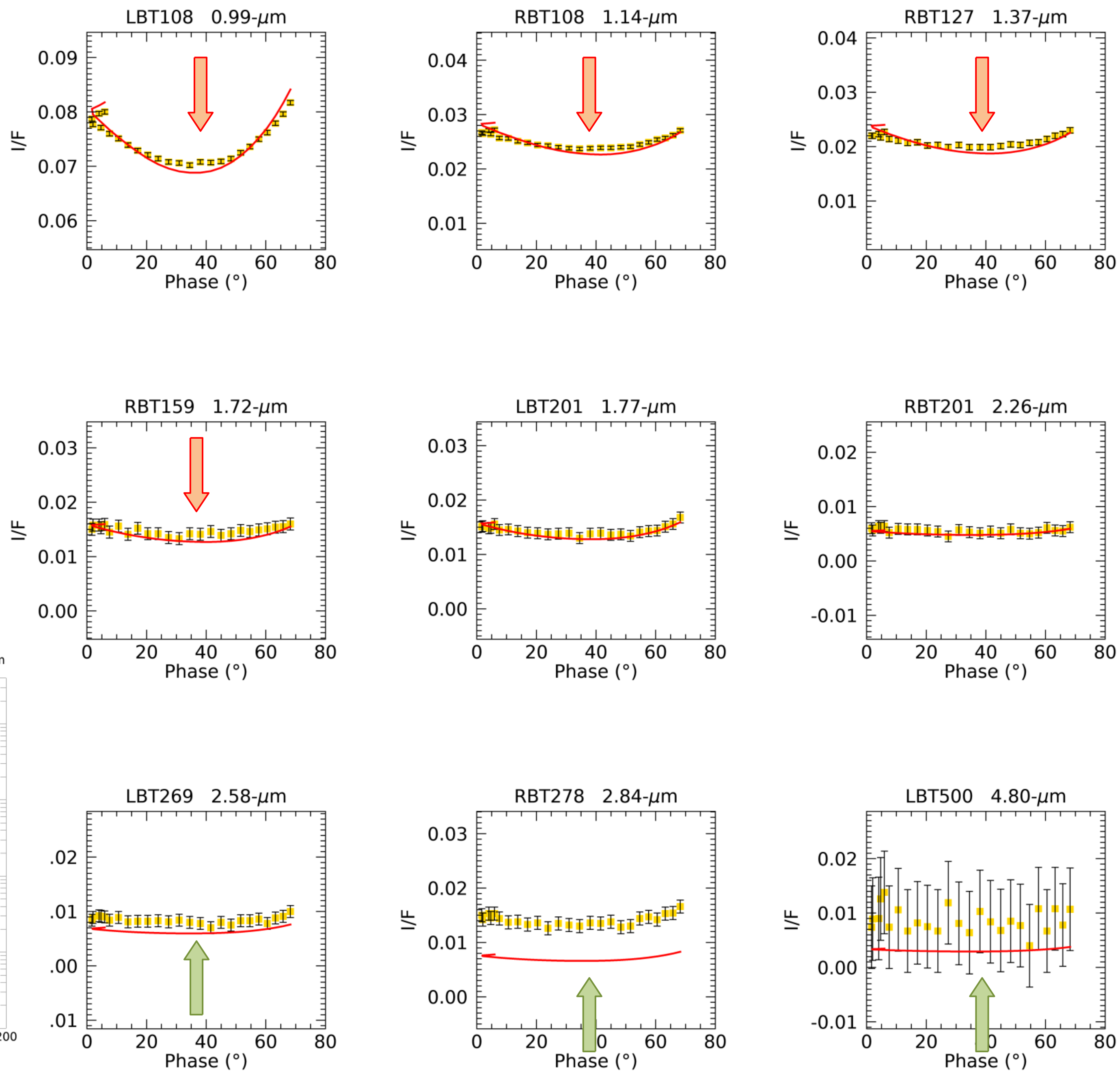
Doose phase function

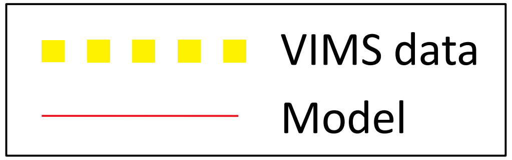
$\chi^2 = 7.14$

Dependence with phase

Haze total brightness





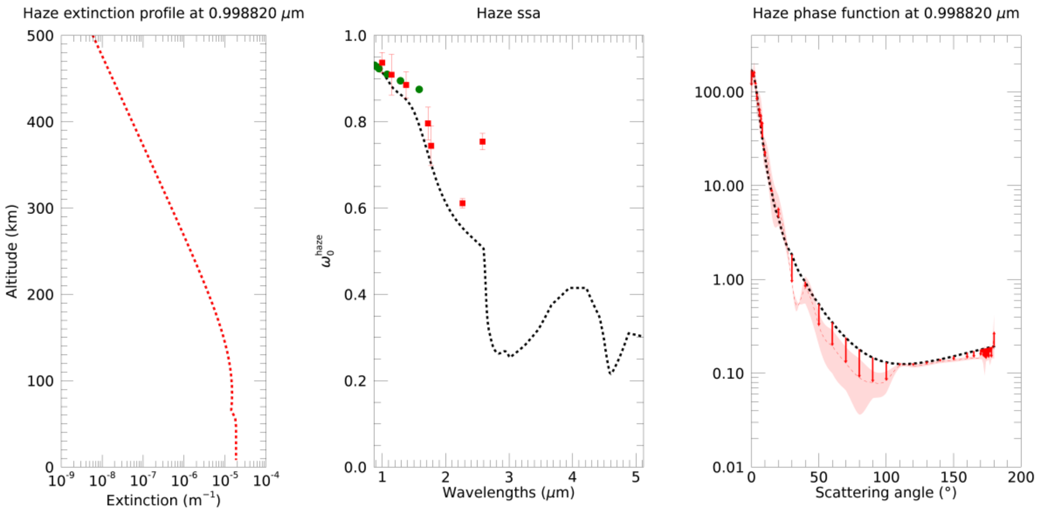


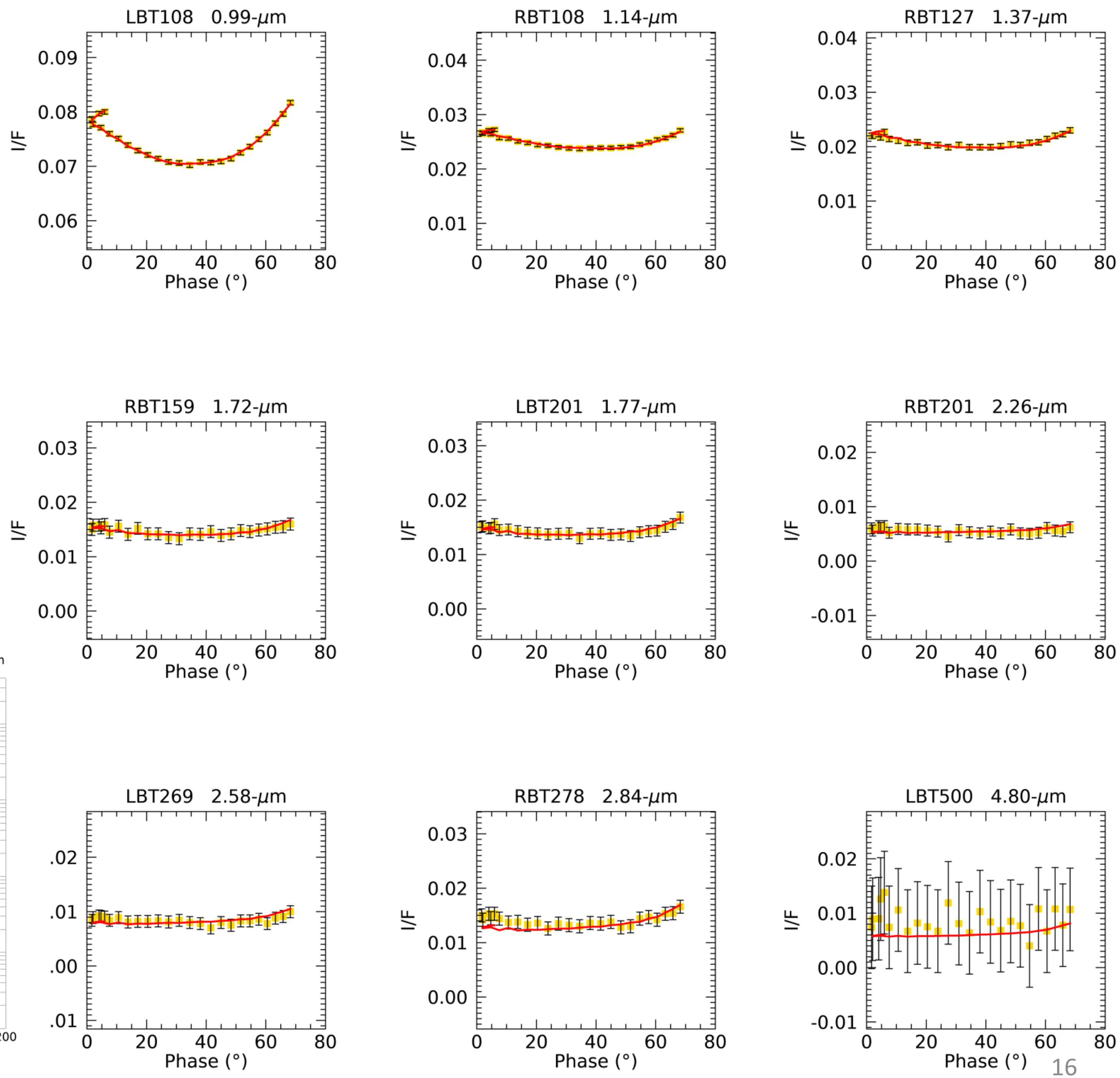
Free haze factor = 1

Free w0

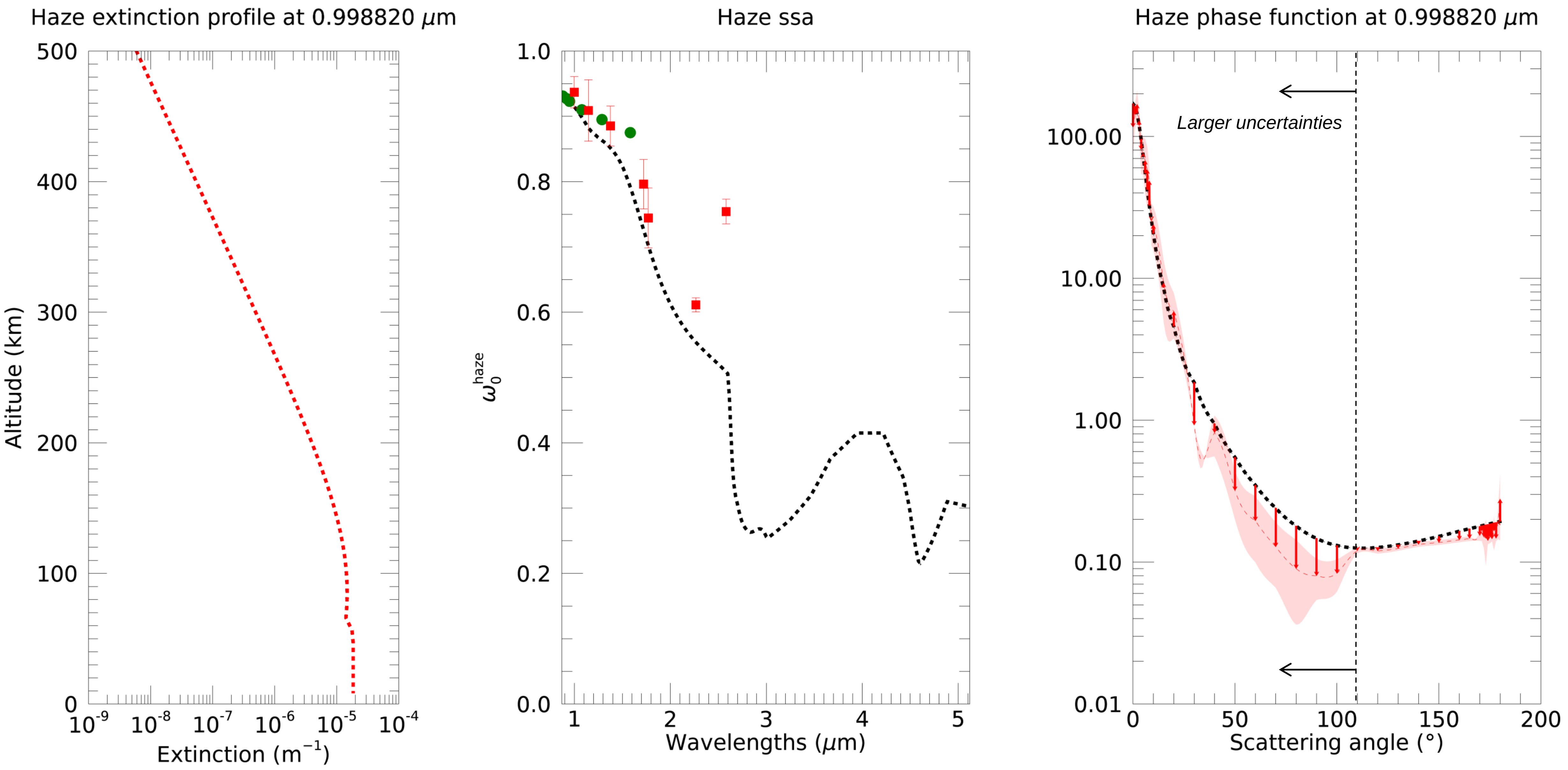
Free phase function

$\chi^2 = 0.4$



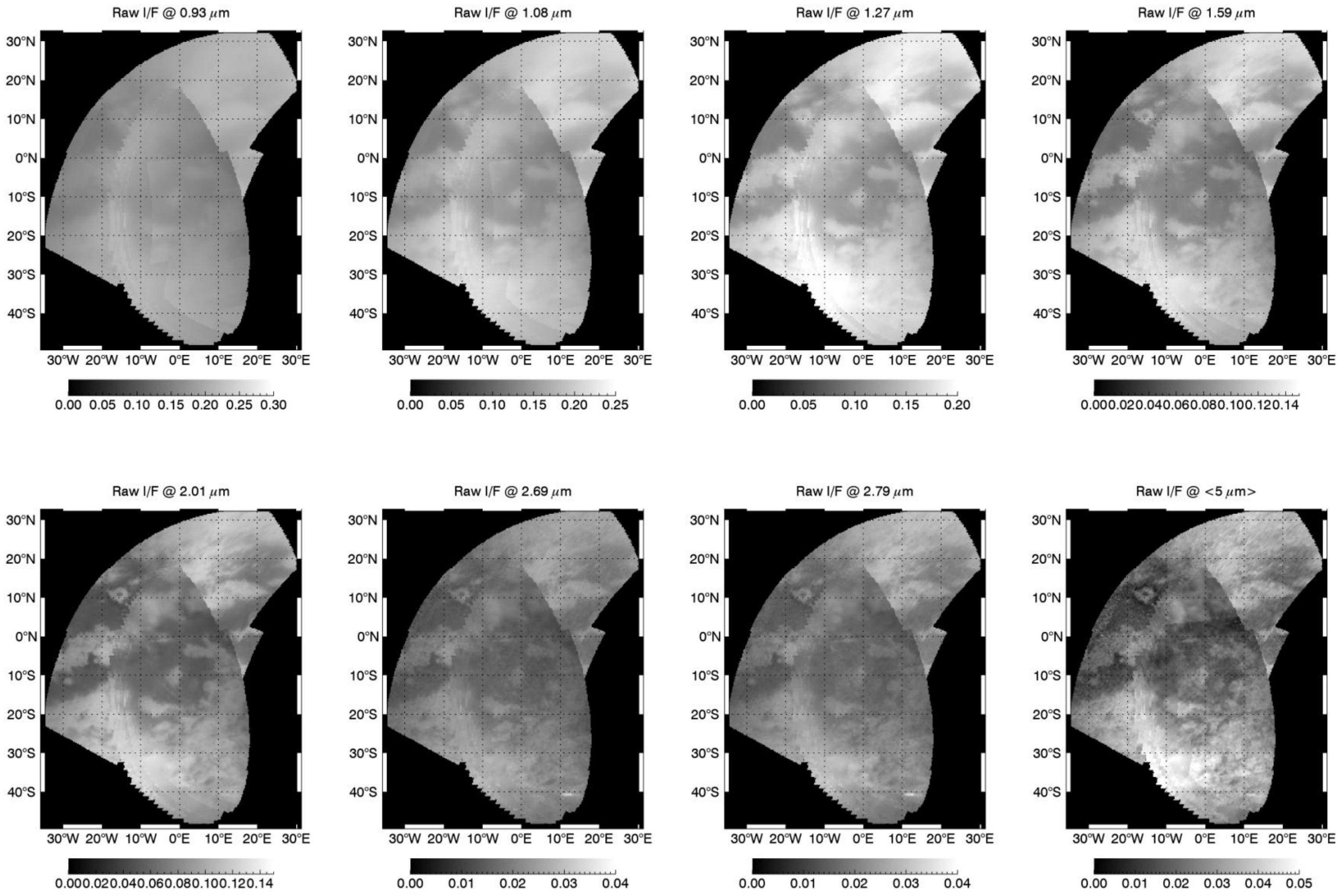


T88 EPF best fit



Test case: the T13-T17 VIMS mosaic with the new haze optical properties

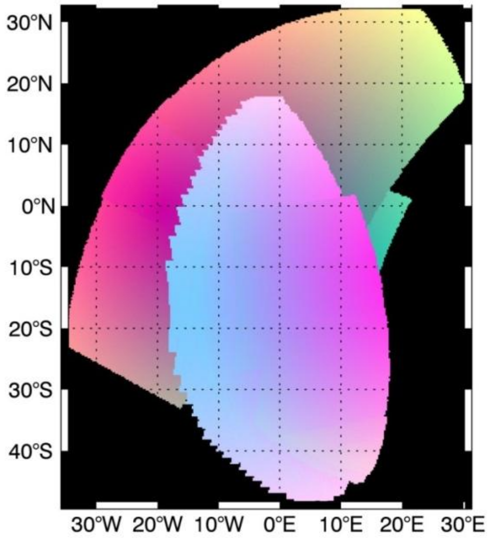
Initial raw mosaics



Why the T13 and T17 flybys ?

- 3 months interval over the same area.
- **Timing test:** 53143 spectra (pixels) to invert ! ⇨ Look-Up Tables

Geometry



7.28°< i <50.00°
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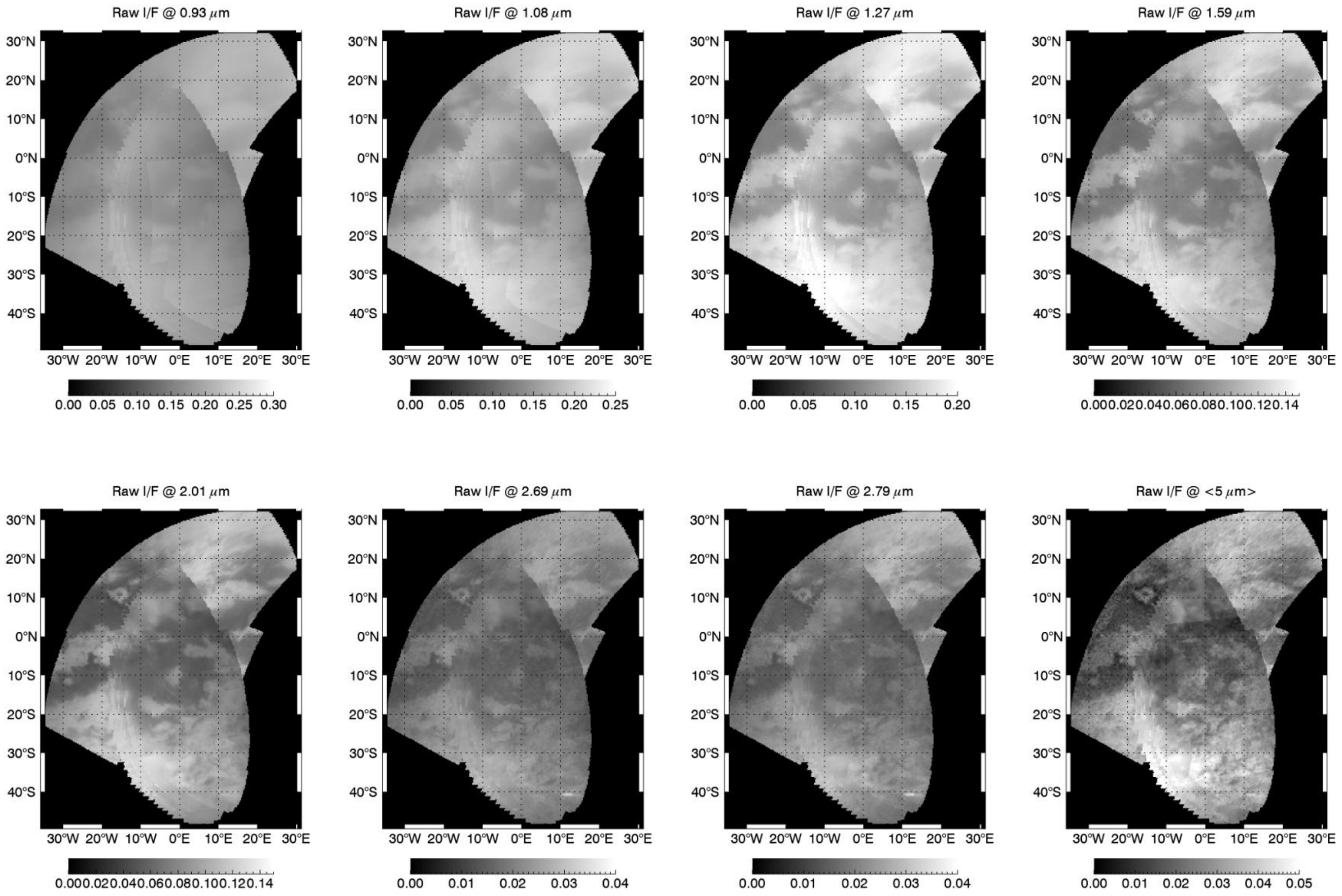


Why the T13 and T17 flybys ?

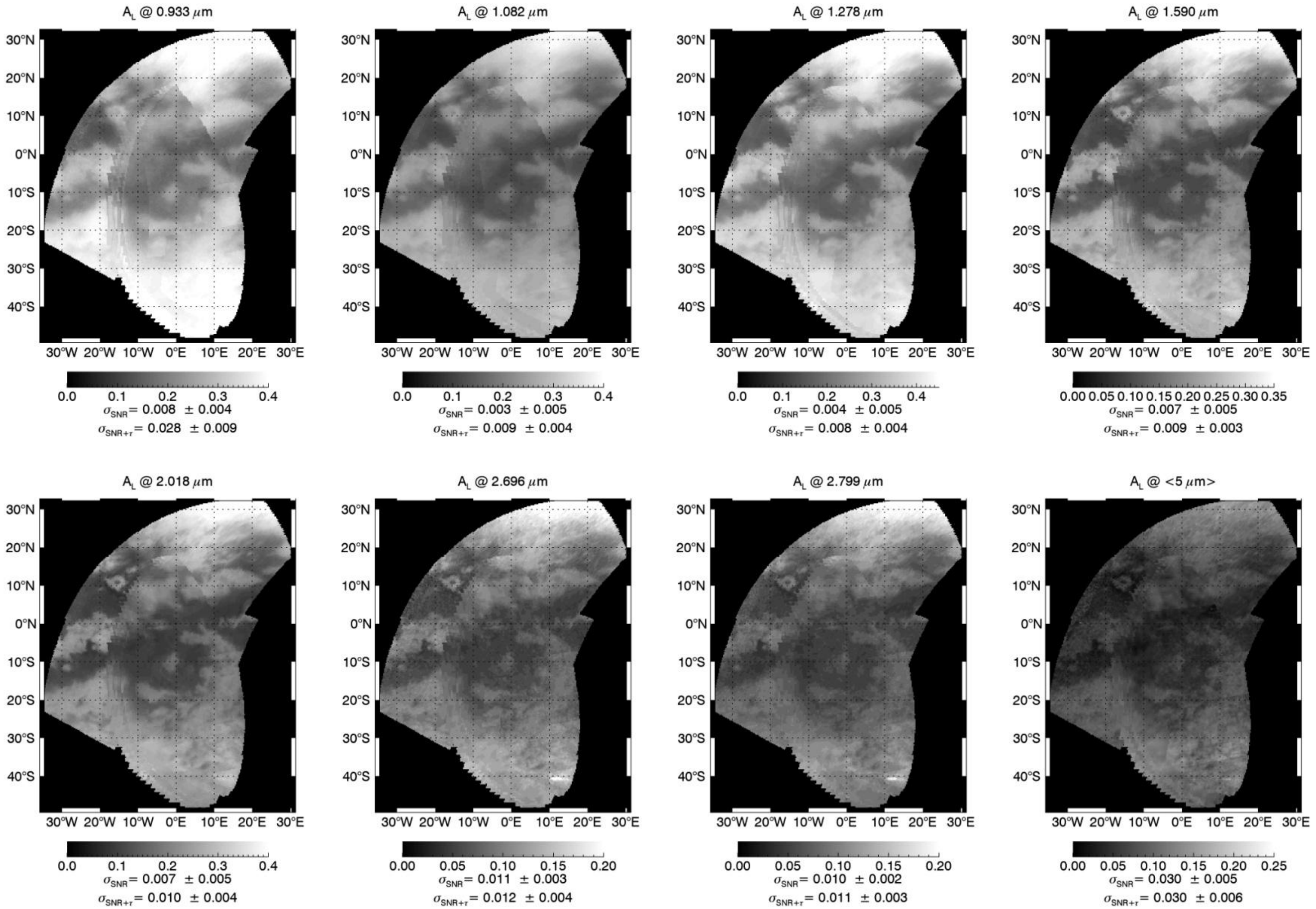
- 3 months interval over the same area.
- **Timing test:** 53143 spectra (pixels) to invert! **~4 hours**

What do we expect ?

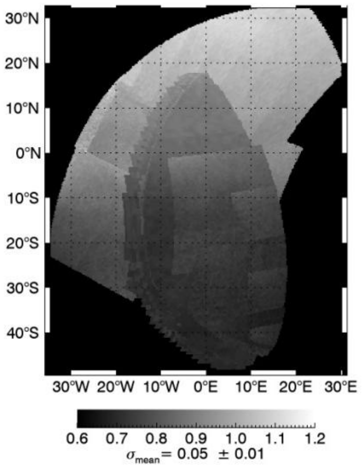
- T13-T17 seams should (significantly) diminish in surface albedo images
- Images at short wavelength should sharpen

Test case: the T13-T17 VIMS mosaic with the new haze optical properties

Inversion with LUTs [modified Hirtzig et al., 2013 ; Doose et al., 2016] **+ New CH_4** [Rey et al., 2017]

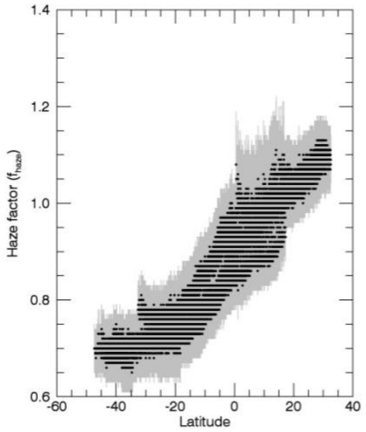


Haze factor



- **Better contrast**
- **Less seams**
- **≈10% difference in haze pop. btw T13 & T17**
- **f_{haze} ≈ 1 near equator**

Trend with latitudes ?



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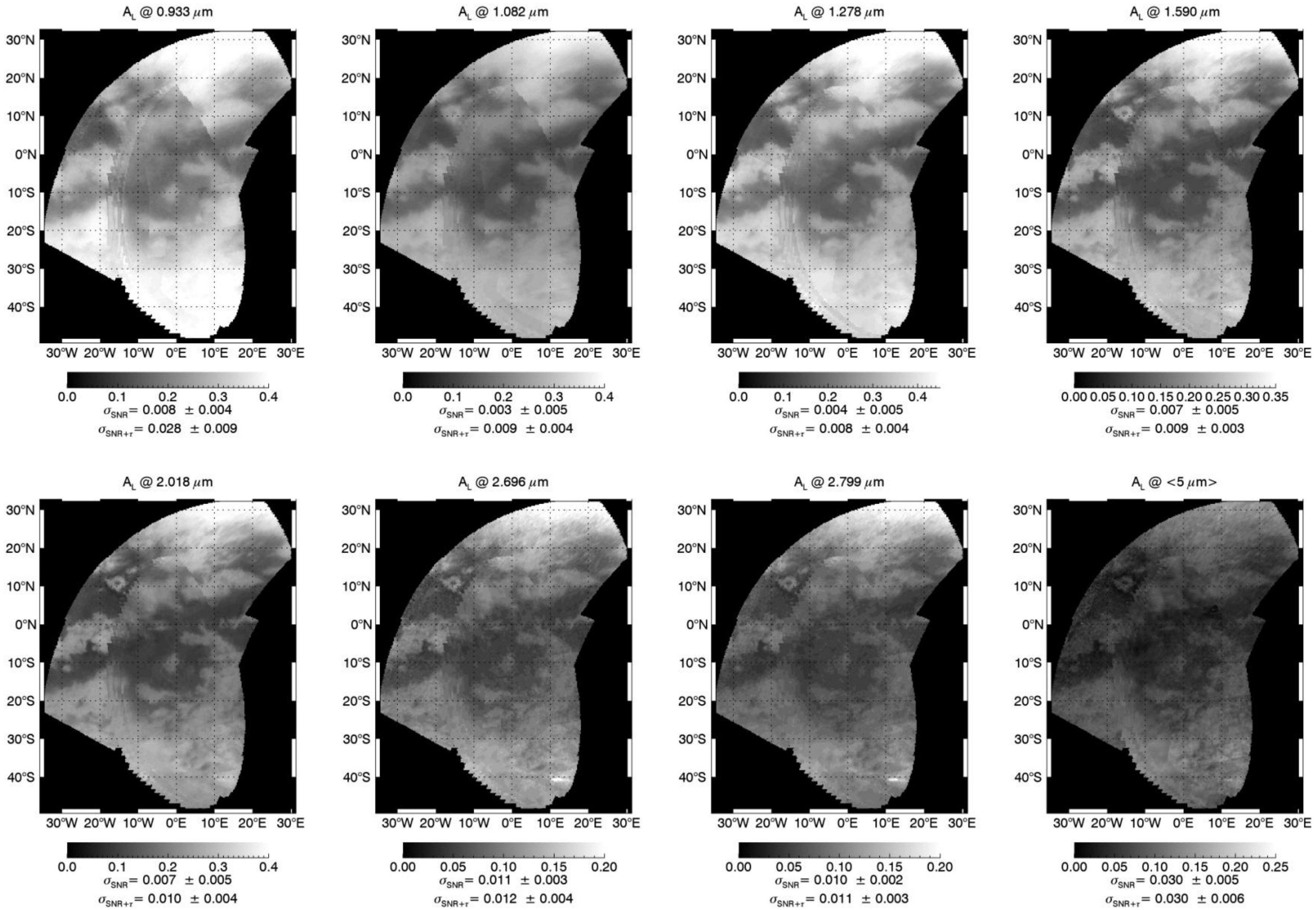
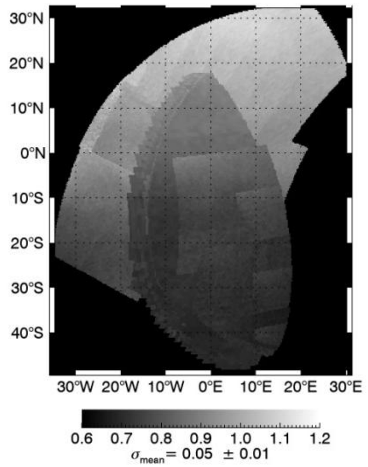


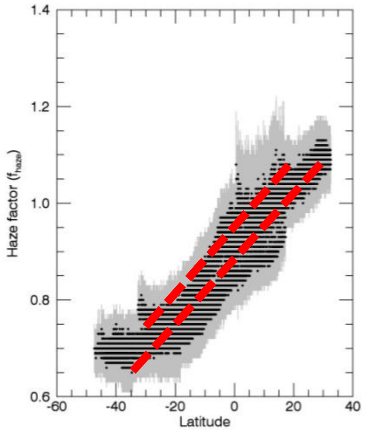
Haze factor



- **Better contrast**
- **Less seams**
- **≈10% difference in haze pop. btw T13 & T17**
- **f_{haze} ≈ 1 near equator**

- **40% diff. in haze pop. within 50° lat.?**
- **But still seams!**
- **Marked visual scattering effect...**

Trend with latitudes ?



Summary

Haze optical properties from Titan's EPF:

- **Unique set** of VIMS observations: large range of emission and phase angles at one place & one time!
- **VIMS haze images extremely sensitive to haze optical properties** (ω_0 and phase function). EPF sequence allows us to test these properties with VIMS at wavelengths and phase angles where we only had access to extrapolations from Huygens.
- Haze above 80 km altitude is **slightly brighter** than expected with a **slightly modified phase function**. Need additional tests.

Moving forward:

- EPF with **a larger range for phase angles** above Titan's northern lakes.
- What kind of particles are compatible with retrieved haze optical properties? What kind of **fractal aggregates,** with what **refractive indices**?
- Inversions in the atmospheric window wings and centres. **Low atmosphere and surface phase curves?**

Summary

Application to Titan's albedo maps:

- We developed a **fast radiative transfer tool** to invert the Cassini/VIMS images of Titan.
- Solver using **pseudo-spherical geometry** is now implemented. **Updated gase and haze optical properties**.
- Inversion based on the computation of **Look-Up Tables** for specific physical and geometric parameters.
- **Very fast** inversion process **(interpolations between LUT nodes):** inversion in **4 hours for a VIMS mosaic > 53000 spectra** (equivalent time for direct computation of these spectra: **120+ days** !).
- We manage to **remove almost all the seams in a "test" regional mosaic (T13/T17)** with reasonable haze and surface albedo retrievals. Most of the remaining seams due to bad co-registration.

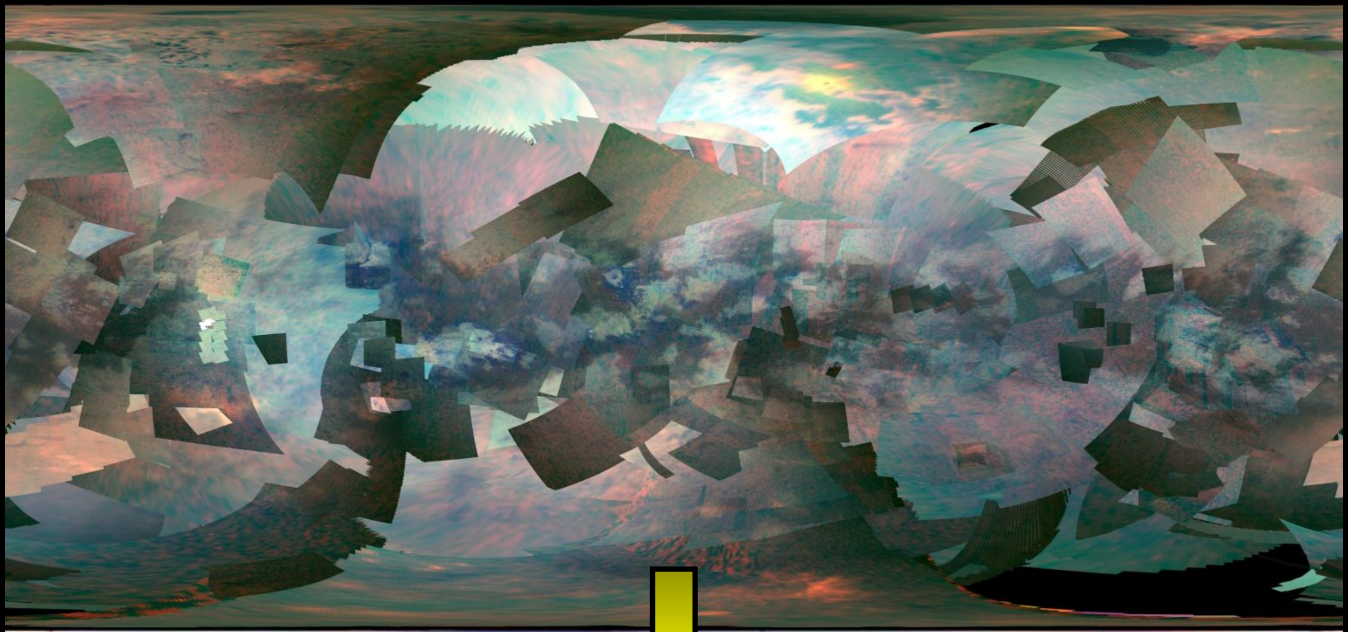
Moving forward:

- **Cassini/VIMS dataset: Global scale albedo maps** (how to implement the effects of latitudes et seasons?)
- Ground-based telescopic observations, JWST and Dragonfly!

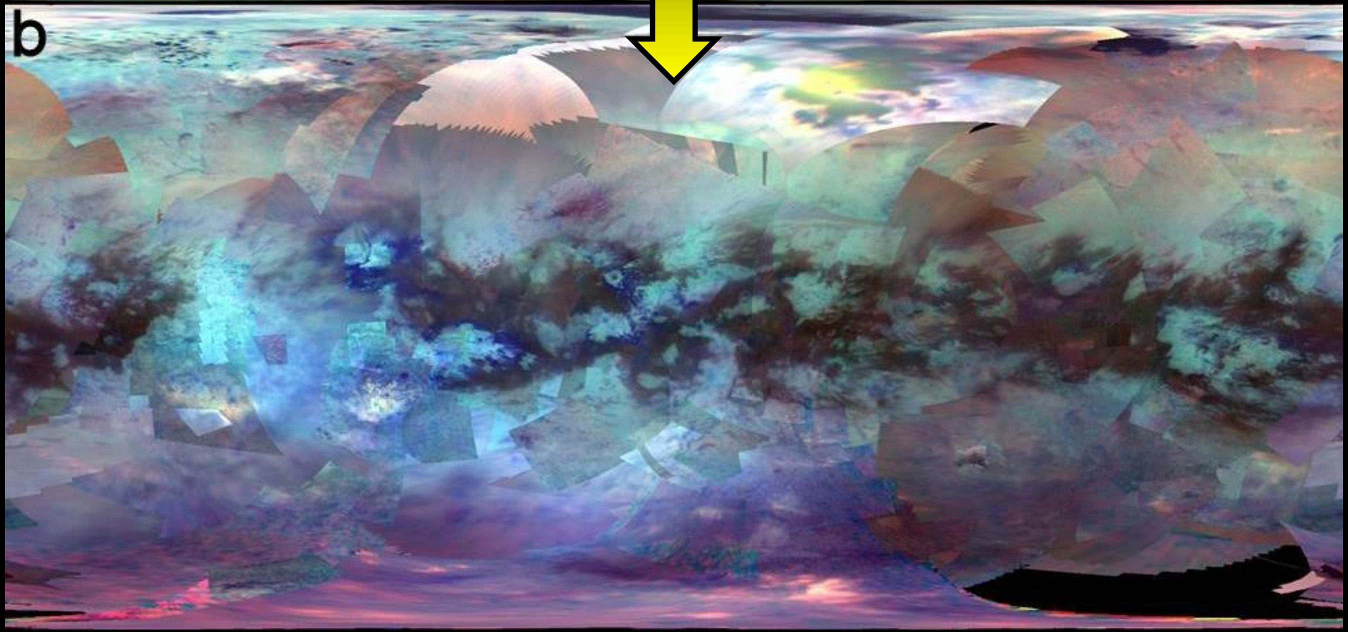
Our goal!

Cassini/VIMS: R5, G2, B1.27 (127 flybys)

RAW

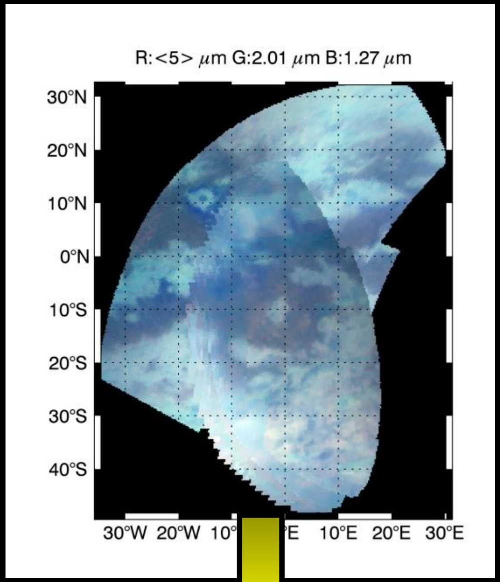


EMPIRICALLY CORRECTED [Le Mouélic et al., subm]

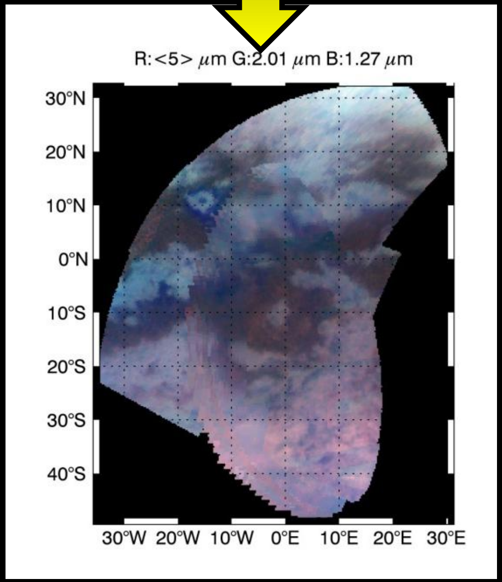


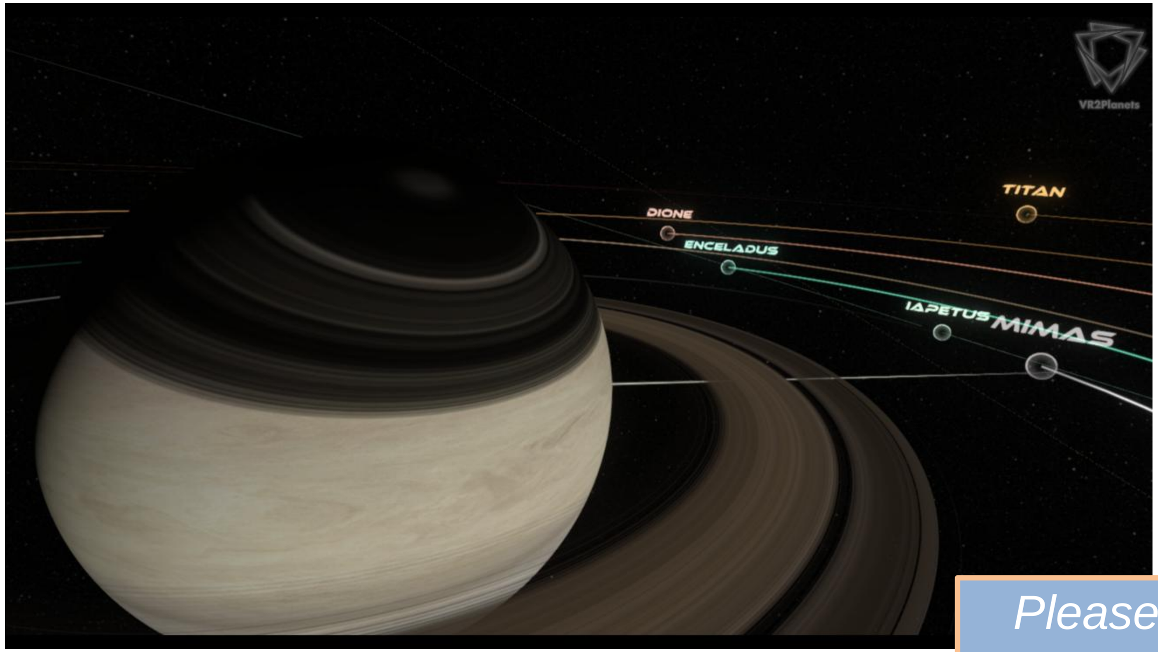
Cassini/VIMS: R5, G2, B1.27 (2 flybys)

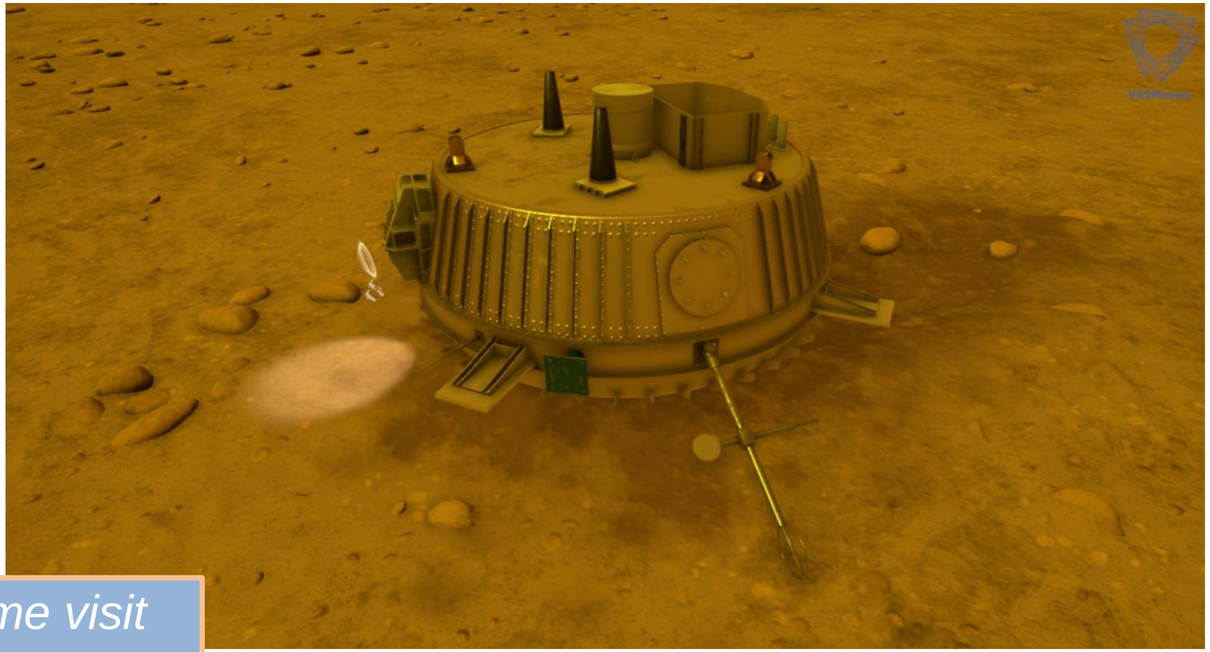
RAW



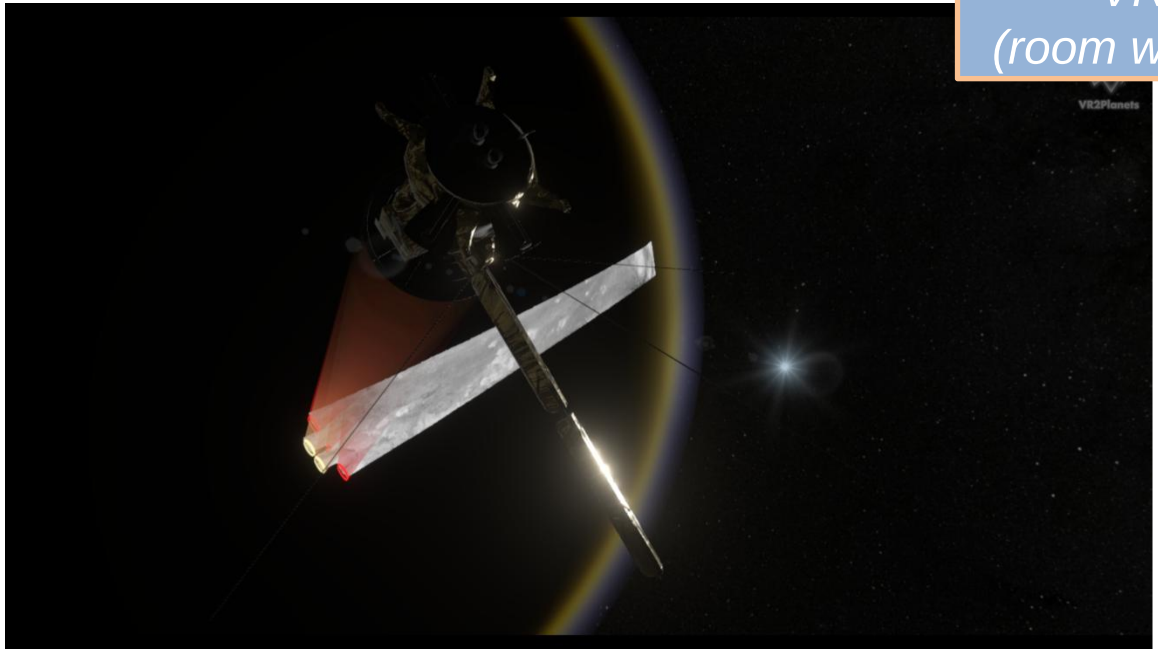
RT CORRECTED [This work]

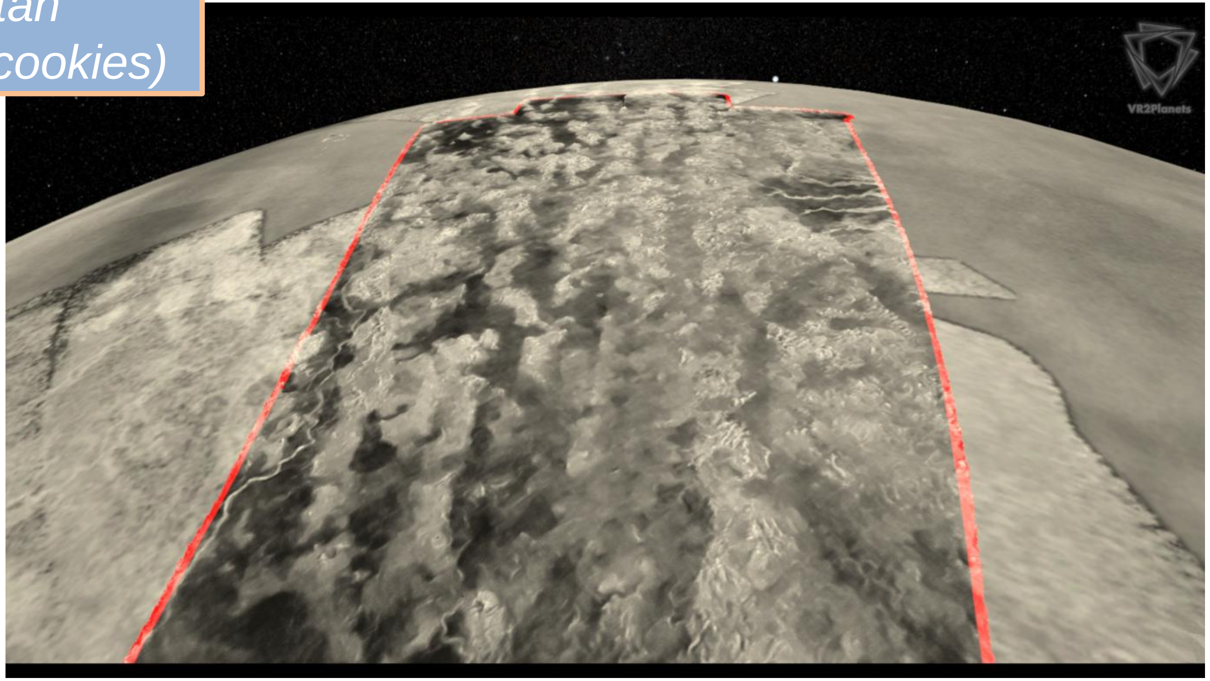






Please come visit VR2Titan (room with cookies)





Back up slides

Titan radiative transfer model

Atmosphere

- Structure (P, T, layers)
- Optical properties of gases and aerosols
- Haze and gaseous population

Surface

Lambert albedo (A_L)

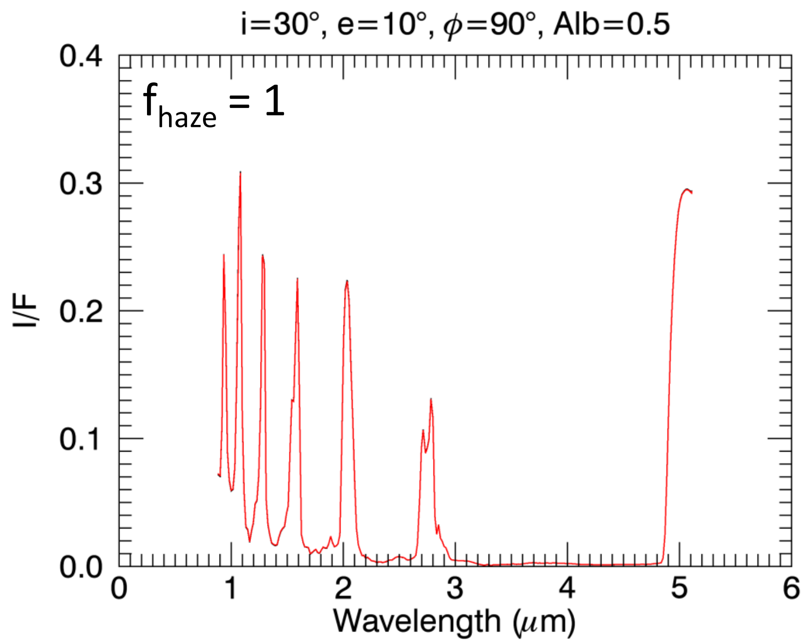
Viewing geometry

Incidence (i), emission (e) and azimuth (ϕ)

Forward model computation
1 full spectrum ~ 4 mins

RTE Solver PP
(SHDOMPP)
[Evans, 2007]

Simulated spectrum



Titan radiative transfer model

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Forward model computation
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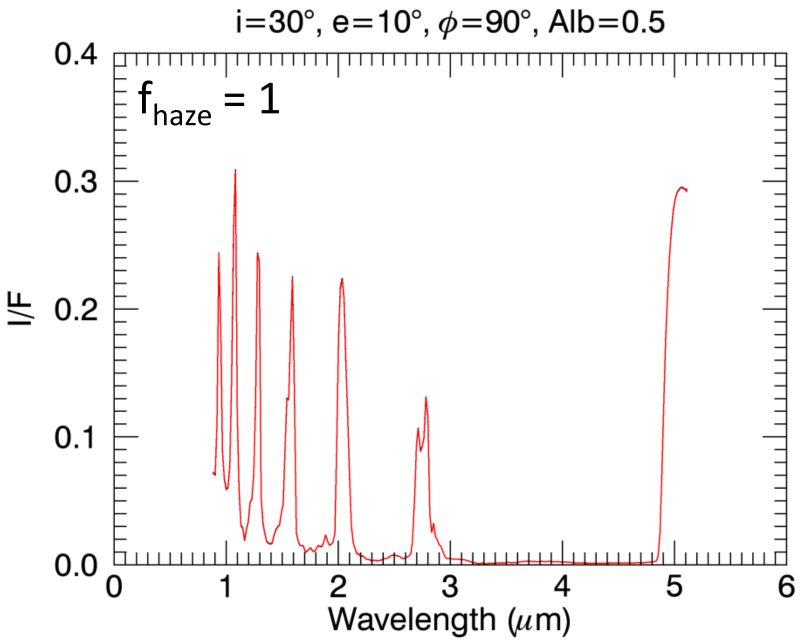
RTE Solver PP (SHDOMPP) [Evans, 2007]

RTE Solver PS (CDISORT) [Buras, 2011]

Simulated spectrum



If we use our model for VIMS data inversion purposes…

Fixed atmospheric inputs
Structure (P, T, layers)
Optical properties of gases and aerosols (from Huygens)

Viewing geometry inputs
Incidence (i), emission (e) and azimuth (ϕ)

Variable atmospheric output
Haze population
[haze factor (f_{haze}) wrt Huygens $k_{ext}(z,\lambda)$]

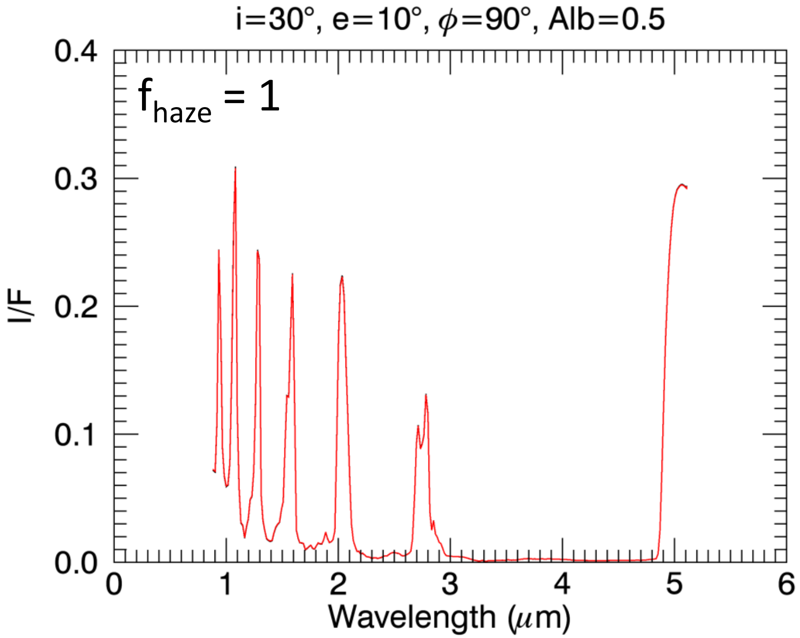
Variable surface property output
Lambert albedo (A_L)

Forward model computation
1 full spectrum ~ 4 mins

RTE Solver PP (SHDOMPP) [Evans, 2007]

RTE Solver PS (CDISORT) [Buras, 2011]

Simulated spectrum



Inverting one single spectrum
= Niter x 4 mins !
… and one single 64x64 VIMS cube
= 4096 spectra !
= 10+ days !

Principle: Inversion using interpolations between nodes of reference Look-Up Tables
[Maltagliati et al., 2015]

Fixed atmospheric inputs
Structure (P, T, layers)
Optical properties of gases and aerosols (from Huygens)

Variable viewing geometry inputs
Incidence (i) & emission (e):
[0°, 7.6°, 16.8°, 24.6°, 38.2°, 48.1°, 59°, 69.5°, 77.2°, 81°, 89°]
[0°, 6.7°, 17.9°, 28.4°, 38°, 47.1°, 55.1°, 66.7°, 75.3°, 81°, 84.9°, 89°]
Azimuth (ϕ):
[0°, 9°, 19.4°, 41.3°, 75°, 89.4°, 120°, 135.4°, 143.9°, 161.3°, 180°]

Variable atmospheric output
Haze factor (f_{haze}) wrt Huygens
[0.3, 0.7, 1.2, 1.7]

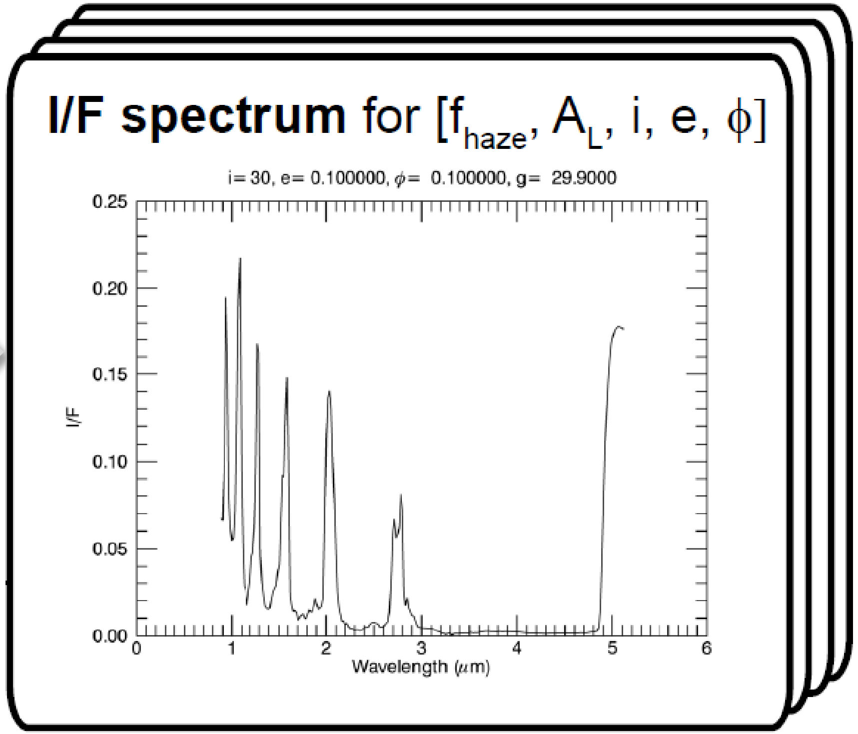
Variable surface property output
Lambert albedo (A_L)
[0.0, 0.5, 1.0]

Forward model computation
1 full spectrum ~ 4 mins

RTE Solver PP (SHDOMPP) [Evans, 2007]

RTE Solver PS (CDISORT) [Buras, 2011]

Look-Up Tables (LUTs) of simulated spectra

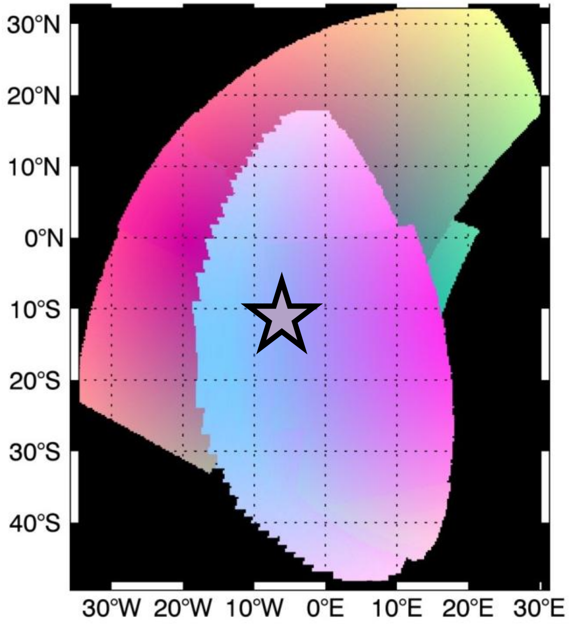


Data inversion: LUT interpolations

Data inversion in 3 steps

1 spectrum = 3-4 sec ; 1 regional mosaic (>53000 spectra) = 4 hours

Starting from the geometry of each pixel/spectrum

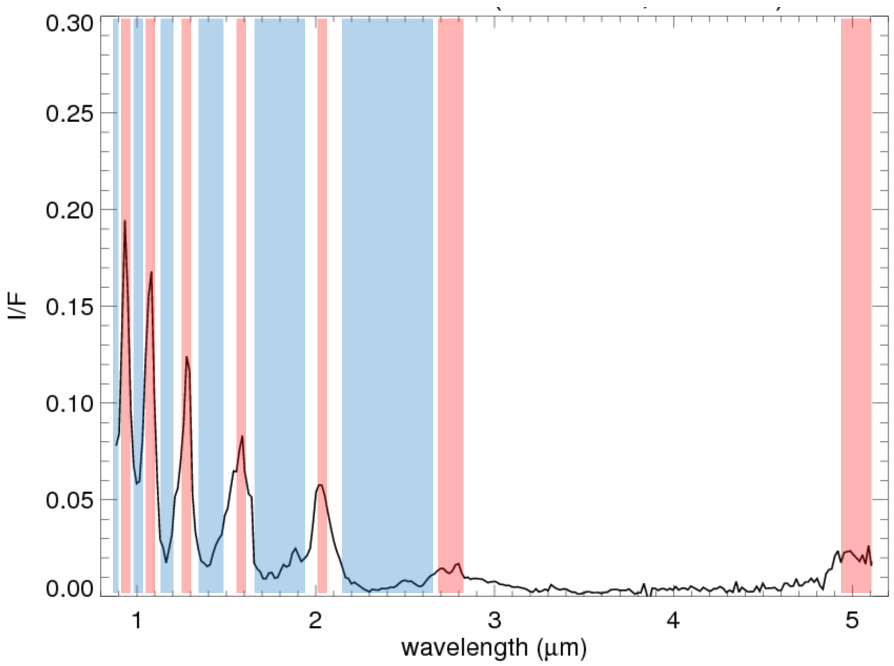


7.28°< i <50.00°
0.25°< e <50.00°
37.29°< g <63.75°

T13-T17 VIMS mosaic

Interpolations on i, e, ϕ

2 steps inversion on the reduced LUT (f_{haze}, A_L, λ)

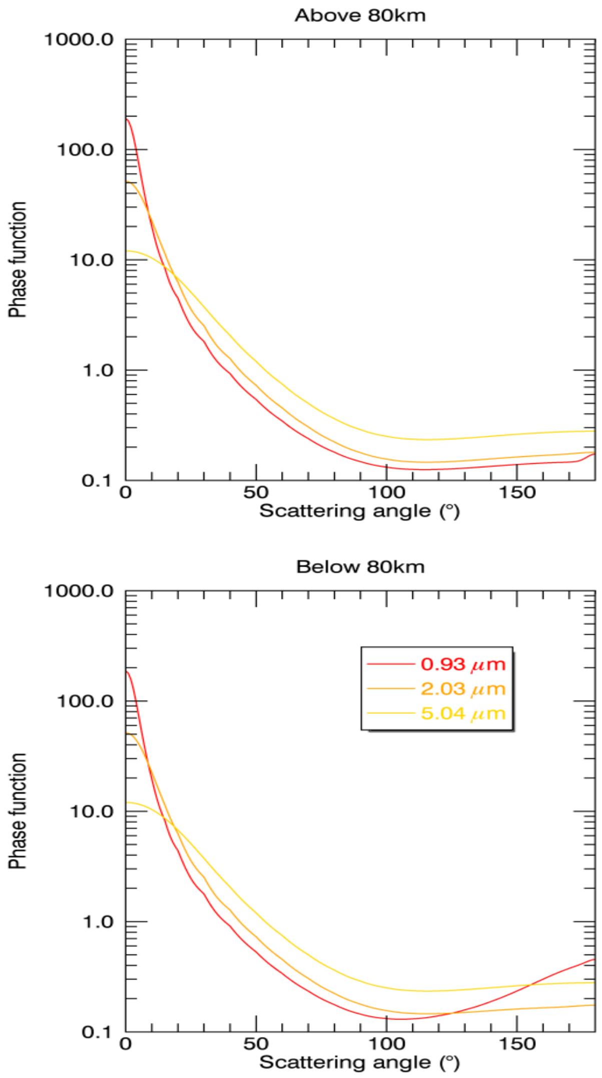


Step 1: retrieval of the best global haze factor

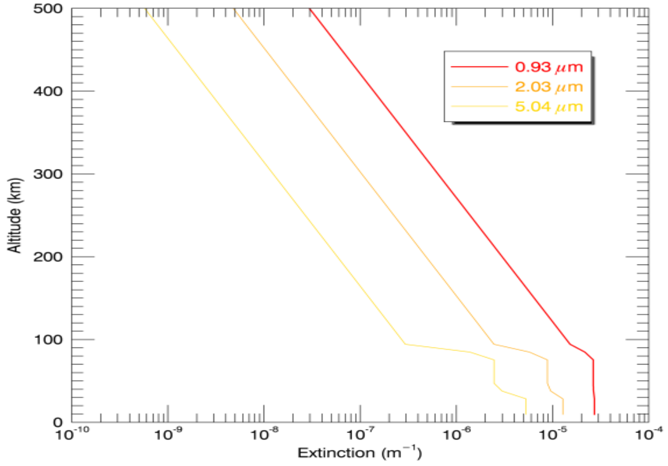
Step 2: retrieval of the best lambert albedo/spectel

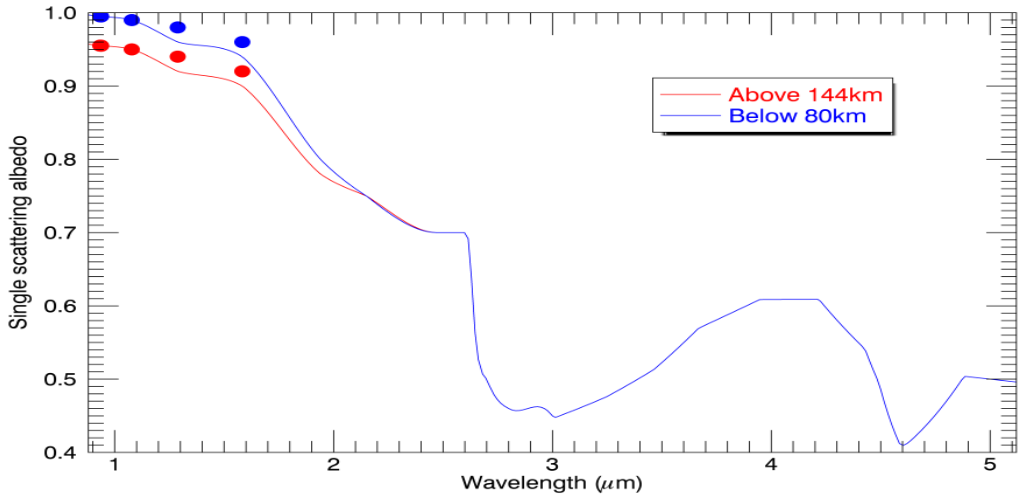
Aerosols' properties?

Phase functions, extinction profiles and ω_0 from Tomasko et al. (2008) and Hirtzig et al. (2013)



Optical Depth = $1.012 \times 10^{7} \lambda^{-2.339}$ (above 80 km)
Optical Depth = $2.029 \times 10^{4} \lambda^{-1.409}$ (30 - 80 km)
Optical Depth = $6.270 \times 10^{2} \lambda^{-0.9706}$ (under 30 km)





Well constrained up to 0.95 μm (1.6 μm?).
In the VIMS wavelength range, provide extrapolation through Tables and Equations.

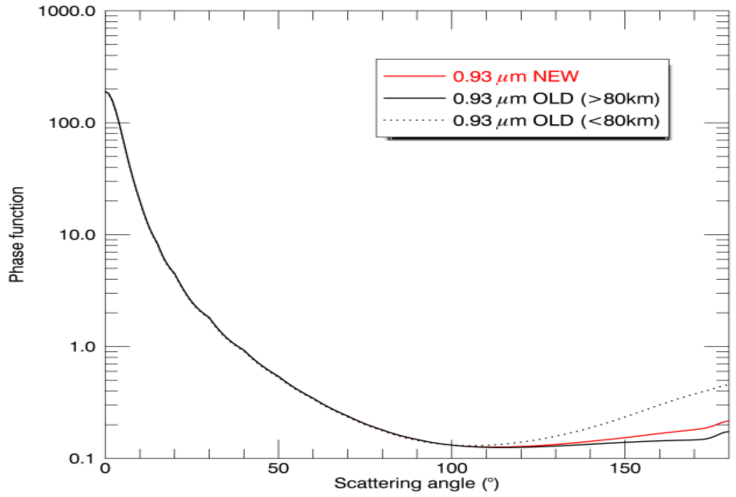
Aerosols' properties?

Phase functions, extinction profiles and ω_0 from Doose et al. (2015)

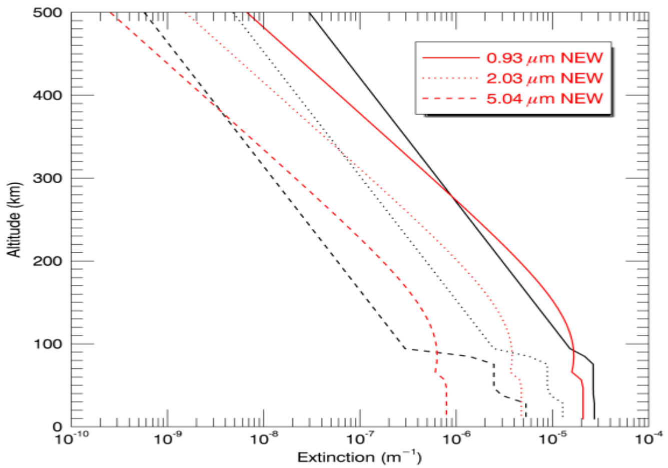
$$\tau(\lambda, z) = \frac{a}{(g + \lambda^f)(b + e^{z/c})}$$

$$E_{55} = \frac{\frac{a}{c} e^{\frac{d}{c}}}{(g + \lambda^f)\left(b + e^{d/c}\right)^2}$$

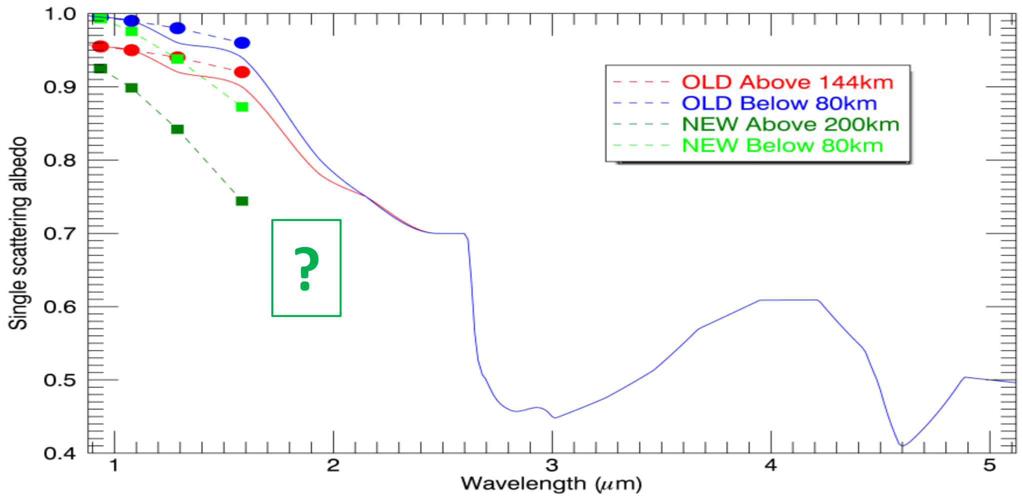
$$\tau(\lambda, z) = \frac{a}{(g + \lambda^f)\left(b + e^{d/c}\right)} + hE_{55}(d - z)$$



1 phase function



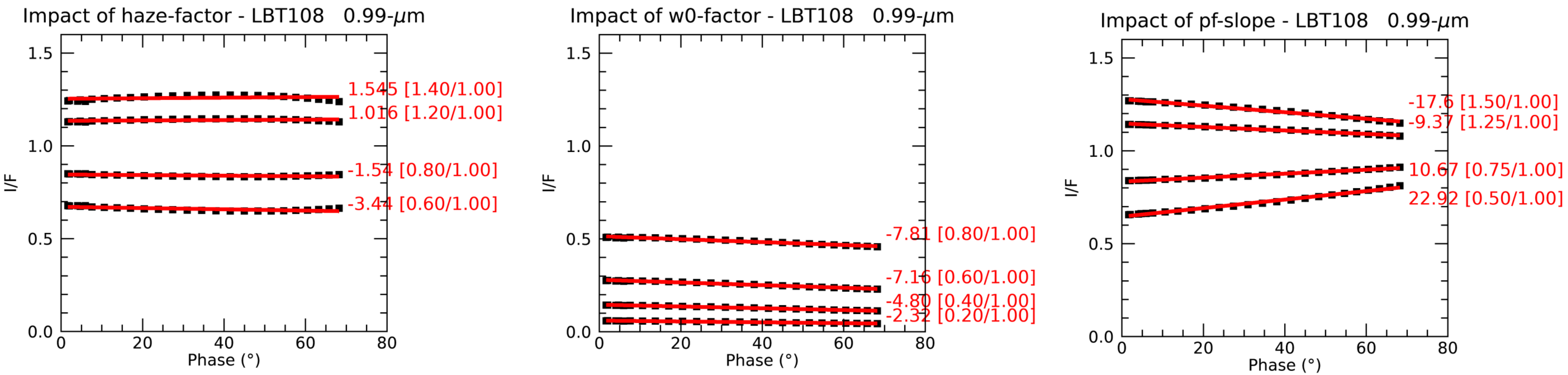
1 transition @ 55 km

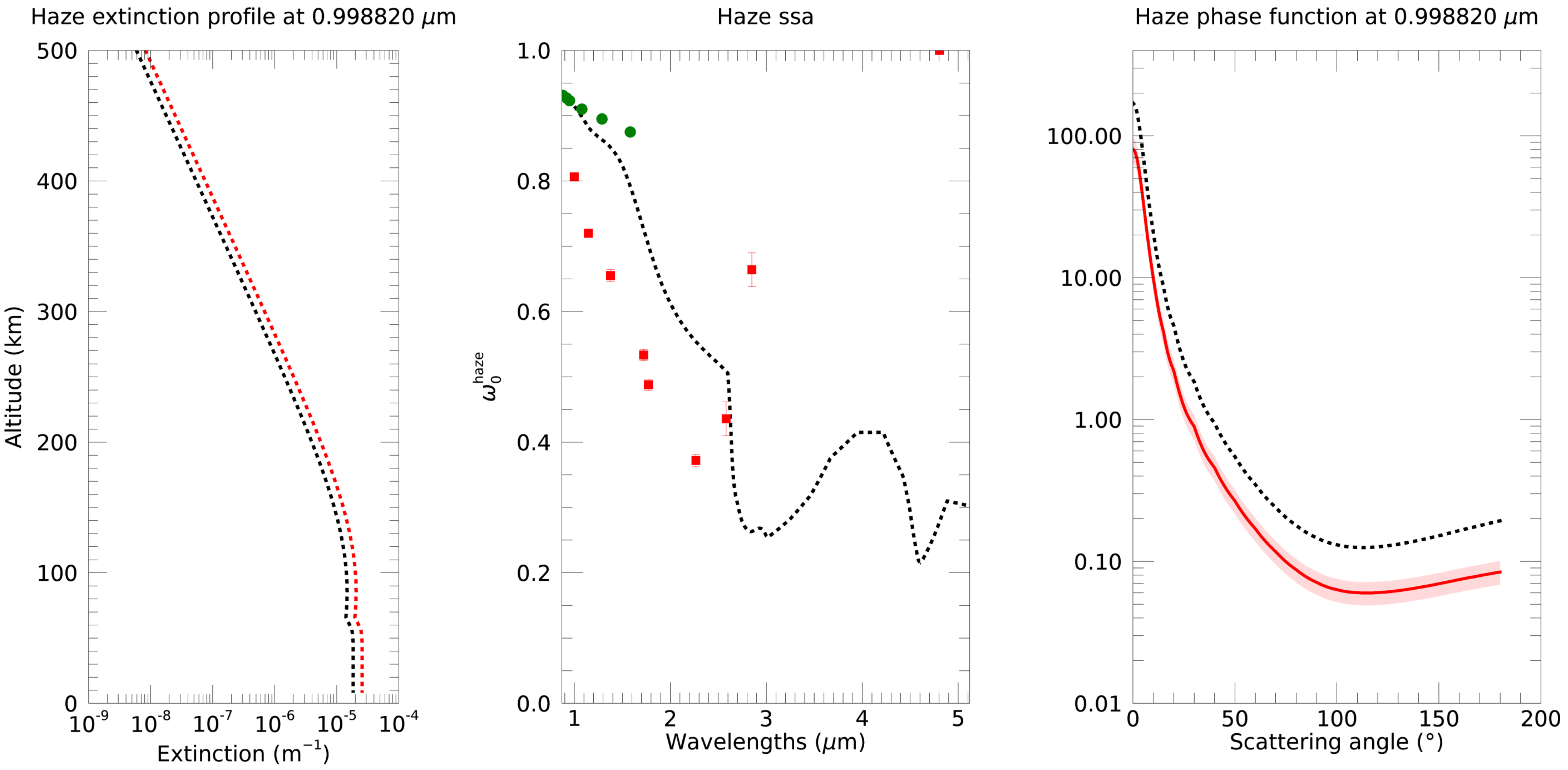


darker aerosols

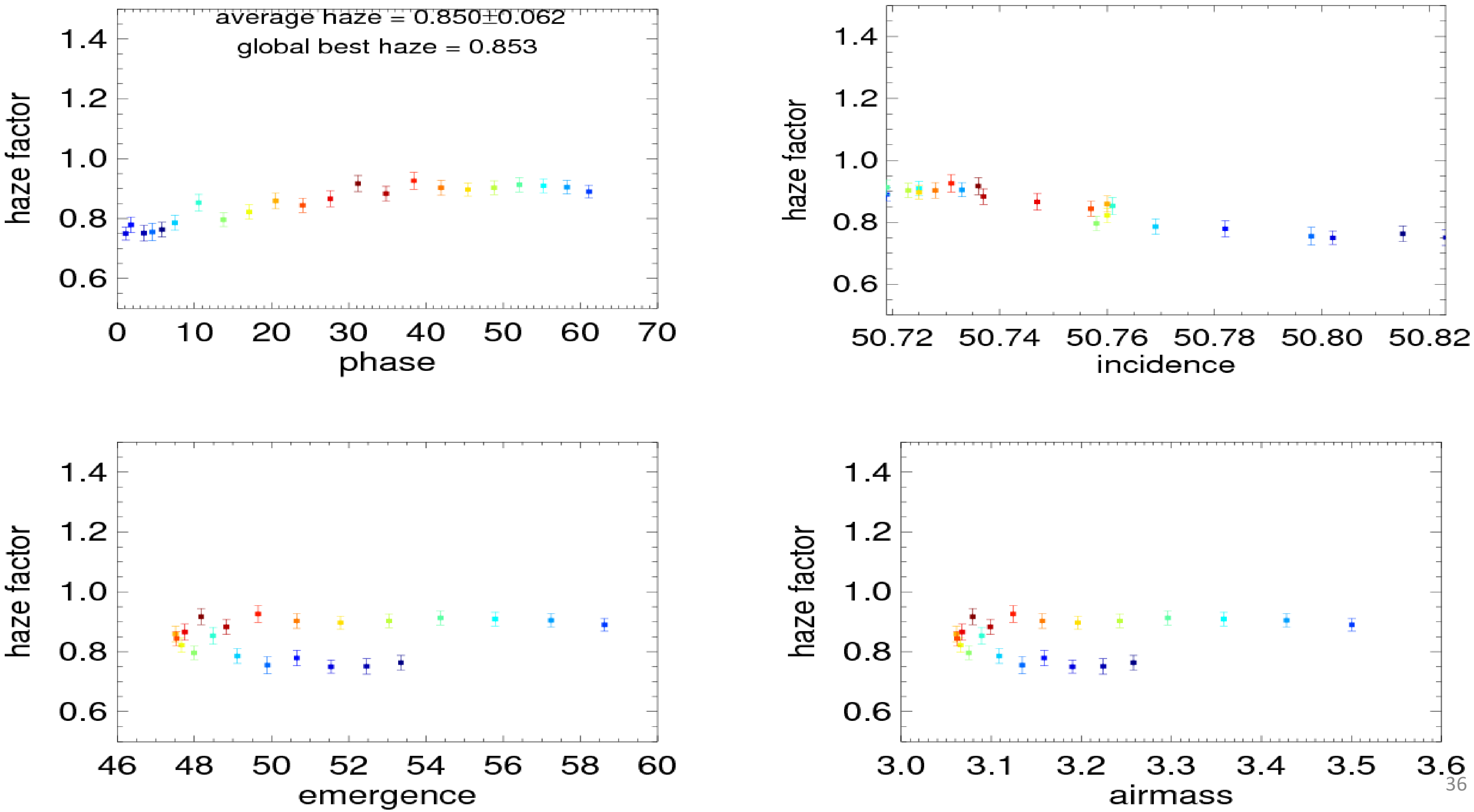
Well constrained up to 0.95 µm (1.6 µm?).
In the VIMS wavelength range, provide extrapolation through Tables and Equations.

Sensitivity of the phase curve to the haze parameters of the model

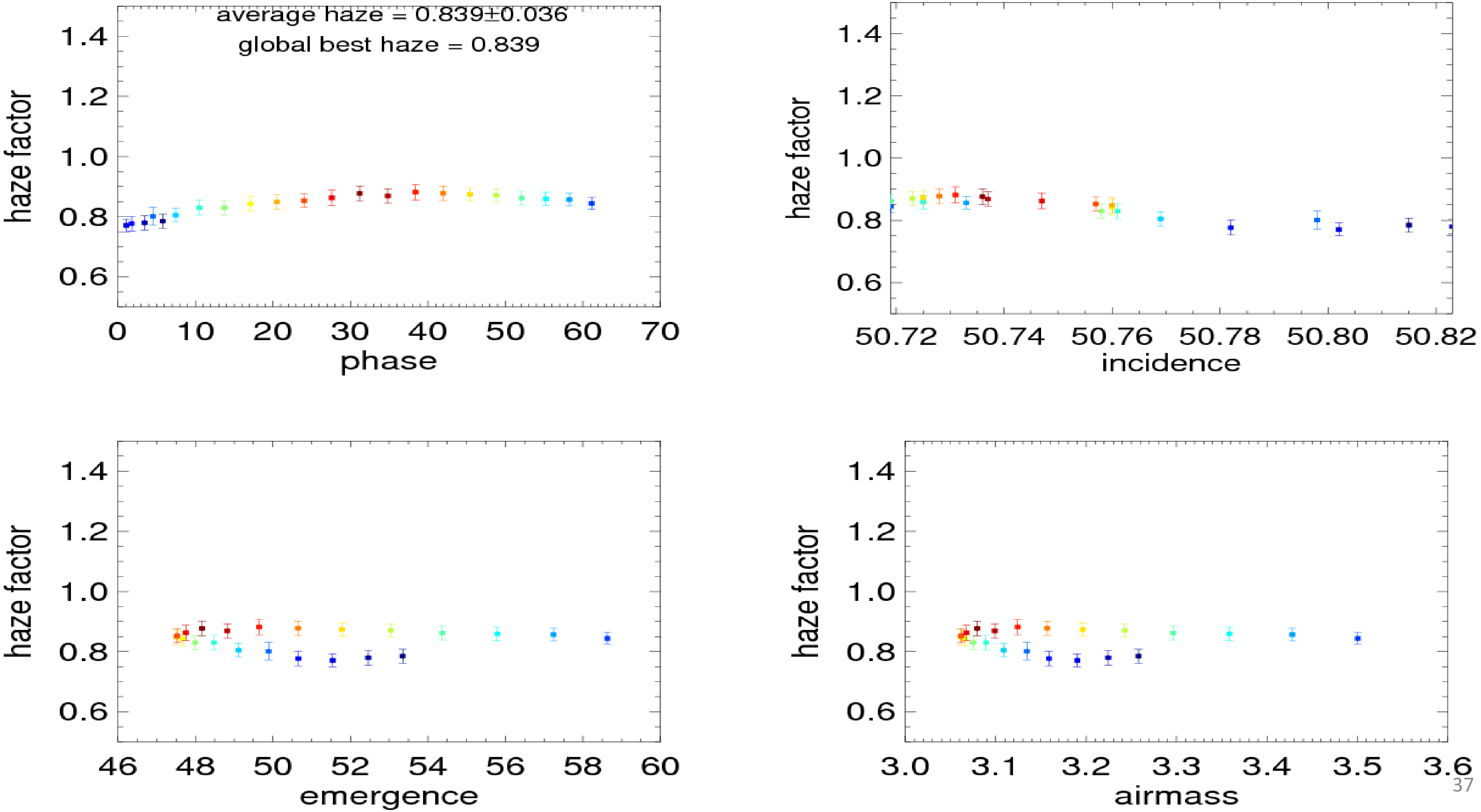



Haze extinction profile at 0.998820 μm
Altitude (km)
Extinction (m⁻¹)
Haze ssa
ω_0^{haze}
Wavelengths (μm)
Haze phase function at 0.998820 μm
Scattering angle (°)

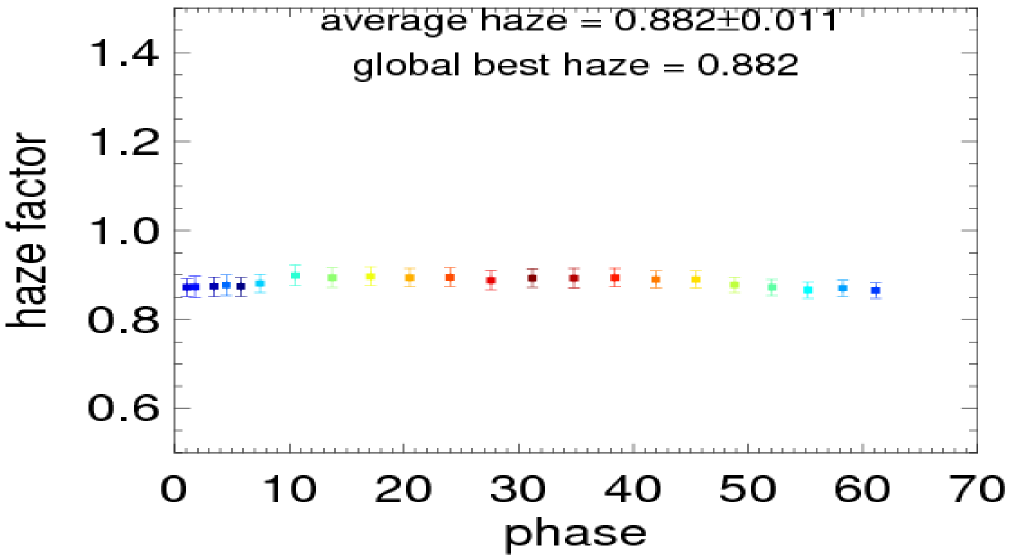
The T88 EPF – ”old” aerosols (Tomasko et al. 2008 and Hirtzig et al. 2013)

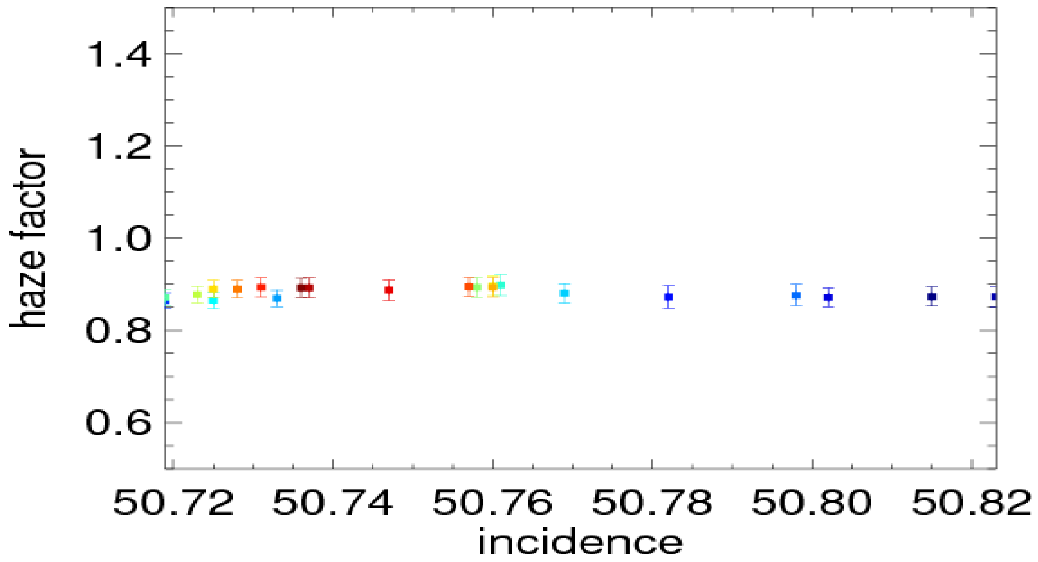


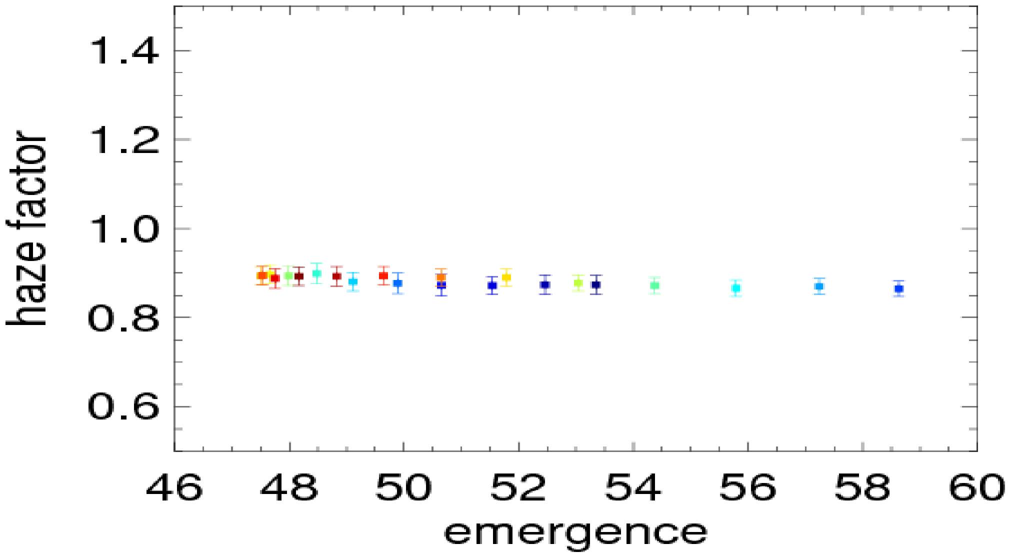
The T88 EPF – “less old” aerosols (Doose et al., 2015)

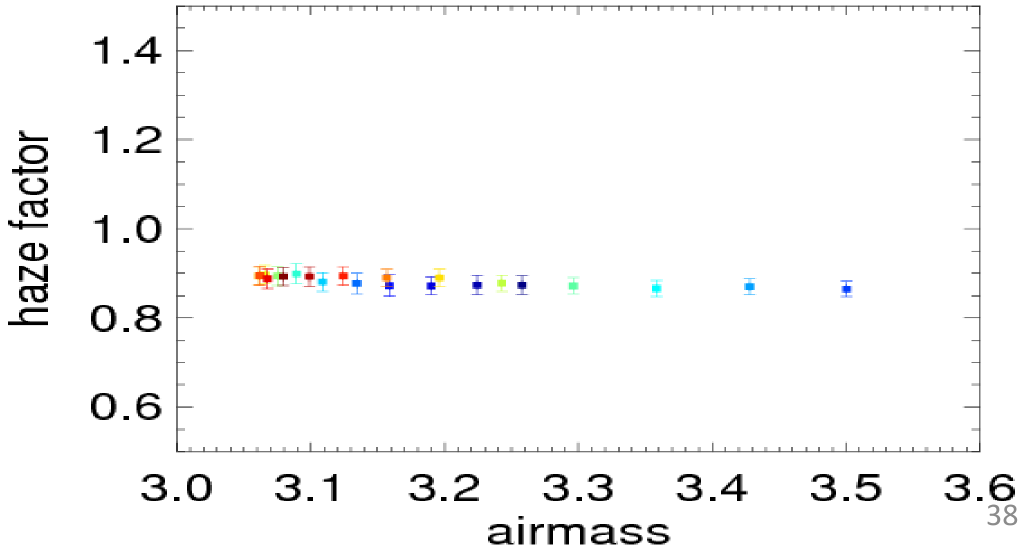


The T88 EPF – currently best result (with new CH_4 & new phase function)

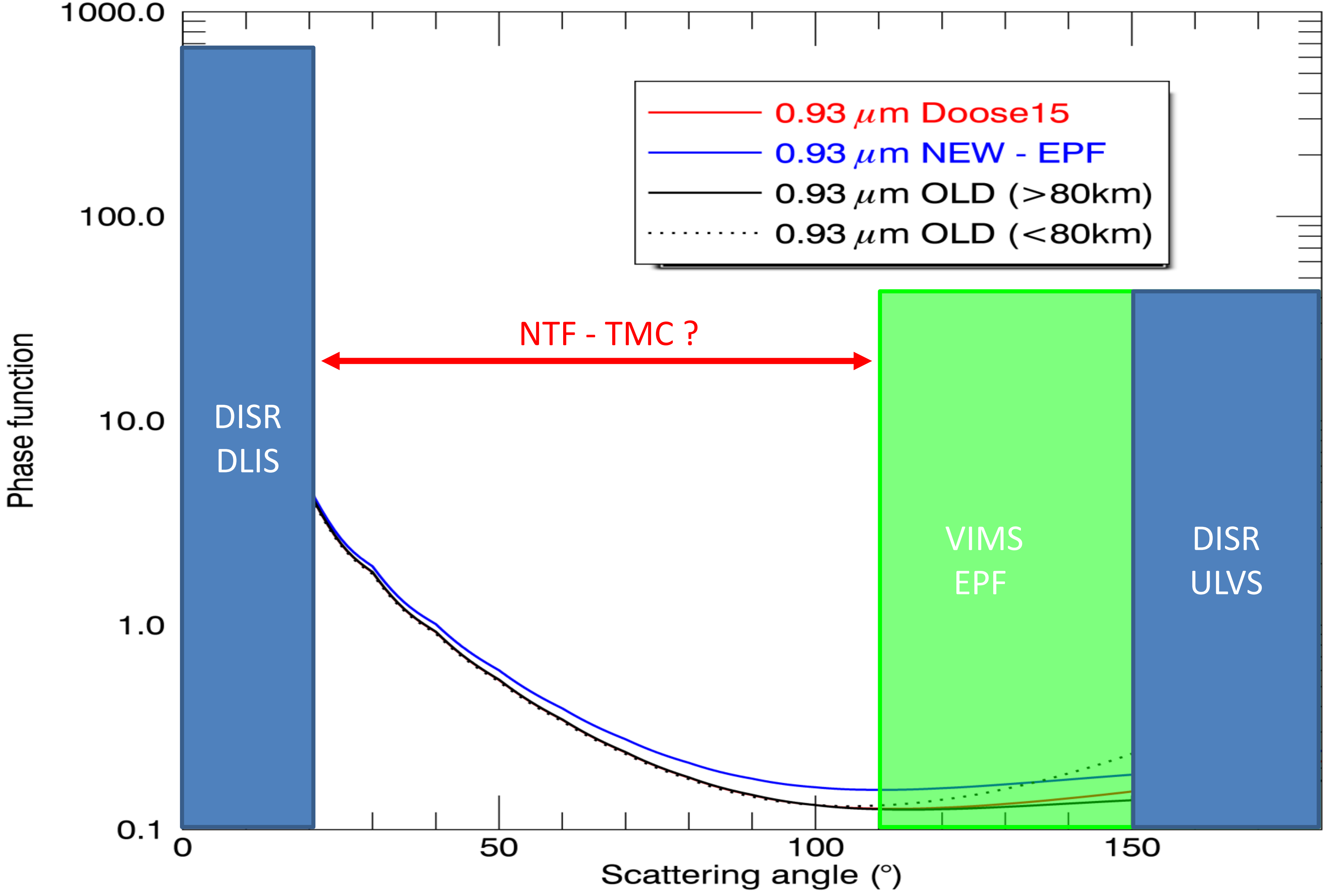






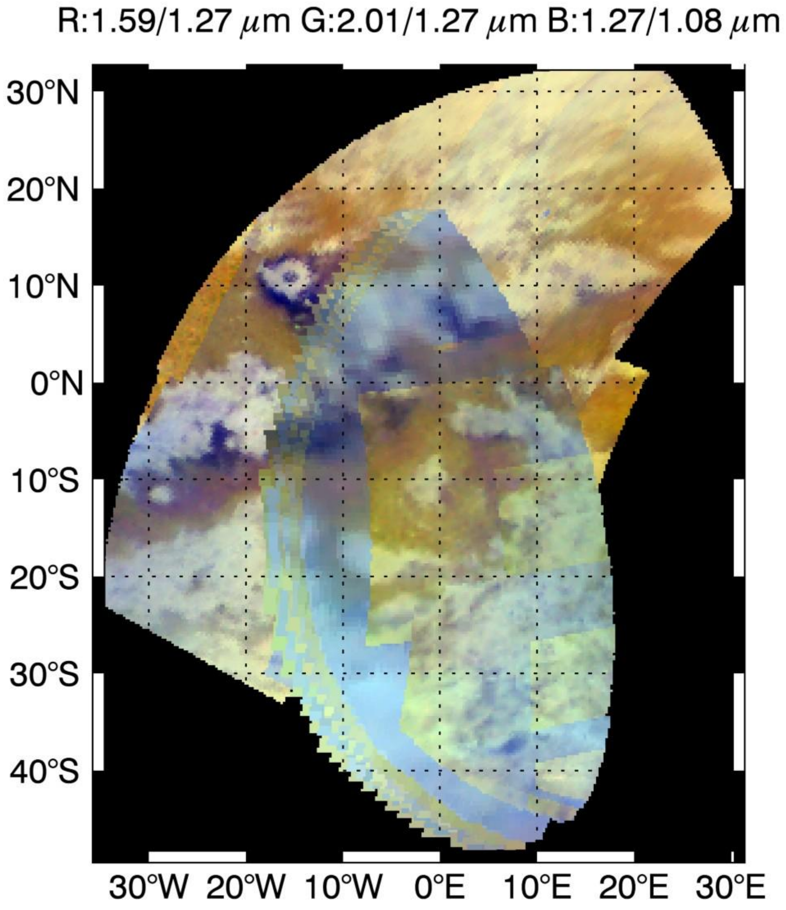


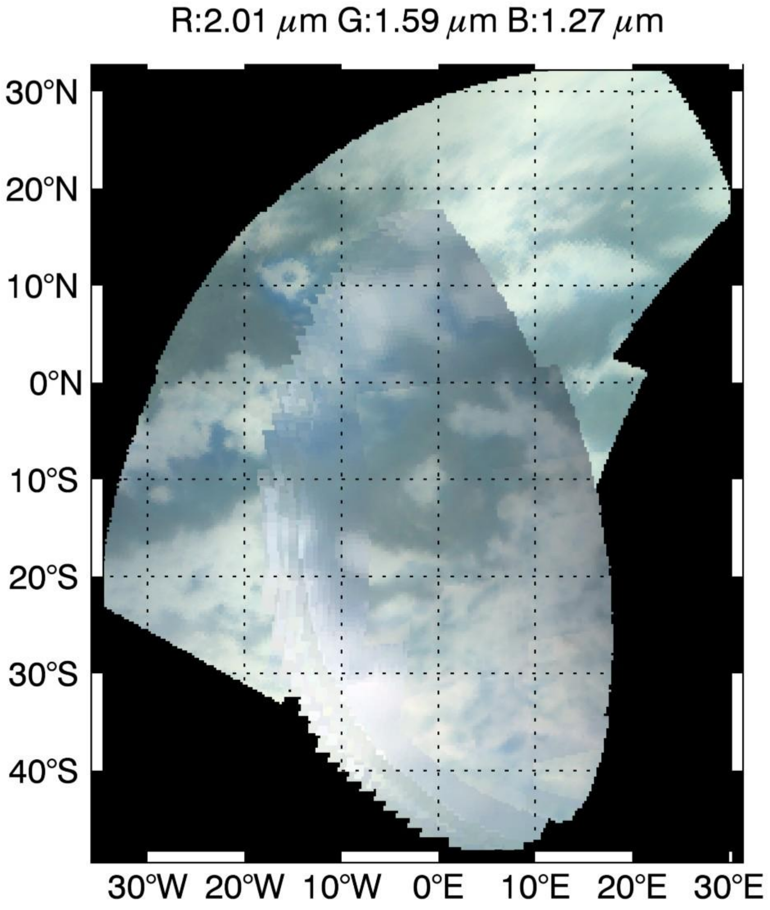
The T88 EPF – currently best result (with new CH_4 & new phase function)

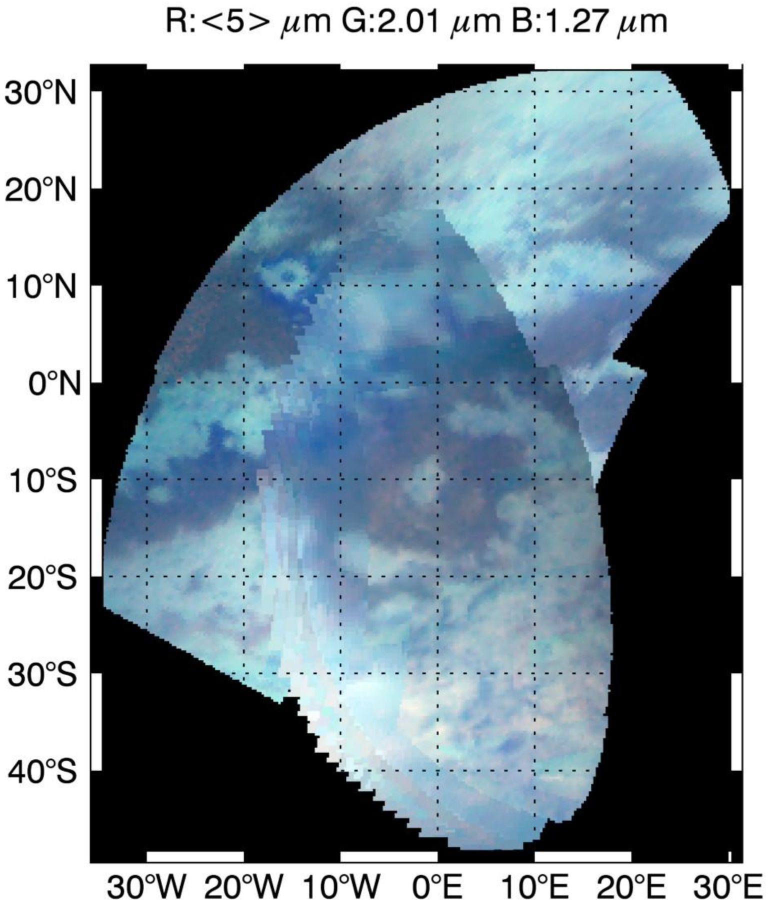


+ 40-50%
more backscattering

Initial raw mosaics

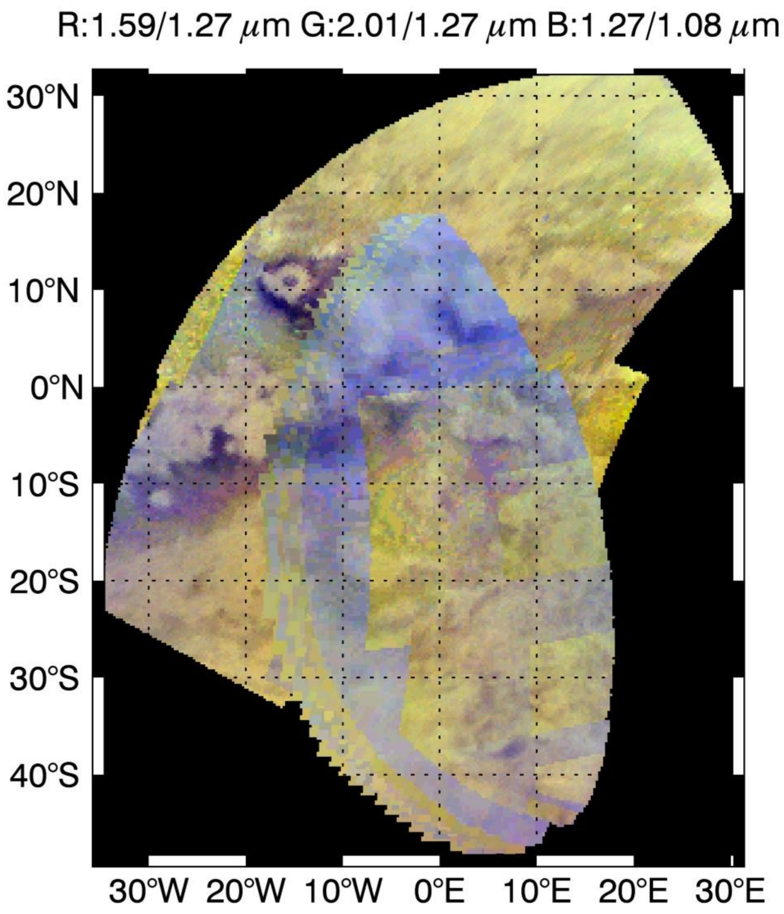


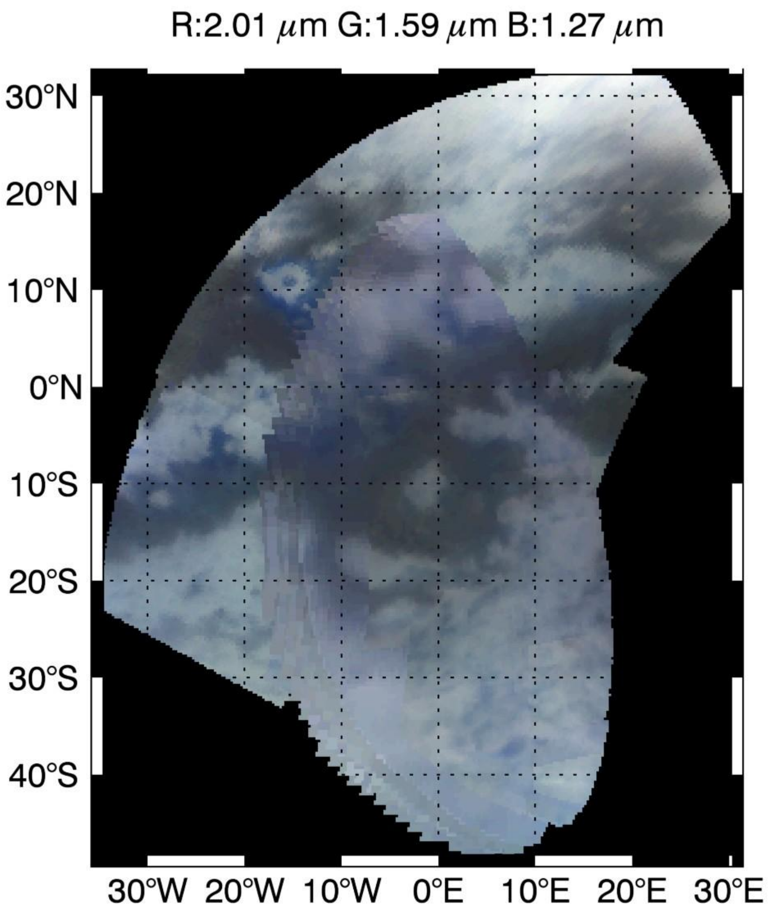


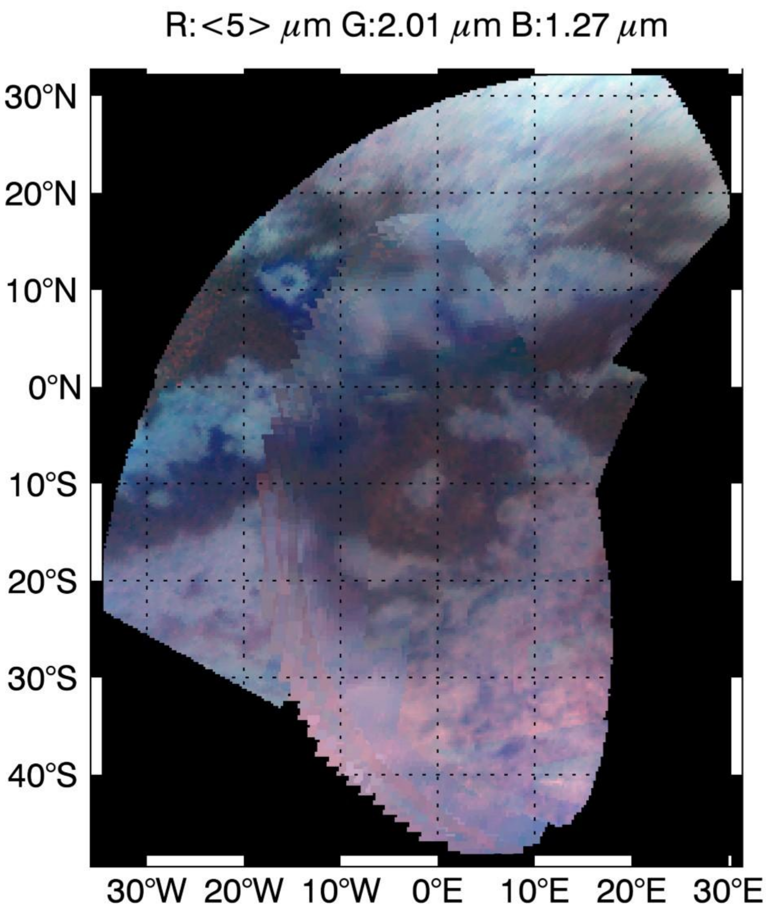


Test case: the T13-T17 VIMS mosaic

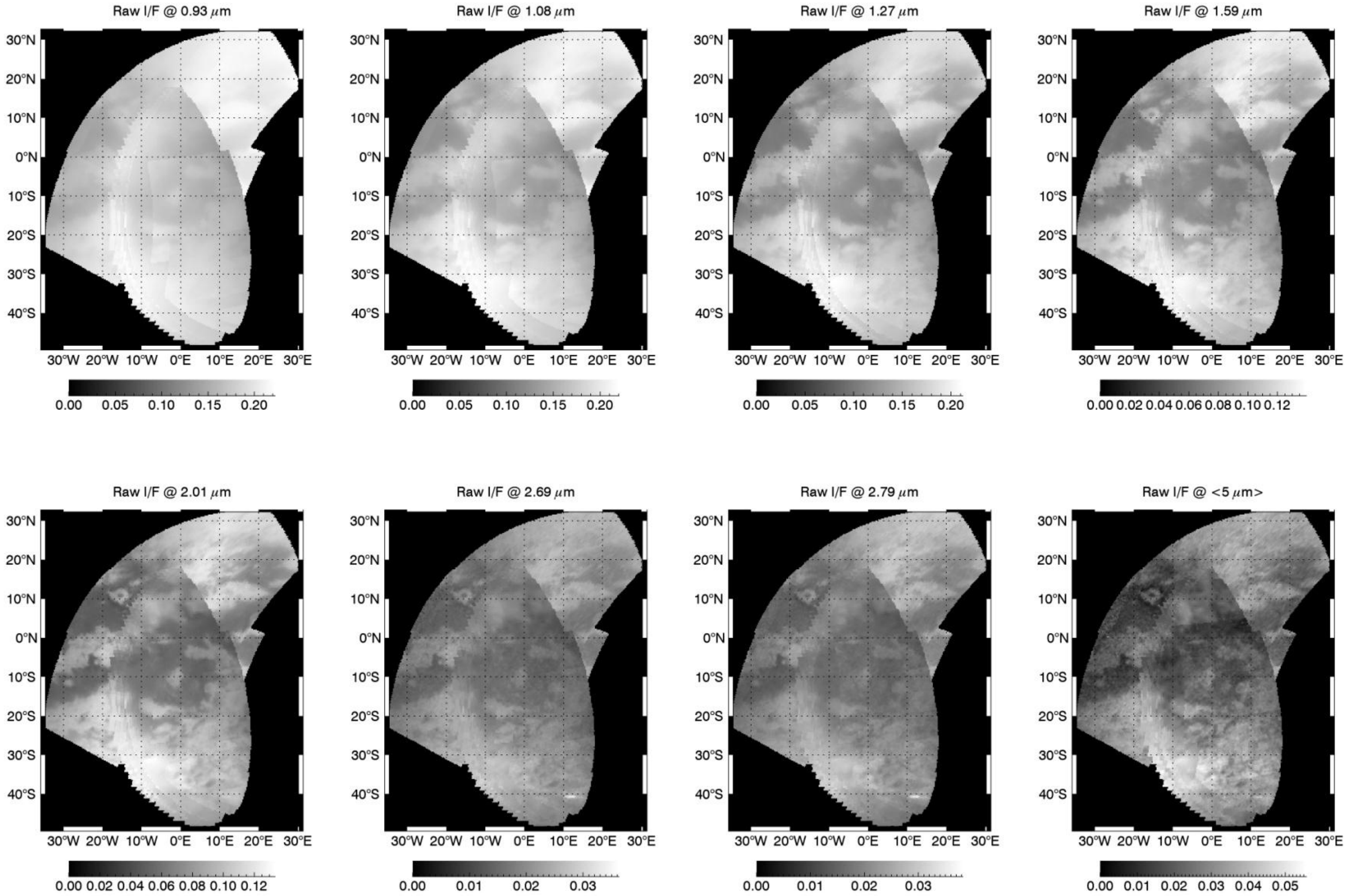
Inversion with LUTs [Hirtzig et al., 2013 ; Doose et al., 2016 + Maltagliati et al., 2015] **+ New CH_4** [Rey et al., 2016]







Initial raw mosaics



[Contrast adjusted between 0 and max for each window]

Test case: the T13-T17 VIMS mosaic

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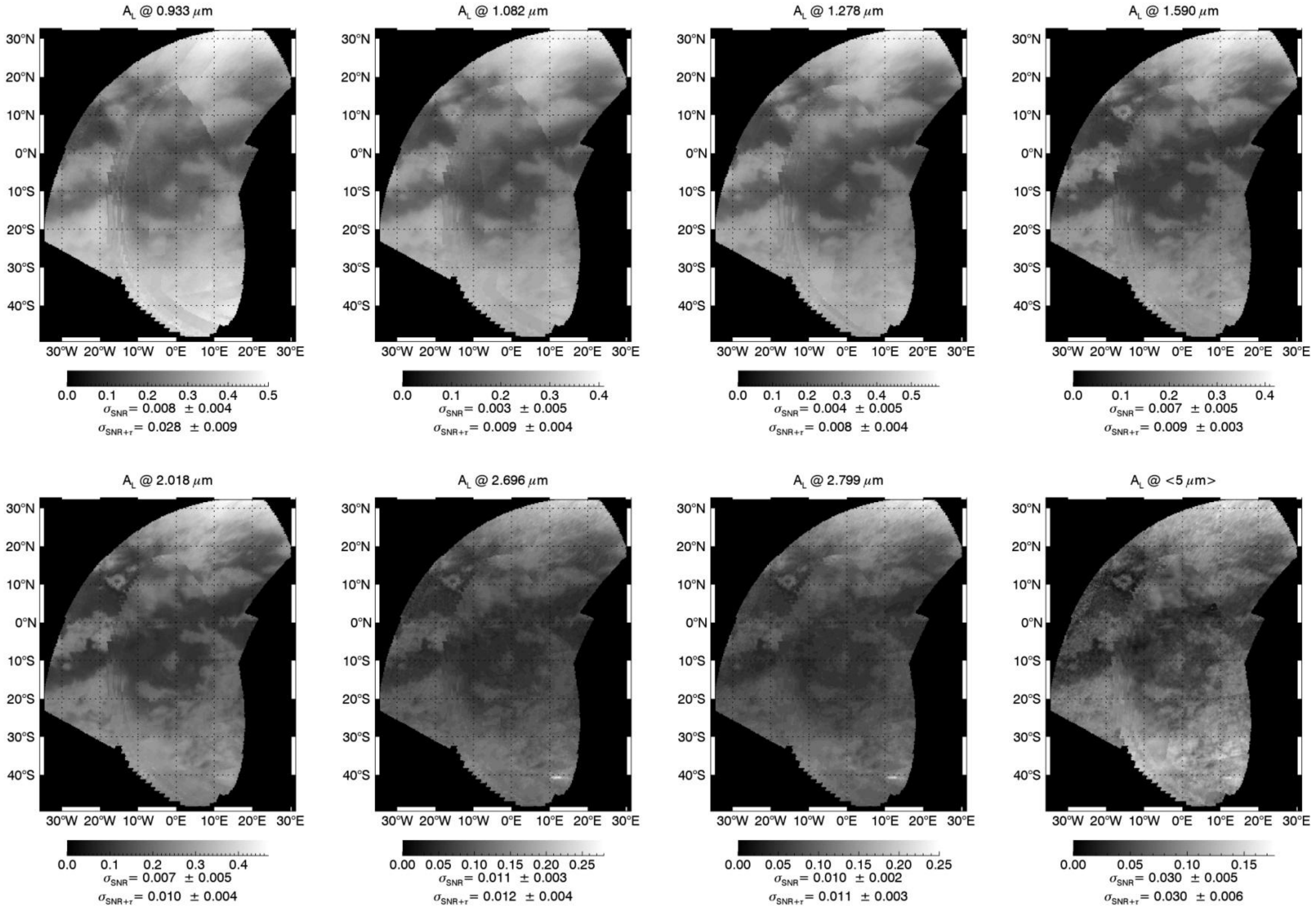
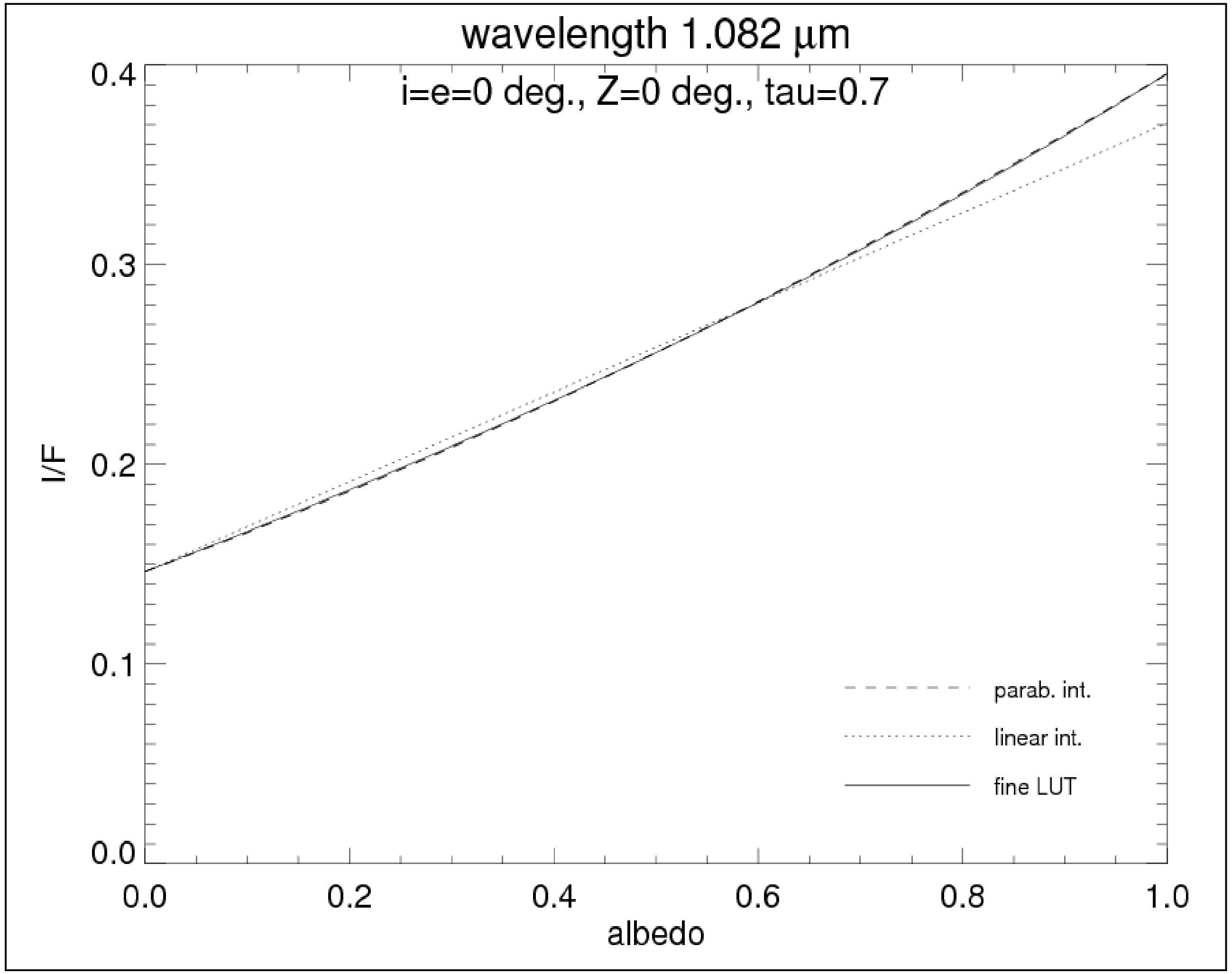


[Contrast adjusted between 0 and max for each window]

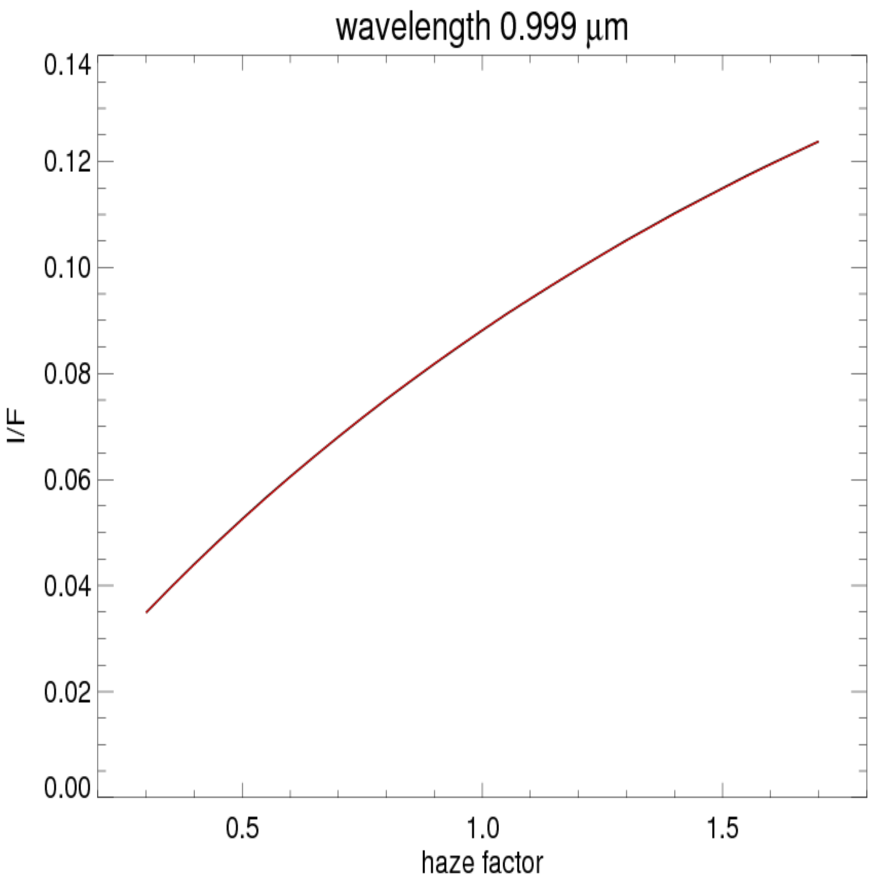
Study of parameters' space: albedo

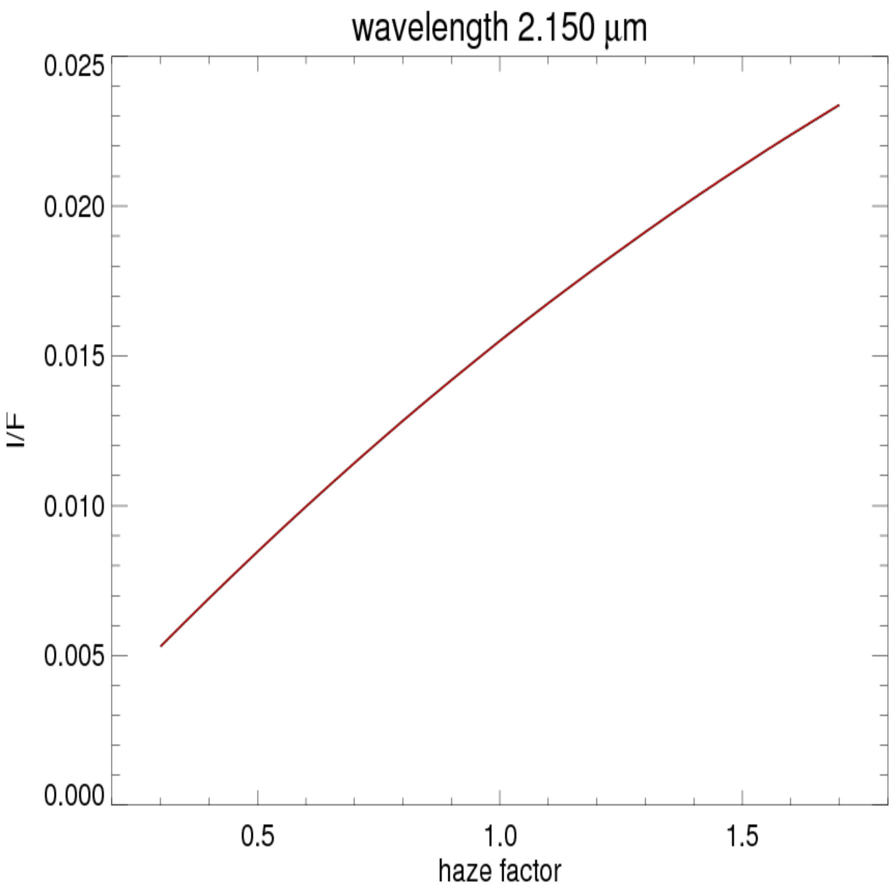
A parabolic fit between values [0.,0.5,1.] always reproduces well the albedo trend at all wavelengths



Study of parameters' space: haze

A cubic fit using 4 haze factor values: [0.3,0.7,1.2,1.7] reproduces well the trend at all wavelengths

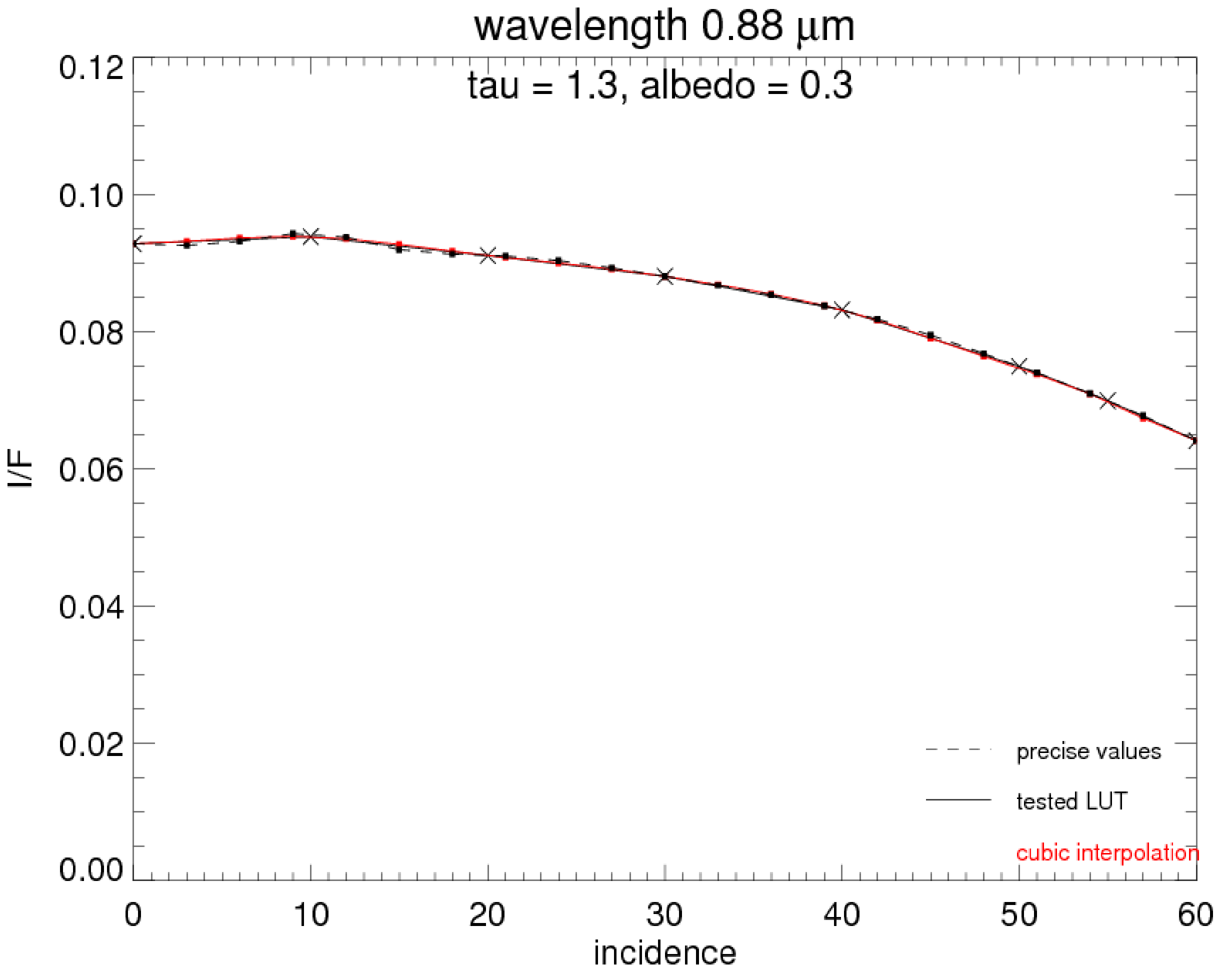




Study of parameters' space: inc, emg

More complex shape, need 8 points each between 0° and 60°

+ use of a spline interpolation



Study of parameters' space: inc, emg

More complex shape, need 8 points each between 0° and 60°

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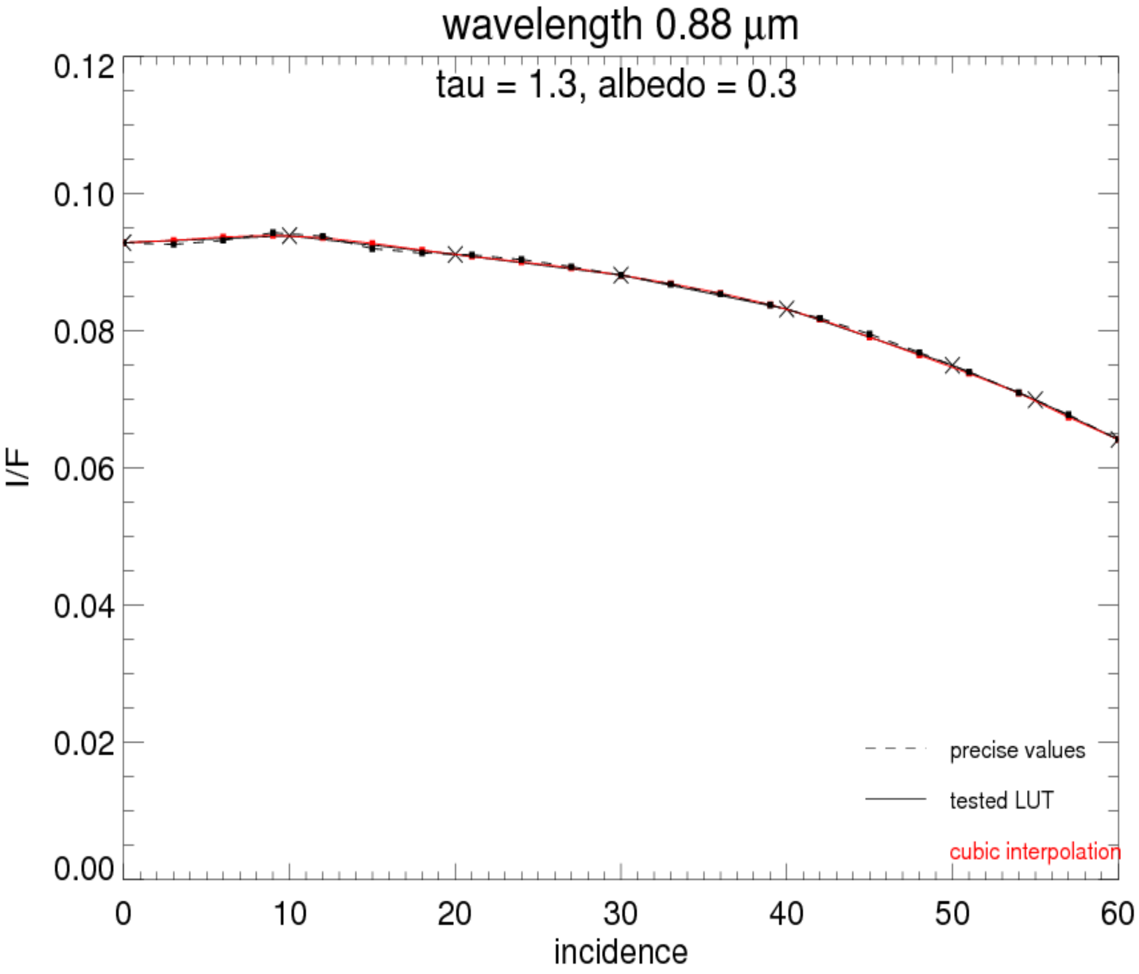
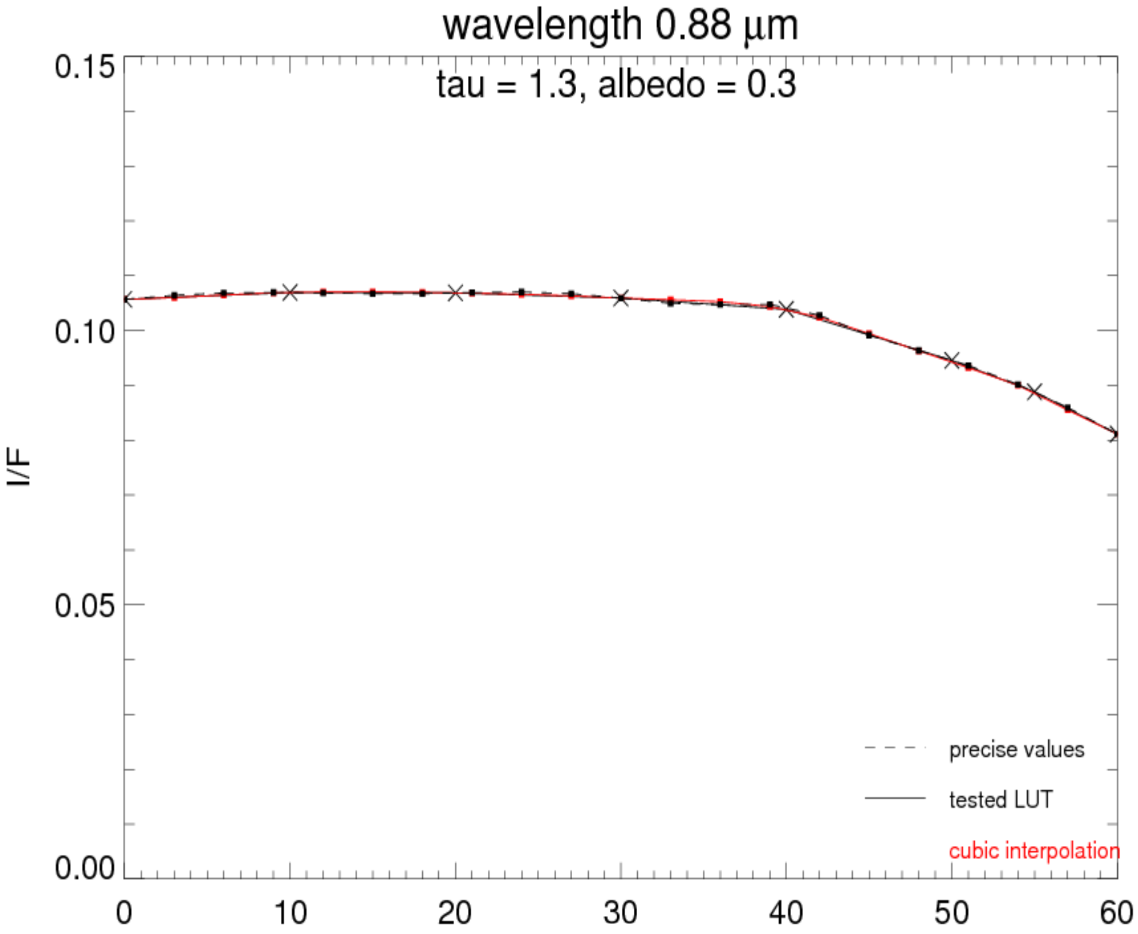


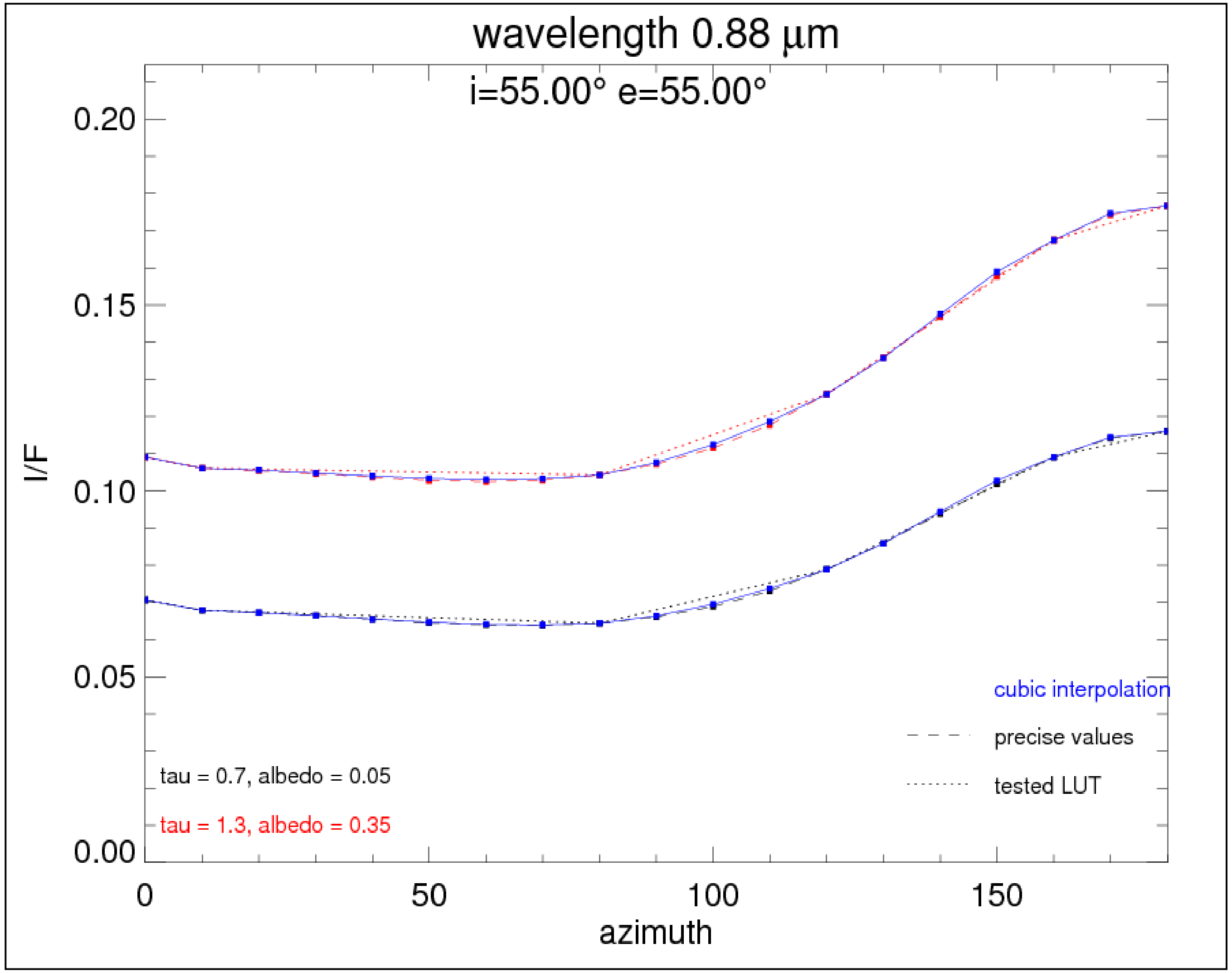


emergence

Study of parameters' space: azimuth

Another complex shape, needs 6 points at specific angles

0°, 10°, 80°, 120°, 160° 180° + use of a spline interpolation



Atmospheric properties updates

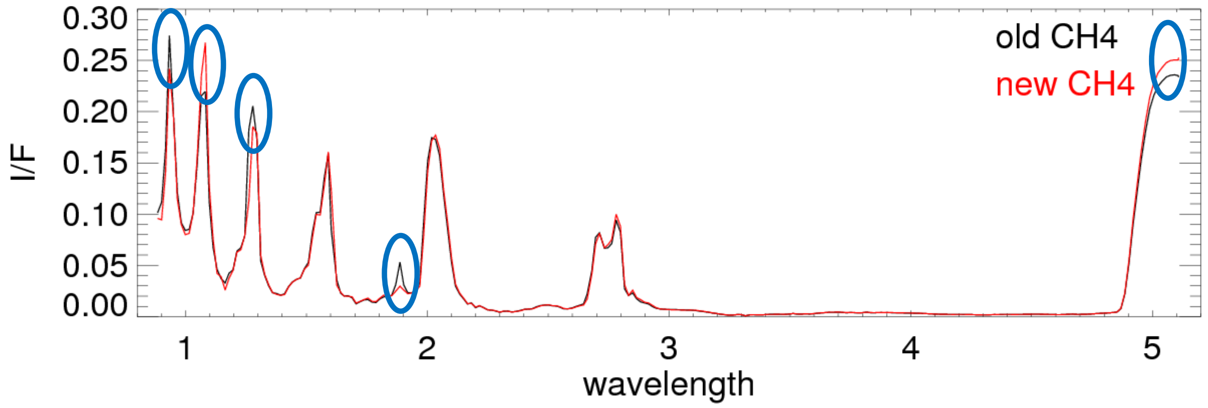
Where we were for mosaic inversions [Maltagliati et al., 2015]

- Haze properties from Tomasko et al. [2008] and Hirtzig et al. [2013]
- Some missing CH_4 absorptions at short wavelengths

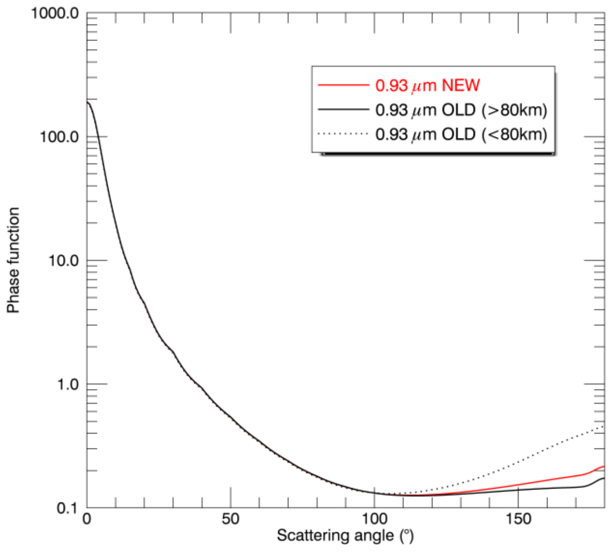
Where we are now for mosaic inversions using LUTs

- New CH_4 absorptions [Rey et al., 2016]
- Haze properties (τ, ω_0, P(g)) [Doose et al., 2016 ; Maltagliati et al., 2015]
- Shift in wavelength can now be taken into account (per unit nm shift)

Change in CH_4 absorptions coefficients (GSMA, Reims, FR)

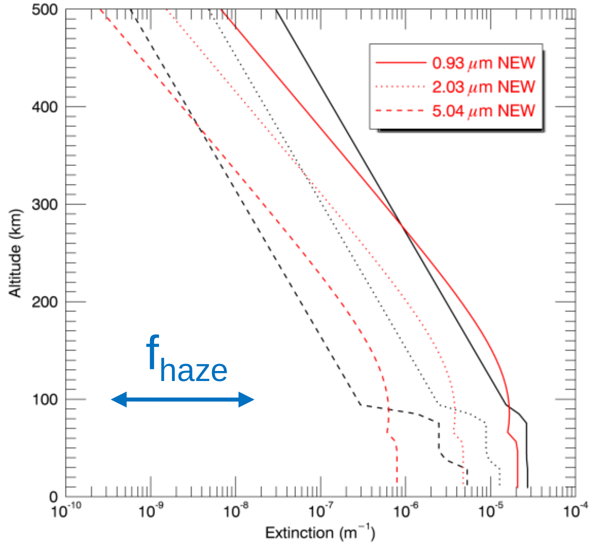


Aerosol phase function (P(g))



1 single P(g)

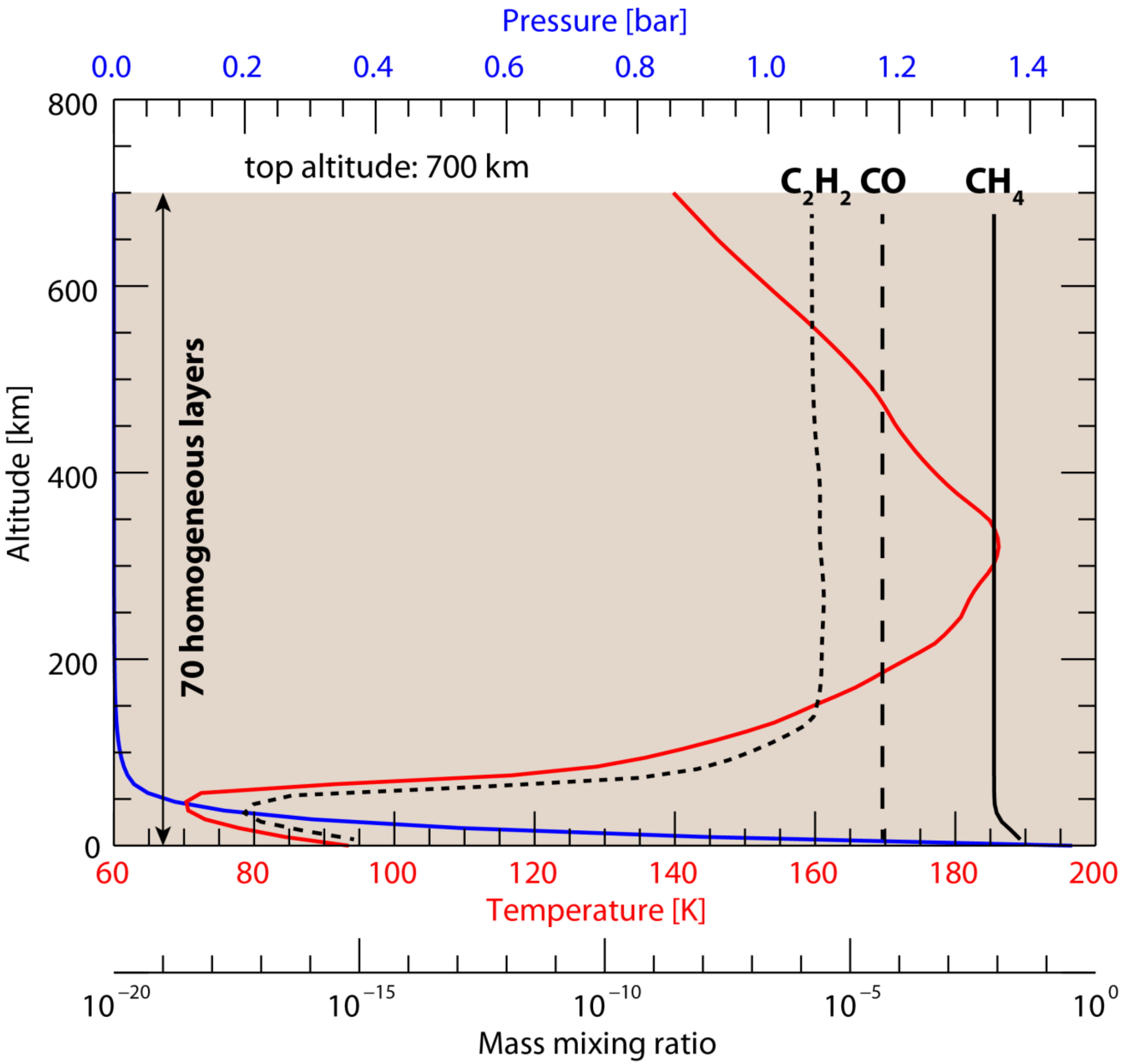
Aerosol extinction (k)



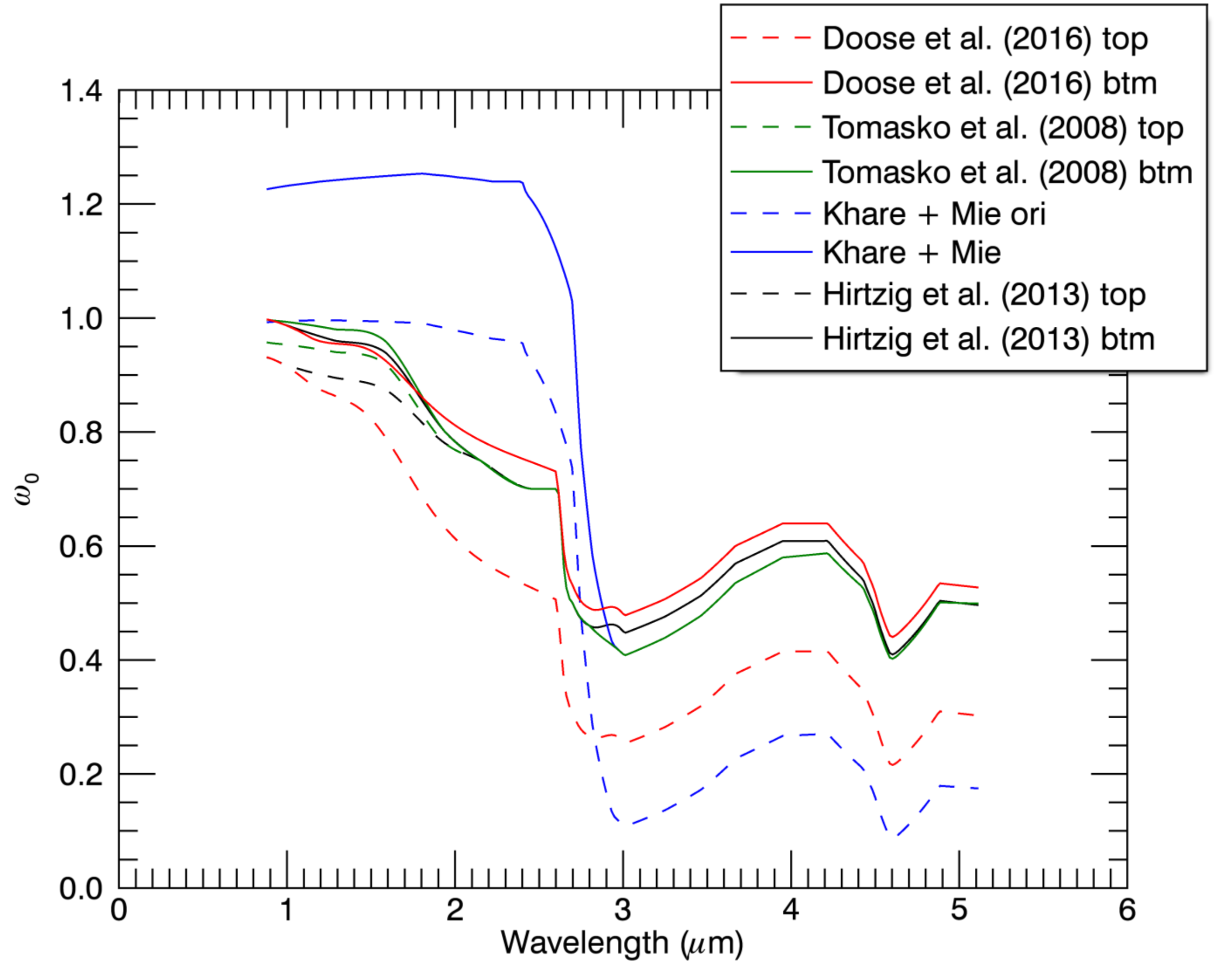
1 transition

(+ darker aerosols)

A few model atmospheric inputs



Haze single-scattering albedo

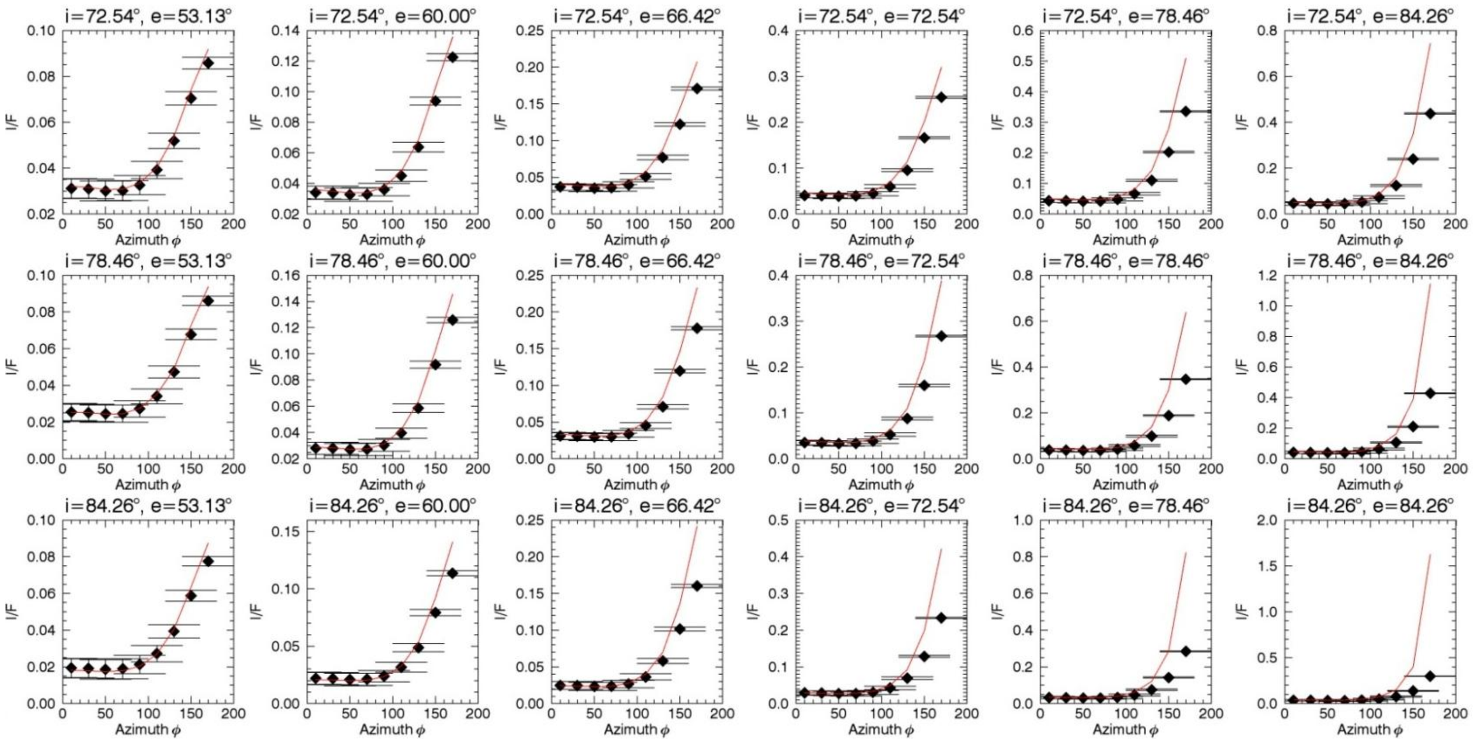


Change of solver to include pseudo-spherical geometry

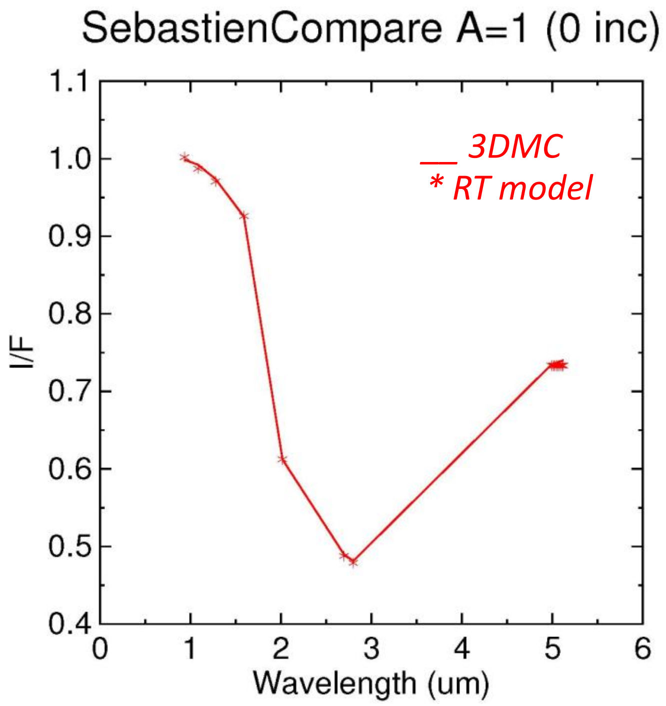
New solver (CDISORT, Buras et al. [2011]): works with pseudo-spherical geometry !

Comparisons with outputs of 3D Monte-Carlo codes to assess the limits of the pseudo-spherical approximation in terms of emission angles [Vincendon et al., 2010; Jason & Shannon's code]

Adaptation of the LUT nodes for interpolations on the viewing geometry (denser i, e, ϕ network of nodes)



Code of Vincendon et al. [2010]



Code of Jason & Shannon