Differential SAR interferometry for estimating snow water equivalent in central Apennines complex orography from Sentinel-1 satellite

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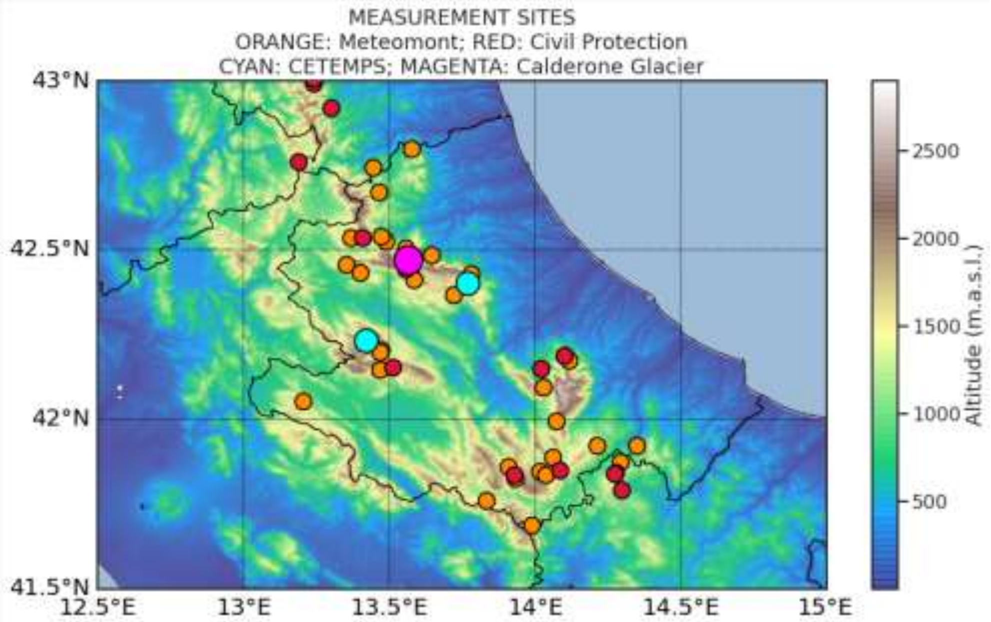
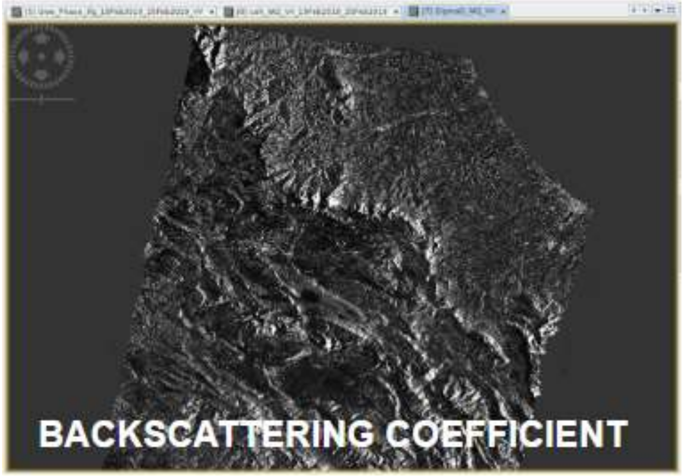
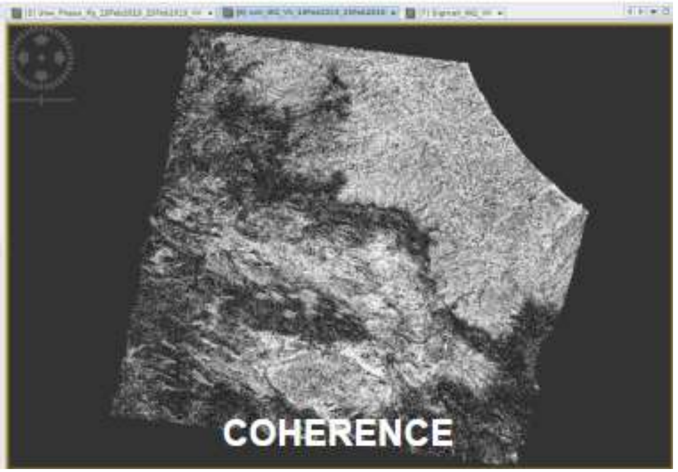
Project supported by ESA Network of Resources Initiative

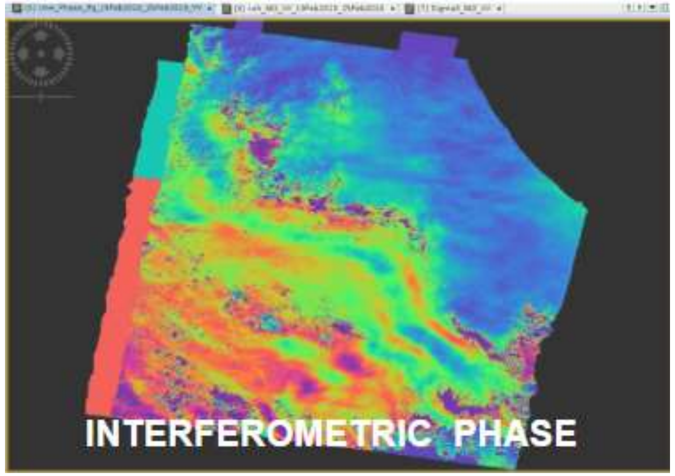
Objectives of the project:

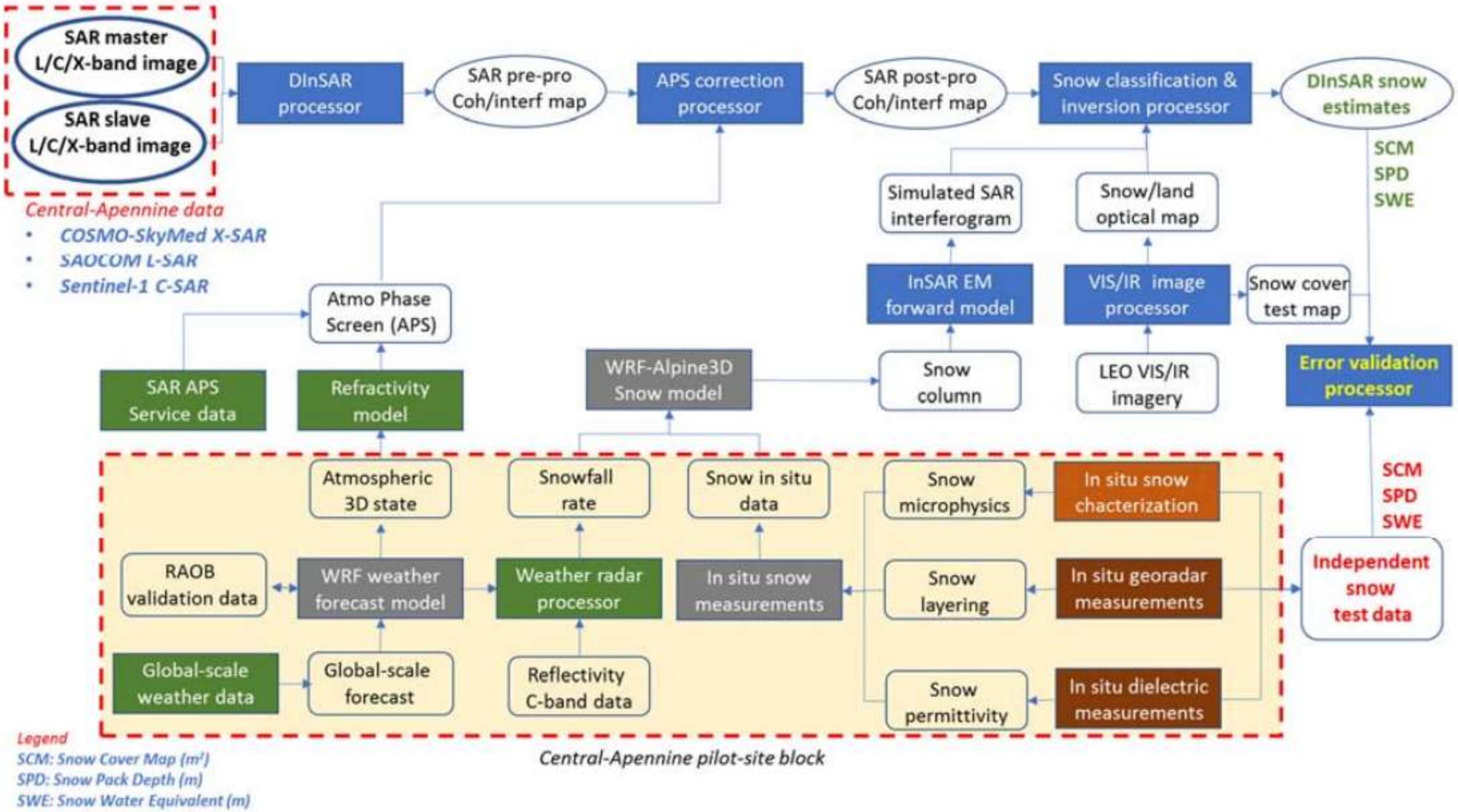
- Retrieve snow properties in the Italian Central Apennine with Differential Interferometric spaceborn SAR data, using some auxiliary data.
- Estimate snow cover extension and classify snow (dry snow, wet snow).
- Estimate snow depth.
- Validate estimates with in-situ data obtained with measurement campaigns.
- **Provide useful information in terms of avalanche warning, monitoring of climate change evolution, flood forecasting and water volumes expected for the hydric supply.**







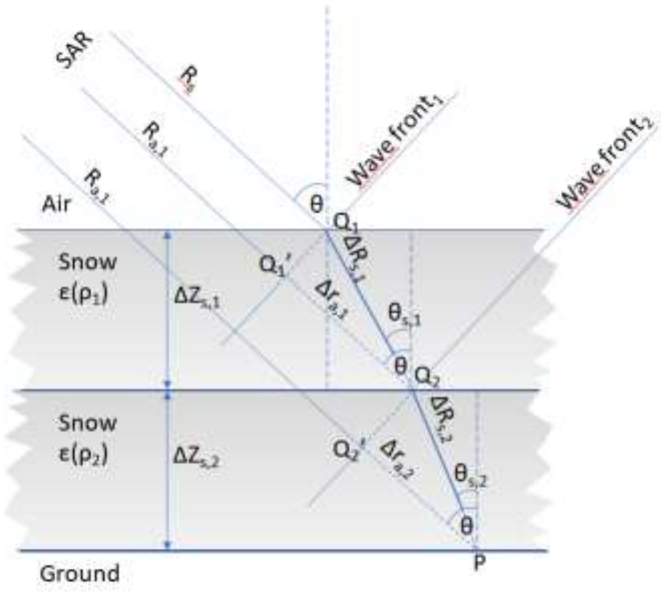




SAR master L/C/X-band image
SAR slave L/C/X-band image
DInSAR processor
SAR pre-pro Coh/interf map
APS correction processor
SAR post-pro Coh/interf map
Snow classification & inversion processor
DInSAR snow estimates
SCM
SPD
SWE
Central-Apennine data
COSMO-SkyMed X-SAR
SAOCOM L-SAR
Sentinel-1 C-SAR
Simulated SAR interferogram
Snow/land optical map
InSAR EM forward model
VIS/IR image processor
Snow cover test map
Atmo Phase Screen (APS)
SAR APS Service data
Refractivity model
WRF-Alpine3D Snow model
Snow column
LEO VIS/IR imagery
Error validation processor
Atmospheric 3D state
Snowfall rate
Snow in situ data
Snow microphysics
In situ snow chacterization
SCM
SPD
SWE
RAOB validation data
WRF weather forecast model
Weather radar processor
In situ snow measurements
Snow layering
In situ georadar measurements
Independent snow test data
Global-scale weather data
Global-scale forecast
Reflectivity C-band data
Snow permittivity
In situ dielectric measurements
Legend
SCM: Snow Cover Map (m²)
SPD: Snow Pack Depth (m)
SWE: Snow Water Equivalent (m)
Central-Apennine pilot-site block

DInSAR snow retrieval method

The signal delay caused by snow refraction can be measured **if snow permittivity is known**.
Therefore snow depth variation between two dates can be estimated by calculating the SAR signal phase difference between two satellite passes.



Snow Permittivity

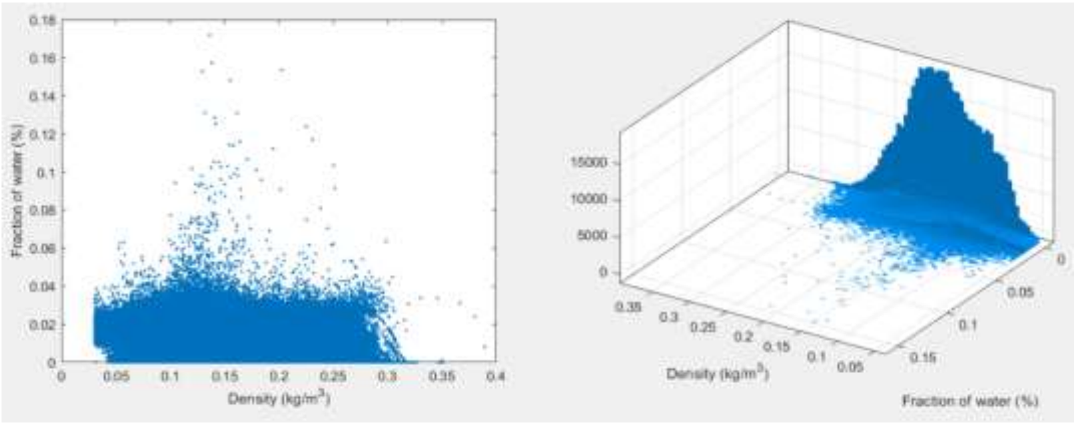
- Snow permittivity depends on snow water fraction and snow density values.
- Different models are available to estimate snow permittivity.

- A very simple model can be used as a rough approximation:

$$\epsilon_{snow} = \epsilon_{dry\text{-}snow} (1-f_w) + \epsilon_{water} f_w$$

- More complex models are available in the literature

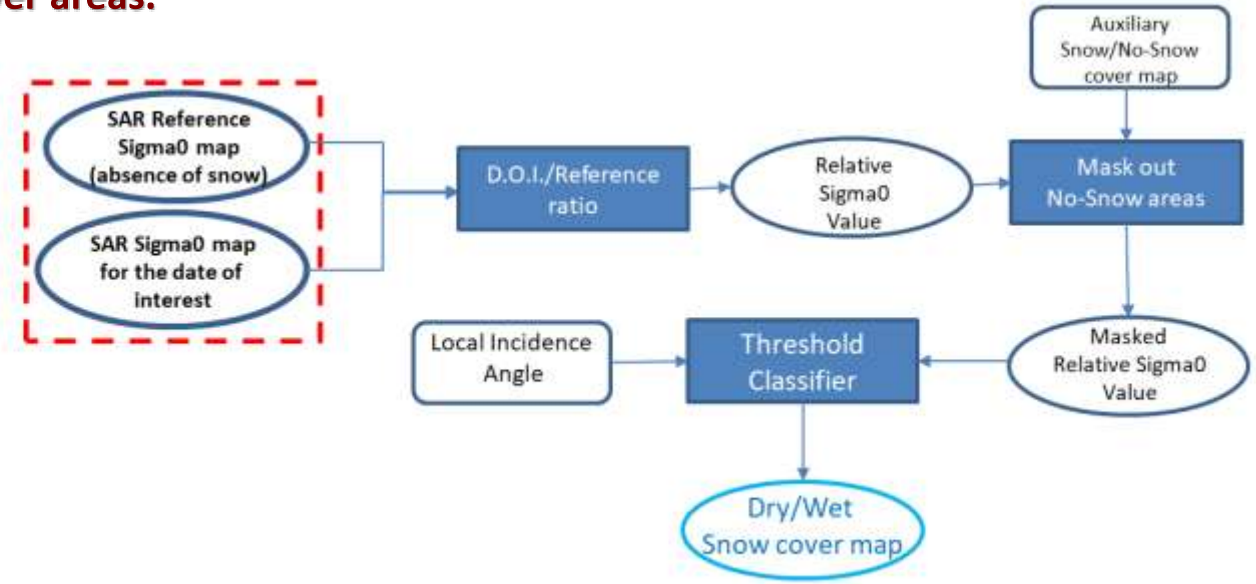
For water fraction and snow density values two options have been explored:
- a synthetic scenario with uniform distributions of values;
- a realistic scenario (shown below) made of estimates calculated by a dynamic snow-mantle evolution model (Alpine3D).



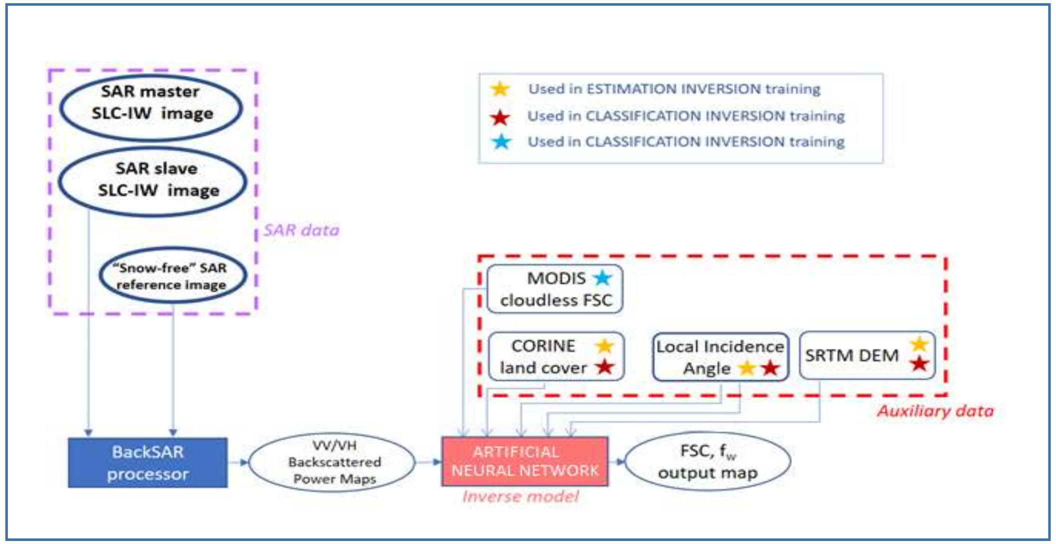
SNOW CLASSIFICATION: identification of dry snow and wet snow cover areas.

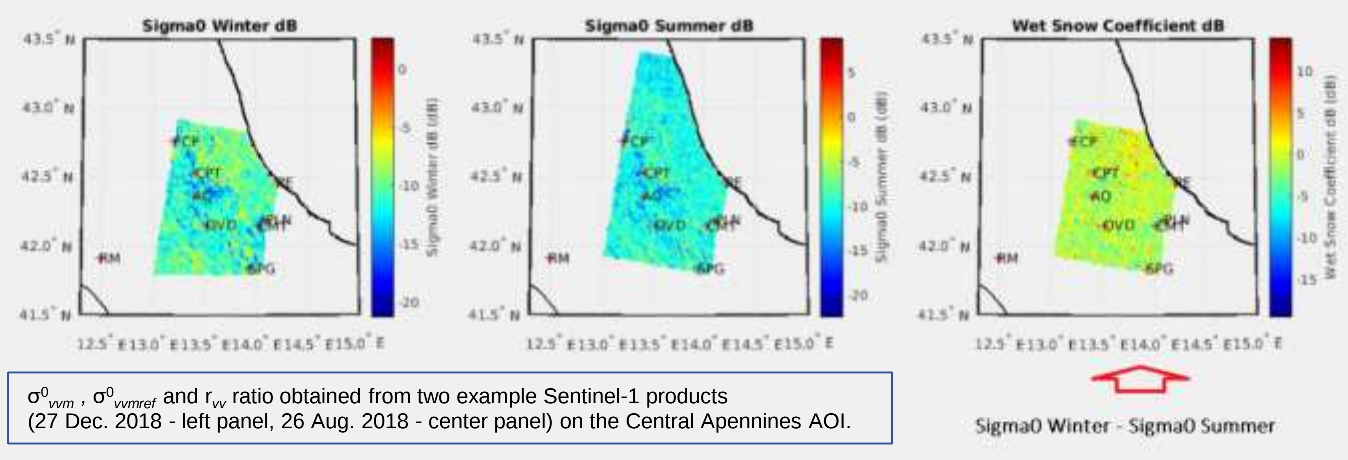
• A first approach has been adopted for the snow classification problem which employed the backscattering-coefficient threshold-based algorithm proposed by Nagler-Rott for the dry-wet snow classification task.

$$r_{vv}(x,y) = \frac{\sigma^0_{vvm}(x,y)}{\sigma^0_{vvmref}(x,y)} = \begin{cases} \leq r_{0wet} & \textit{Wet snow} \\ > r_{0wet} & \textit{Dry snow} \end{cases}$$



- This approach showed poor results on the considered AOI (Italian Central Apennines)
- Another approach based on an Artificial Neural Network (ANN) is currently being experimented.





σ^0_{vvm} , σ^0_{vvmref} and r_{vv} ratio obtained from two example Sentinel-1 products (27 Dec. 2018 - left panel, 26 Aug. 2018 - center panel) on the Central Apennines AOI.

SNOW ESTIMATION: retrieval of snow depth and snow density.

- The **PAI algorithm,** which is obtained by inverting the DInSAR equation with $\Delta h_s = \Delta Z_s$:

$$\Delta \hat{h}_s(x,y) = \frac{\Delta\Phi_{ppsm}(x,y)}{2\,k_i\left(\sqrt{\varepsilon_{Rrs} - \sin^2\theta_l} - \cos\theta_l\right)}$$

The main limitation of the PAI inversion algorithm is that it requires ρ and f_w values to be known in order to perform the inversion; since ρ and f_w are, in general, not known, they need to be assigned estimated values, potentially resulting in a poor accuracy of the model.

- The **LRI algorithm** which is based on the statistical linear-regression approach and is described by the following equation:

$$\Delta \hat{h}_s(x,y) = a_{h0} + a_{h1}\,\Delta\Phi_{ppsm}(x,y)$$

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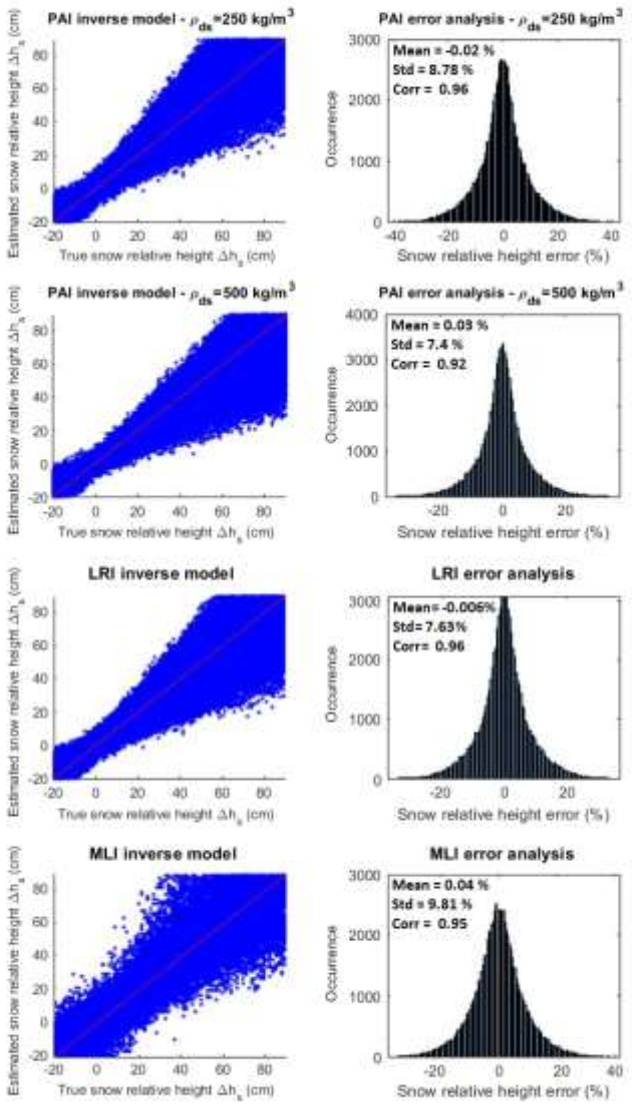
•The **MLI algorithm** which uses a statistical approach where the error probability density function is maximized, under a Gaussian hypothesis its negative argument is minimized.

$$\begin{bmatrix} \Delta \hat{h}_s(x,y) \\ \hat{\rho}_s(x,y) \end{bmatrix} = argmin\left\{\left[\Delta\Phi_{ppsm}(x,y) - \Delta\Phi_{pps}(x,y)\right]^2\right\}$$



CONCLUSIONS

Main achievements:

- We have implemented some dielectric models for snow permittivity estimation.
- We have used a realistic scenario based on a snow-mantle evolution model (Alpine-3D)
- We have implemented and tested a threshold-based algorithm which uses the backscattering-coefficient as input. This algorithm showed poor results on the Italian Central Apennine AOI.
- We have implemented and tested three different inverse models for snow depth estimation. They use differential SAR phase as input. MLI showed better performances.

Future developments:

- Multiband/multimission integrated analysis: combine C-Band (Sentinel-1), L-band (SAOCOM), and X-band (Cosmo SkyMed 1st and 2nd generation) data to take advantage of the different characteristics of each band.
- Implementing Artificial Neural Network based models to improve accuracy.
- Validation of the results with in-situ data.

Advantages derived from using tools and data within cloud environments sponsored by NoR:

- High-performing computing virtual machine allows a substantial reduction of processing times especially on time series
- The availability of the Sci-Hub Catalog products directly on the virtual machine as a mounted local disk make the process of dat acquisition smoooth and seamless.
- High network speed is available for external data transfer.

Potential benefits to society derived from this project:

- Provision of useful information in terms of avalanche warning, monitoring of climate change evolution, flood forecasting and water volumes expected for the hydric supply.

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