Estimating the different backscatter contribution with the iterative solution in SMRT

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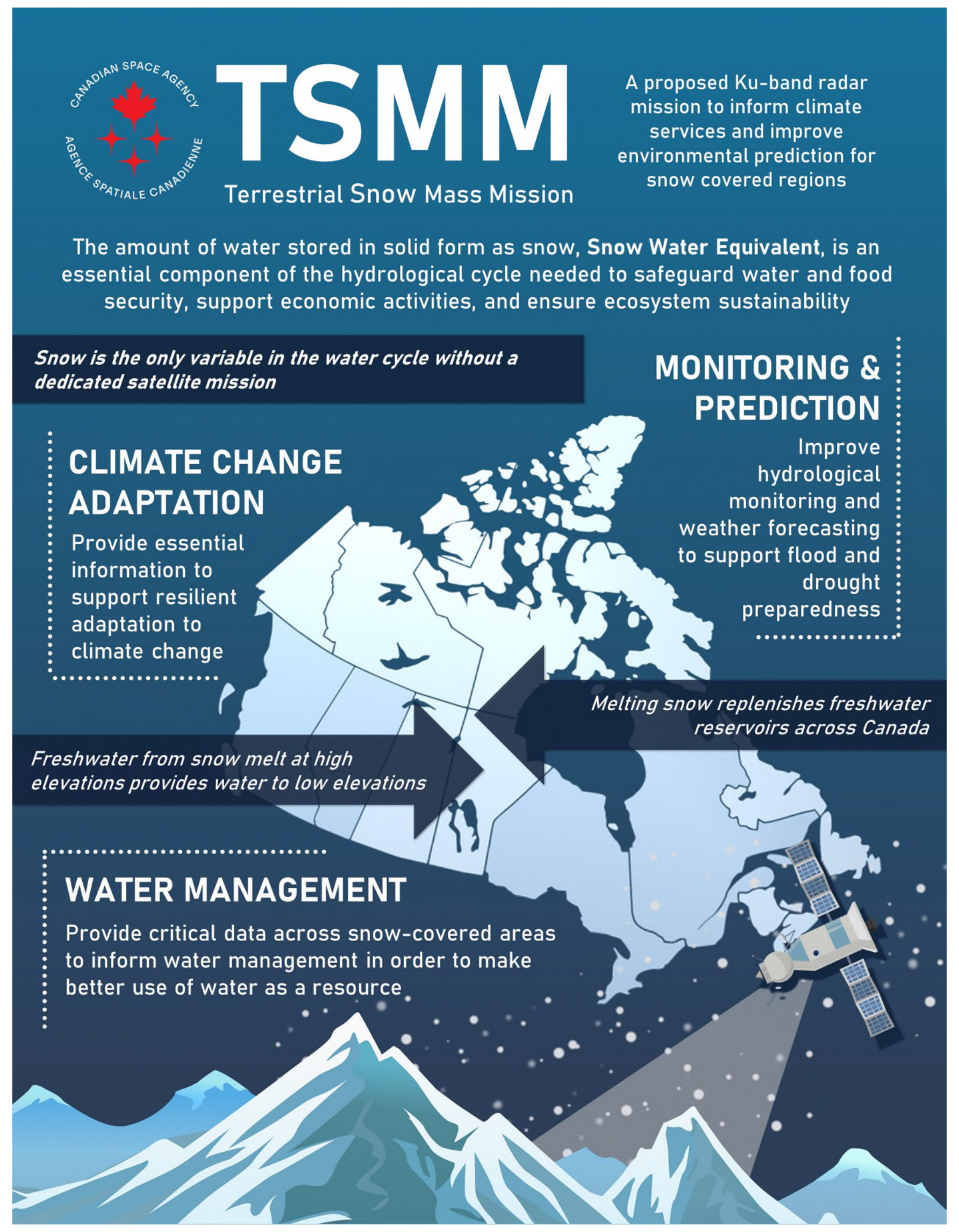
Terrestrial Snow Mass Mission and Snow Microwave Radiative Transfer



TSMM
Terrestrial Snow Mass Mission

A proposed Ku-band radar mission to inform climate services and improve environmental prediction for snow covered regions

The amount of water stored in solid form as snow, **Snow Water Equivalent**, is an essential component of the hydrological cycle needed to safeguard water and food security, support economic activities, and ensure ecosystem sustainability

Snow is the only variable in the water cycle without a dedicated satellite mission

MONITORING & PREDICTION
Improve hydrological monitoring and weather forecasting to support flood and drought preparedness

CLIMATE CHANGE ADAPTATION
Provide essential information to support resilient adaptation to climate change

Melting snow replenishes freshwater reservoirs across Canada

Freshwater from snow melt at high elevations provides water to low elevations

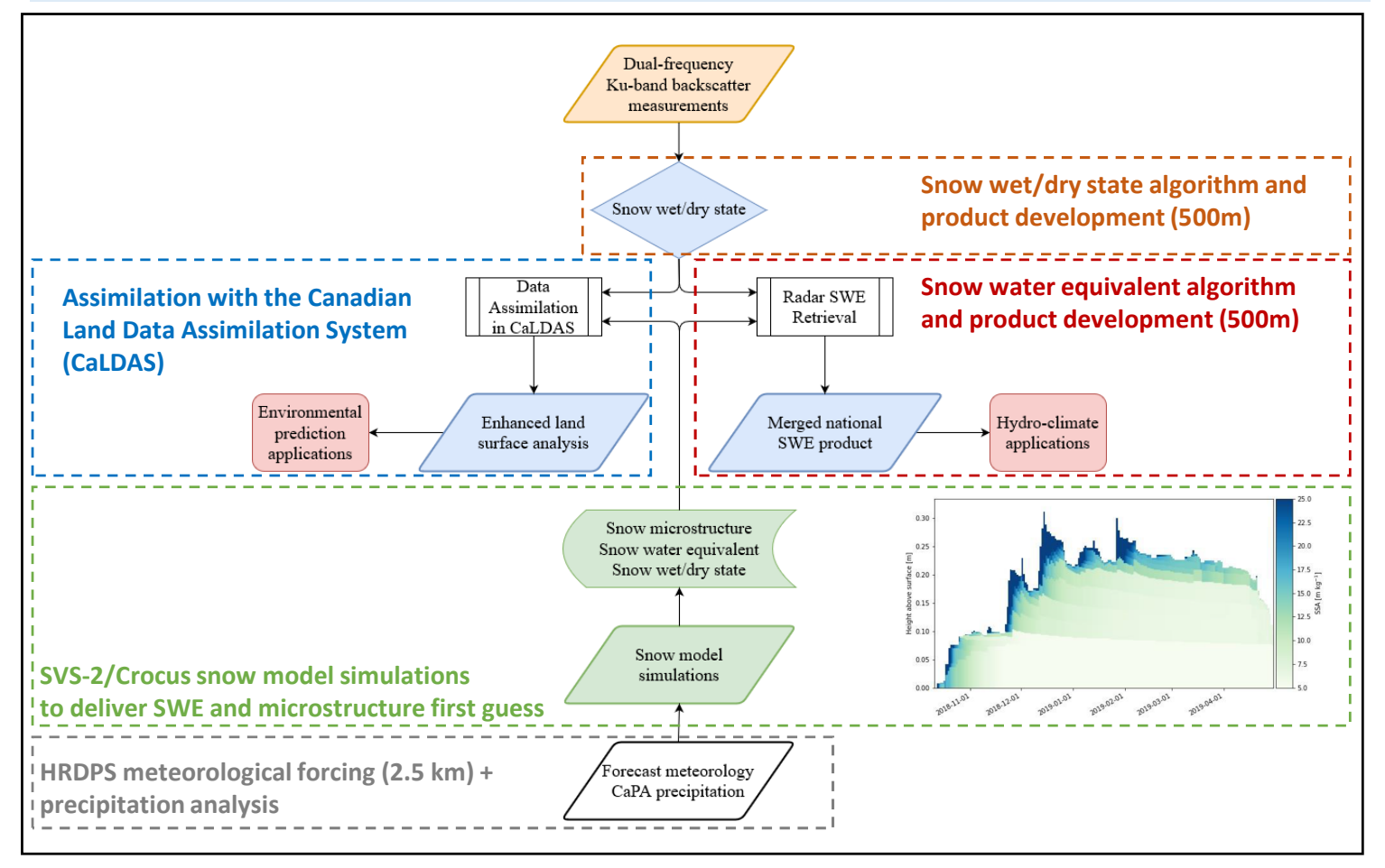
WATER MANAGEMENT
Provide critical data across snow-covered areas to inform water management in order to make better use of water as a resource

Current Status

- ✓ Budget request for full mission implementation is in preparation
- ✓ Science to operations mission, with a target launch early 2030s
- ✓ Detailed cost estimates are underway, science and technical development is ongoing
- ✓ Socio-Economic Benefits Study completed

Characteristic	Mission Design
Frequencies	Dual-band operation, 13.5 and 17.25 GHz
Polarizations	VV; VH
Ground Resolution	500 x 500 m
Number of Looks	>4
Incidence Angle Range	25° - 55°
NESZ – 13.5 GHz	<-26 dB (VV & VH)
NESZ – 17.2 GHz	<-25 dB (VV & VH)
Azimuth and Range DTAR	<-20 dB
Radiometric stability	<0.5 dB
Radiometric accuracy	1 dB

Field campaign data and mission simulator experiments are in progress to demonstrate the viability of all five components of the TSMM snow mass retrieval approach



Snow Microwave Radiative Transfer (SMRT)

- The SMRT model will be used for TSMM in the SWE retrieval.
- The current solver used to solve the radiative transfer equation is based on the discrete ordinate and eigenvalue method (DORT) (Picard et al. 2004, 2013).
- This solver works for both passive and active sensors. It is a robust solver but can be computationally heavy.

$$\mu\frac{\partial \boldsymbol{I}(\mu,\phi,z)}{\partial z} = -\kappa_e(\mu,\phi,z)\boldsymbol{I}(\mu,\phi,z) + \frac{1}{4\pi}\iint \boldsymbol{P}(\mu,\phi;\mu'\phi',z)\boldsymbol{I}(\mu',\phi',z')d\Omega'$$

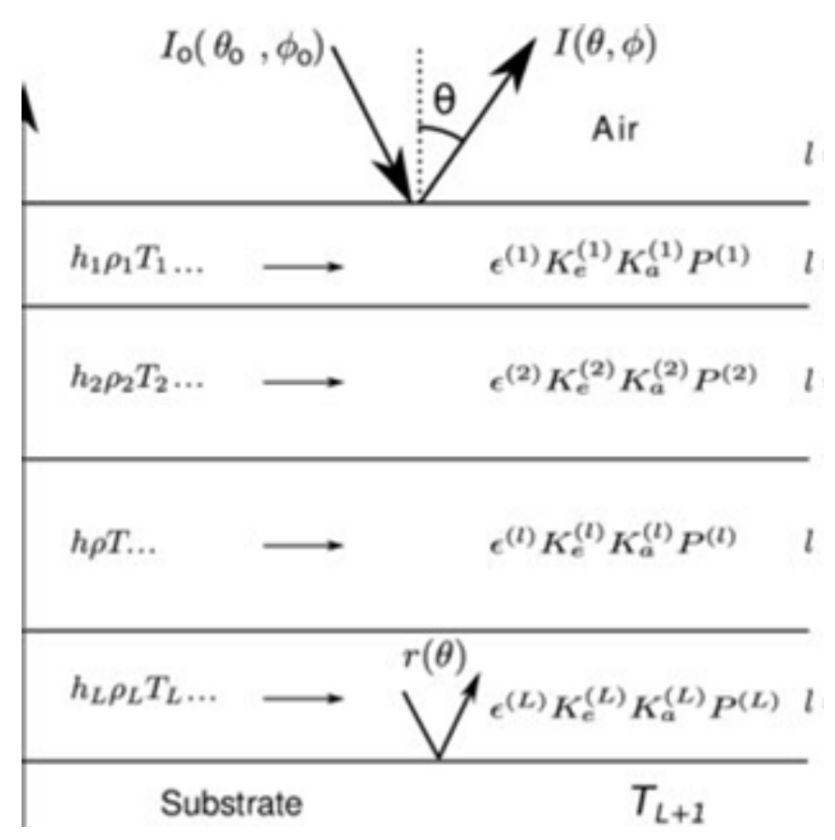
Snow properties

h: thickness
ρ: density
T: temperature
SSA: Specific surface area

Electro-mag coefficients

k_e: extinction
k_s: scattering
k_a: absorption

$$\kappa_e = \kappa_s + \kappa_a$$



Gap in Modelling

- The current solver DORT cannot separate or estimate different contributions of the backscatter.
  - The cross-polarisation signal (VH) is underestimated with respect to observation. More difficult to model than co-polarisation. Multiple scattering is link to cross-pol scattering.

Backscattering mechanisms

Zeroth order (I_0):

- Background backscatter: this term is the attenuated background backscatter. It needs diffuse reflection at the background interface (large roughness) otherwise it is neglected.

First order (I_1):

- Direct backscatter (solid): this is the upward backscatter with the snow microstructure, no reflection at the bottom interface. It is the strongest component at Ku-band. The signal is attenuated twice by the layer.

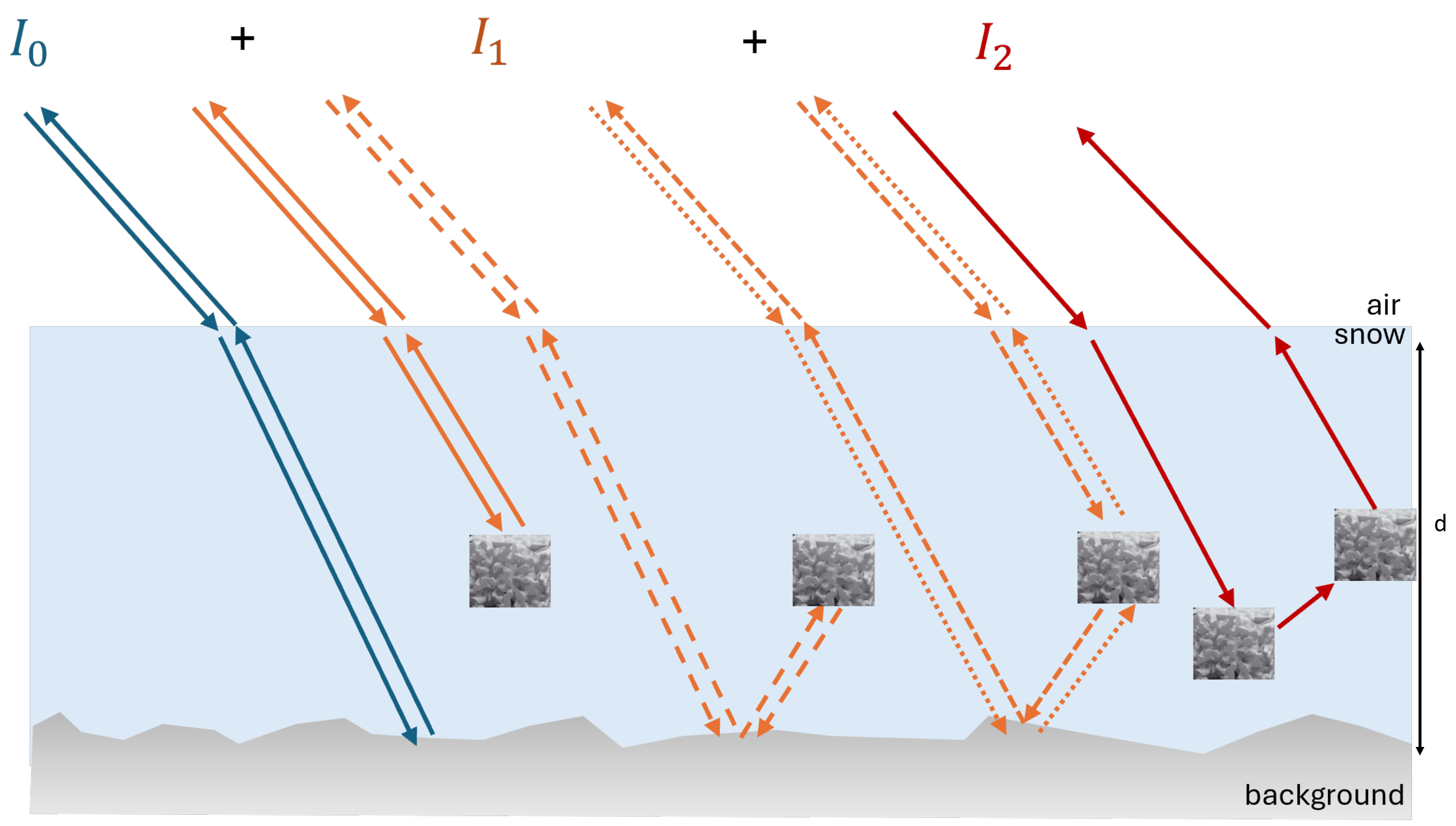
- Reflection backscatter (dashed): this term is the reflected signal at the bottom interface with a downward backscatter with the microstructure. This term needs some specular reflection at the bottom interface otherwise it is neglected. This terms is usually the smallest of the three.

- 2x Reflected bi-static scattering (dot and squared dot): those two terms (dashed and dotted) are the reflected bi-static scattering. The incident and scattered angle are not the same. Those terms also need some specular reflection at the bottom interface otherwise they are neglected.

Second order (I_2):

- Multiple scattering: this terms is double bi-static scattering where the final scattered angle is the same at the incident angle. The signal is scattered twice by the microstructure. This terms is usually associated with cross polarization because the second scattering will depolarize the signal.

$$\begin{aligned}\sigma^0_{snow} &= \sigma^0_{background} + \sigma^0_{interface} + \sigma^0_{vol}\\ \sigma^0_{snow} &= 4\,\pi\cos\theta_i\,(I_0) + 4\,\pi\cos\theta_i\,(I_1+I_2)\end{aligned}$$



Iterative solution theory

The iterative solution is not a new model or solution. Numerous implementations and descriptions can be found (Jin et al. 2006, Tsang et al. 1992, Tsang et al. 2000, Ulaby and Long, 2013). It is an approximation of the radiative transfer equation solution that cast the radiative transfer equation into an integral form and solved iteratively (Ulaby and Long, 2013). The main advantage other than its computation efficiency, is that the solution gives insight on the importance of the different scattering processes. However, the solution assumes small scattering and is only valid for weakly scattering medium, where the scattering albedo ($\frac{\kappa_s}{\kappa_e} = \omega_0$) is low. When the ω_0 increases (> 0.3), multiple scattering becomes important, and the solution is no longer valid and requires a more general solution like DORT.

The scattered intensity (stokes vector) can be written as a function of the incident intensity and the Mueller matrix (backscattering operator in a radar case).

$\overline{I_s} = \bar{\bar{M}}\overline{I_i}$ and $\bar{I} = \overline{I_0} + \overline{I_1} + \overline{I_2} + \dots$ the intensity can be a series of perturbation order with a correspondence to the multiple scattering process

So $\overline{I_s} = (\bar{\bar{M}}_0 + \bar{\bar{M}}_1 + \bar{\bar{M}}_2 + \cdots)\overline{I_i}$

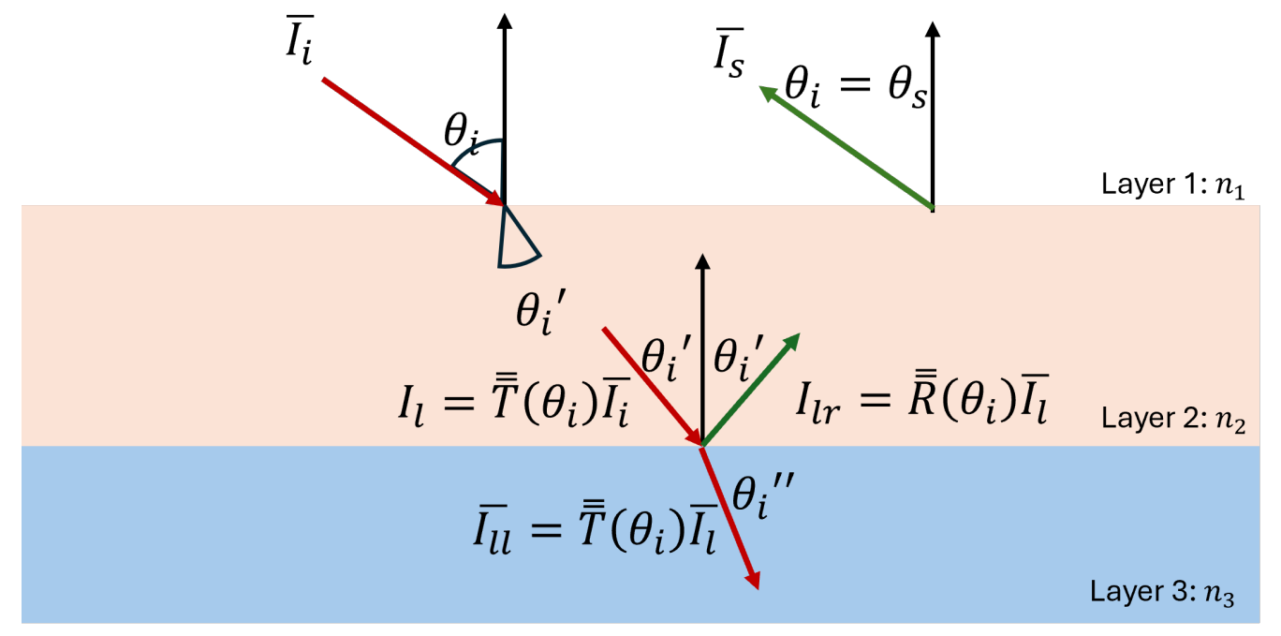
With
$\gamma^2 = e^{-2\kappa_e d/\mu_i}$ is the attenuation of the signal
$\bar{\bar{R}}$ is the reflection matrix
$\bar{\bar{P}}$ is the phase matrix (sometimes define as the bi-static coefficients)
μ_i is the cosine of the incident angle

The first two order of the Mueller matrix :

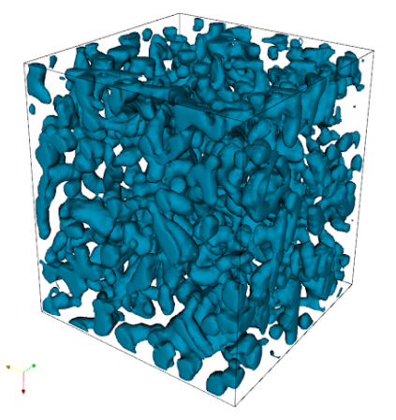
$$\overline{\overline{M_0}} = \gamma^2\bar{\bar{R}}$$
$$\overline{\overline{M_1}} = \left(\frac{1-\gamma^2}{2\kappa_e}\right)\left[\bar{\bar{P}}(\mu_i;-\mu_i) + \gamma^2\bar{\bar{R}}(\mu_i)\bar{\bar{P}}(-\mu_i;\mu_i)\bar{\bar{R}}\ \right] + \frac{d\gamma^2}{\mu_i}\left[\bar{\bar{P}}(-\mu_i;-\mu_i)\bar{\bar{R}}(\mu_i) + \bar{\bar{R}}(\mu_i)\bar{\bar{P}}(\mu_i;\mu_i)\right]$$

For M_2, see references for more details (Jin et al. 2006, Tsang et al. 1992, Tsang et al. 2000, Ulaby and Long, 2013)

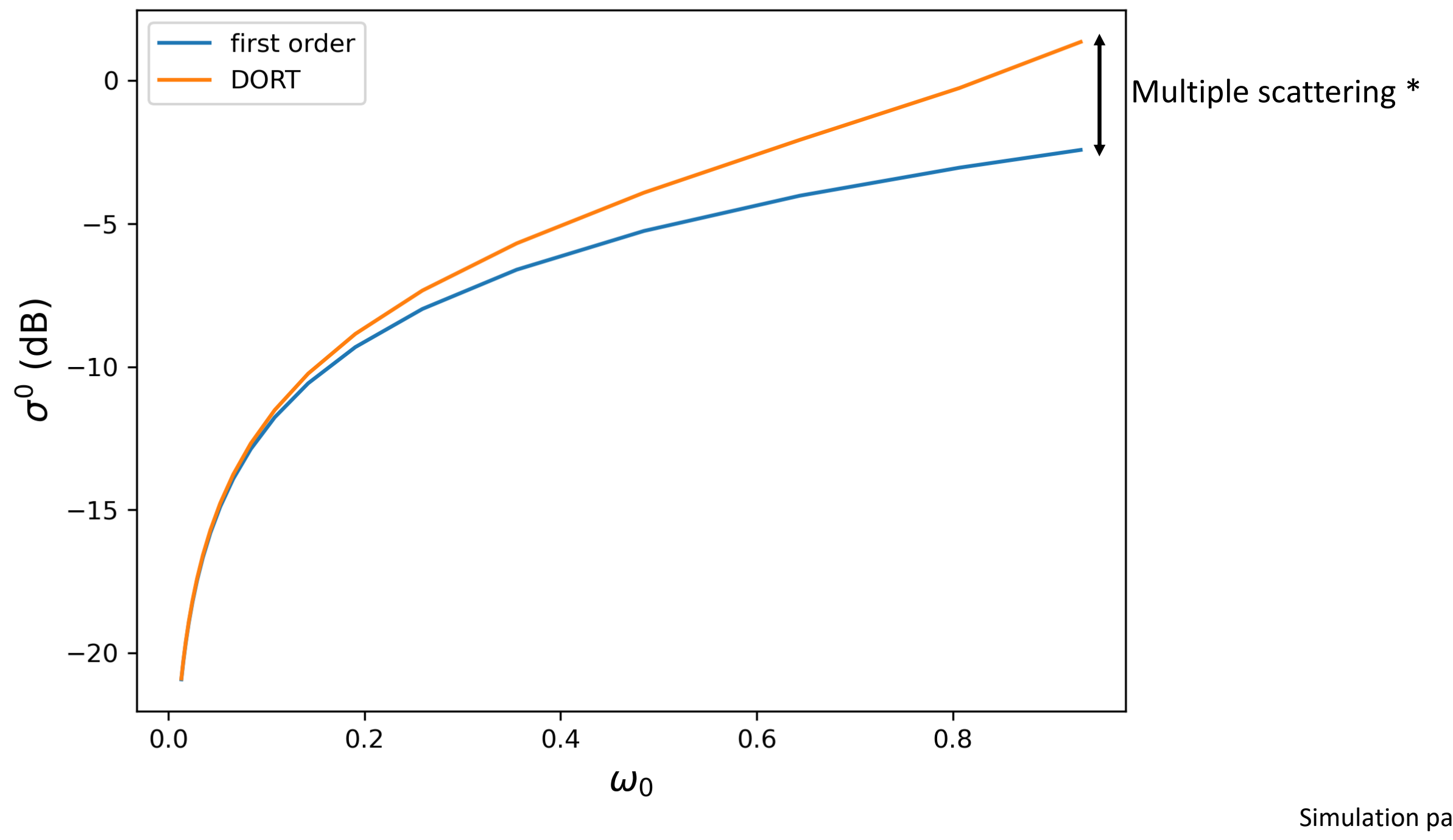
For a distinct upper boundary like snow, the transmission matrix also needs to be taken into account. SMRT allows to define the interface properties ($\bar{\bar{R}}, \bar{\bar{T}}$) of each layer with different surface scattering models



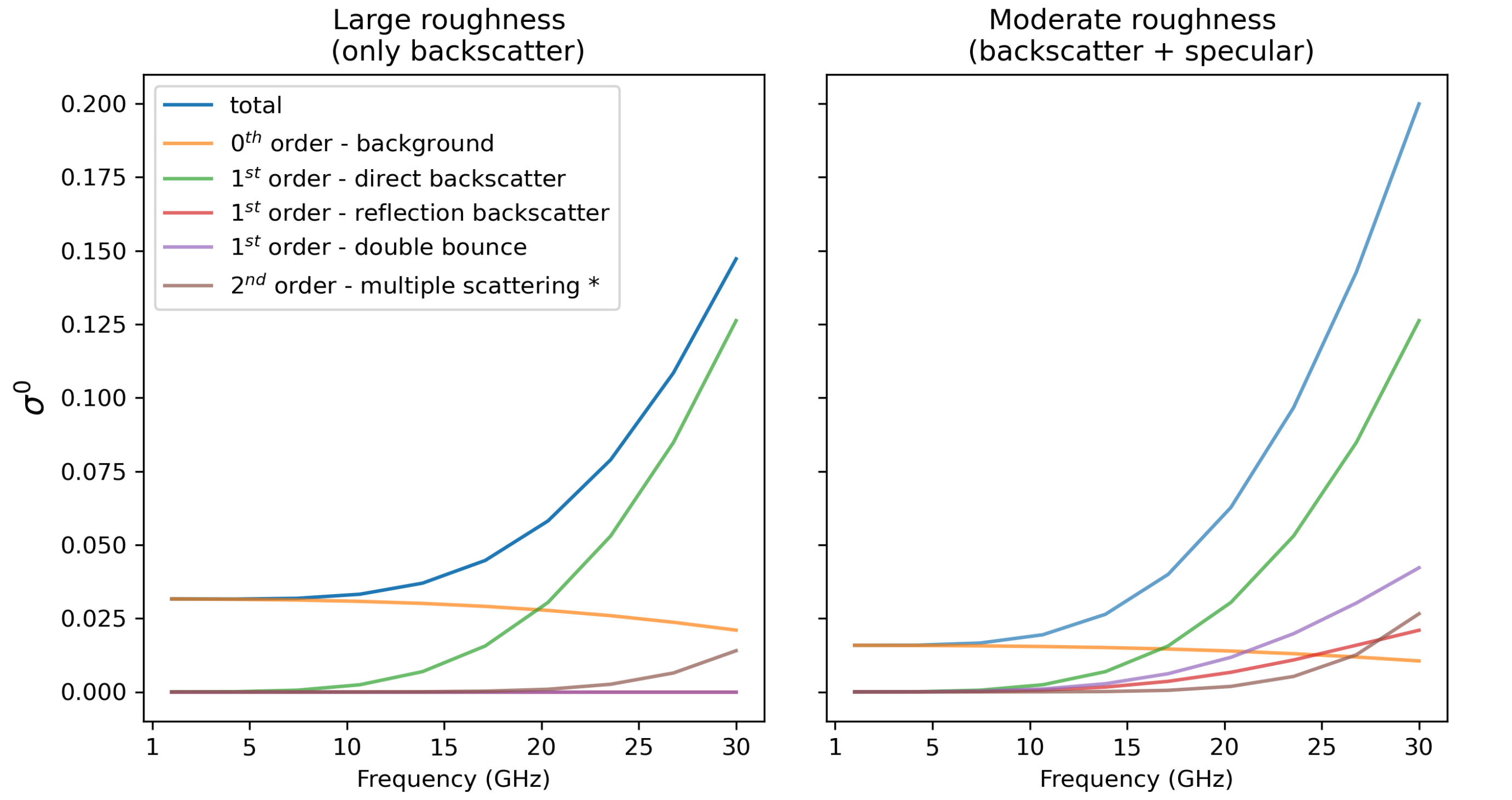
The phase function is defined by the electromagnetic and the microstructure model in SMRT



Backscatter simulations



Simulation parameters:
SSA = [5 – 50], Density = 100, Temperature = 250 K, frequency = 17GHz
1 layer, Microstructure = independent sphere, EM = Rayleigh



Simulation parameters:
1 layer
SSA = 20
Density = 100
Temperature = 250 K
Microstructure = independent sphere
EM = Rayleigh

Background with large roughness:
Specular reflection = 0
Sigma0 = 0.031 (-15 dB)

Background with moderate roughness:
Specular reflection = 0.5
Sigma0 = 0.016 (-18 dB)

* : second order (multiple scattering) is estimated by DORT – first order. Second order is under dev.

Discussion and Status

- This is not a new solution but simply gives the users more tools in backscatter modelling. It should not be used with high scattering medium.
- The iterative solution is under implementation in SMRT to allow the computation of the different scattering processes.
- SMRT was design for research and education, this allows even more comparison with different EM and microstructure models and their impact on the different backscatter contributions.
- A comparison with DORT can also allow to estimate "multiple scattering" not estimated by the iterative solution.
- Cross-polarized signal will be investigated with this solver and validated with measurements, since cross-pol is linked to multiple scattering.
- The iterative solution should be available soon.

SMRT model
https://github.com/smrt-model

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