Spaceborne SAR data processing for snow and ice monitoring.

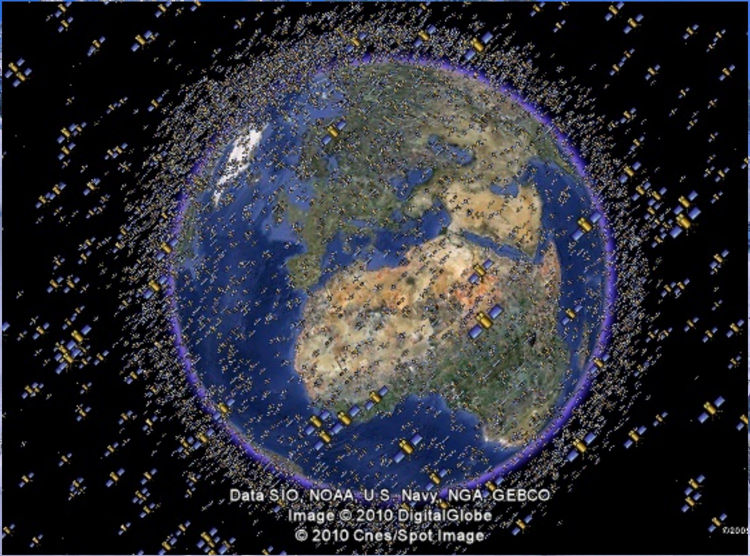
M. Gay, G. Vasile, M. Leclainche[1]

CNRS - GIPSA-lab Equipe Sigmaphy

[1]Grenoble Image Parole Signal et Automatique laboratoire

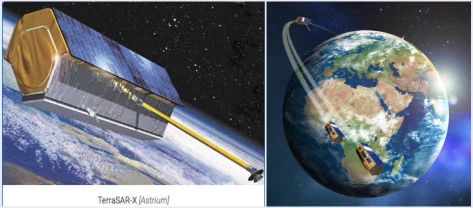
Why use satellites to monitor the evolution of the cryosphere?

1738 operational satellites in orbit around the Earth
including 380 imagers (from Union of Concerned Scientists.)



Why use radar satellites to monitor the evolution of the cryosphere?

Greenland



DLR Satellites (TerraSAR-X)

Cryosphere (snow, firn, ice):

- High spatial and temporal variation of snowpack.
- Long period of polar night in Arctic and Antarctic with rapid changes.
- Various shape: iceberg, sastruggi...

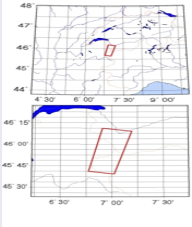
Advantages of SAR data:

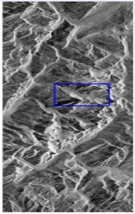
- Interaction of electromagnetic waves with snow, ice... with high spatial resolution (metric).
- Active sensor, "all-weather" -> regular data.
- Coherent / polarized waves -> interferometry, polarimetry, change detection.

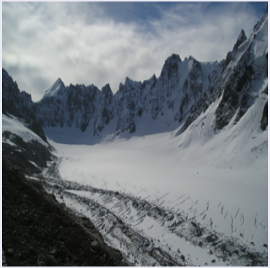
1. Permanent experimental site near Grenoble.
2. Interactions of electromagnetic waves with snow
3. Radar backscattering model applied to snow
4. SWE extraction from interferometric phase
5. Conclusion

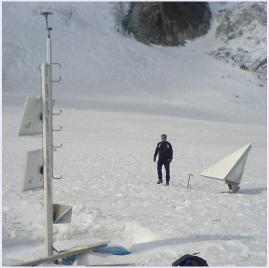
Contents

Since 2004, permanent experimental site near Grenoble: Argentière glacier







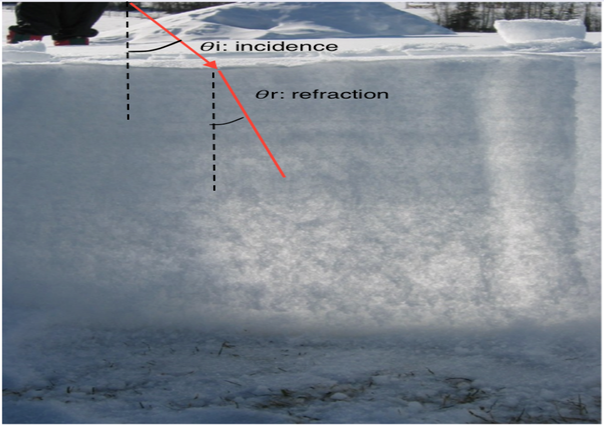


- Corners reflectors on ice and under snow
- Ongoing GPS on glacier and on mountain hut.
- Seismic sensors (accelerometers).

Contents

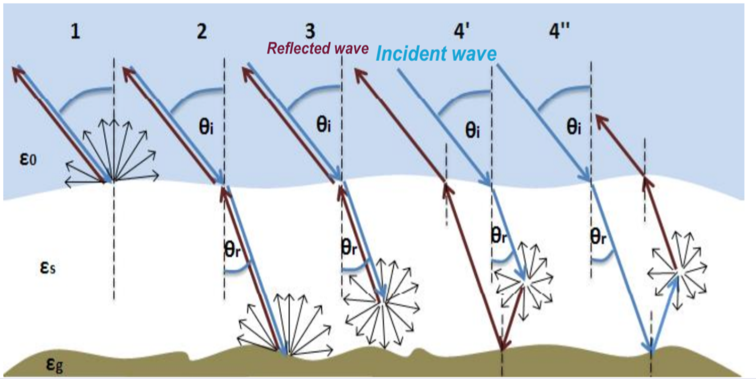
What is the snowpack?

- Dense media composed of air, ice and sometimes of water
- Multi-layer, stratified media
- Each layer -> different physical properties (thickness, density, grain size, liquid water content-LWC. . .).
- Strong spatial and temporal variations in physical properties.



Electromagnetic waves interact with the snowpack (ex. : X band, 3.1 cm).

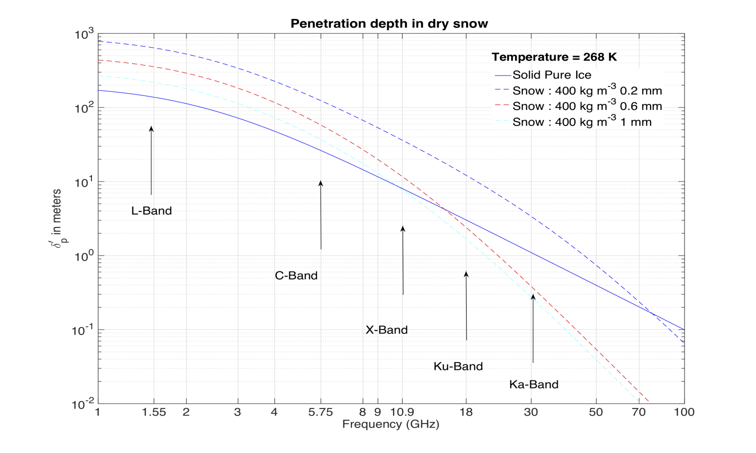
- The four main interaction mechanisms at X-band.



- Theoretically the maximum penetration depth δ_p' can be calculated by the equation :

$$\delta_p' = \frac{\lambda}{4\pi} \frac{1}{\sqrt{\{[1 + (\frac{\varepsilon''}{\varepsilon'})^2]^{\frac{1}{2}} - 1\} * \frac{\varepsilon'}{2}}} \tag{1}$$

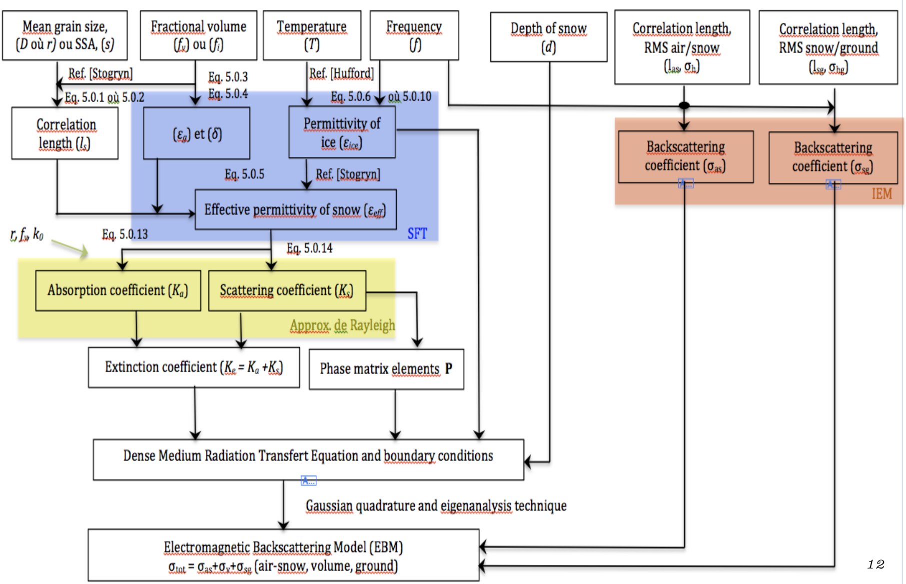
Penetration depth δ'_p in dry snow.



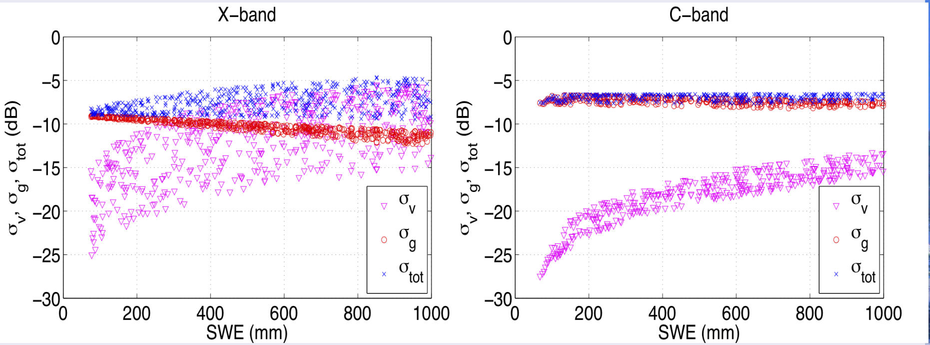
- As the size of the snow gains increases, the depth of penetration decreases.
- Diffusion losses for the same type of snow are greater in Ku-band (1.5 cm) than in X-band (3.1 cm) -> the penetration depth decreases.

Contents

Use of a Dense Media Radiative Transfer DMRT *(L. Ferro-Famil, S. Allain, N. Longépé, X.V. Phan...)*



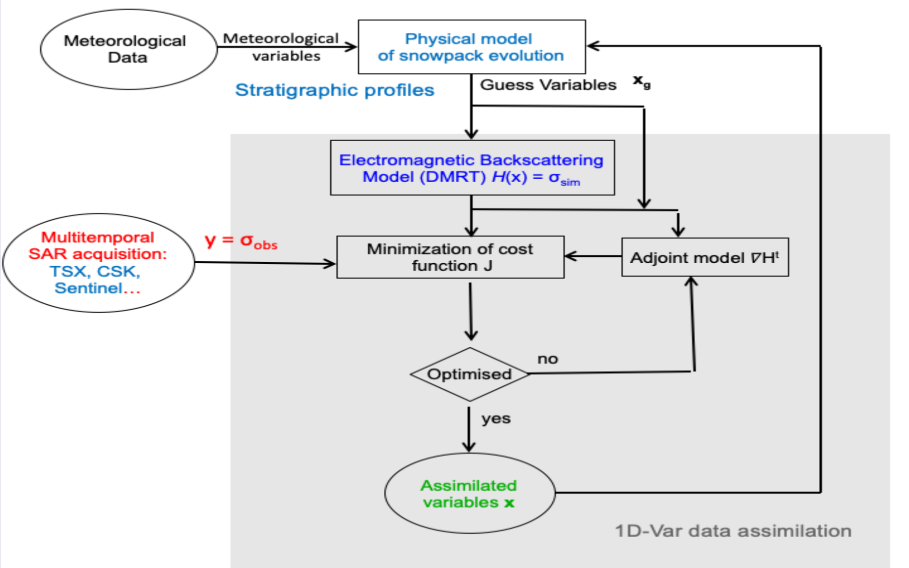
Simulation: single-layer snowpack (*X.V. Phan*)



- Incidence angle : $\theta_0 = 30^o$
- Snow height = 30-400 cm
- Snow density = 250 $kg\ m^{-3}$
- **Optical grain size = 0.5-2 mm.**

-> Strong influence of grain size.
-> Significant ground contribution.

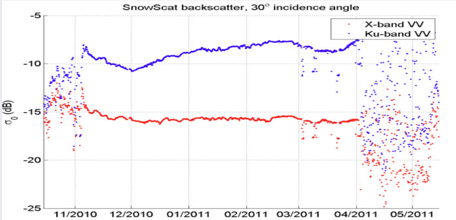
SAR data assimilation algorithm *(X.V. Phan)*.



Two-winter ground radar acquisitions at several frequencies, incidences and polarizations, Snow Scat. Instrument (SSI)

Fréquences	9.2-17.8 GHz
Incidences	$30^o < \theta < 60^o$
Polarisations	HH, HV, VH, VV

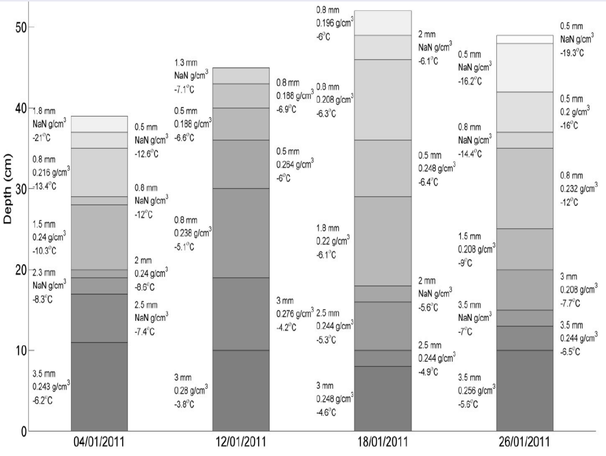
Backscattering measured at 10.2 GHz, and 14 GHz



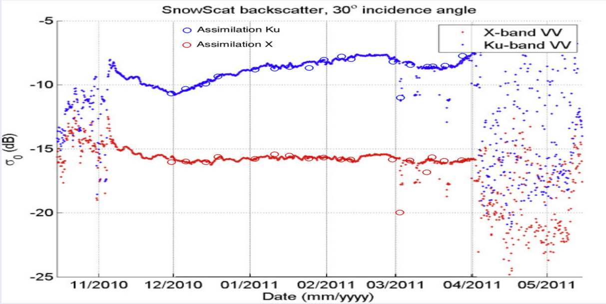
Sodankyla: stratigraphic snow profiles at several dates

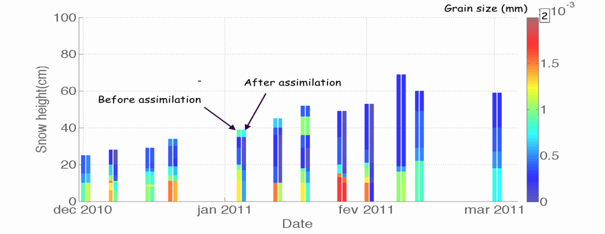
Pits in the snow, allowing to measure:

- layer height
- grain size
- density
- temperature...



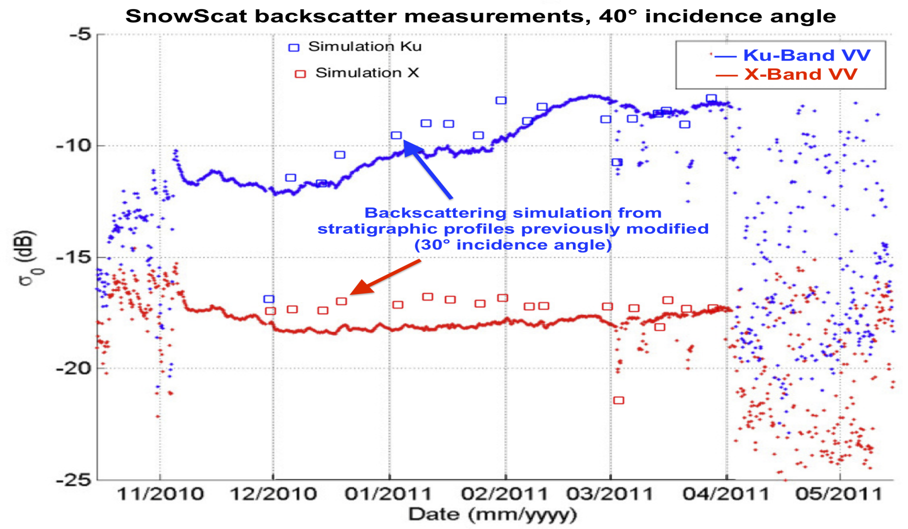
Assimilation -> modification of measured profiles ($\theta_i = 30°$).





-> Convergence of this algorithm

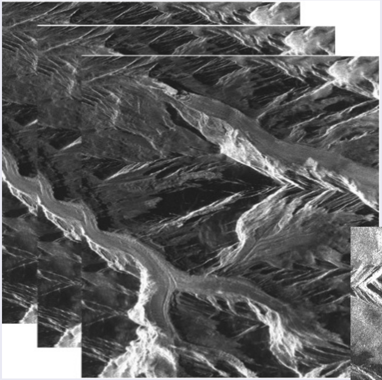
Backscattering simulation from the modified incidence profiles at $\theta_i = 30°$.

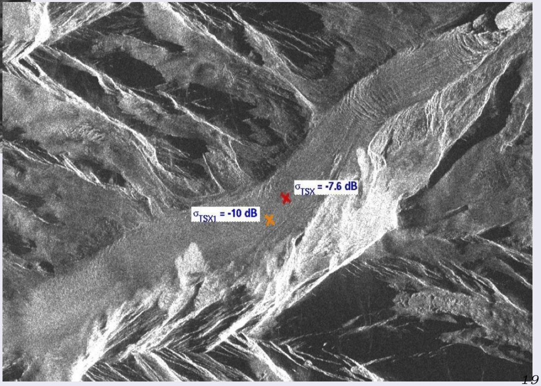


-> Excellent agreement between simulations and measurements.

-> Validation of the radiative transfer model (DMRT).

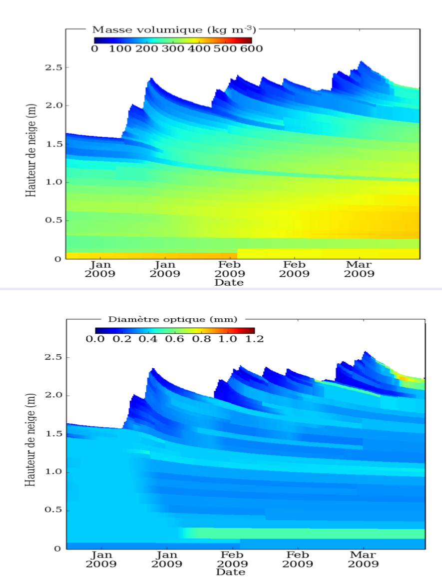
Argentière Glacier: time series of TerraSAR-X images (each 11 days)



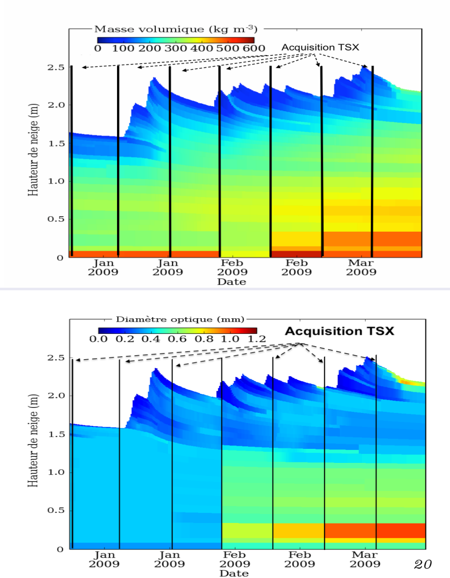


Evolution of density and size of the snow grains in the snowpack without and with assimilation of TerraSAR-X radar data (Argentière glacier, altitude : 2400 m).

Without assimilation



With assimilation



Contents

Can we directly extract the SWE with the interferometric phase?

Formula proposed by S. Leinss:

$$\Delta SWE(t, t_0) = \frac{\Delta\Phi_s(t, t_0)}{\alpha.k_i(1.59 + \theta^{5/2})}$$

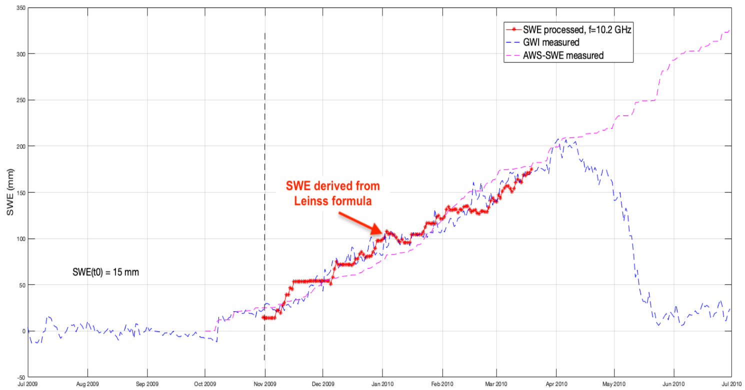
$\Delta SWE(t, t_0)$: change in SWE between time periods t_0 et t
$\Delta\Phi_s(t, t_0)$: difference in phase between time periods t_0 et t (every 6 hours)
α: empirical coefficient ($\alpha = 1$)
$k_i = \frac{2\pi}{\lambda}$: wave vector ($\lambda$ wavelength)
θ: incidence angle

S. Leinss "Snow Water Equivalent of dry snow mesured by differential interferometry", IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, august 2015

SWE measured from Snow Scat. Instrument (SSI) data and derived from the Leinss formula (*M. Leclainche*)

GWI: Gamma Water Instrument ⟼ SWE direct

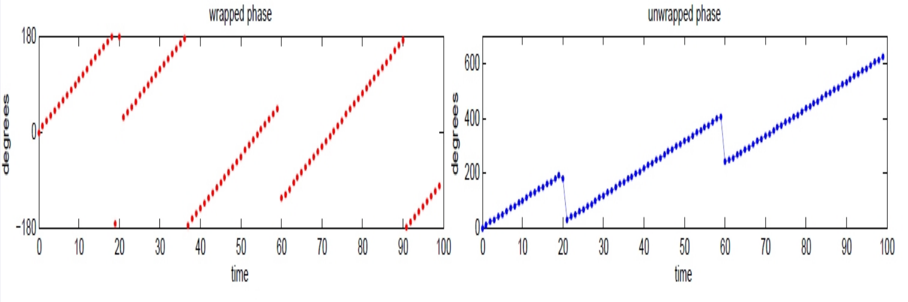
AWS: Automatic Weather Station ⟼ SWE indirect



We can extract the SWE from the inteferometric phase with radar measurements every 6 hours.

Is it possible to reconstruct the SWE from interferometric phase, in space and time, from radar satellite data every 11 days (Sentinel-I revisit time)?

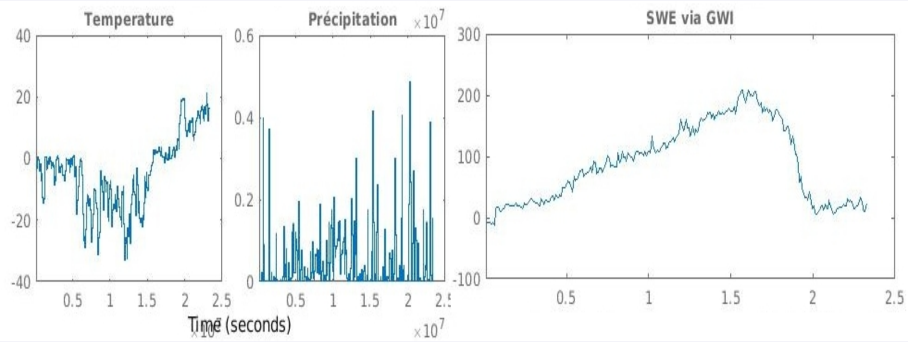
Main problem: during the 11 days, the phase is wrapping numerous times.



Increase and/or stabilization of SWE

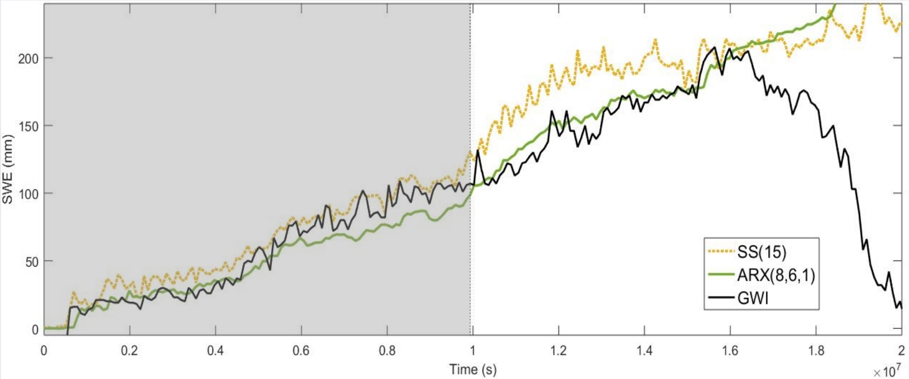
From measurement station, identify a SWE model to be able to predict the number of wrapping phases:

- Input $\longmapsto$ Temperature and precipitations
- Output $\longmapsto$ GWI



Increase and/or stabilization of SWE - Identification

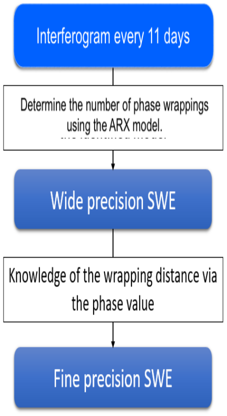
Identification on the first part of the winter (first 115 days) to find the rest of the same winter.

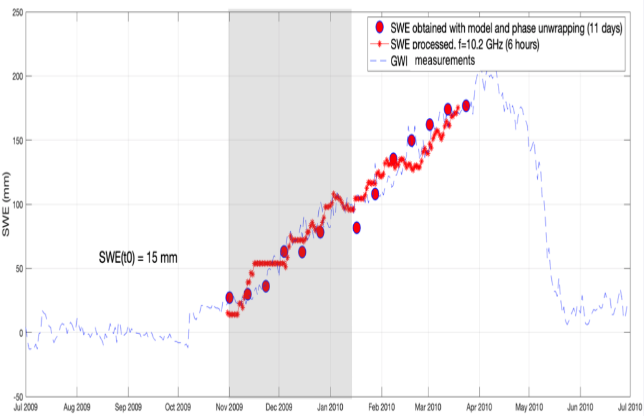


The Auto Regressive model with eXternal inputs ARX(8,6,1) is the most relevant (rms = 9.44mm).

$$y(k) = -Ay(k-1) + Bu(k-1) + \eta(k) \tag{2}$$

Increase of SWE - unwrapping phase



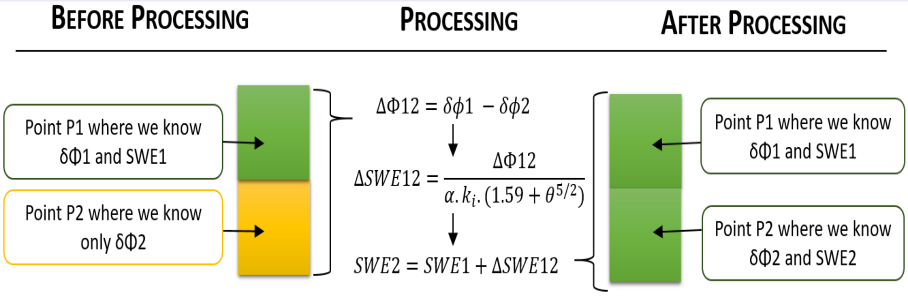


⟼ Good fit between measurement and model

⟼ **It is possible to rebuild the SWE using SAR satellites data during an increased period of snow fall (specifically in Artic zones)**

Spatial reconstruction - Processing

On the same principle as the phase unwrapping from interferometric images.



Contents

Conclusion.

- Can we extract the characteristics of snowpack using the backscattering radar?

  Yes, we can with 2 models, an assimilation process and the X-band satellite data.

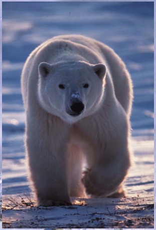
- Can we build the SWE using the interferometric phase (every 6 hours)?

  This is possible with Leinss formula using the X-band and/or the C-band.

- Can we use the radar satellite Sentinel (C-band, 6 days) to directly obtain the SWE?

  Yes, we can, with an identification model, several measurement stations of GWI and/or AWS and the interferogram calculated from C-band satellite data.

Thank you for your attention



May be satellite observation will help to save the Arctic icepack and my home...