→ 6th ESA ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

Atmospheric corrections - Fundamentals

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- Atmosphere and TPOA radiance
- Atmosphere (gas, aerosol) parameters for atmosphere correction
- Atmosphere correction of Sentinel 2 images

Pre-processing of satellite data

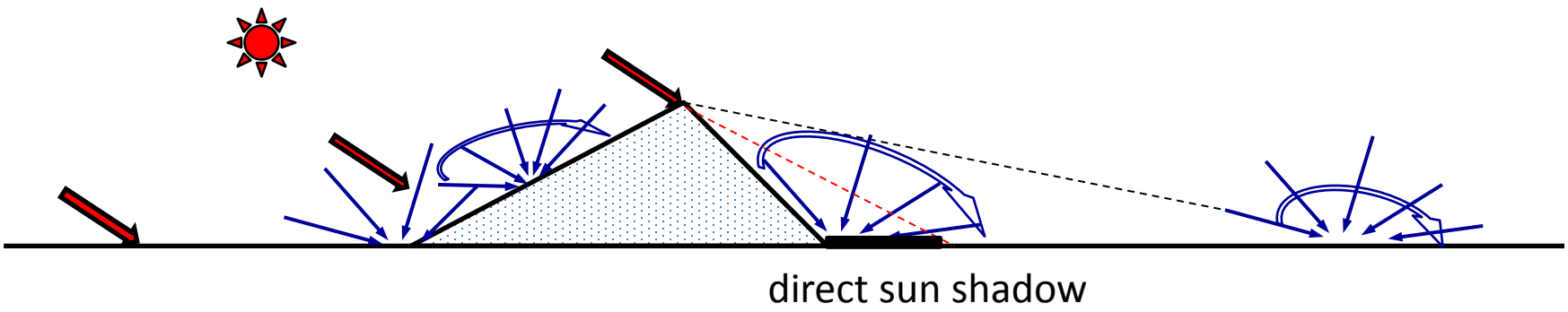
Objective: to remove the noise and distortion in the signal that is measured by the satellite when observing an Earth surface in order to compute a parameter (reflectance $\rho_{BOA}(\Omega_s, \Omega_v)$) that characterizes that surface.

- Radiometric calibration (noise removal,…): measured signal → TOA radiance L_{TOA}
  - Pre-launch radiometric calibration to traceable standard (accepted reference)
  - Post launch calibration campaigns to maintain/monitor in flight calibration (vicarious)
  - On-board calibration (radiometric and spectral)
- Geometric correction: essential for multi-sensor, multi-temporal,… analyses
- Cloud screening: threshold on TOA reflectance and spectral slope $\frac{\partial \rho}{\partial \lambda}$
- Atmospheric correction
- Topographic correction

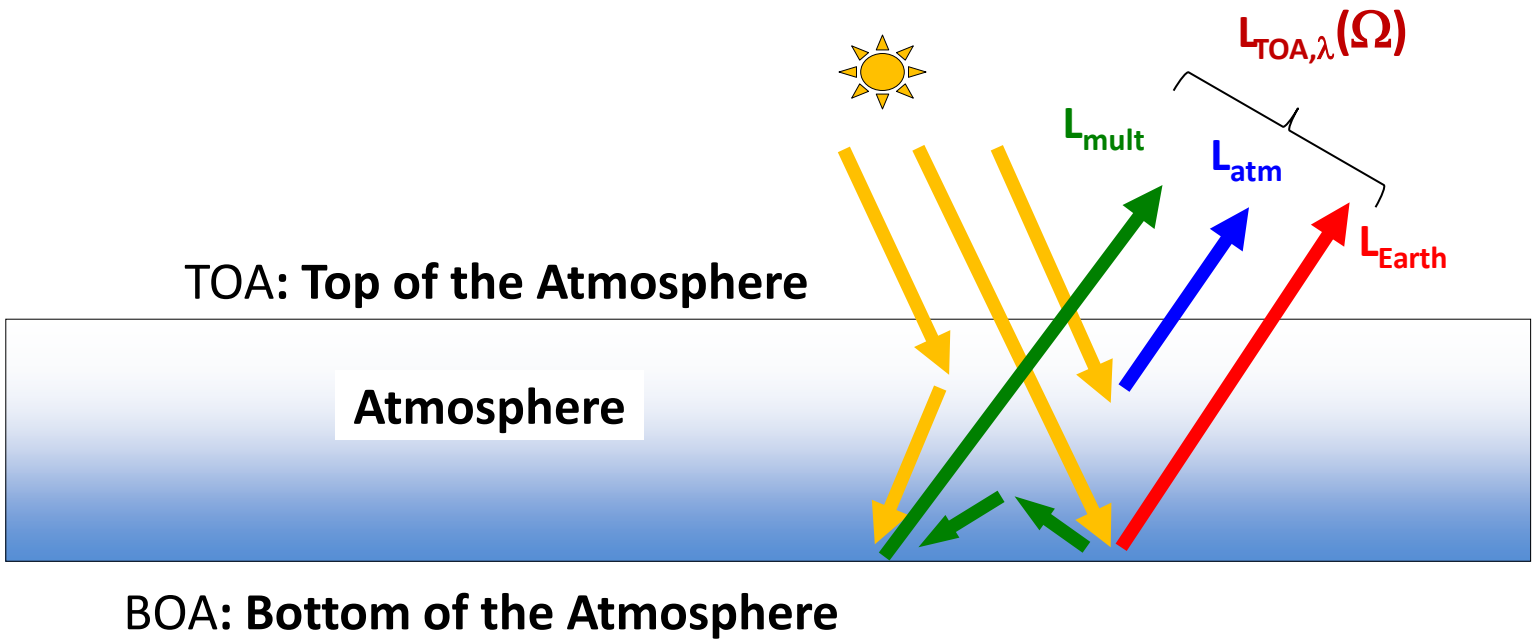
Atmospheric correction

Objective: to remove the impact of atmosphere in satellite measurements (TOA radiance L_{TOA}) in order to get a parameter (reflectance) that characterize the observed Earth surface.

Topography impacts also satellite signals with effects linked to atmosphere effects. It affects local direct and diffuse (atmosphere / sky) irradiance



Physical bases about radiation: ***Satellite signal (TOA radiance) $L_{TOA,\lambda}(\Omega)$ - short wavelengths***



$L_{TOA,\lambda}(\Omega)$ = "Radiance $L_{Earth,TOA,\lambda}(\Omega)$ due to scattering of sun flux by the Earth, only"

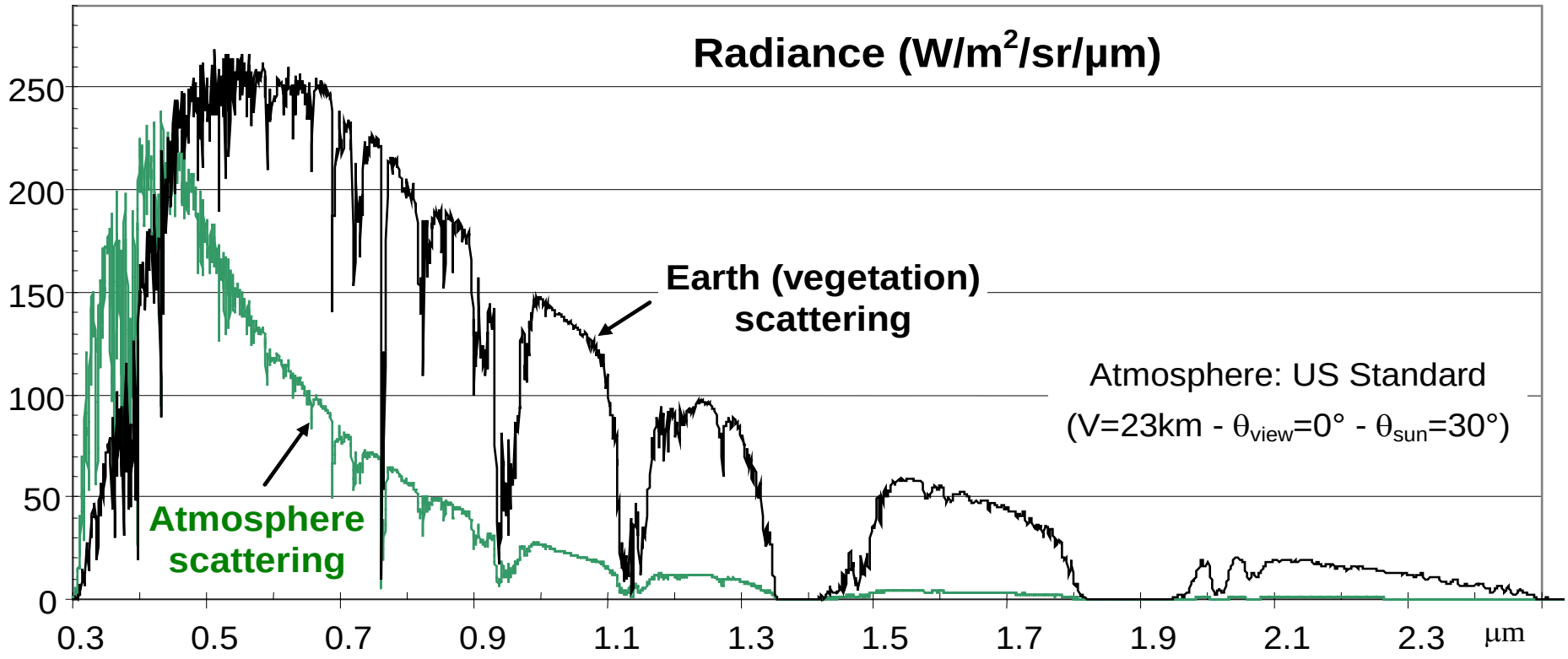
+

"Radiance $L_{atm,TOA,\lambda}(\Omega)$ due to scattering of sun flux by the Atmosphere, only

+

"Radiance $L_{mult,TOA,\lambda}(\Omega)$ due to scattering of sun flux by {Earth + Atmosphere}"

TOA radiance components: Earth and atmosphere scattering

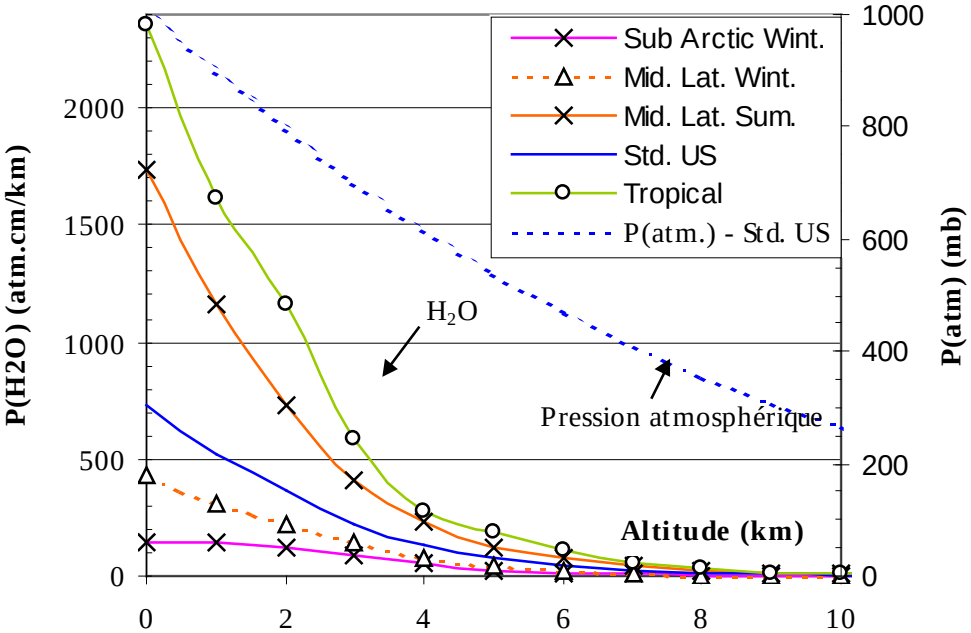


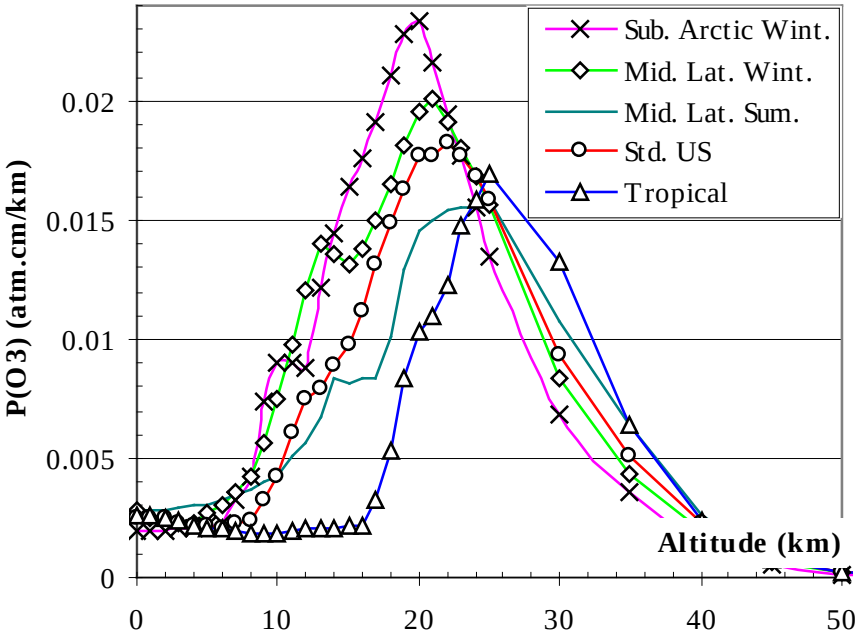
☞ How does the relative influence of atmosphere change with (θ_v, θ_s, V, etc.)?

Parameters used to characterize the atmosphere

Gasses

1) *Gas vertical distribution*





Parameters used to characterize the atmosphere

2) Gas capacity to intercept radiation:

Extinction coefficient α_e= absorption α_e + scattering α_e

Extinction coefficient (m^{-1}) = Cross section for interception per molecule (m^2/mol)
x
Density of molecules (mol / m^3)

Optical depth of a medium over a distance Δr: $\Delta\tau(\lambda) = \int_{\Delta r} \alpha_e(\lambda, r).dr$

Transmittance of a medium over a distance Δr: $T(\lambda, \Delta r) = e^{-\Delta\tau(\lambda)}$

This expression is usually accepted. It is not exact for spectral bands $\Delta\lambda$. Why?

Parameters used to characterize the atmosphere

Usual approximation: at λ, gas either absorbs (H_2O, O_3, O_2,…) or scatters radiation

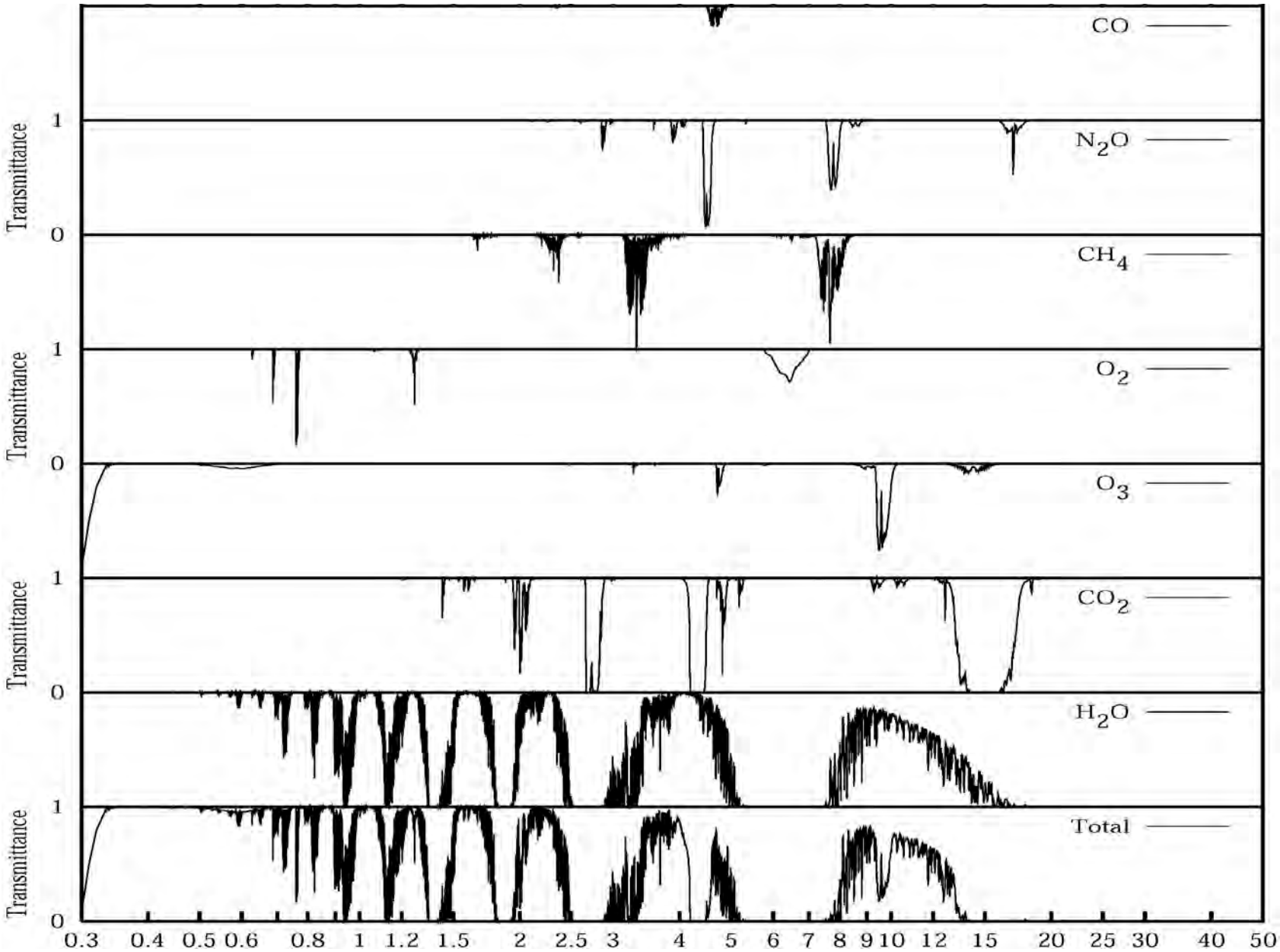
$\Rightarrow$ Transmittances of absorbing gas $T_{abs}(\lambda,\Delta r)$ & scattering gas $T_{scat}(\lambda,\Delta r)$ are independent

For satellite applications, one uses the gas optical depth $\Delta\tau_{gas}(\lambda)$ of total atmosphere along the vertical direction, and the associated transmittance $T_{gas}(\lambda)=e^{-\Delta\tau(\lambda)}$

For an oblique direction $\Omega(\theta, \phi)$: $\Delta\tau_{gas}(\lambda,\Omega) = \frac{\Delta\tau(\lambda)}{cos\theta}$ and $T_{gas}(\lambda,\Omega)=e^{-\frac{\Delta\tau(\lambda)}{cos\theta}}$

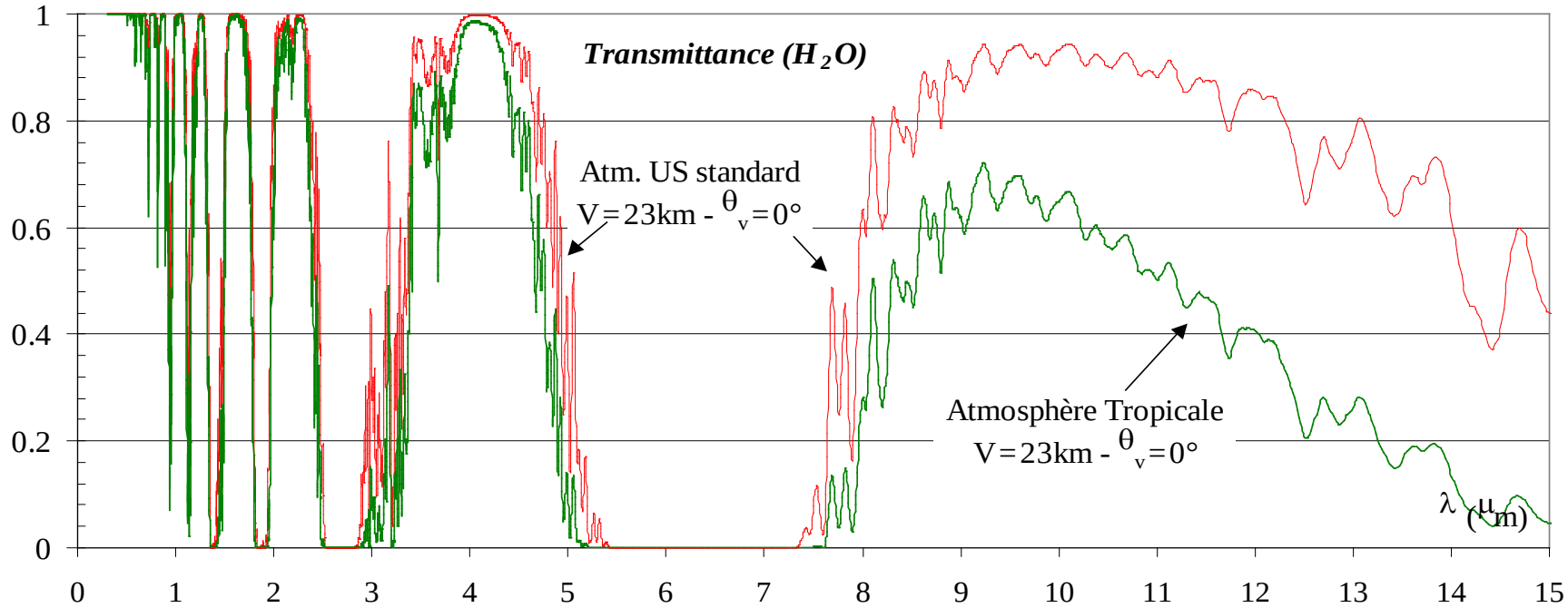
This expression becomes more and more inexact with oblique view and /or sun directions. Why?

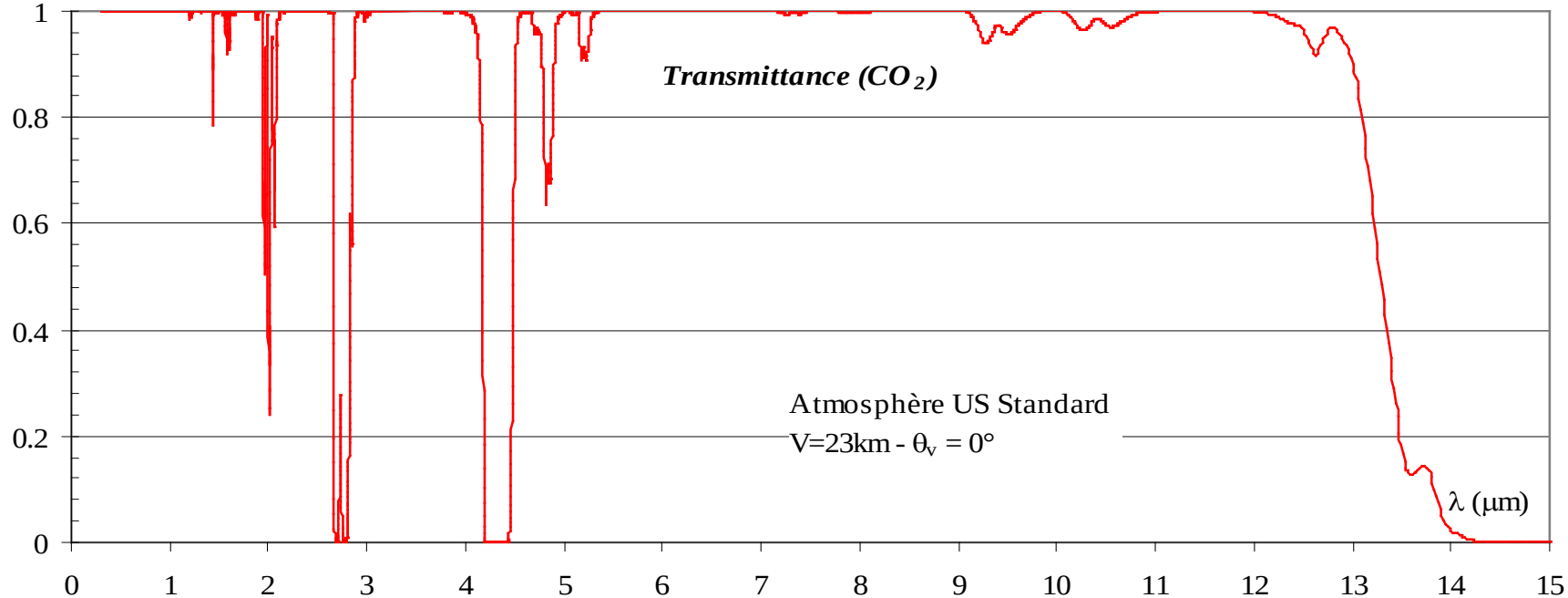
Gas transmittance (mid latitude summer atmosphere, without aerosols & clouds)



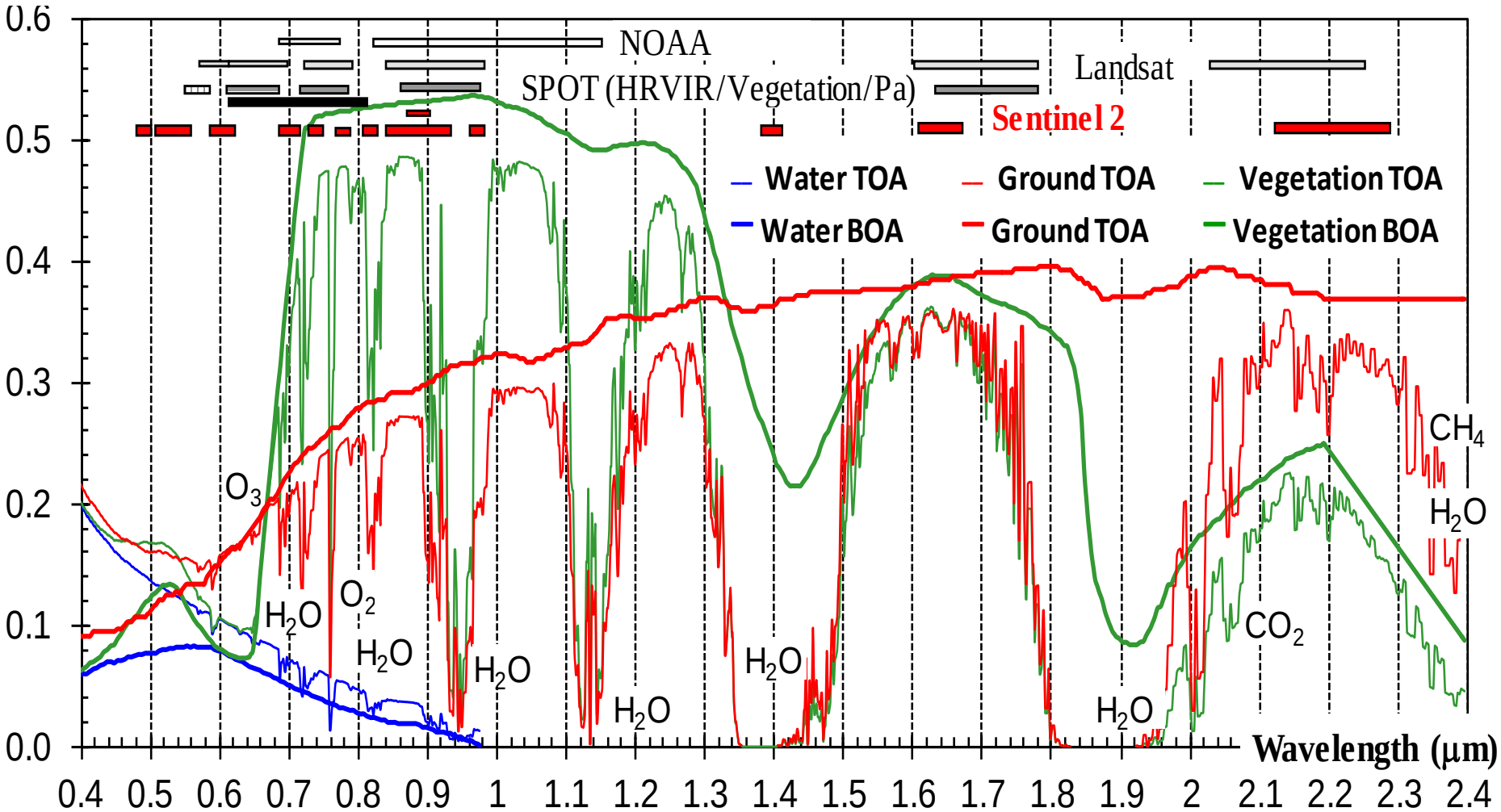
Atmosphere transmittance = Product of gas transmittances. Transmittance = 1 in VIS?

Gas transmittance: H_2O, CO_2





BOA and TOA spectra of water, ground and vegetation



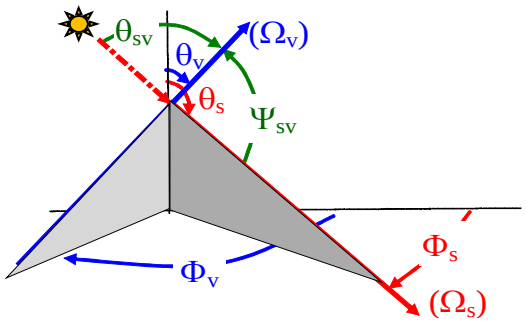
- For all surfaces, with $\lambda < 0.55\mu m$, TOA reflectance is larger than BOA reflectance. Why?
- For ground, TOA reflectance is larger than BOA reflectance for $\lambda < 0.55\mu m$, and smaller for $\lambda > 0.65\mu m$, whereas TOA water reflectance is always larger than BOA water reflectance. Why?

Parameters used to characterize the scattering gasses

Optical depth $\Delta\tau(\lambda)$: very variable for absorbing gasses.
For non absorbing gasses , $\Delta\tau(\lambda) \equiv \lambda^{-4} \Rightarrow$ blue color of the sky, etc.

Normalized phase function (for scattering): $\frac{P(\Omega_S,\Omega_v)}{4\pi}$

Scattering gas: scattering phase function: $\frac{P_{gas}(\Omega_s,\Omega_v)}{4\pi}$

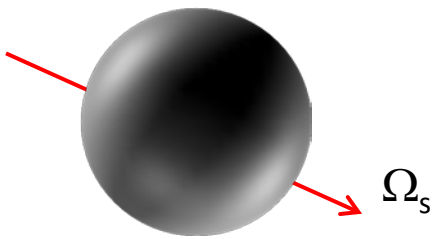


Scattering of a photon along incident direction $\Omega_s \rightarrow$ Sensor

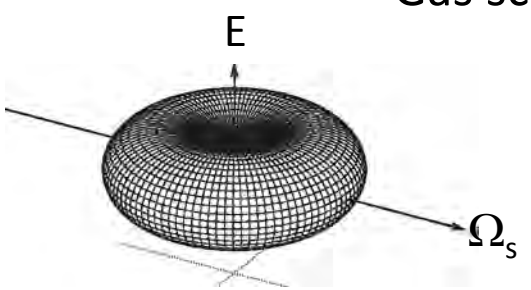
Phase angle: Ψ_{sv}. Scattering angle: $\pi - \Psi_{sv}$

Forward scattering: $\Psi_{sv} = 0$. Backward scattering: $\Psi_{sv} = \pi$.

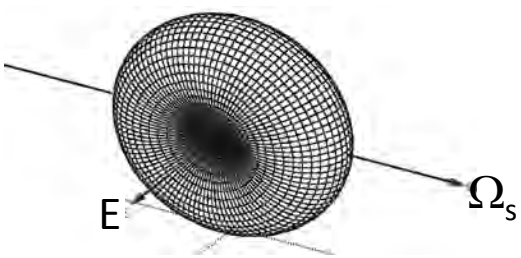
Isotropic scattering: $P(\Omega_s, \Omega_v) = 1$



Gas scattering of unpolarized radiation:



Vertical polarisation E



Horizontal polarisation E

Unpolarized incident radiation

$$P_R(\Psi_{sv}) \approx \frac{3}{4}\cdot\frac{1}{1+2\delta}.[1+3\delta) + (1-\delta).\cos^2\Psi_{sv}] \approx 0.7603 + 0.7190.\cos^2\Psi_{sv} \approx \frac{3}{4}.(1+\cos^2\Psi_{sv})$$

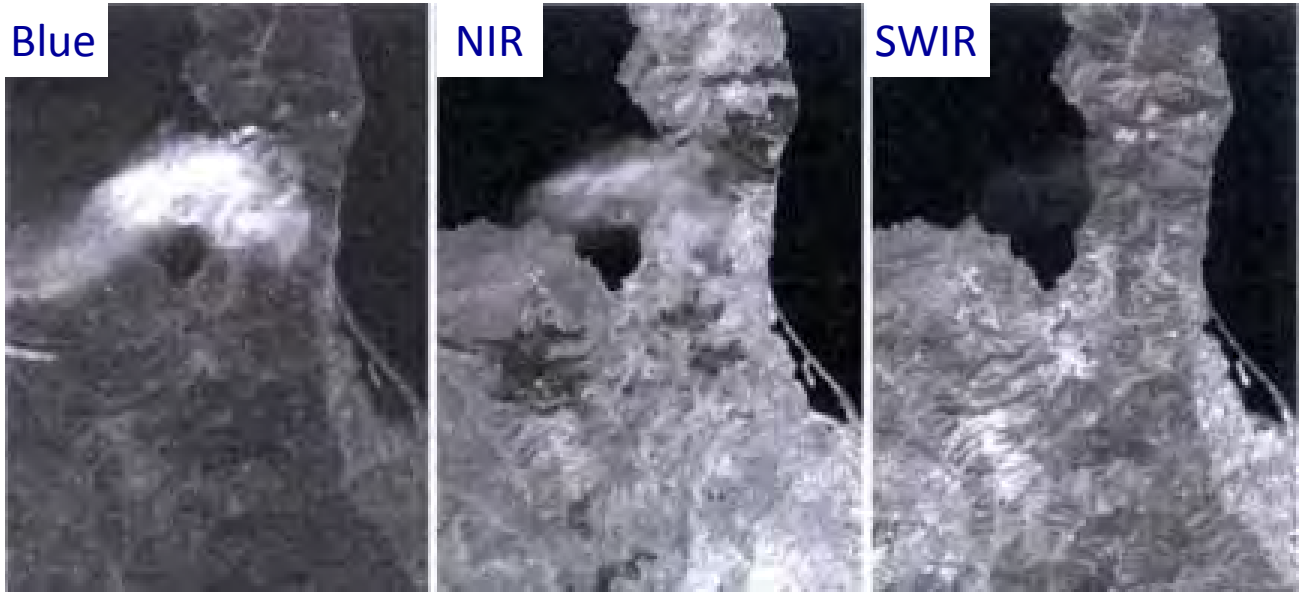
Scattering gas: spectral optical depth $\Delta\tau(\lambda)$

Empirical expresssions (λ: µm), for P =1atm :

- $\tau(\lambda) \approx 0.0088\ \lambda^{-4.15+0.2\lambda}$ (Arpège model of Météo France: $\tau \approx 0.00879\ \lambda^{-4.09}$)

- $\tau(\lambda) \approx 0.008569.\lambda^{-4}.(1+0.0113.\lambda^{-2} + 0.00013.\lambda^{-4})$

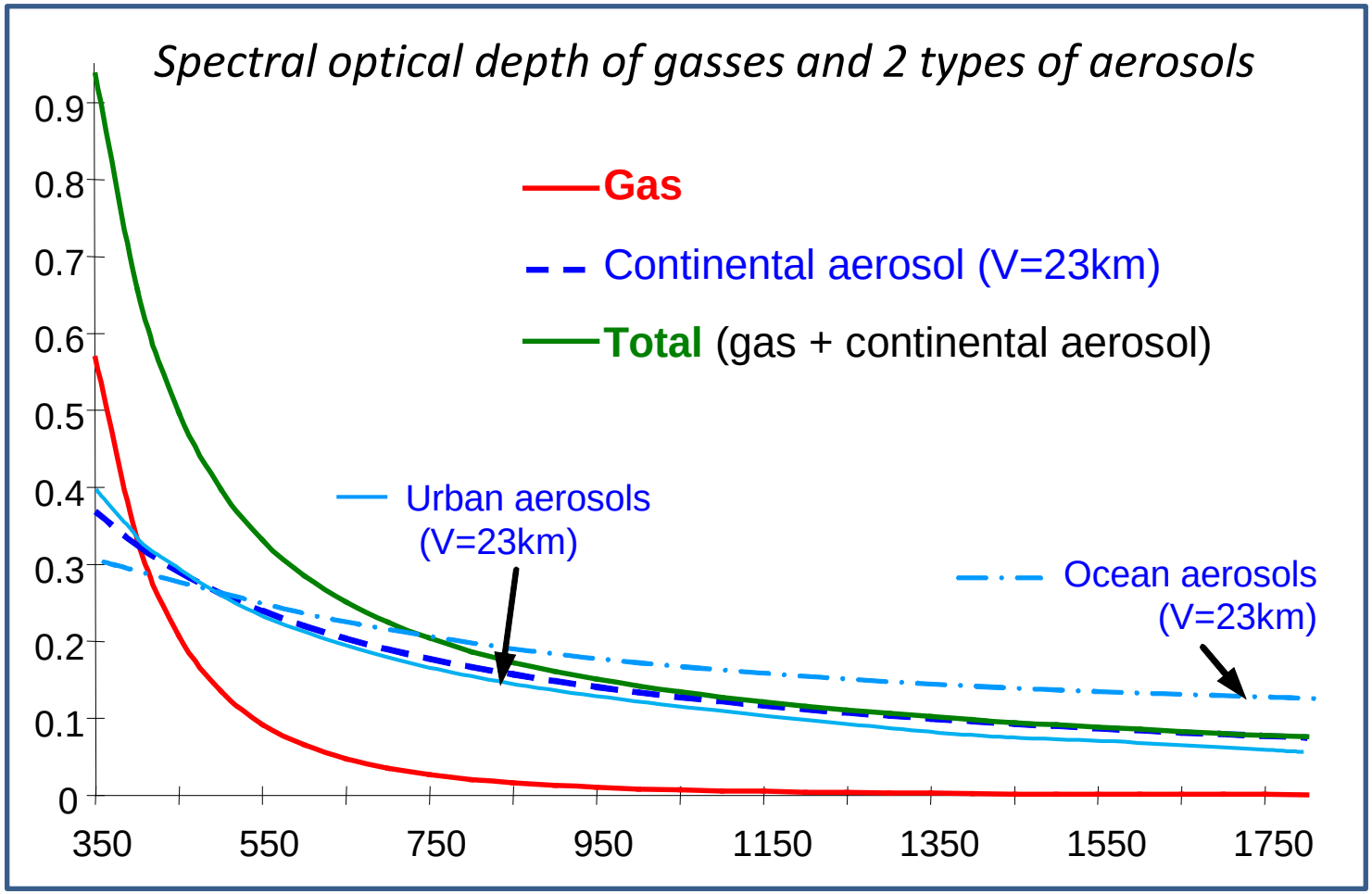
$\Rightarrow$ blue color of sky



Fire in Corsica

Aerosols: spectral optical depth $\Delta\tau(\lambda)$ and single scattering albedo $\omega(\lambda)$

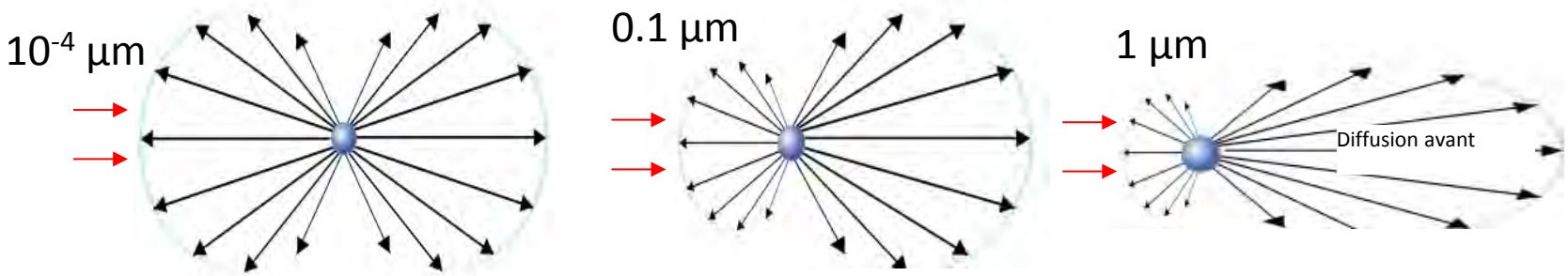
$\Delta\tau(\lambda)$ and $\omega(\lambda)$, and their spectral variation, depend on the type of aerosols



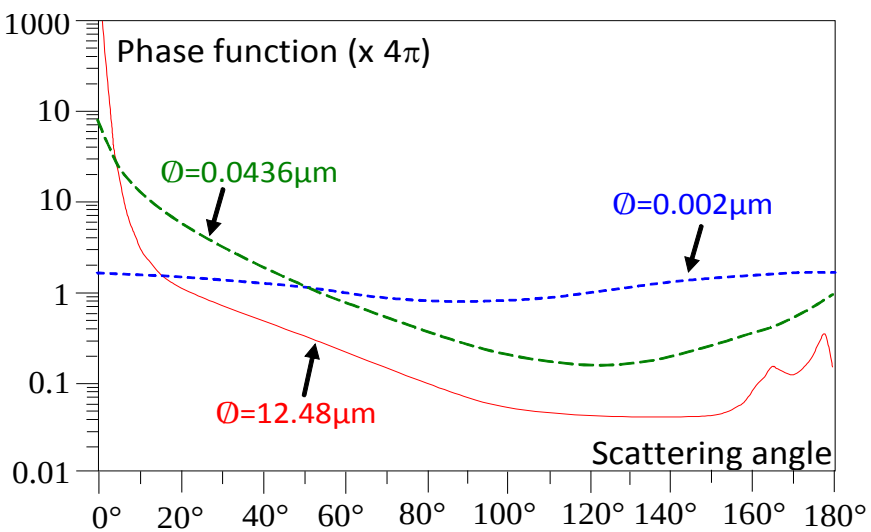
Aerosols and gas optical depths: AVHRR and TM (from 6S model)

	AVHRR		TM					
	1	2	1	2	3	4	5	6
- Min λ (50%)	569.8	714.3	452.4	528.0	626.4	776.4	1567.4	2097.2
- Max λ (50%)	699.3	982.2	517.8	609.3	693.2	904.5	1784.1	2349.0
- Peak	680.0	760.0	503.0	594.0	677.0	800.0	1710.0	2200.0
- λ equivalent (λ_{eq})	639.0	844.6	486.2	586.9	662.7	837.3	1662.7	2188.6
- τ_m^d (gas scattering)	0.0540	0.0180	0.159	0.0841	0.0449	0.0176	0.0012	0.0004
- $\tau_{O_3}^a$ (absorption O_3)	0.0240	0.00064	0.00663	0.0317	0.0174	0.0000	0.0000	0.0000
- $\tau_{H_2O}^a$ (absorption H_2O)	0.00605	0.0933	0.0000	0.0002	0.0068	0.0410	0.0957	0.0741
- $\tau_{CO_2}^a$ (absorption CO_2)	0.00071	0.0146	0.0000	0.0000	0.0000	0.0021	0.0077	0.0091
Albedo of aerosols	0.941	0.911	0.948	0.943	0.940	0.913	0.829	0.865

Aerosols: phase function $\frac{P_{aer}(\Omega_s,\Omega_v)}{4\pi}$



Aerosol VIS scattering. $\frac{P_{aer}(\Omega_s,\Omega_v)}{4\pi}$ varies with λ and the type of aerosols

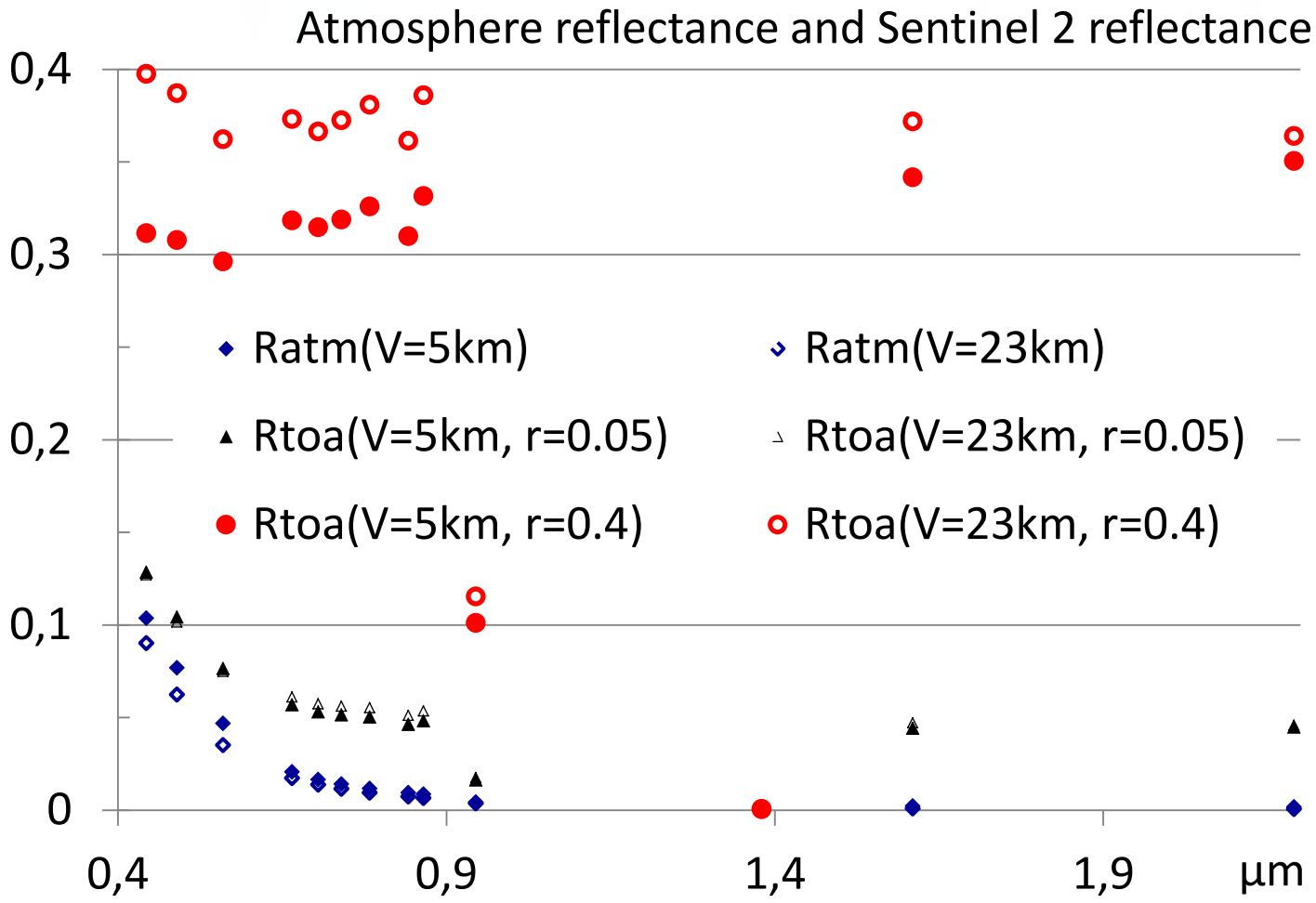


Phase function of 3 types of desert aerosols, for λ=0.7µm (Shettle, 1984):

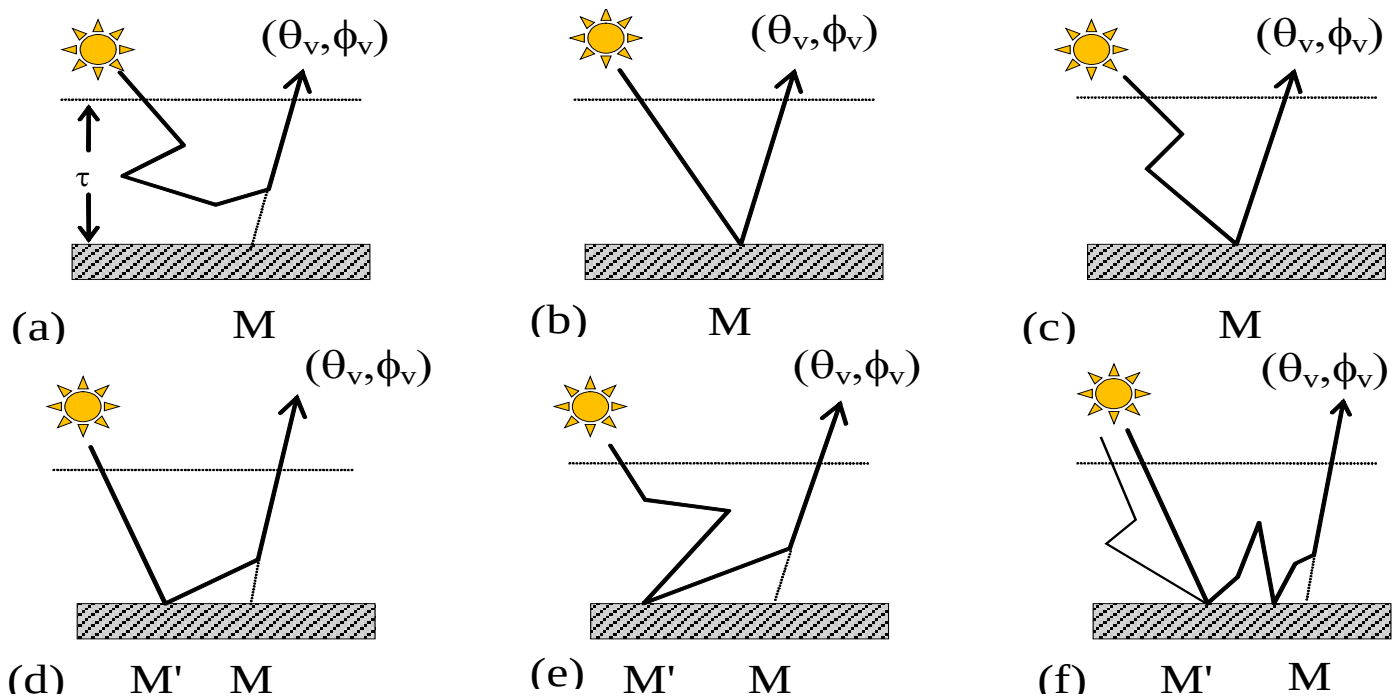
- Volume density: 2.5g/cm^3.
- Single scattering albedo: 0.94.
- Specific extinction coefficient: 0.82m^2/g
- Angstrom exponant: 0.3.
- Refraction index: 1.55-0.005 i.

Usual approximation (double Henyey Greenstein function):

$$P_{aer}(\Psi) = \frac{a.(1-g_1^2)}{[1+g_1^2-2g_1.\cos\Psi]^{1.5}} + \frac{(1-a).(1-g_2^2)}{[1+g_2^2+2g_2.\cos\Psi]^{1.5}} \quad \text{with} \int_{4\pi} \frac{P_{aer}(\Psi)}{4\pi}.d\Omega = 1$$


Atmosphere reflectance and Sentinel 2 reflectance
0,4
0,3
0,2
0,1
0
0,4
0,9
1,4
1,9
µm
Ratm(V=5km)
Ratm(V=23km)
Rtoa(V=5km, r=0.05)
Rtoa(V=23km, r=0.05)
Rtoa(V=5km, r=0.4)
Rtoa(V=23km, r=0.4)

Example of atmosphere model (from 6S model) and Atmosphere correction

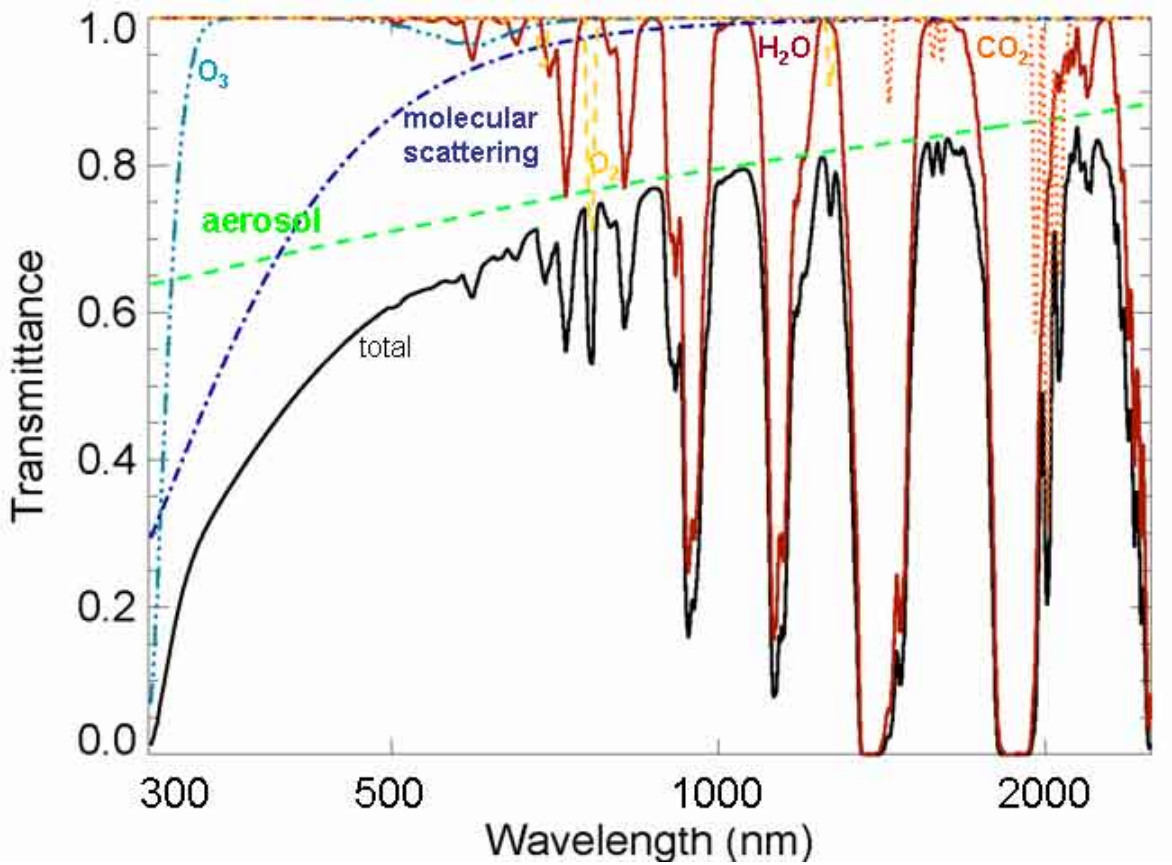


$$\rho_{sat}(\Omega_s;\Omega_v) = \frac{\pi.L_{sat}(\Omega_v)}{\mu_s.E_s} = [\rho_a(\Omega_s,\Omega_v) + \rho.\frac{T(\theta_s).e^{-\tau/\mu_v}}{1-\rho_e.s} + \rho_e.\frac{T(\theta_s).t(\theta_v)}{1-\rho_e.s}].T_g(\theta_s,\theta_v)$$

Atmosphere correction:

- Need to know atmosphere parameters (τ_{aer}, $\tau_{gas,scat}$, P_{aer}, T_g, s....), if possible from the image to correct, depending on available spectral bands. They can be derived from in-situ measurements (Aeronet,...), MODIS, meteorological modeling (ECMWF,...),...
- Analytical inversion if we assume: environment reflectance ρ_e = target reflectance ρ

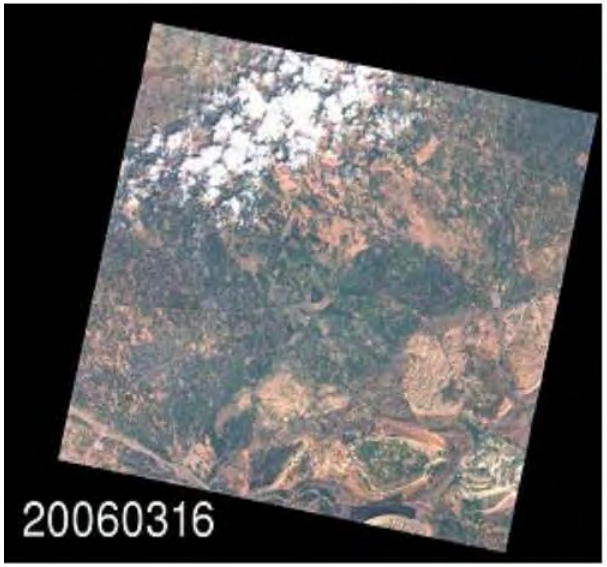
Example of atmospheric correction



(Moreno, 2014)

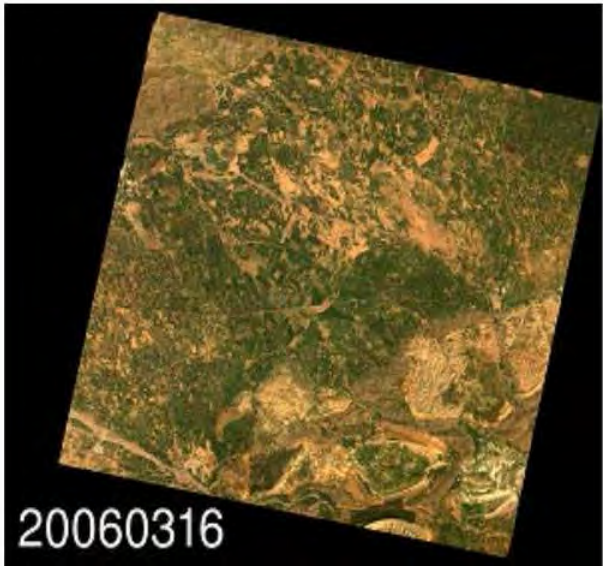
Simulation of level 1C, 2A, 3A products with FORMOSAT 2 images

Preparation of MACCS (atmospheric correction, cloud screening) for Sentinel 2 (Hagolle, 2015).



Level 1C: Top of tmosphere reflectances calibrated and orthorectified.

Level 2A: Single date surface reflectance after cloud masking and atmospheric correction.



Level 3A: 15 days time composite of surface reflectance produced every week

(Hagolle: the MACCS method)

Atmospheric correction of Sentinel 2 images

Mainly due to the high data volumes, the **atmospheric correction of Sentinel-2 data will not be performed by the ground segment**, but will rely on software packages to be run by the users on their data sets. (Guanter et al., 2012).

Sentinel-2 atmospheric correction is being developed, using algorithms of the Atmospheric/Topographic Correction for Satellite Imagery (**ATCOR**, Richter & Schlaepfer, 2011) and **libRadtran** radiative transfer model (Mayer & Kylling, 2005).

A large look-up table (**LUT**) created by libRadtran for a wide variety of atmospheric conditions, solar geometries and ground elevations is used as simplified model to invert the radiative transfer equation, and to calculate BOA reflectance.

The algorithm additionally generates an enhanced cloud-mask.

Note: present uncertainties on atmosphere modeling and parameter retrieval lead to a minimal RMSE on BOA reflectance $\approx 0.005 + 0.05\ \rho_{surf}$ (Vermote & Kotchenova

Atmospheric correction of Sentinel 2 images

- Orthoimage reflectance product (Level-2A)

- Classification map: quality indicators for cloud (Cirrus: 1380nm) and snow (Δ=60 m)

- Aerosol map: use of short wavebands with

  - Adaptation of the dark target method (Richter et al., 2011) to Sentinel 2: it uses the correlation of blue, red and shortwave infrared reflectance of dense vegetation.

    MODIS: $\rho_{0.47} = 0.25\,\rho_{2.13}$ and $\rho_{0.66} = 0.5\,\rho_{2.13}$

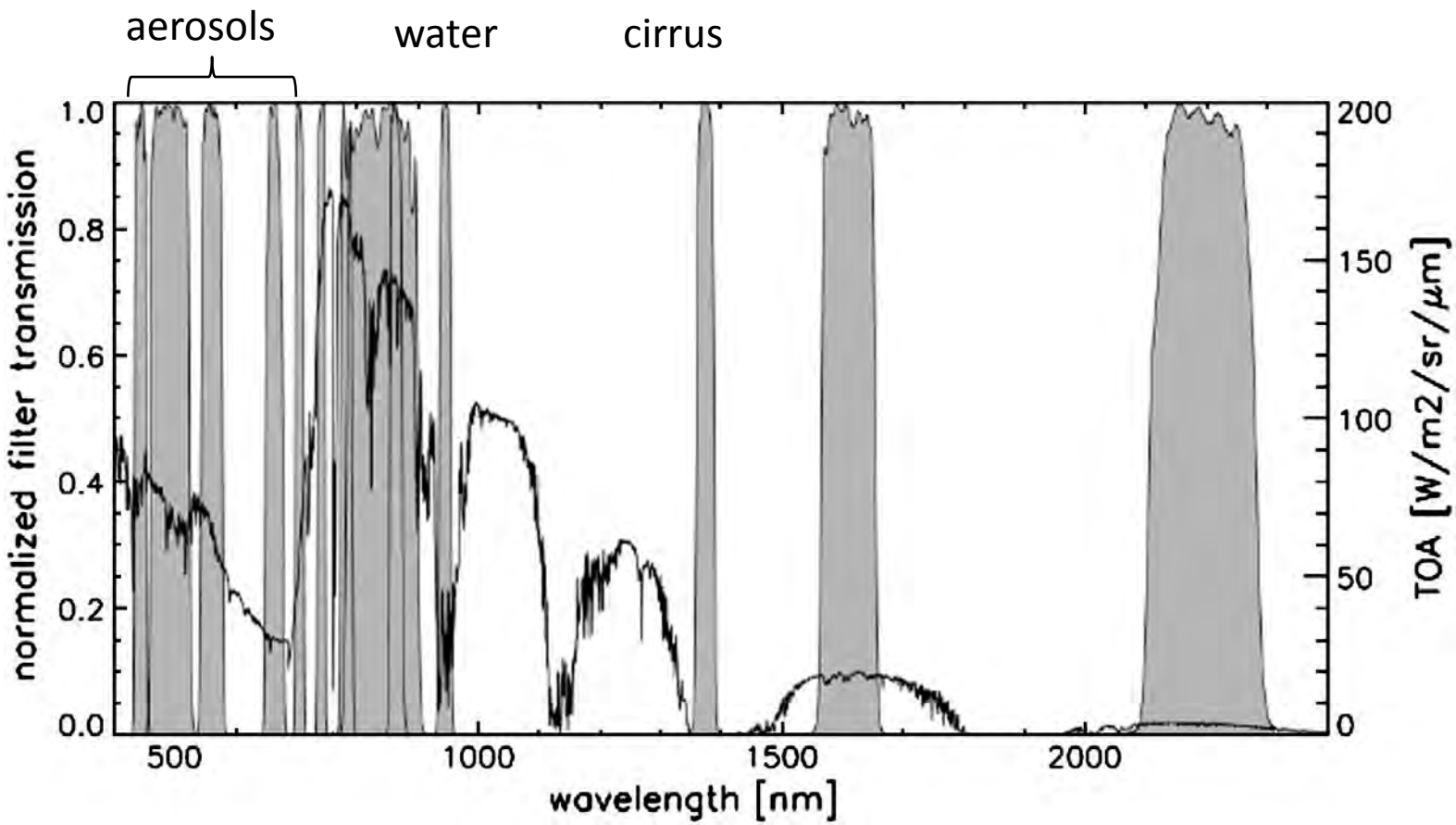
    Landsat 5: $\rho_{blue} = 0.409\,\rho_{swir} - 0.007$, $\rho_{red} = 0.766\,\rho_{swir} - 0.026$, $\rho_{blue} = 0.568\,\rho_{red} + 0.002$

    Landsat 7: $\rho_{blue} = 0.32\,\rho_{swir}$, $\rho_{red} = 0.671\,\rho_{swir} - 0.016$, and $\rho_{blue} = 0.479\,\rho_{red} + 0.007$

  - Multi-temporal aerosol retrieval algorithms that use a “clean” image as a reference to quantify the impact of aerosol extinction on the rest of the images in the series, thanks to the Sentinel-2 high revisit time (Hagolle et al., 2015).

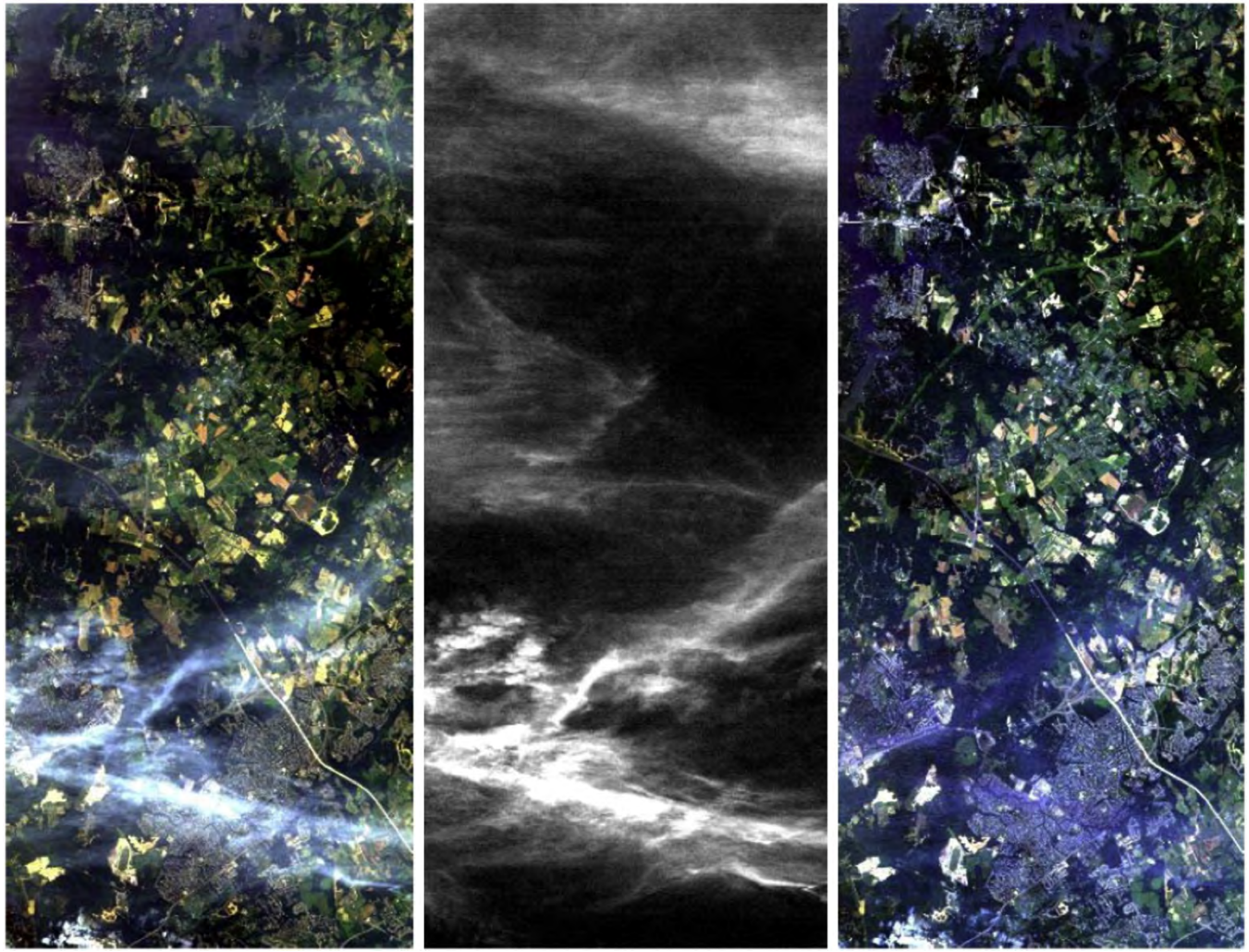
- Water vapor map: the ratio between the MSI spectral channels in 865 and 940 nm can be used as a proxy for water vapor transmittance, which can be converted to a measure of columnar water vapor after inversion against look-up tables

Bands of Sentinel 2 for deriving atmosphere information for atmosphere correction



Normalized filter transmissions and modeled TOA radiances for deciduous forests.

Example of atmosphere correction



Simulated Sentinel-2 scene containing cirrus clouds. True color coding: R/G/B = bands 4/3/1 (665, 560, 443 nm). Left: original scene, center: cirrus band (1.375 µm), right: after cirrus and atmospheric correction. (Dursch et al, 2011)