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TAKING THE PULSE OF OUR PLANET FROM SPACE

Monitoring soil water content from space in the solar domain: the power of radiative transfer models

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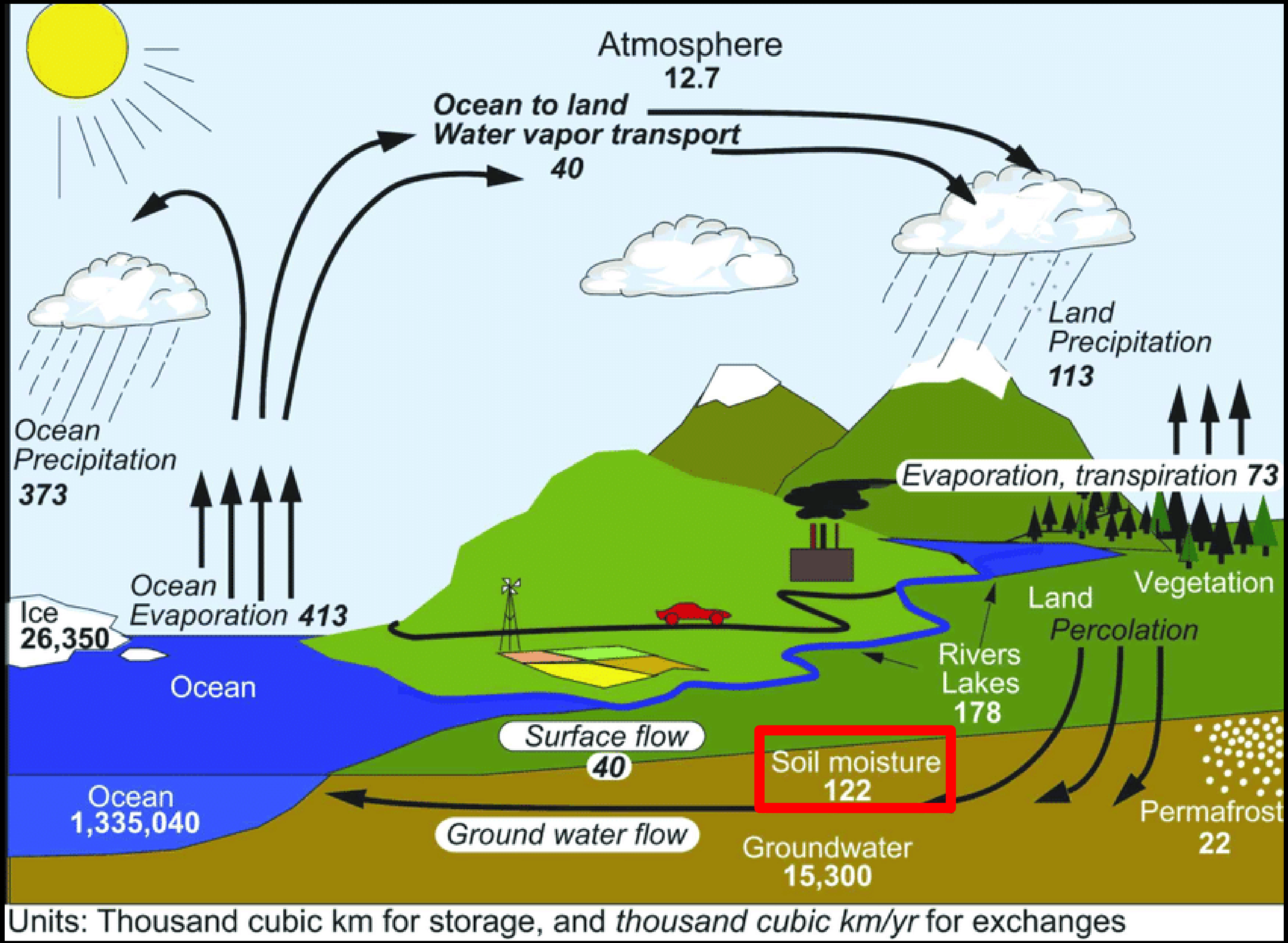
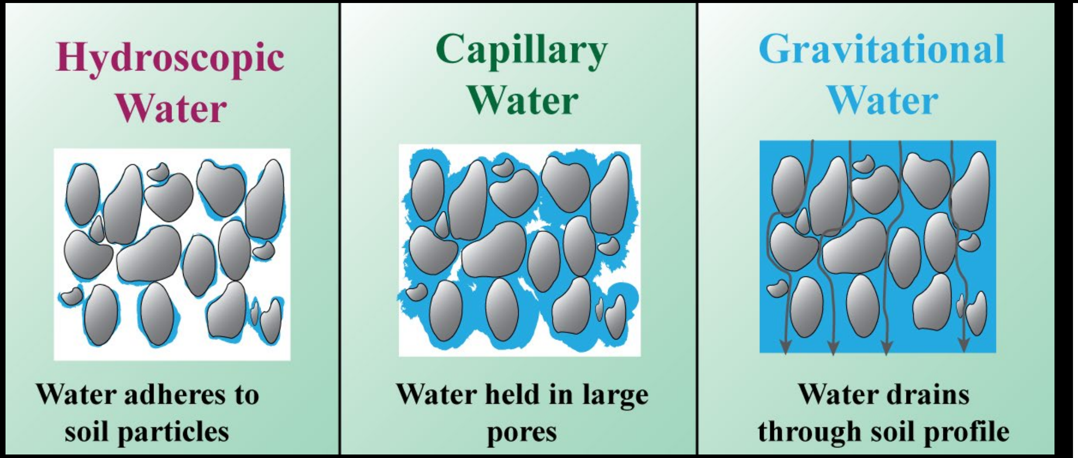
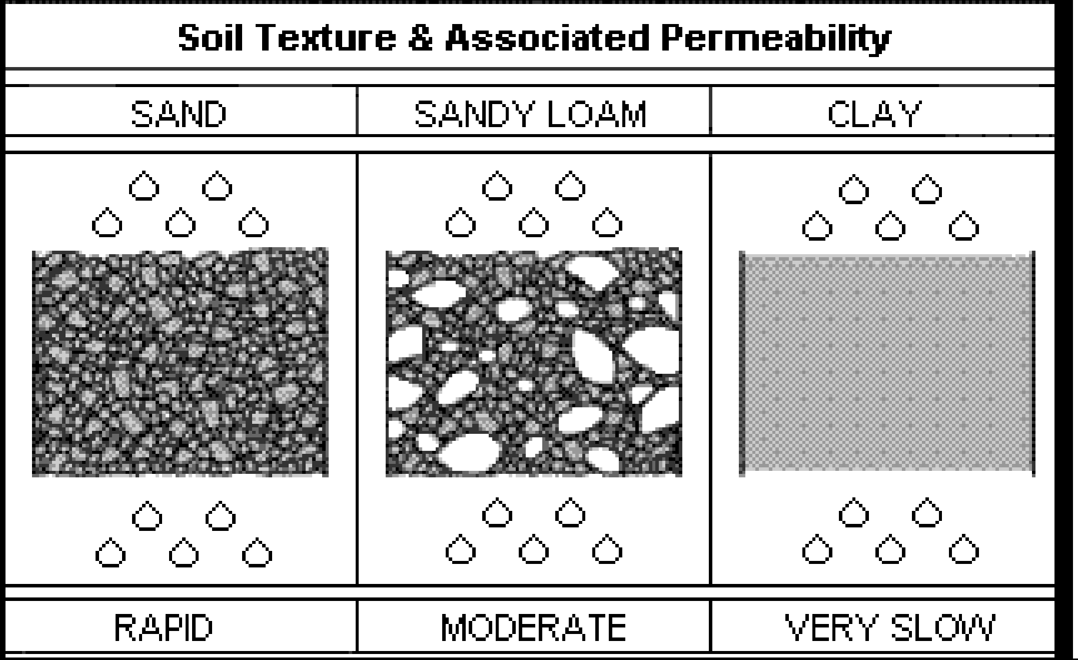
The hydrological cycle

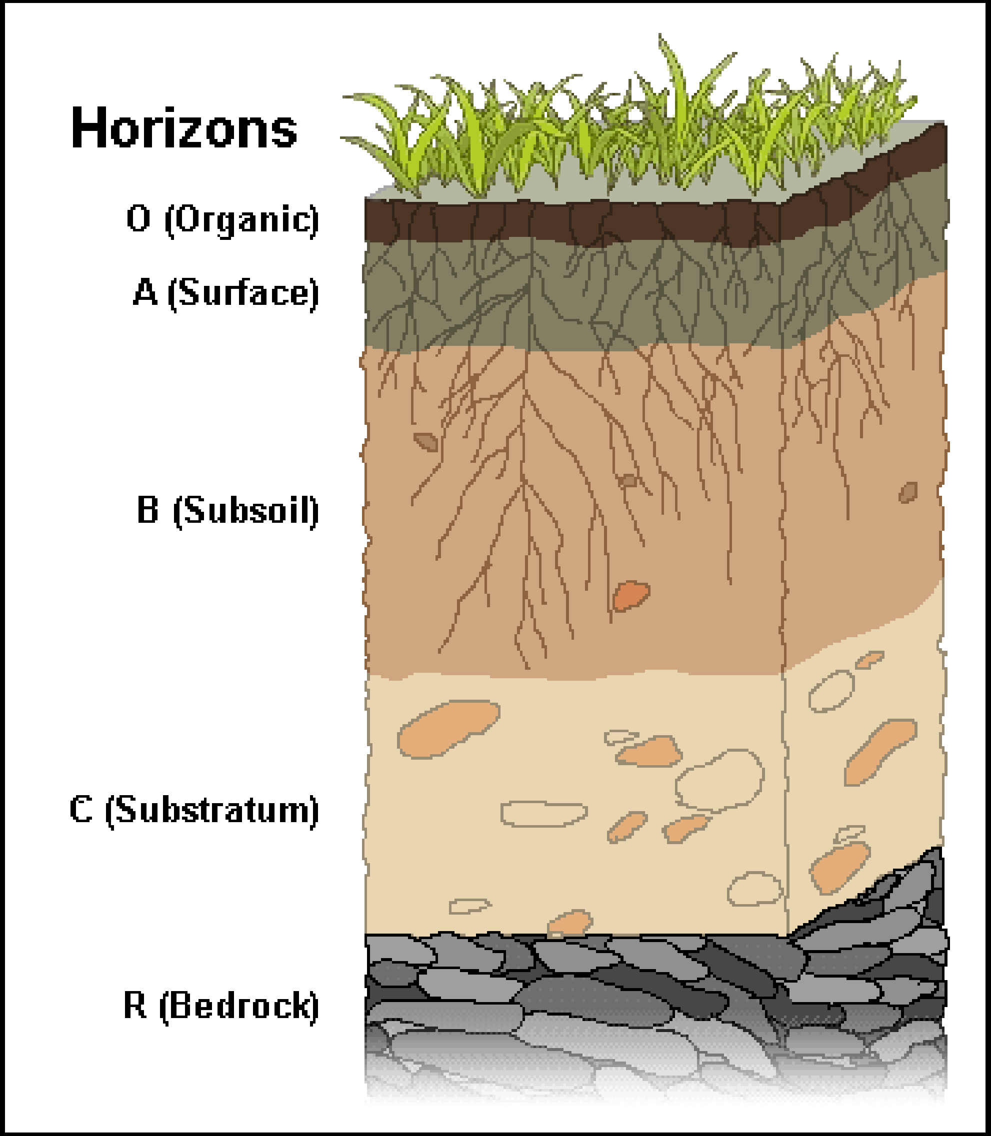


Trenberth et al. (2007)

Water in soil







Fields of application

Knowledge of soil surface water content is essential for many areas of research in the critical zone:

- Climate: desertification, water and wind erosion
- Micrometeorology: temperature, evaporation
- Agriculture: soil sensitivity to wind erosion, gas exchange, soil aeration
- Continental hydrology: runoff, infiltration and water storage processes
- Defense or homeland security: trafficability
- Planetary studies: surface processes

But also

- Critical zone: best estimate of soil organic carbon (SOC)
- Mineralogy: best estimate of mineral composition and content

Remote sensing measurements

Spectral domain		Penetration depth	☺	☹	Satellite / sensor
Microwaves 1 mm – 1 m	Active	cm/dm/m	Transparent atmosphere Spatial resolution Ground penetration	Surface roughness Topography	SMAP, ALOS, SENTINEL-1
	Passive		Transparent atmosphere Ground penetration	Surface roughness Spatial resolution	SMOS, SMAP, AMSR-E
Thermal infrared 3 – 14 µm		mm	Spatial resolution Surface measurement	Cloud, wind, and air temperature	LANDSAT, ASTER, MODIS
Solar domain 300 – 3000 nm		< 1 mm	Spatial resolution Surface measurement	Cloud	LANDSAT, MODIS, SPOT, SENTINEL-2, Pleiades, PRISMA, EnMAP

Light scattering properties of bare soils

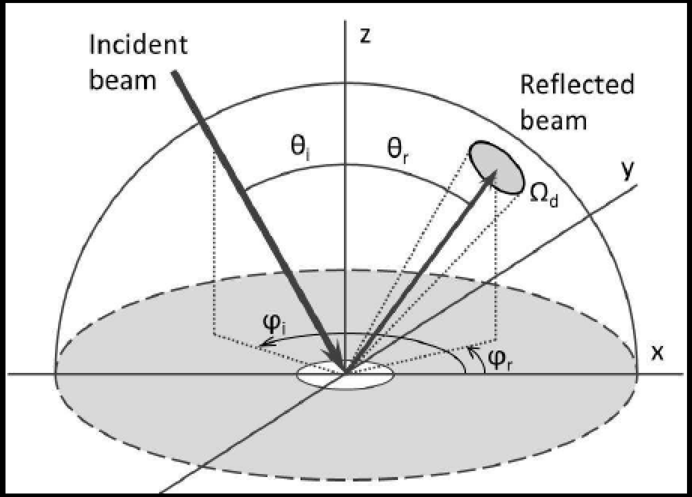
Irradiance [W m^{-2}]

Radiance [W m^{-2} sr^{-1}]

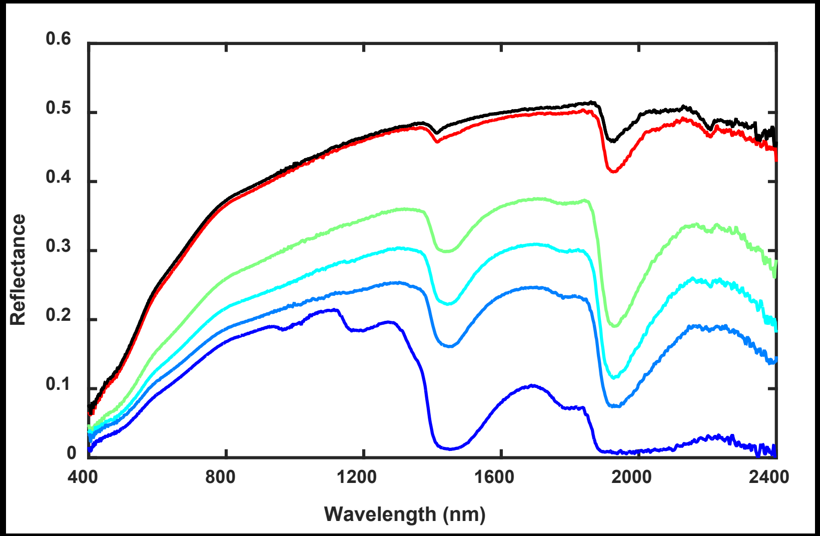
Bidirectional Reflectance Distribution Function [sr^{-1}]

$$BRDF(\theta_s,\varphi_s,\theta_v,\varphi_v,\lambda)=\frac{L_R(\theta_s,\varphi_s,\theta_v,\varphi_v,\lambda)}{E_I(\theta_s,\varphi_s,\lambda)}$$

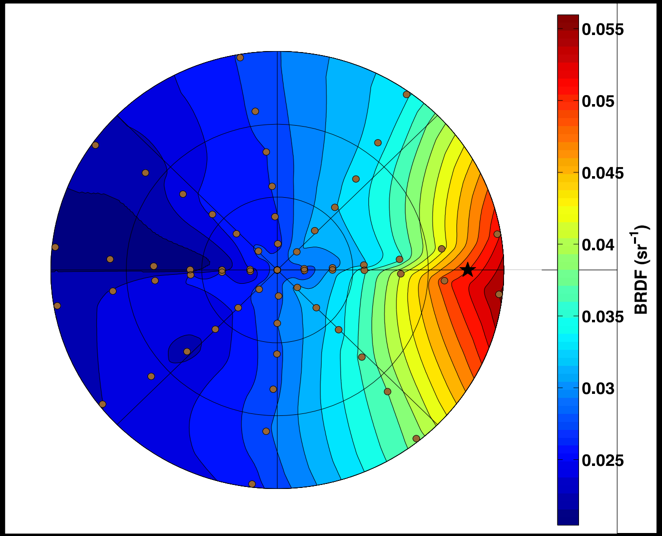
→ Bidirectional Reflectance Factor



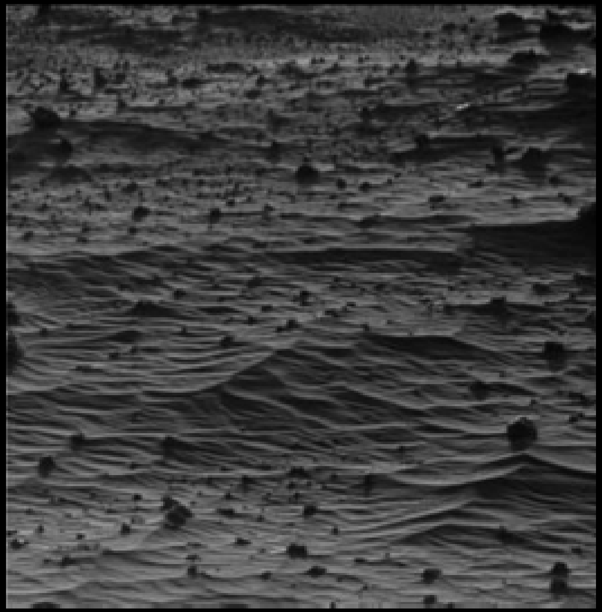
Spectral optical properties



Directional optical properties



The dark side of soils…

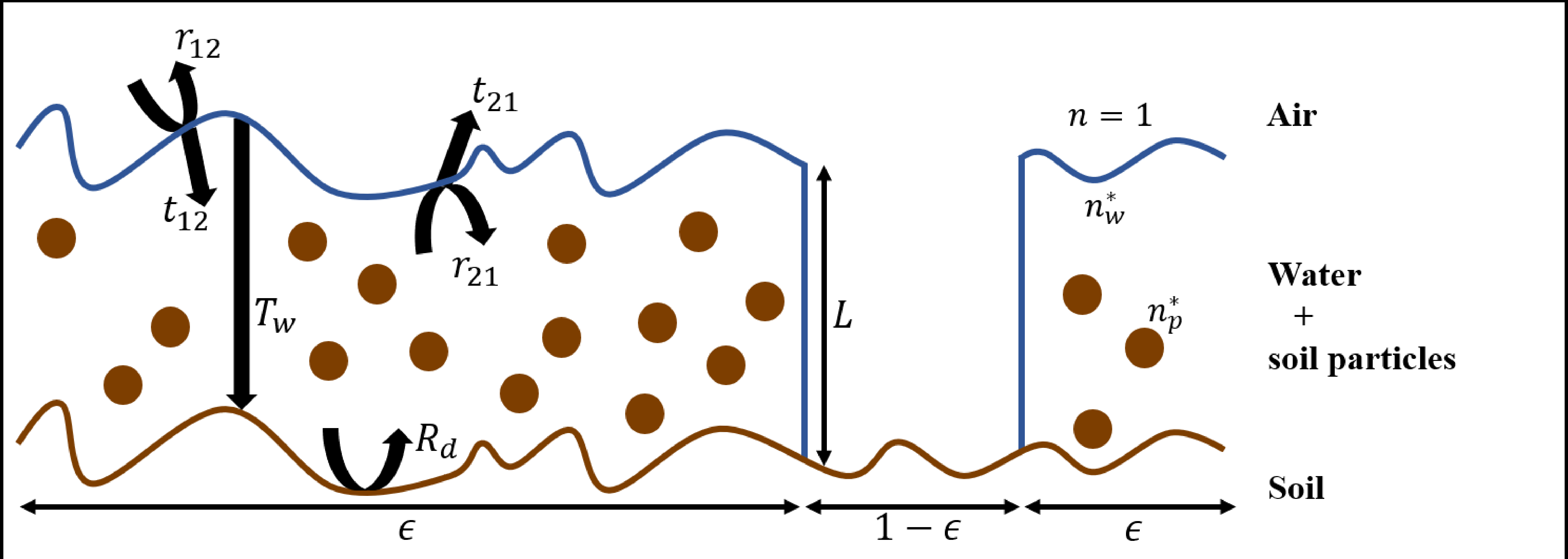


Radiative transfer models: several approaches

<table>
<tr><th>Model</th><th>Spectral → water content</th><th>Bidirectional → surface roughness</th></tr>
<tr><td>Layer</td><td>Ångström (1925), Lekner & Dorf (1988), Bach & Mauser (1994), Tian and Philpot (2015), Bablet et al. (2018, 2019, MARMIT), Verhoef et al. (2018, BSM), Dupiau et al. (2022, MARMIT-2)</td><td></td></tr>
<tr><td>Kubelka-Munk</td><td>Sadeghi et al. (2015)</td><td></td></tr>
<tr><td rowspan="2">Radiative transfer equation</td><td>Twomey et al. (1986, TBM) | Tavin et al. (2008), Gao et al. (2021) → HAPKE</td><td>Hapke (1981, 1984), Despan et al. (1999), Chappell et al. (2006), Wu et al. (2009), Johnson et al. (2013), Labarre et al. (2017, 2019) → HAPKE</td></tr>
<tr><td colspan="2">Jacquemoud et al. (1992), Pommerol et al. (2013), Yang et al. (2011), Yao et al. (2018), Zang et al. (2020) → HAPKE</td></tr>
<tr><td>Geometrical / particulate</td><td>Garay et al. (2016)</td><td>Cierniewski (1987), Cierniewski & Karnieli (2002), Sadeghi et al. (2018)</td></tr>
<tr><td>Ray tracing</td><td>Kimmel & Baranoski (2007, 2009, 2010, SPLITS)</td><td>Stankevich & Shkuratov (2004), Ciarniello et al. (2014), Labarre et al. (2017, LuxRender)</td></tr>
</table>

Soil radiative transfer modeling: the MARMIT model

https://pss-gitlab.math.univ-paris-diderot.fr/marmit/marmit



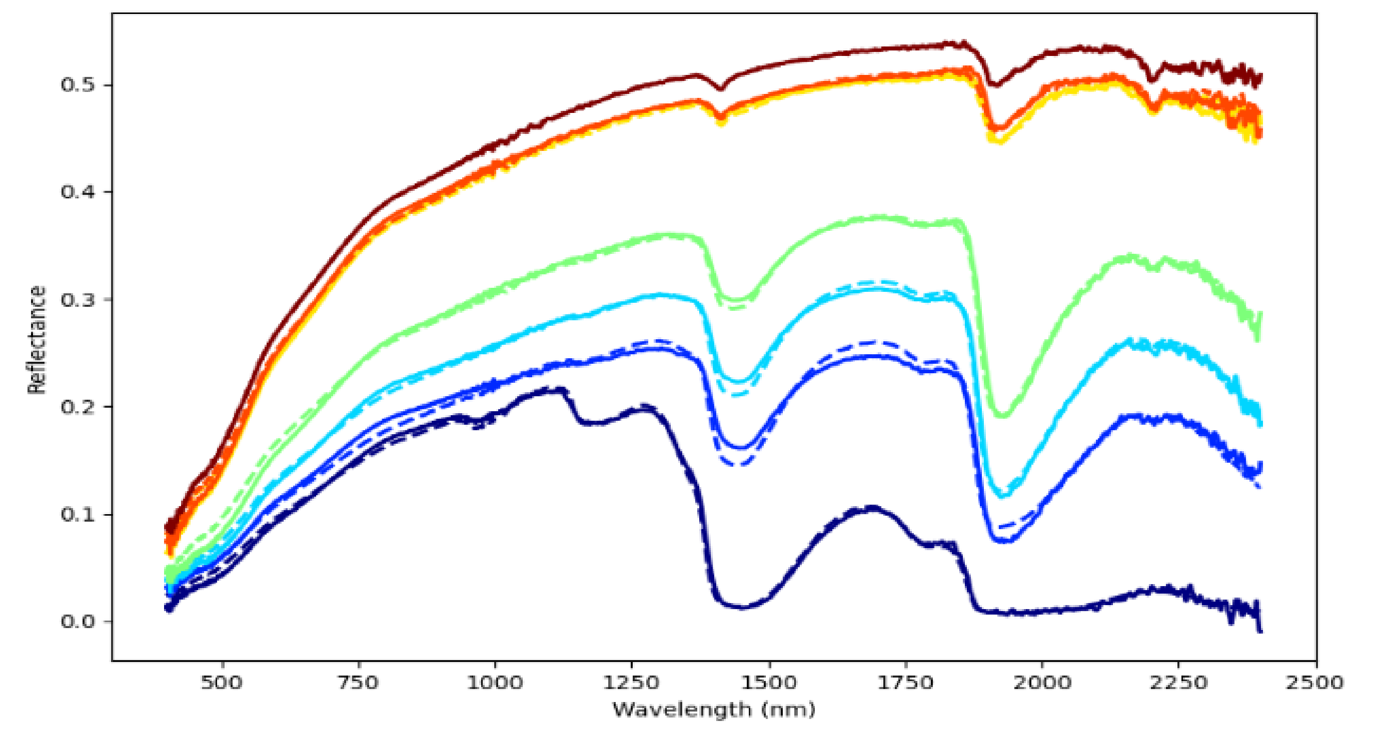
Bablet et al. (2018), Dupiau et al. (2022)

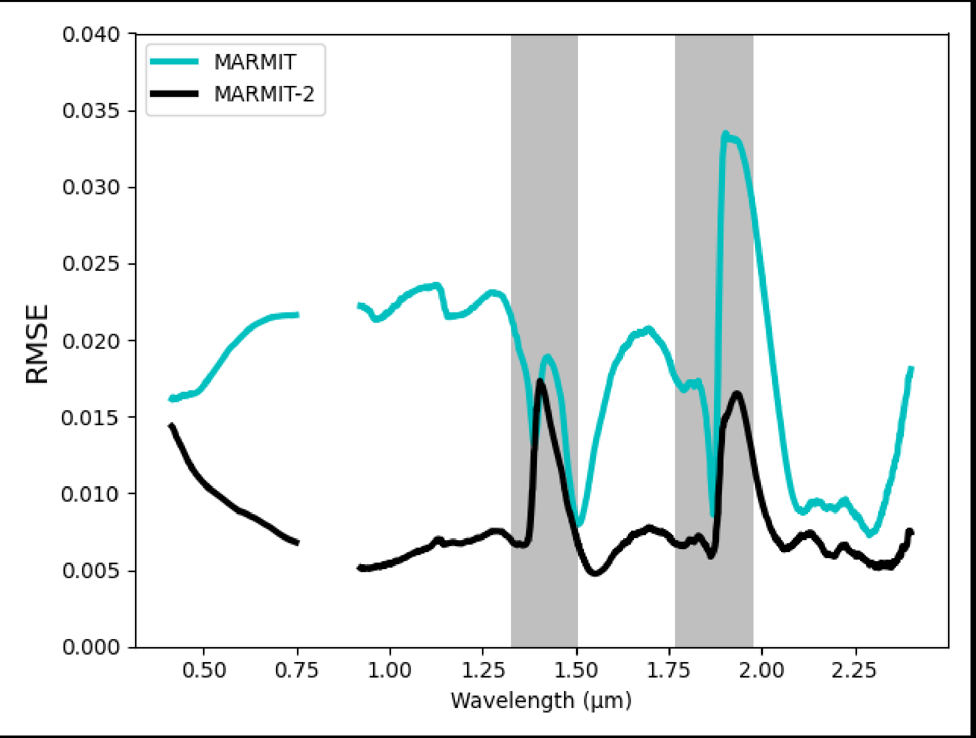
Spectral database: 340 soil samples

https://pss-gitlab.math.univ-paris-diderot.fr/marmit/marmit

Dataset	N	SMC (g g^{-1}) Number of levels	SMC (g g^{-1}) Range	Drying protocol	Sieving	θ_i	Density (g cm^{-3})	Characteristics
Lob02	4	9 to 15	0-118 %	Oven-dried	2 mm	15°	0.64-1.54	Various mineralogy
Liu02	92	4	0-83 %	Oven-dried	2 mm	15°	0.98-1.88	Various texture
Whit04	60	10 to 12	0-45 %	Oven-dried	2 mm	15°	0.88-1.36	30 samples rich in $CaCO_3$ 30 clayey samples
Les08*	32	6	0-87 %	Oven-dried	no	15°		Various texture and color
Mar12	9	25 to 30	0-50 %	Humidification	no	25°		Limestone samples
Noc13	111	5	0-25 %	Humidification	2 mm			Various provenance and composition
Phil14	3	97 to 205	0-45 %	Oven-dried	2 mm	30°	0.95-1.53	White sand, dark sand and silt
Bab16*	17	6 to 8	0-40 %	Oven-dried	2 mm	15°		Various composition
Dup20*	8	9	0-68 %	Oven-dried	2 mm	15°		Various provenance and composition
Eon21	4	10 to 18	0-32 %	Humidification		0°		Various texture
Total	340	4 to 205	0-118 %			15-30 °	0.64-1.88	

Soil radiative transfer modeling: the MARMIT model

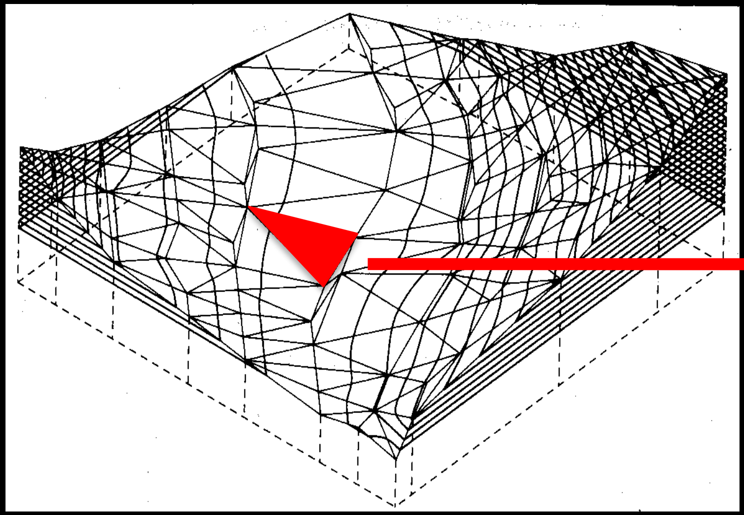


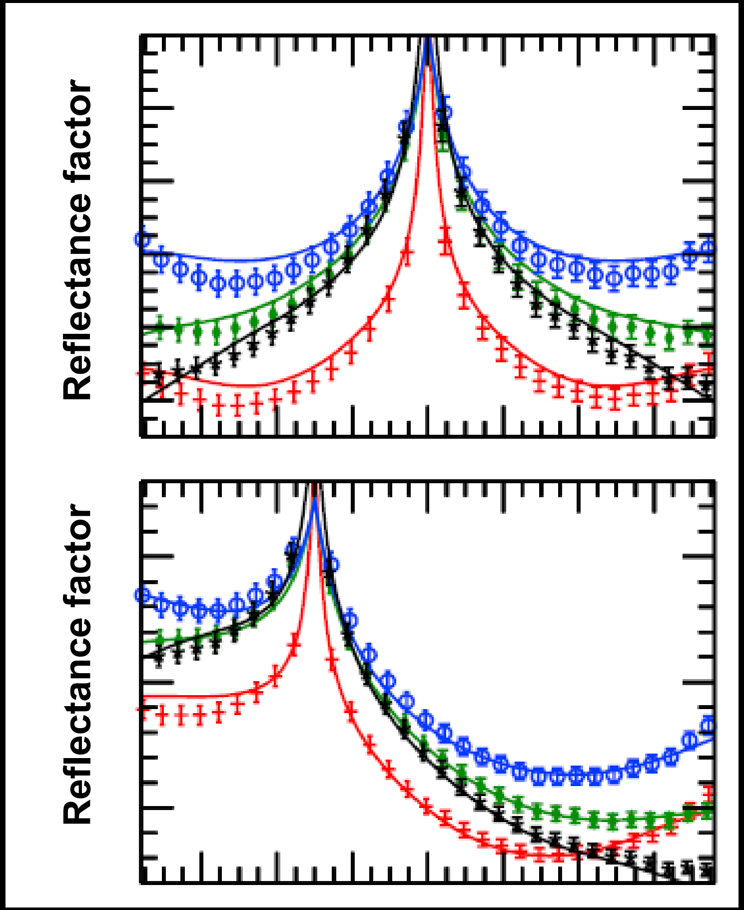


Bablet et al. (2018), Dupiau et al. (2022)

Soil radiative transfer modeling: the DART-Lux model

Step 1



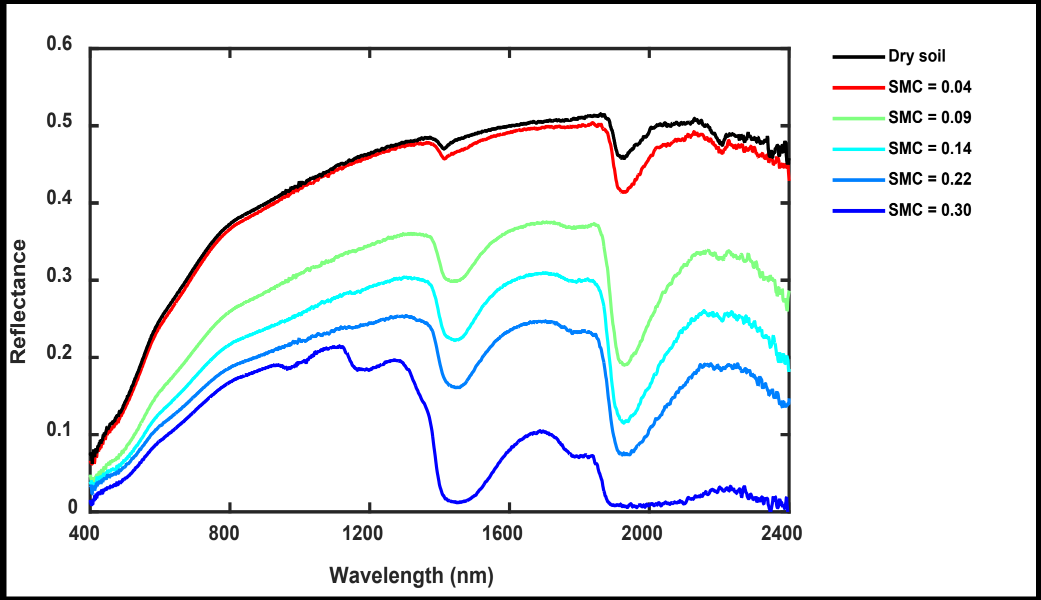


i = 0°

Step 2

i = 30°

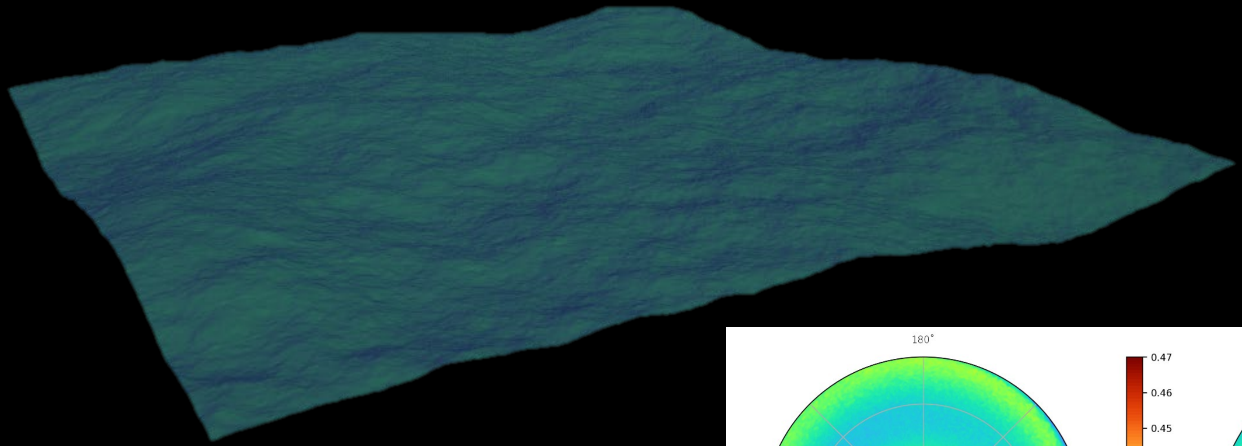
Step 3



Step 4

DART = ?

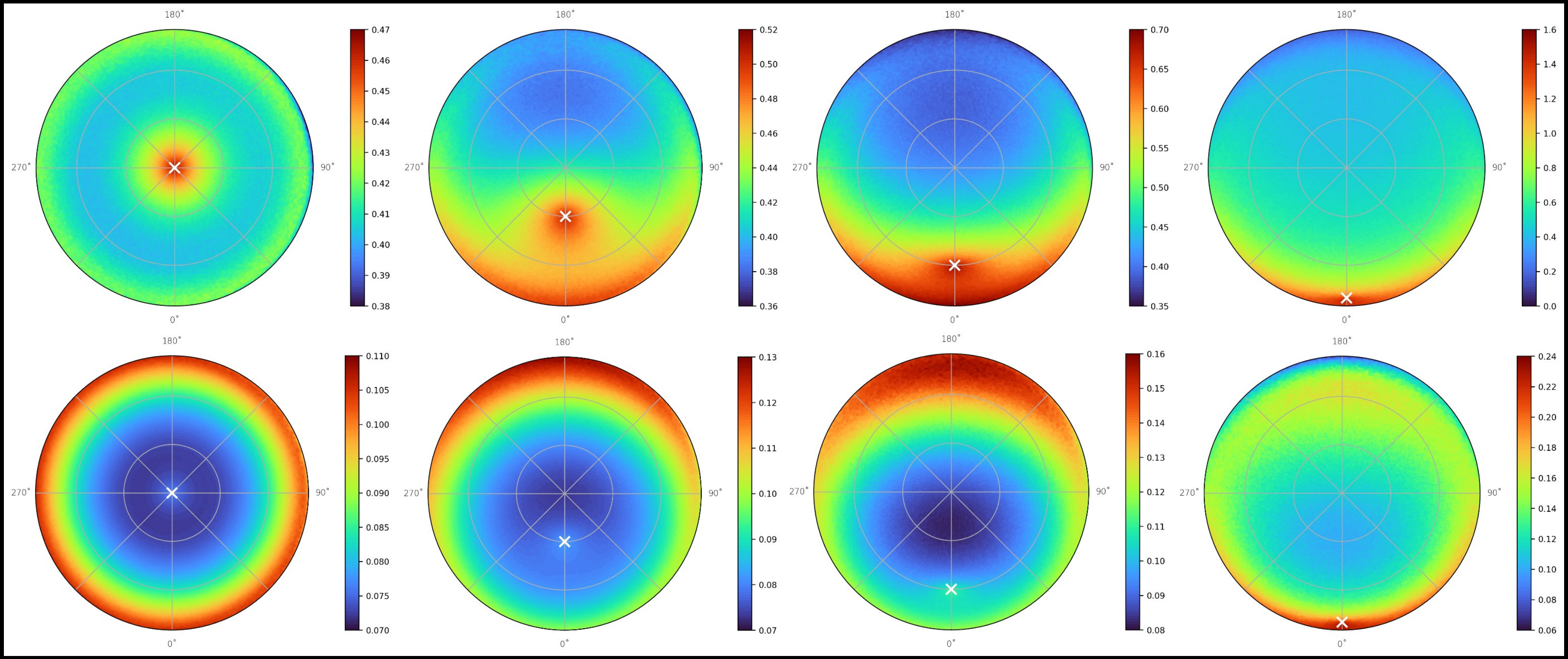
Soil radiative transfer modeling: the DART-Lux model



Moderately rough surface

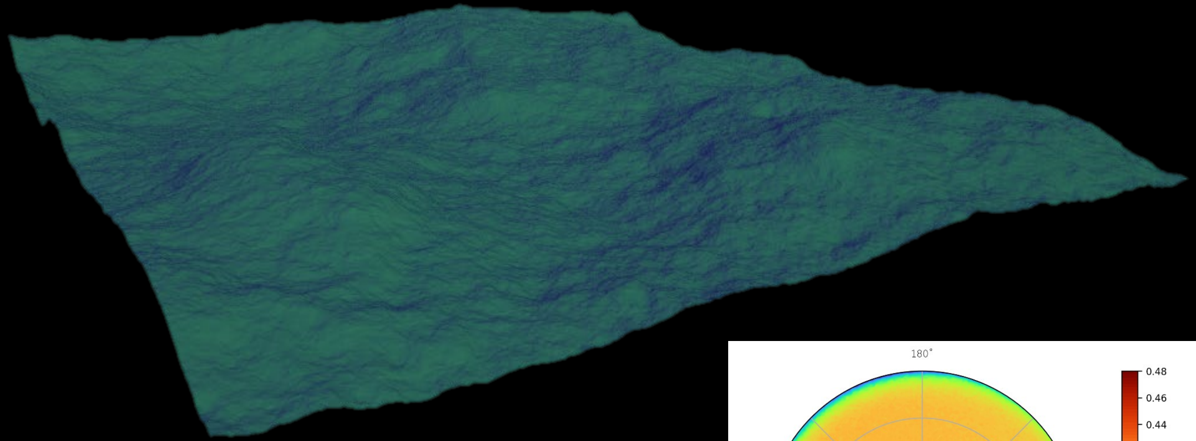
SMC = 0%

SMC = 60%



Roosjen et al. (2015), Champion-Legendre (2021), Dupiau et al. (2022)

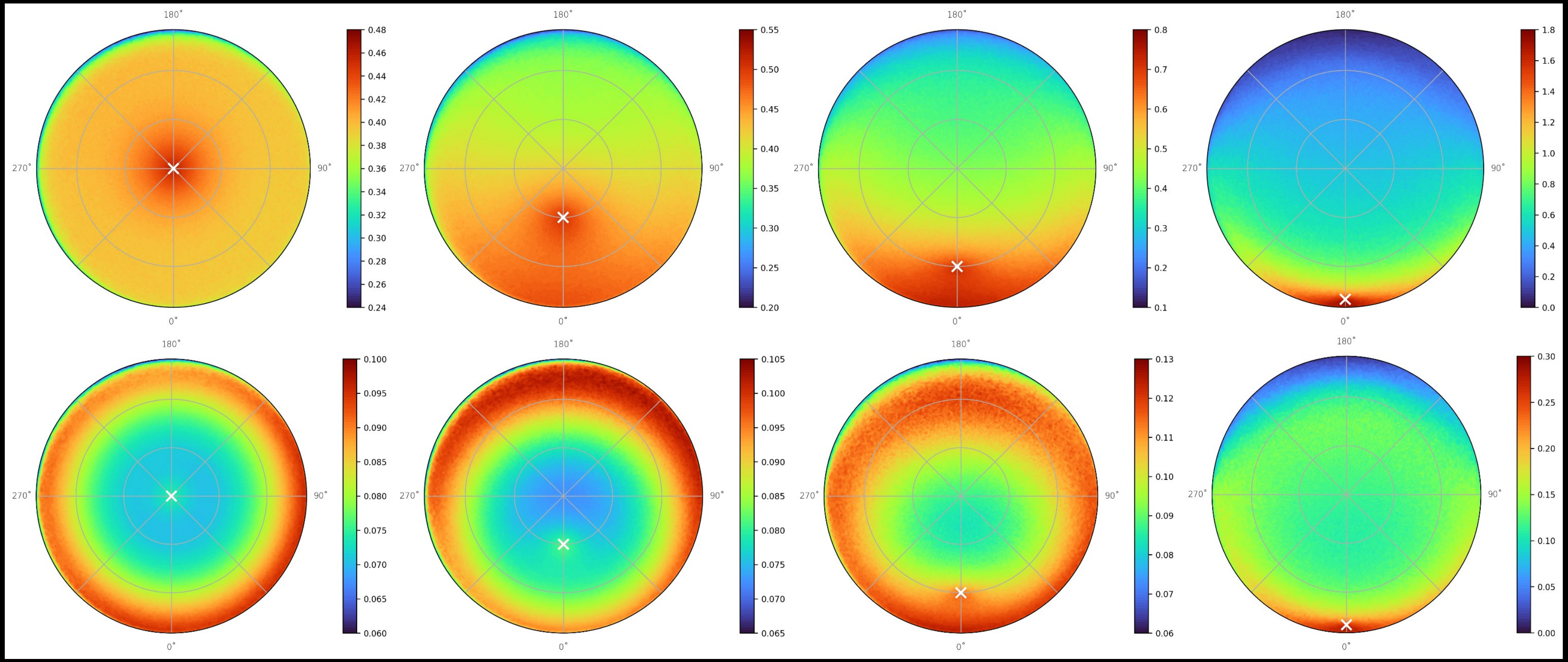
Soil radiative transfer modeling: the DART-Lux model



Fairly rough surface

SMC = 0%

SMC = 60%



Roosjen et al. (2015), Champion-Legendre (2021), Dupiau et al. (2022)

Conclusion

Modeling work

- Reflectance spectra of « flat » wet soils → MARMIT-2
- BRDF simulations of bare soils at different levels of humidity and/or surface roughness → DART-Lux

Experimental measurements

- In the laboratory: https://pss-gitlab.math.univ-paris-diderot.fr/marmit/marmit
- In the field: HySpex images acquired in the field in Orléans (France) + PRISMA images acquired on the Maccarese farm site (Fiumicino, Italy)

Soil moisture content retrieval

- Inversion of a radiative transfer model → MARMIT+RPV, MARMIT+Hapke, or DART-Lux