Enabling SAR altimetric simulations in the Snow Microwave Radiative Transfer (SMRT) model

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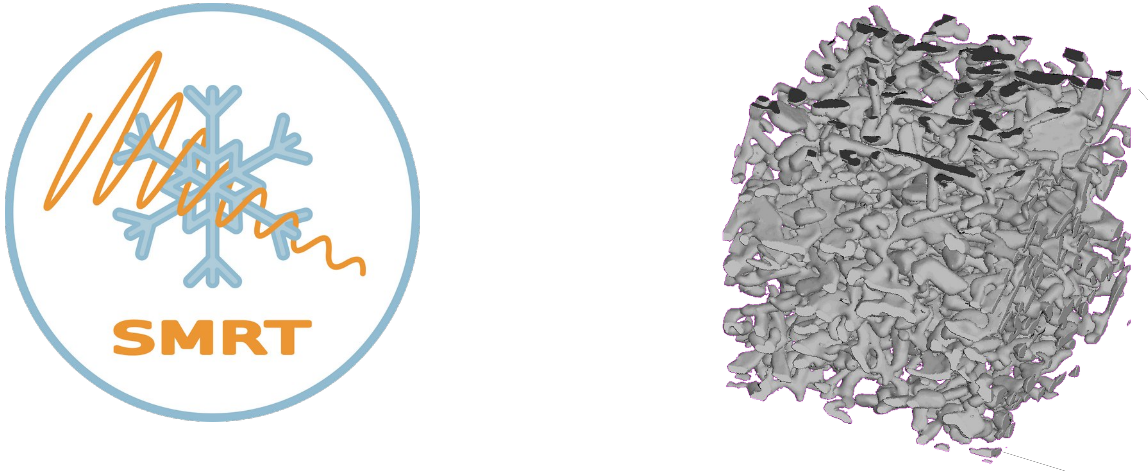
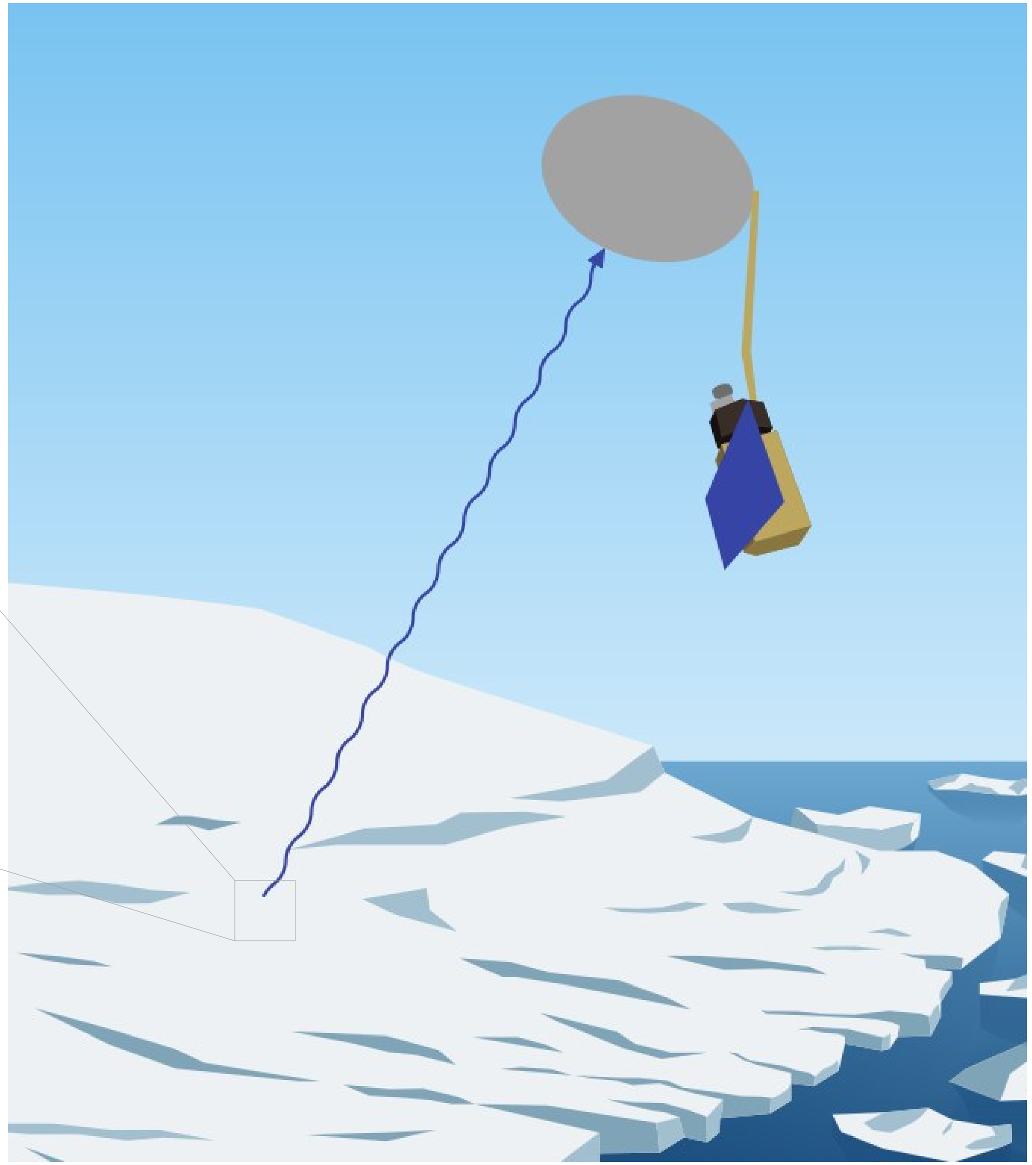
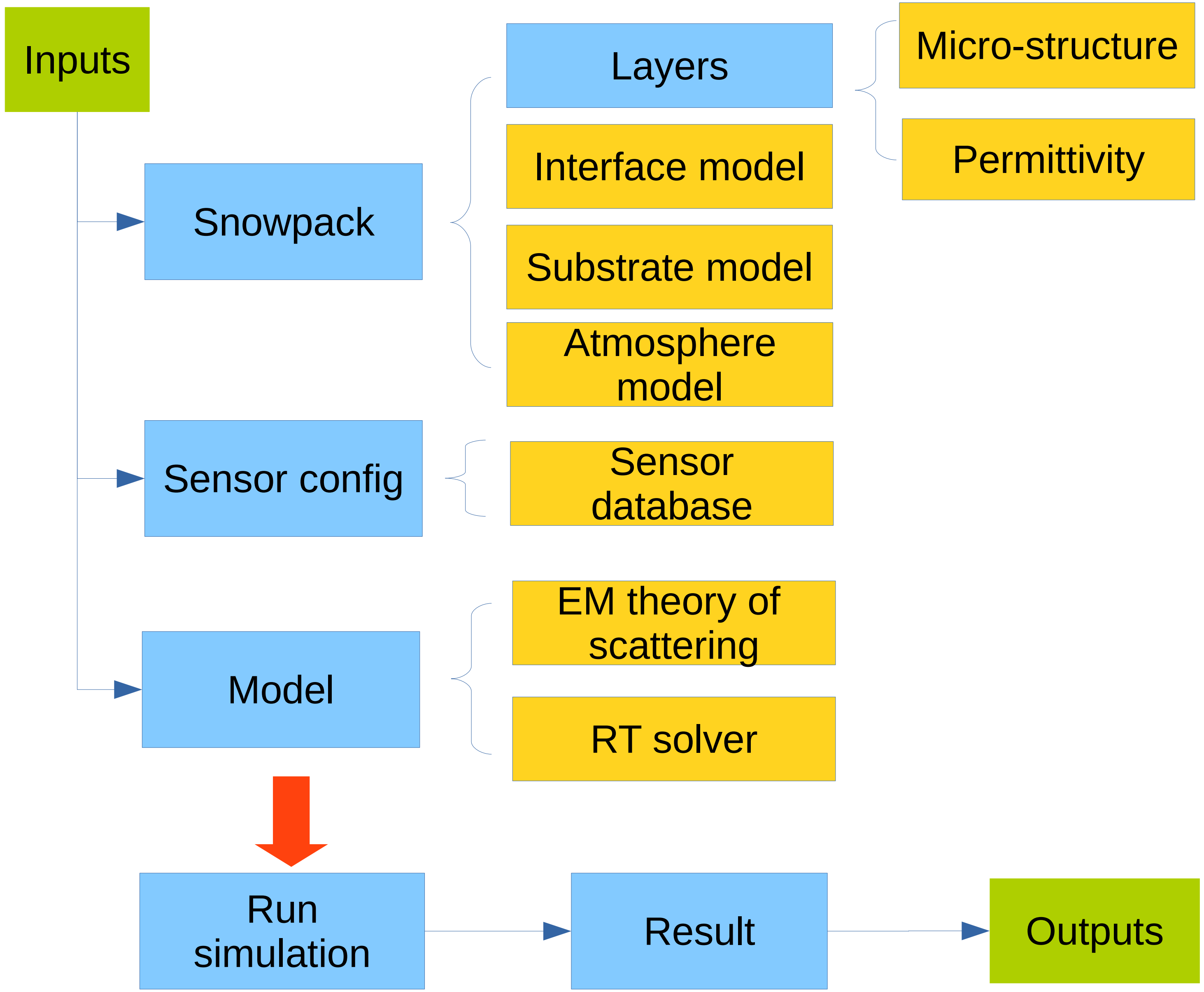
2015→ SMRT aimed to solve snow microstructure issues for passive microwaves





Snowpack description, volume scattering, stratification.
Extensive validation.

SMRT has:
- simple and clear architecture
- modularity using plugins



SMRT has:
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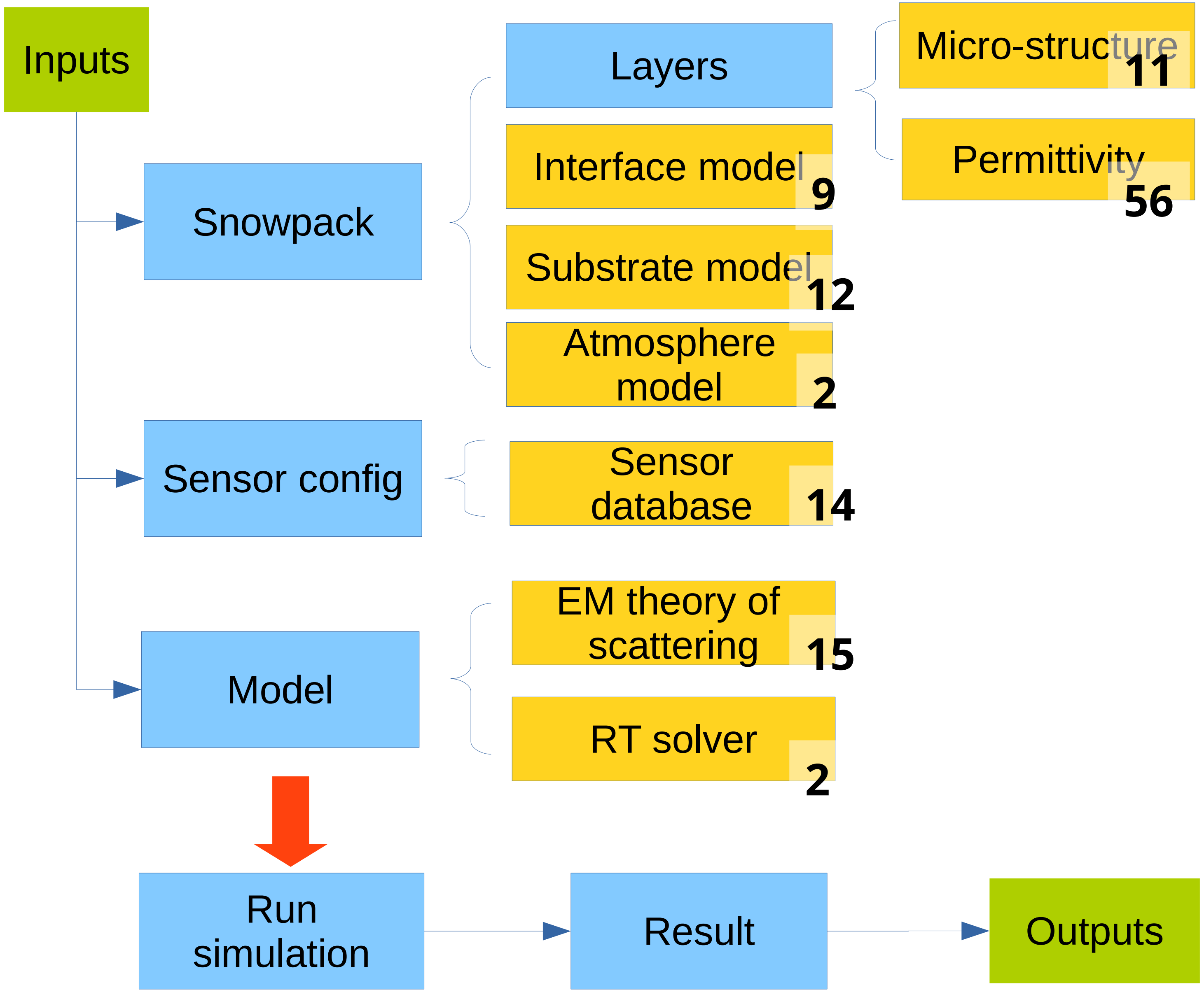

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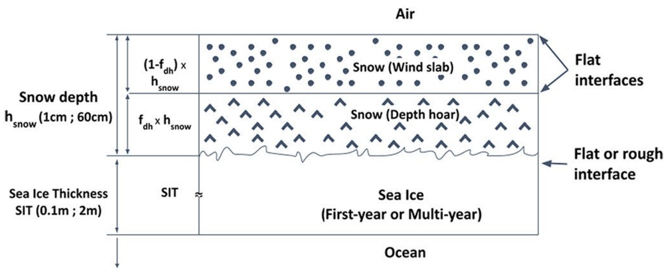
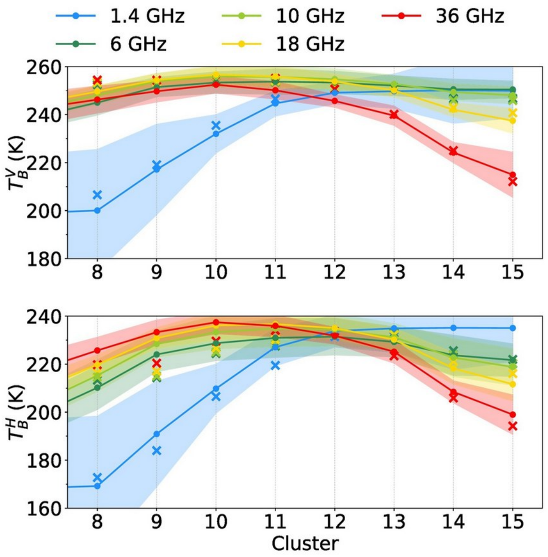
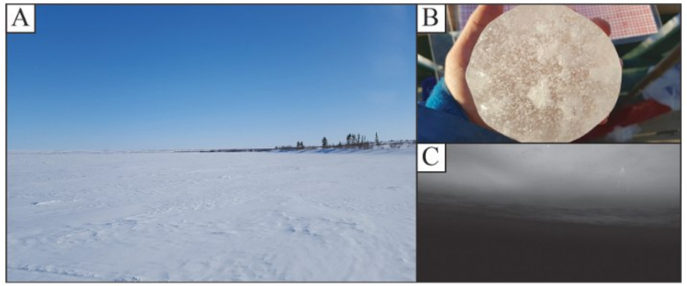
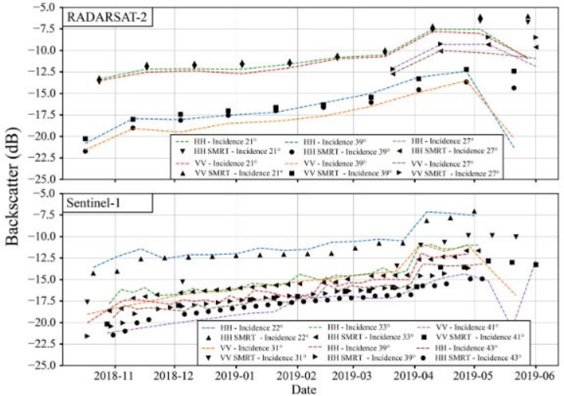
2018 → sea-ice and lake ice (coll. DMI, UH, NASA)



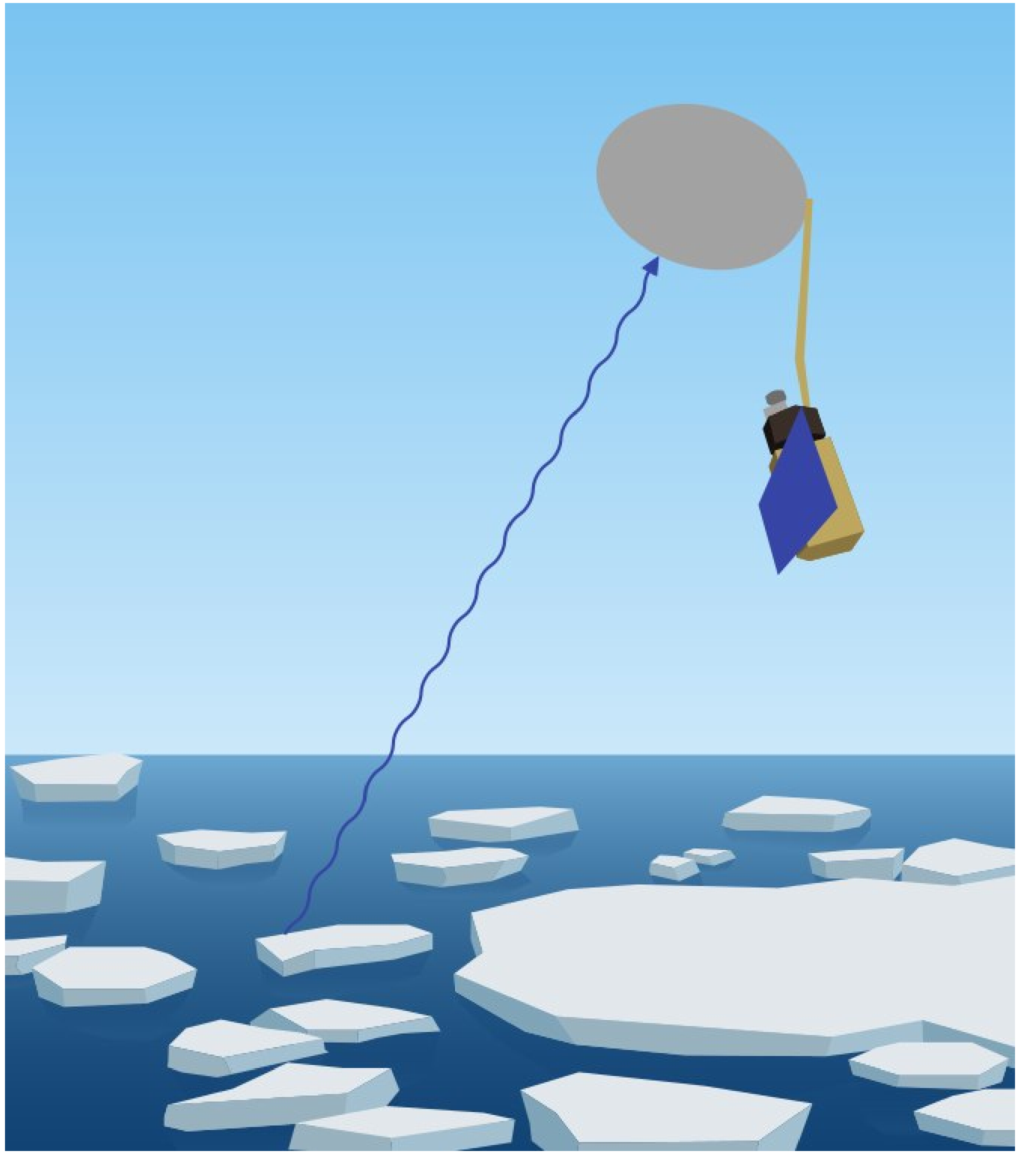


Soriot et al. 2022





Murfitt et al. 2023

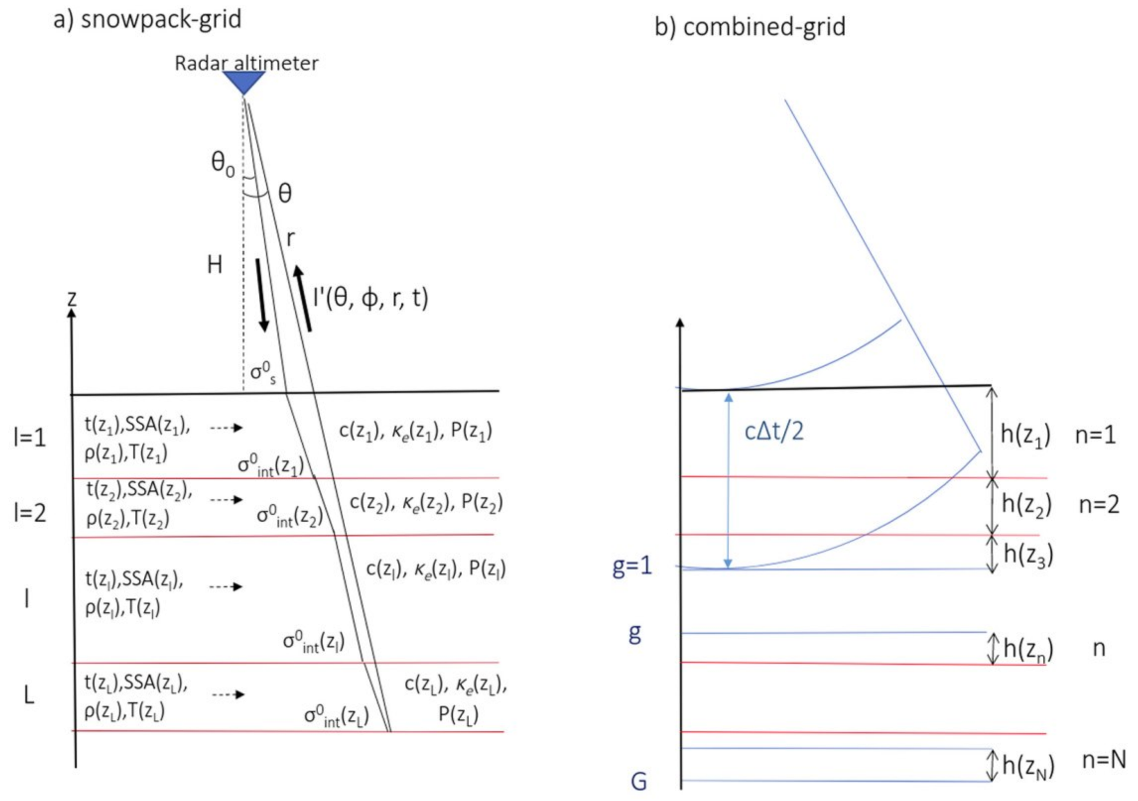


2019 → development and validation of a LRM altimeter RT solver (collab CLS)

1- Solve the time-dependent radiative transfer equation (vertical delay)

$$\frac{1}{c(\mathbf{r})}\frac{\partial}{\partial t}I'(\theta,\phi,\mathbf{r},t)+\frac{\partial}{\partial s}I'(\theta,\phi,\mathbf{r},t) = -\kappa_{\mathrm{e}}(\mathbf{r})I'(\theta,\phi,\mathbf{r},t) + \frac{1}{4\pi}\int_{4\pi}P(\theta,\theta',\phi-\phi',\mathbf{r})I'(\theta',\phi',\mathbf{r},t)d\Omega'$$

2- Combine with the Brown 1977 model (horizontal delay)



Output : waveform

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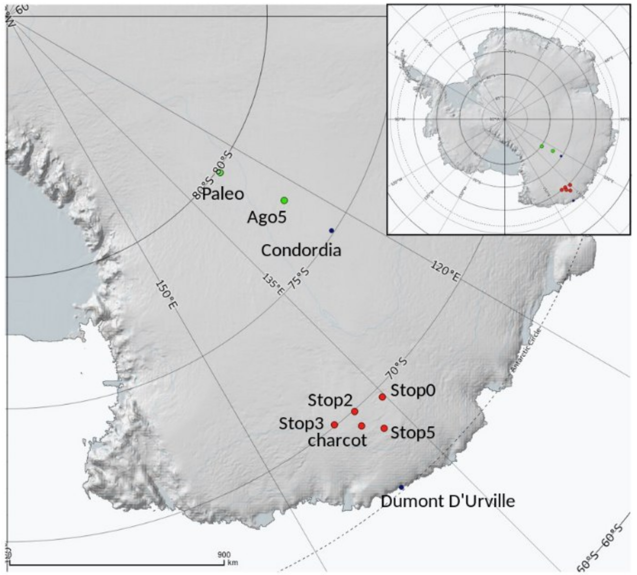
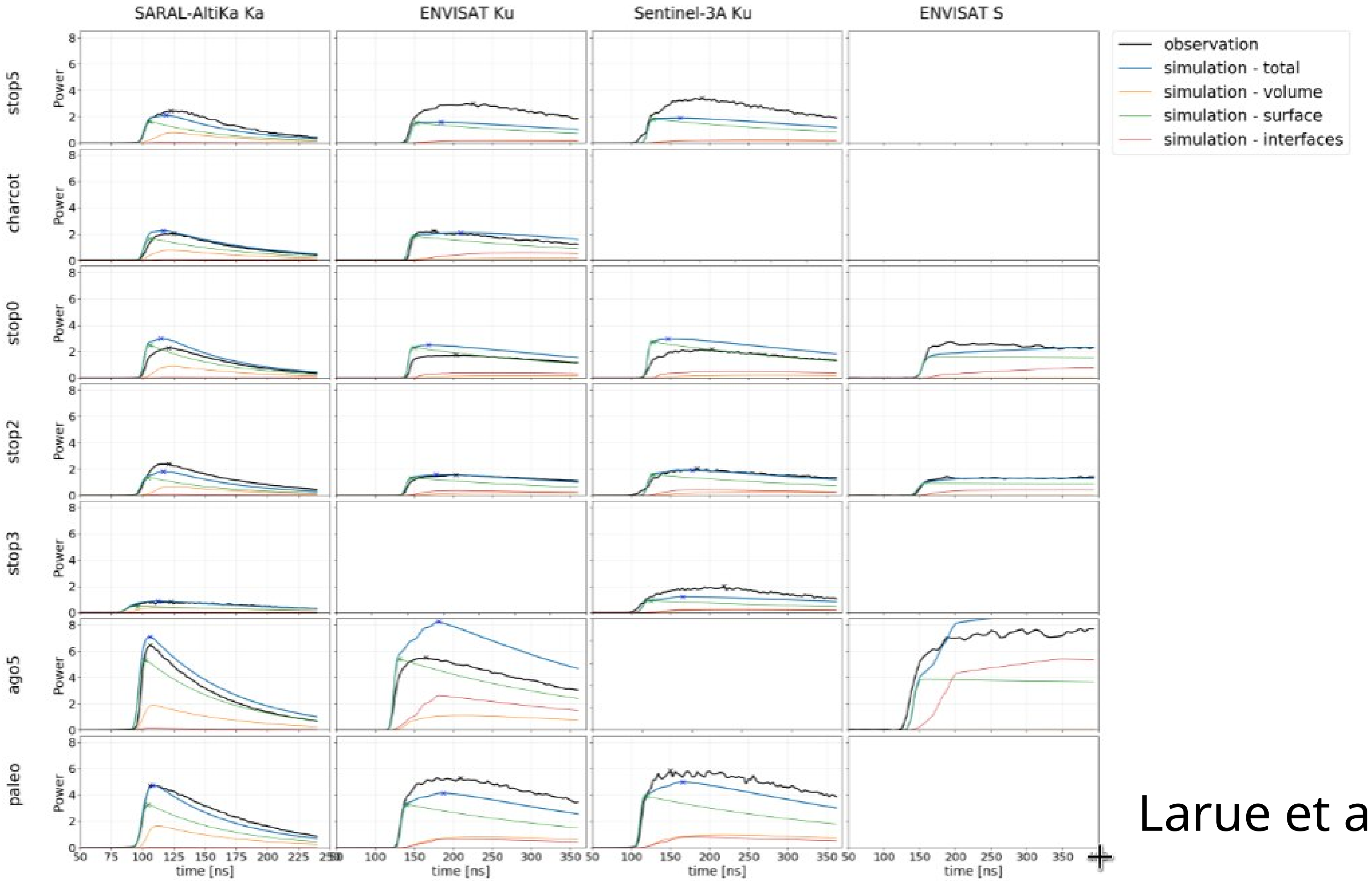
2019 → development and validation of a LRM altimeter RT solver (collab CLS)





Larue et al. 2021

2024 → SAMS-Cryo: Development of a SAR Altimetry Module in SMRT for Cryosphere Applications

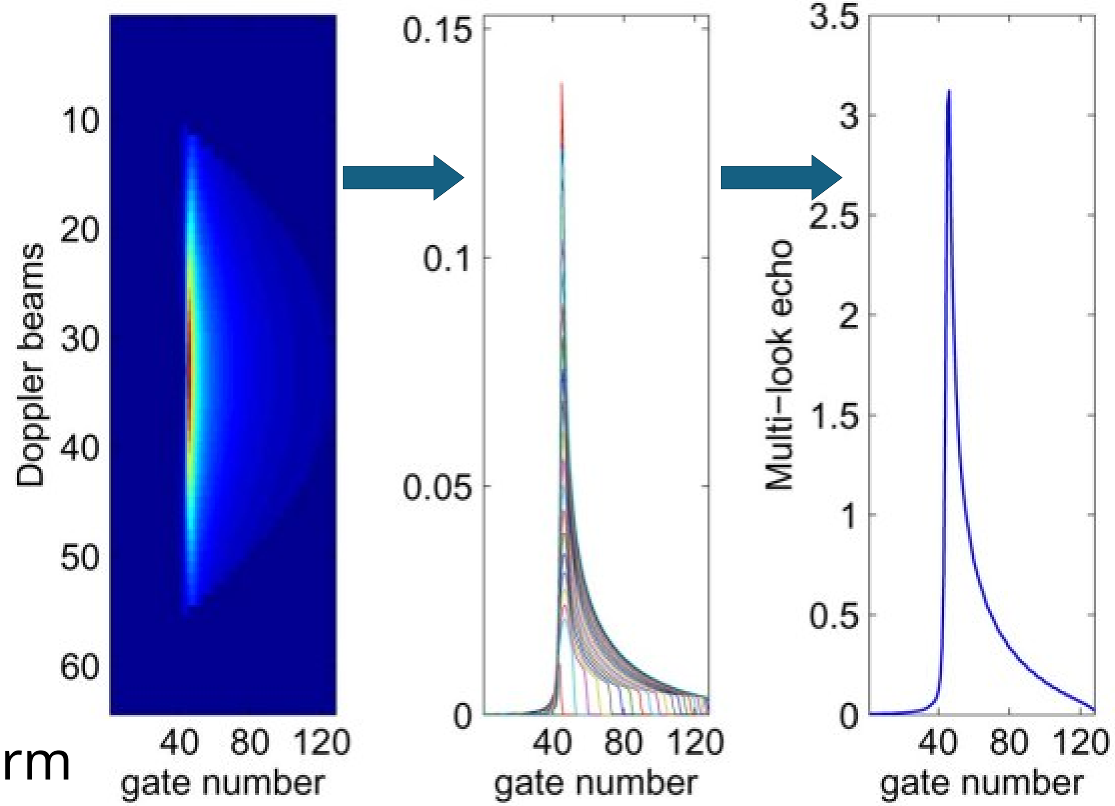
1- Solve the time-dependent radiative transfer equation (vertical delay)

$$\frac{1}{c(\mathbf{r})}\frac{\partial}{\partial t}I'(\theta,\phi,\mathbf{r},t)+\frac{\partial}{\partial s}I'(\theta,\phi,\mathbf{r},t)=-\kappa_e(\mathbf{r})I'(\theta,\phi,\mathbf{r},t)$$
$$+\frac{1}{4\pi}\int_{4\pi}P(\theta,\theta',\phi-\phi',\mathbf{r})I'(\theta',\phi',\mathbf{r},t)d\Omega'$$

2- Combine with the **?????** model (horizontal delay)

Output : delay Doppler map and multi-looked waveform

Halimi et al. 2014



Review of a selection of delay Doppler models (ocean, ice-sheet, vegetation):

- Raney 1998

- Wingham et al. 2004
- Kurtz et al. 2014
- Halimi et al. 2014+2015
- Ray et al. 2015
- Boy et al. 2017
- Dinardo et al. 2018
- Wingham et al. 2018
- Buchhaupt et al. 2018
- Landy et al. 2019
- De Felice Proia et al. 2022 (I and II)
- Aublanc et al. in review

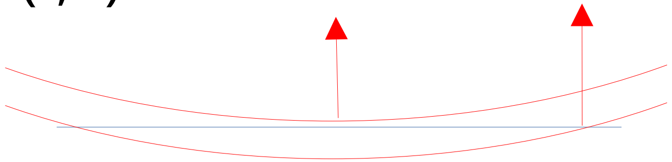
Review of a selection of delay Doppler models:

	Wingham et al. 2004	Kurtz et al. 2014	Halimi et al. 2014	Ray et al. 2015	Boy et al. 2017	Dinardo et al. 2018	Wingham et al. 2018	Buchhaupt et al. 2018	Landy et al. 2019	De Felice Proia et al. 2022 (I and II)	Aublanc et al. submitted
Starting point	Radar eq.	Radar eq.	Radar eq.	SAR processing+ Radar eq.	Radar eq.	Based on Ray et al. 2015	Radar eq.	Radar eq.	Based on Wingham et al. 2004	Radar eq.	Radar eq.
Full DEM	no	no	no	no	no	no	no	no	yes	yes	yes
Analytical-Numerical	AN	AN	AN	AN	N	A	AN	N	N	N	N
Antenna pattern	Circ. Gaussian	Ellip. Gaussian	Circ. Gaussian	Free function	Free function	Ellip. Gaussian	Ellip. Gaussian	Ellip. Gaussian	Ellip. Gaussian	Free function	Circ. Gaussian
Satellite pitch and roll	yes	no	no (see Halimi 2015)	yes	yes	yes	yes	yes	yes	no	
Terrain slope	yes	no	no	no		no	yes		DEM-based		DEM-based
Surface elevation distribution	Gaussian	Gaussian	Gaussian	skewed Gaussian	Free pdf (Gaussian)	Gaussian	Gaussian	Free pdf (Gaussian)	DEM-based	DEM-based	DEM-based
Surface backscatter	constant	Hagfors (1970) ?	constant	free function	constant	GO	constant	GO	IEM	AIEM	constant
Volume backscatter	exponential	no	no	no	no	no	no	no	Snow (Mie)	vegetation	no
point target response	Gaussian	sinc²	sinc²	Gaussian	sinc²	Gaussian	sinc²	sinc²	sinc²	Gaussian	sinc²
Azimuth point target response	Gaussian	FT Hamming	sinc²	Gaussian	Free function (sinc2)	Gaussian	FT rectangle or Hamming	sinc²	Ft Hamming	300 m rectangle ?	Iso-doppler. Rectangle ?
Main numerical step	3 convolution	1D integral + 2 convolutions	2 convolutions	3 x 1D integrals	2D integral + 3 convolutions	Special functions	1D integral	2D IFFT	x,y, t integration (heavy computationally)	x,y integration	x,y integration + muti DDM
Speckle	yes	no	yes	no	no	no	yes	no	no	no	no
Interferometry	yes	no	no	no	no	no	yes	no	no	no	no
Correspondin retracker name		CS2WfF		SAMOSA		SAMOSA+		SINCS			AMPLI

1. Starting point: decomposition of the problem in convolutions (or not):

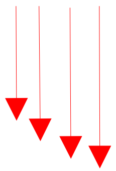
t: time, f: doppler frequency

$$p_r(t, f) = p_t(t) * pdf(t) * sigma0(t, f) * p_f(f) * FSIR(t, f)$$

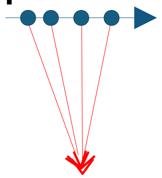


Flat surface response

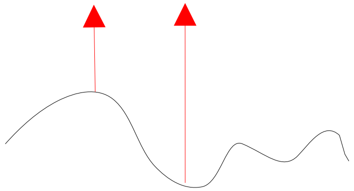
Shape of the emitted pulse



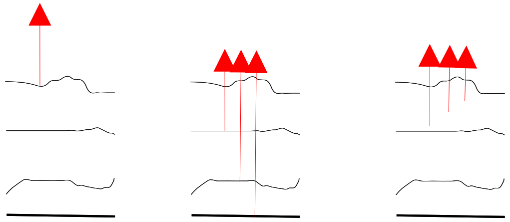
Shape of the SAR processing (along track)



Height distrib of the surface (roughness)



Backscatter of the surface and volume



1. Starting point: decomposition of the problem in convolutions (or not):

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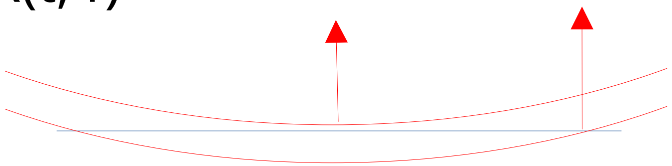
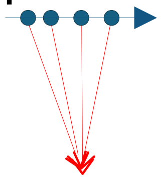


Flat surface response

Shape of the SAR processing (along track)

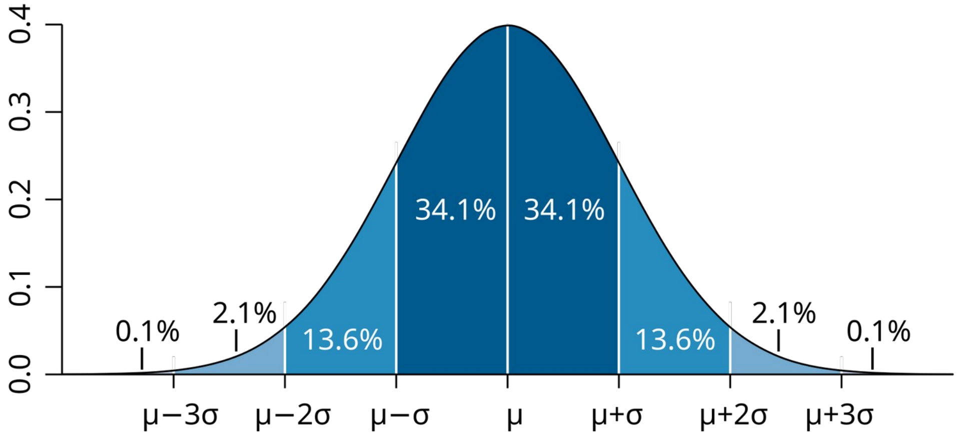


Derived from basic principles in Ray et al. 2015

The models differ in the way the FSIR and the SAR processing effect is taken into account

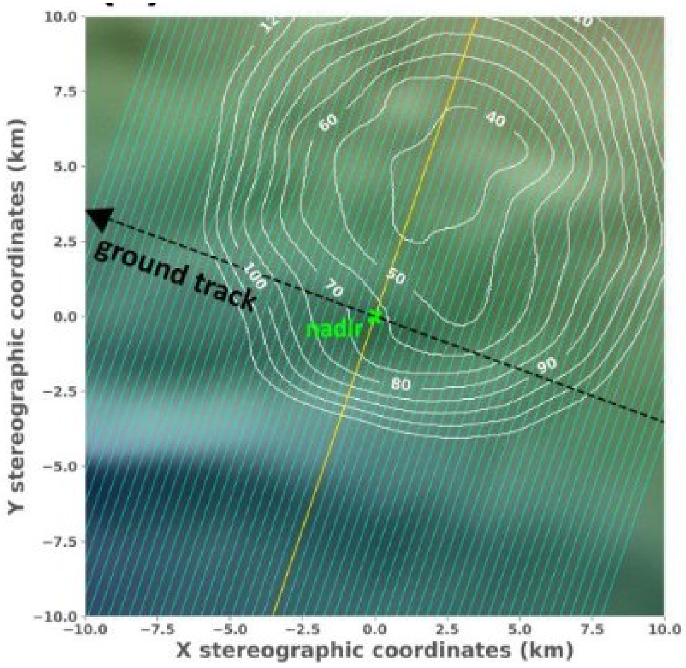
2. description of the surface height within the footprint

Random surface with known pdf — or — Digital Elevation Model (DEM)



Common assumption: normal distribution

→ amenable to analytical derivation



Aublanc et al. in review

→ requires intensive numerical calculations

3. Many other differences

- Antenna shape: circular or elliptic
- Satellite mis-pointing (non-nadir)
- Terrain slope
- Shape of the pulse: gaussian or $sinc^2$
- Backscatter model: constant, empirical or physical
- Volume backscatter
- Addition of speckle noise
- Used in a retracker.

- Analytical vs numerical derivations → computation time
  Pure analytical: Dinardo et al. 2018
  The most numerically intensive: Landy et al. 2019

<u>Conclusion:</u> no model supersets all the other models

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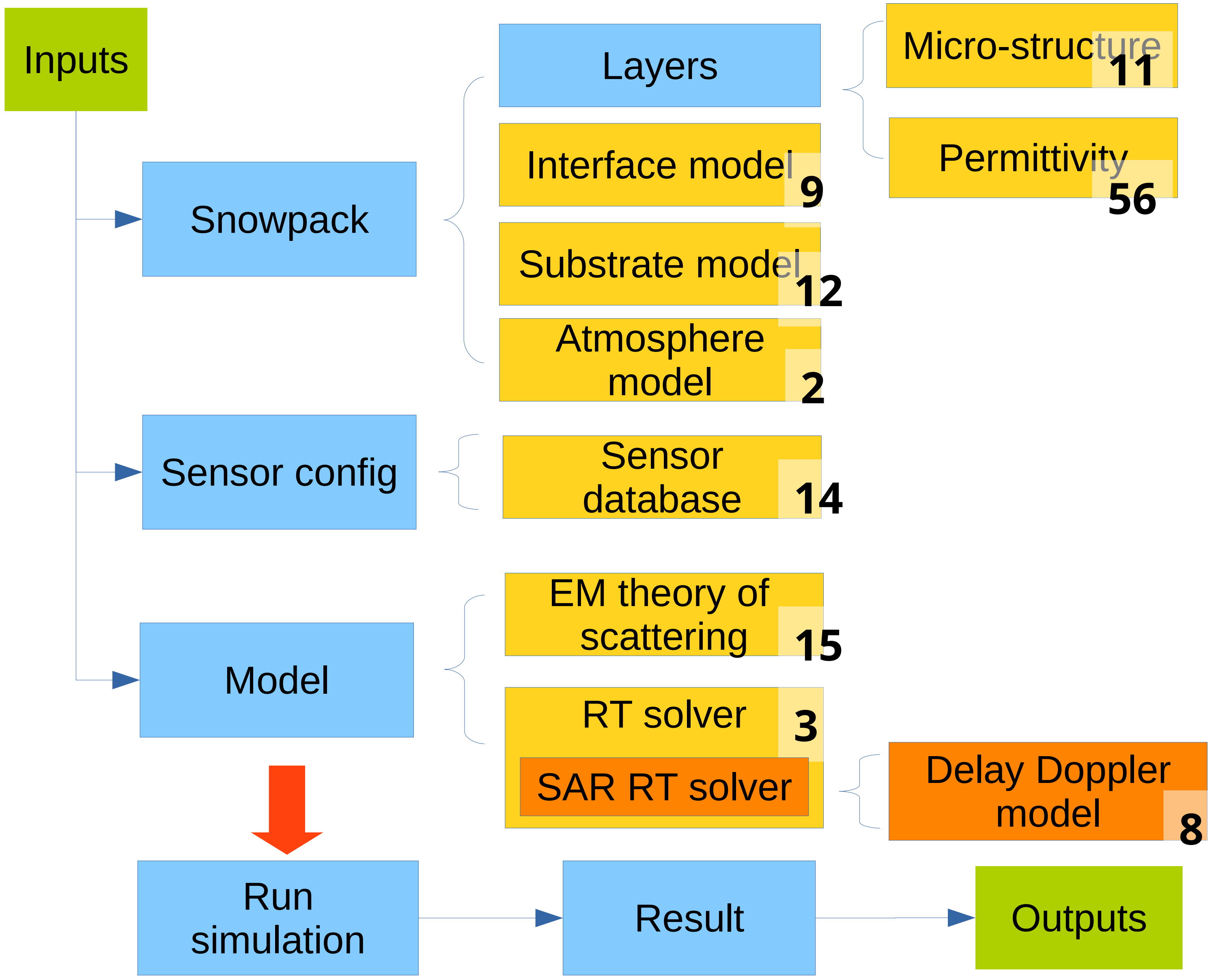
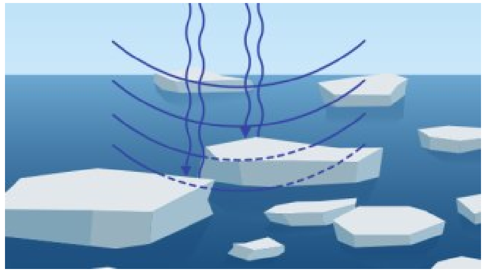


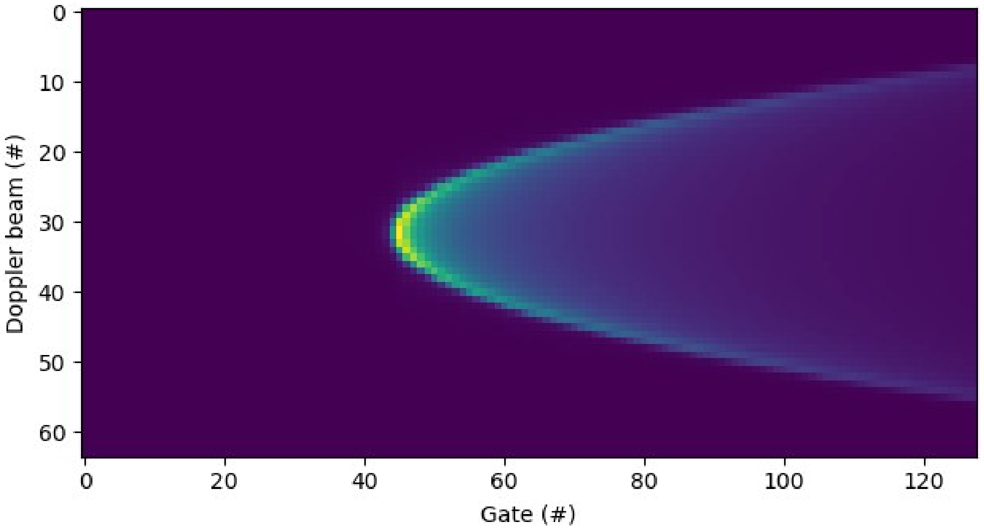
- Wingham et al. 2004
- Halimi et al. 2014
- Ray et al. 2015
- Boy et al. 2017
- Dinardo et al. 2018
- Wingham et al. 2018
- Buchhaupt et al. 2018
- Landy et al. 2019

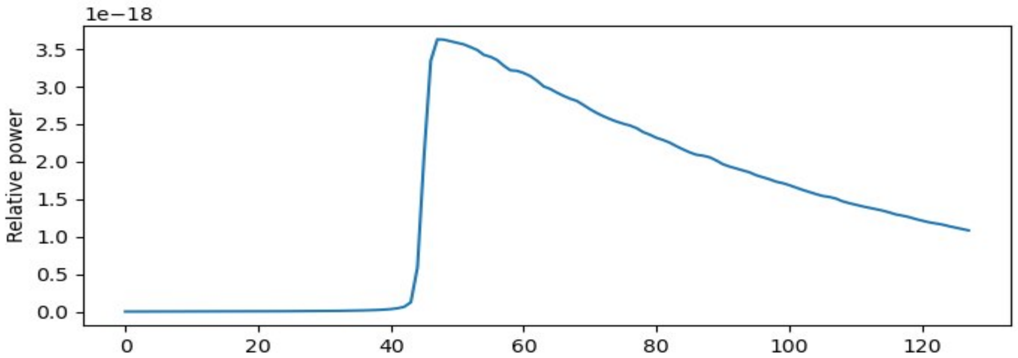
Example of a delay Doppler map using Halimi et al. 2014:



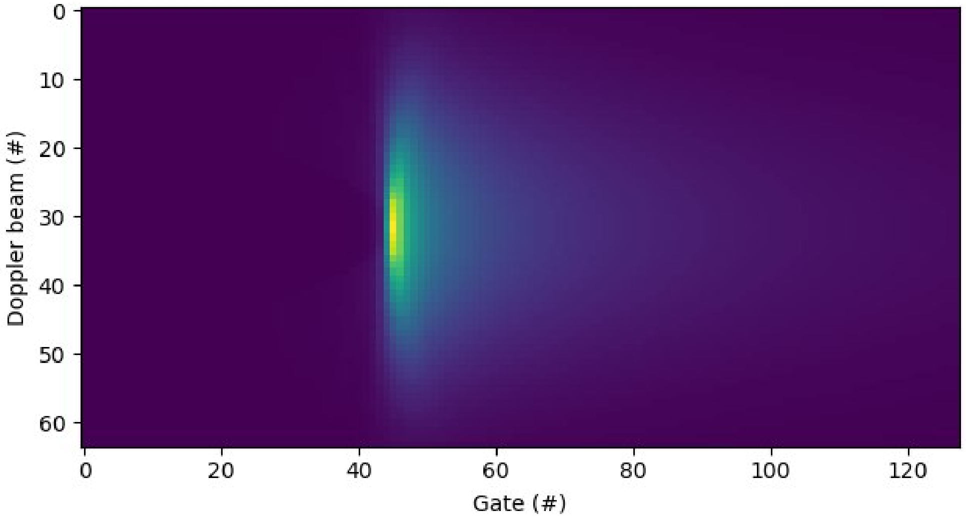
Slant range correction

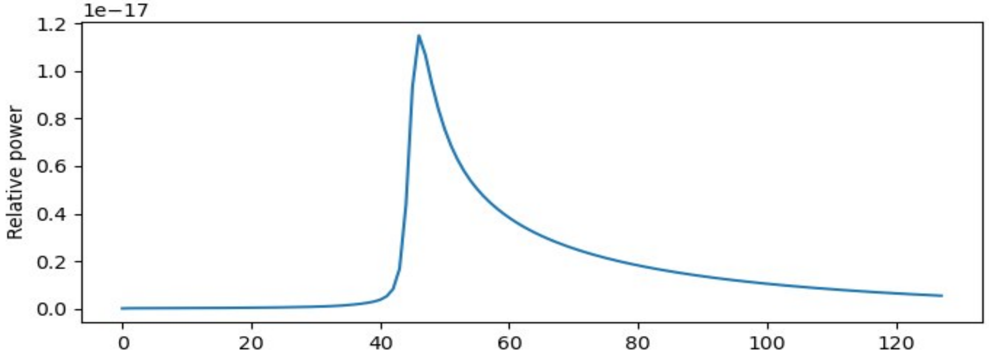
Before





After





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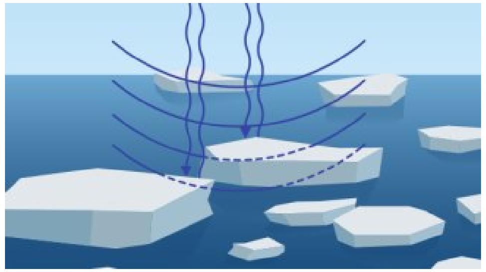
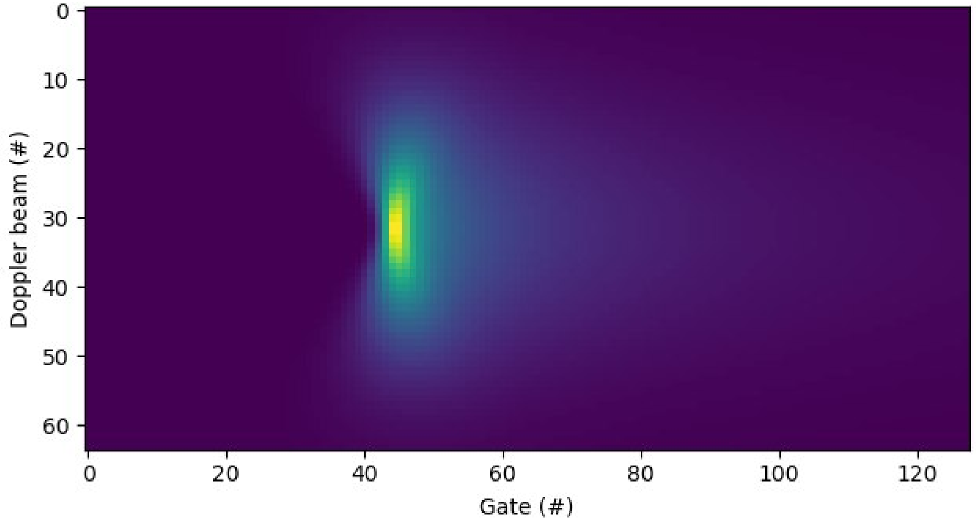
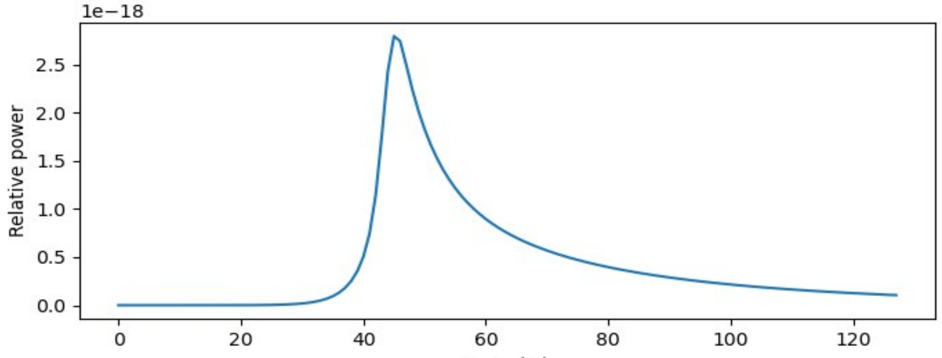
Example of differences between the models (preliminary results)

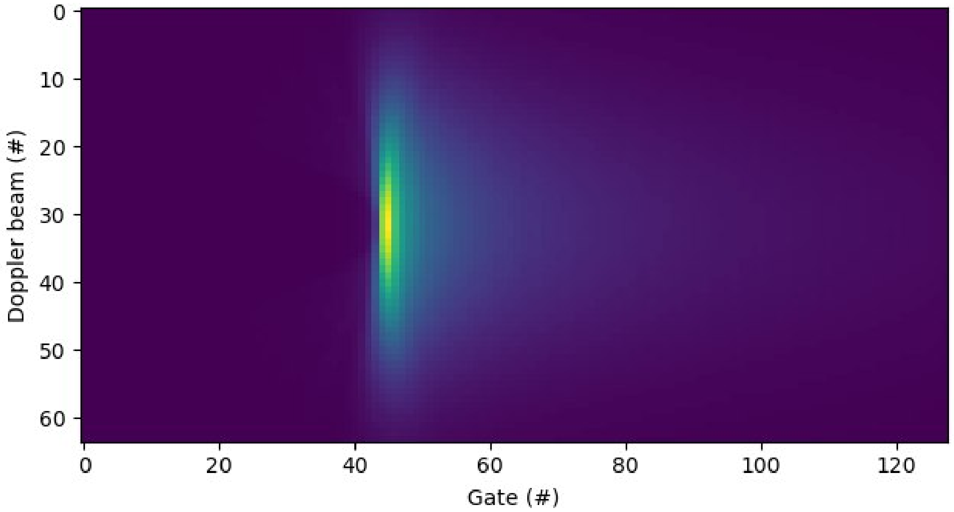


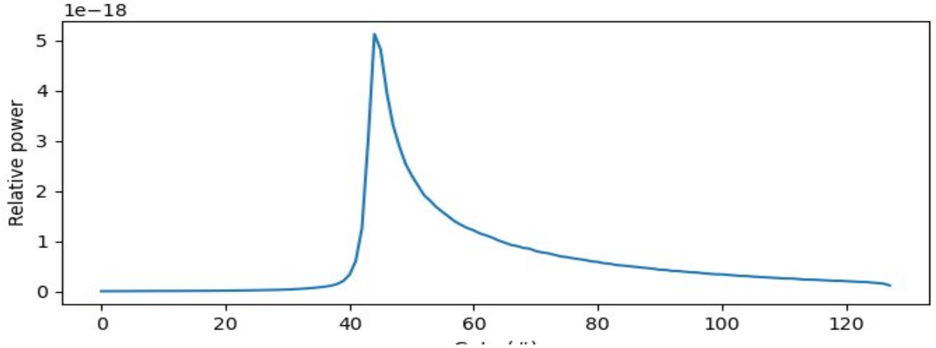
Dinardo et al. 2018





Landy et al. 2019





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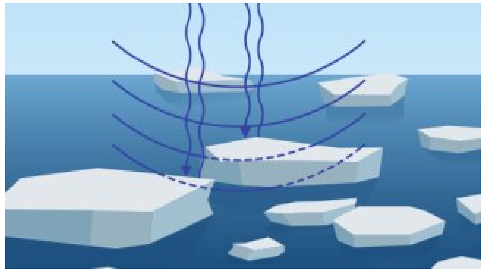
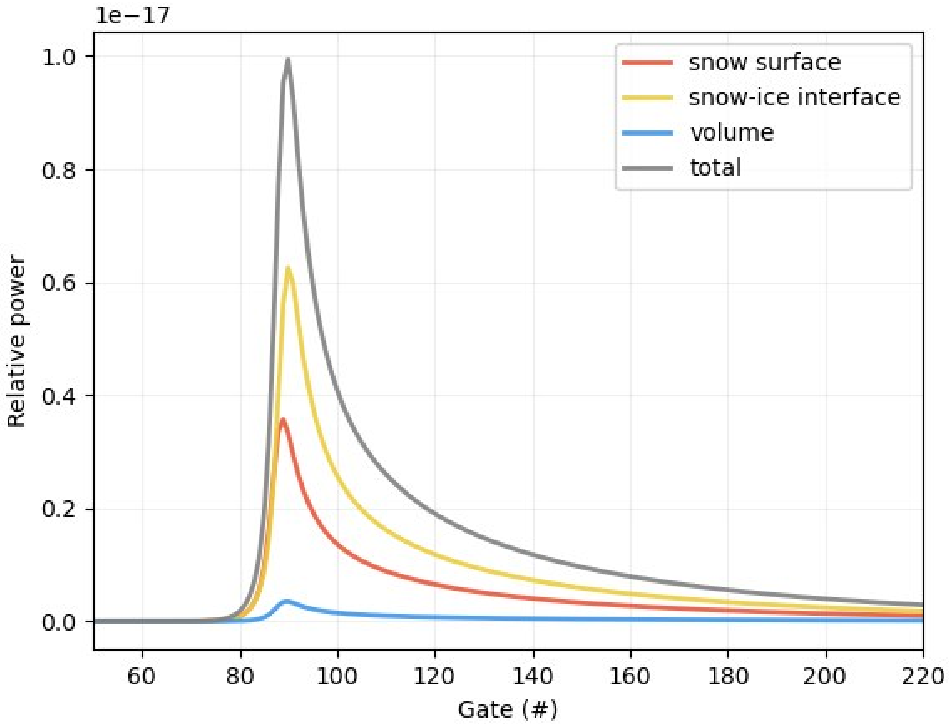
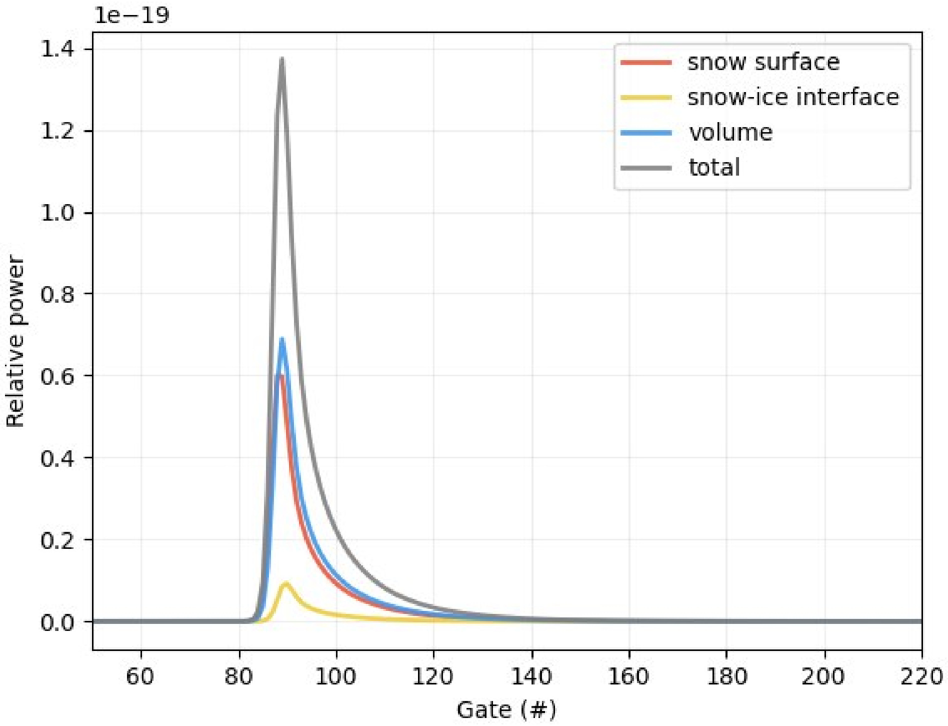


Surface vs Interface vs Volume contribution at different frequencies:

Ku band



Ka band



Same conclusion as the experimental work by Fredensborg Hansen et al. Submitted, EGUSphere

Conclusion & Perspectives

The SMRT framework is being extended !

SAR mode altimetry is enabled in SMRT:

- comparison between 8 existing delay Doppler models (DDM)
- easily extendable to other DDMs
- extendable to FFSAR, InSAR

The code is to be consolidated and will be released as open source in SMRT.

See also the online SMRT simulator (using the open source version):
https://snow.univ-grenoble-alpes.fr/smrt-app/

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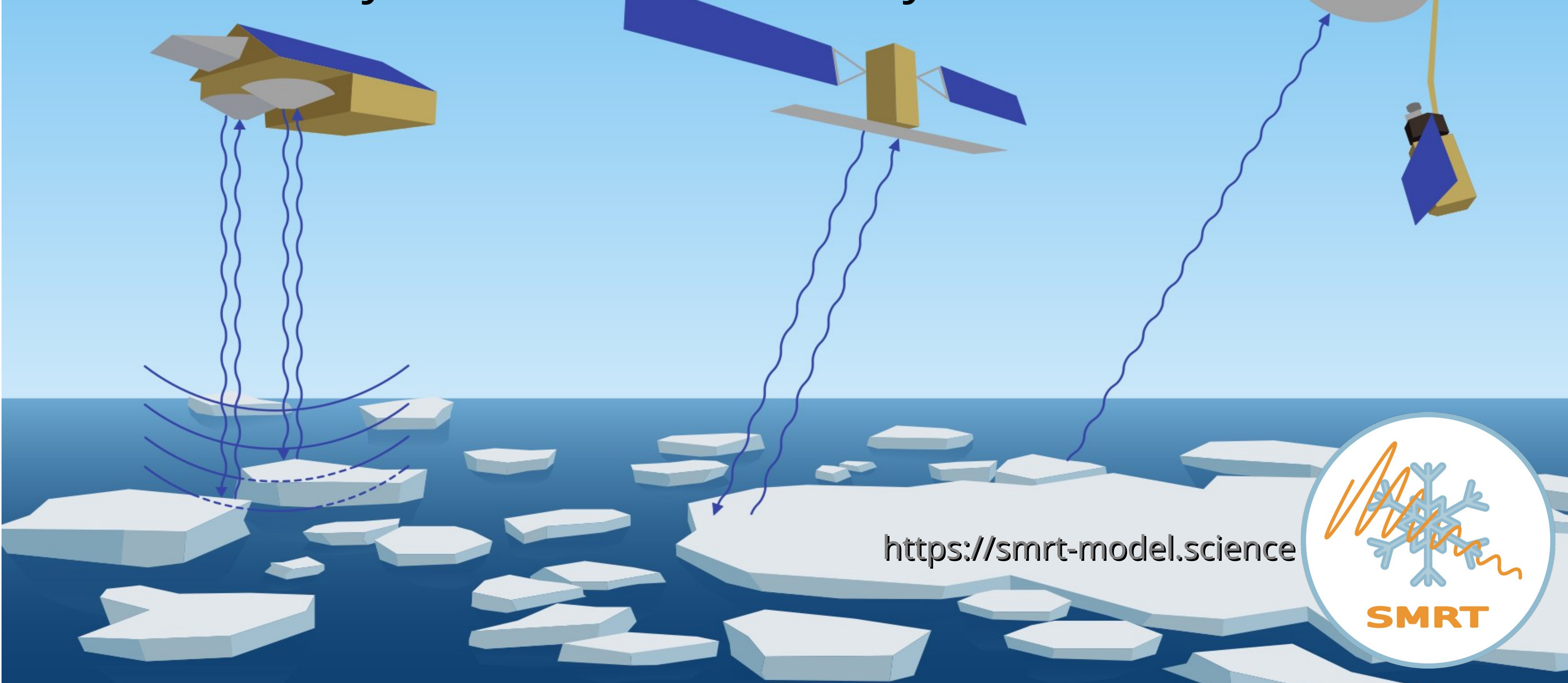
Thank you for your attention !



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Example of code:

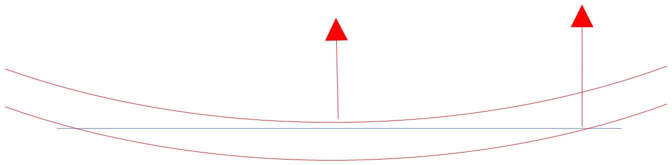
1 layer of snow
1 layer of ice

Dinardo et al. 2018

```
sensor = cryosat2_sarm()


medium = make_snowpack(
                    thickness=[0.2],
                    microstructure_model="exponential",
                    corr_length=300e-6, density=300,
                    surface=make_interface("geometrical_optics_backscatter",
                                           mean_square_slope=0.02)
                    ) + \
          make_ice_column("firstyear",
                          thickness=[1],
                          temperature=270, salinity = 5 * PSU,
                          microstructure_model="exponential",
                          corr_length=100e-6, density=907)

medium.terrain_info = TerrainInfo(sigma_surface=0.2)


model = make_model(emmodel("iba"),
                   rtsolver("nadir_sarm_altimetry", delay_doppler_model="dinardo18"))

result = model.run(sensor, medium)
```

The development of the radar equation

Flat surface reponse: FSR(t, f)



All models use the radar equation :

$$\mathrm{FSIR}(t') = \frac{\lambda^2}{(4\pi)^3 L_p} \int_{\mathbb{R}+\times[0,2\pi[} \frac{\delta\left(t' - \frac{2r}{c}\right) G^2(\rho,\phi)\sigma^0}{r^4} \rho\, d\rho\, d\phi$$

But they differ in how this equation is calculated and implemented