



# CryoTop Evolution

CS-2 Swath Processing for resolution of DEM and rate of elevation change

**Flora Weissgerber**, N. Gourmelen, M.-J. Escorihuela, A. Garcia-Mondéjar, M. Rocca, J. Wuite, A. Hogg, T. Nagler, M. Drinkwater

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## Goals of the project :

- CryoSat-2 Swath elevation
- Gridded product
  - Rate of elevation change maps (dhdt)
  - Digital Elevation Model (DEM)

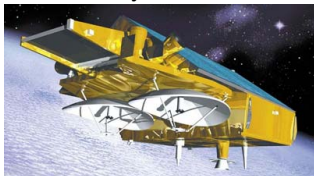
Over the Greenland and Antarctic IceSheet

## Outlines of the talk :

1. Swath elevations
  - Interferometric capacities of CS2
  - Densification of the elevations measurement by Swath Processing
2. Rate of elevation change
  - Impact of penetration
  - Model choice
  - Denoising the rate of elevation change maps

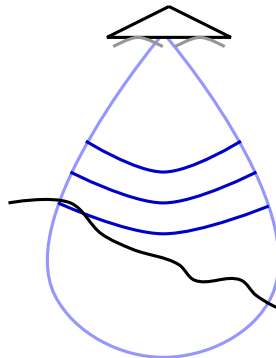
## CryoSat-2

## CryoSat-2

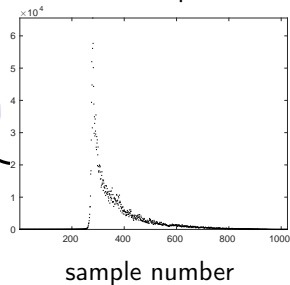


- Ku Band  
 $\lambda_0 = 0.0221\text{m}$ ,  
 $f_0 = 13.575\text{GHz}$
- Bandwidth = 320 MHz
- Resolution 0.47 m
- Repeat cycle : 369 days  
Sub-cycle : 30 days

## Measuring the range

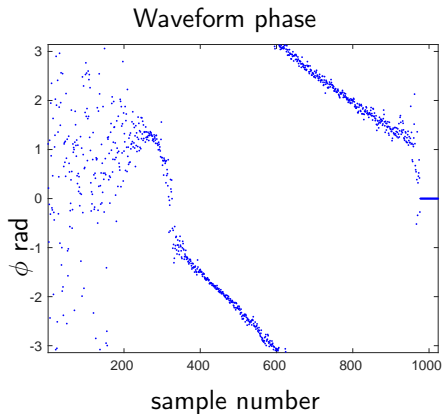
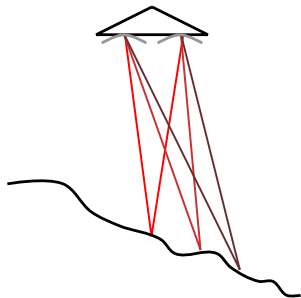


## Waveform power



Classic altimetry : Selecting the  
Point-Of-Closest-Approach (POCA)

## Interferometry : measuring the angle of arrival

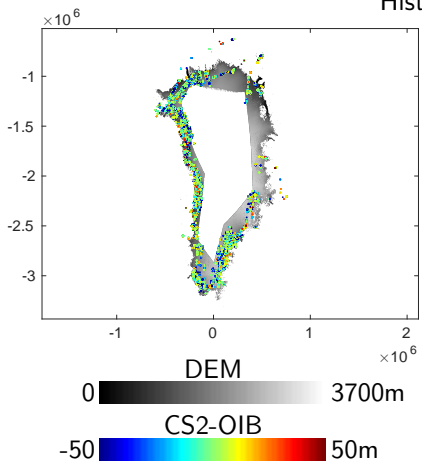


- $\phi \rightarrow$  Angle of arrival (AoA)
- From distance and AoA  $\rightarrow (\hat{x}, \hat{y}, \hat{z})$

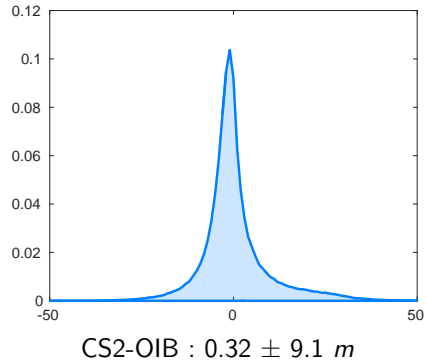
## Densification of the elevation measurement and validation

In the SARIn mask  
(margins)

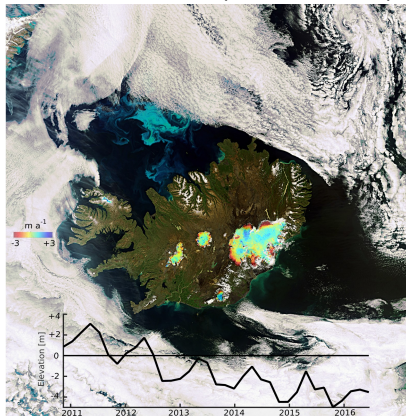
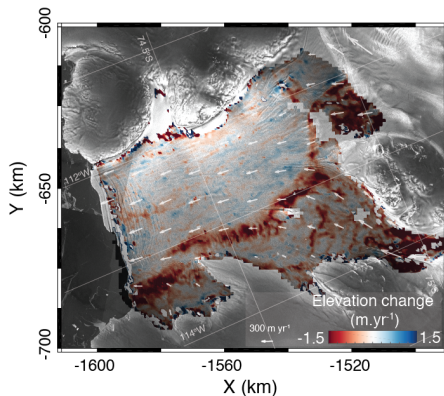
Number of :    swath elevations    POCA elevations  
                                  $6 \times 10^9$                      $1 \times 10^8$



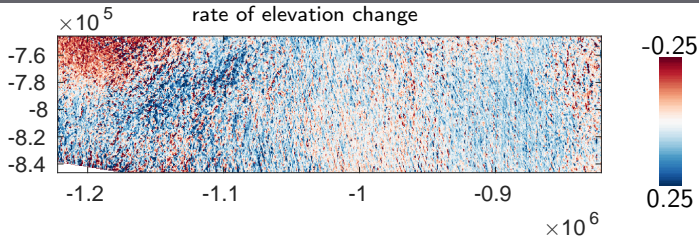
Histogram CS2-OIB (316774 collocated points)



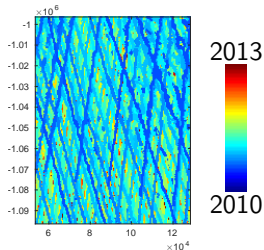
## 500m resolution on various ice bodies

Icelandic ice-caps (**Foresta 2016**)Dotson ice-shelf (**Gourmelen 2016**)

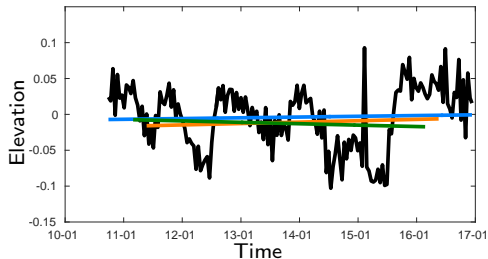
## Heterogeneous timespan



## Year of the first sample



## Time series of elevation



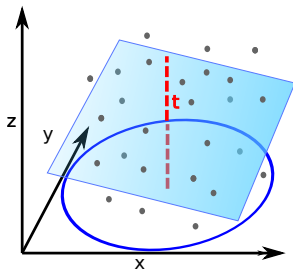
Two steps process : a) The choice of the model b) The post-processing (denoising)

## Computing the rate of elevation change

Linear model of the measured elevation (**Foresta 2016**)

$$\hat{z}(\hat{x}, \hat{y}, t) = c_0 + c_{\hat{x}}\hat{x} + c_{\hat{y}}\hat{y} + \dot{h}t + n$$

- $(\hat{x}, \hat{y})$  spatial position
- $t$  acquisition time
- $\dot{h}$  rate of elevation change (or  $dh/dt$ )
- $n$  Gaussian noise

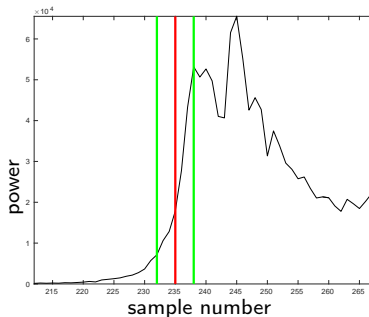
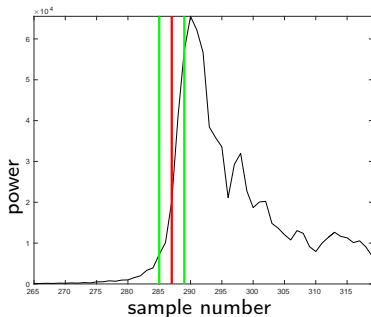




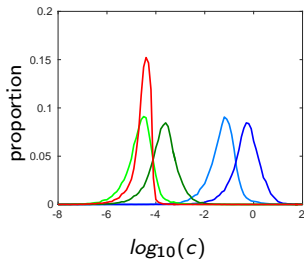
## Adding waveform parameters

Waveform parameters :

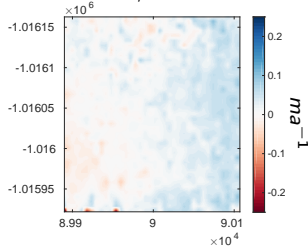
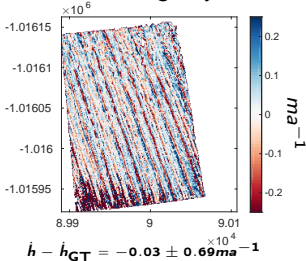
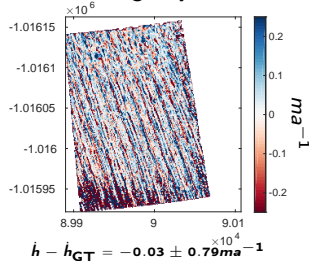
- The leading edge width  $LeW$ , the averaged leading edge width  $\overline{LeW}$
- The poca backscattered power  $Pb_{poca}$  (TFMRA retracker), the averaged poca backscattered power  $\overline{Pb_{poca}}$
- The sample backscattered power  $Pb$



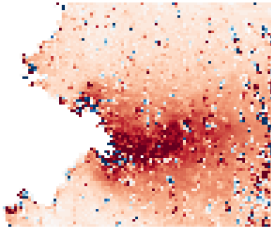
## Adding waveform parameters doesn't improve the rate retrieval



- $LeW \sim 1, 10$
- $\overline{LeW} \sim 1, 10$
- $Pb_{poca} \sim 10^4, 10^5$
- $\overline{Pb_{poca}} \sim 10^4, 10^5$
- $Pb \sim 10^4, 10^5$

 Ground Truth :  
POCA, 3km

 Swath, 500m  
Ascending only

 Swath, 500m  
Ascending only,  $\overline{LeW}$ 


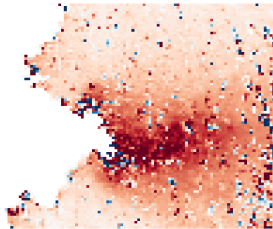
## Modelling the rate of elevation change



$$\hat{h} = \begin{cases} \hat{h}_{bg} + n \\ \hat{h}_{bg} + \hat{h}_{out} + n \end{cases}$$

- $\hat{h}_{bg}$  the background image
- $n \sim \mathcal{N}(0, \sigma)$  the Gaussian noise
- $\hat{h}_{out}$  outliers

## Modelling the rate of elevation change



$$\dot{h} = \begin{cases} \dot{h}_{bg} + n \\ \dot{h}_{bg} + \dot{h}_{out} + n \end{cases}$$

- $\dot{h}_{bg}$  the background image
- $n \sim \mathcal{N}(0, \sigma)$  the Gaussian noise
- $\dot{h}_{out}$  outliers

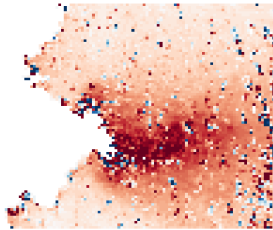
- Denoised rate of elevation change close to the original

→ Bayesian denoising scheme

$$\mathcal{E}(\dot{h}, \dot{h}_{bg}, \dot{h}_{out}) = \frac{(\dot{h} - \dot{h}_{bg})^2}{2\hat{\sigma}}$$

Minimized through Iterative Conditional Mode (ICM)

## Modelling the rate of elevation change



$$\dot{h} = \begin{cases} \dot{h}_{bg} + n \\ \dot{h}_{bg} + \dot{h}_{out} + n \end{cases}$$

- $\dot{h}_{bg}$  the background image
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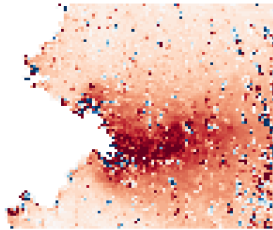
- Denoised rate of elevation change close to the original
- Neighbouring pixels having close values

→ Bayesian denoising scheme

$$\mathcal{E}(\dot{h}, \dot{h}_{bg}, \dot{h}_{out}) = \frac{(\dot{h} - \dot{h}_{bg})^2}{2\hat{\sigma}} + \mu_{bg} \|\text{grad}(\dot{h}_{bg})\|_2^2$$

Minimized through Iterative Conditional Mode (ICM)

## Modelling the rate of elevation change



$$\dot{h} = \begin{cases} \dot{h}_{bg} + n \\ \dot{h}_{bg} + \dot{h}_{out} + n \end{cases}$$

- $\dot{h}_{bg}$  the background image
- $n \sim \mathcal{N}(0, \sigma)$  the Gaussian noise
- $\dot{h}_{out}$  outliers

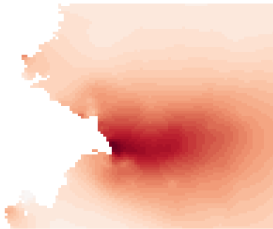
- Denoised rate of elevation change close to the original
- Neighbouring pixels having close values
- Remove the outliers

→ Bayesian denoising scheme

$$\mathcal{E}(\dot{h}, \dot{h}_{bg}, \dot{h}_{out}) = \frac{(\dot{h} - \dot{h}_{bg})^2}{2\hat{\sigma}} + \mu_{bg} \|\text{grad}(\dot{h}_{bg})\|_2^2 + \mu_{out} \|\dot{h}_{out}\|_0$$

Minimized through Iterative Conditional Mode (ICM)

## Modelling the rate of elevation change



$$\dot{h} = \begin{cases} \dot{h}_{bg} + n \\ \dot{h}_{bg} + \dot{h}_{out} + n \end{cases}$$

- $\dot{h}_{bg}$  the background image
- $n \sim \mathcal{N}(0, \sigma)$  the Gaussian noise
- $\dot{h}_{out}$  outliers

- Denoised rate of elevation change close to the original
- Neighbouring pixels having close values
- Remove the outliers

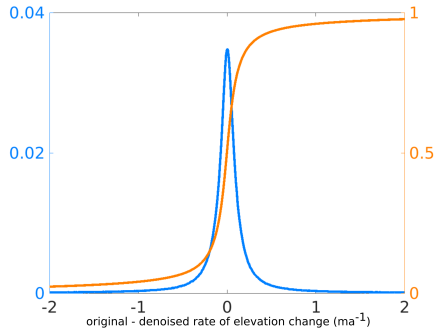
→ Bayesian denoising scheme

$$\mathcal{E}(\dot{h}, \dot{h}_{bg}, \dot{h}_{out}) = \frac{(\dot{h} - \dot{h}_{bg})^2}{2\hat{\sigma}} + \mu_{bg} \|\text{grad}(\dot{h}_{bg})\|_2^2 + \mu_{out} \|\dot{h}_{out}\|_0$$

Minimized through Iterative Conditional Mode (ICM)



## Impact of the denoising of the mass change

**Initial mass change**

removal of the  $|\dot{h}| > 100 \text{ ma}^{-1}$   
upscaled according to missing data  
proportion.

$$-2.09 \times 10^{11} \text{ m}^3 \text{ a}^{-1}$$

**Denoised mass change**

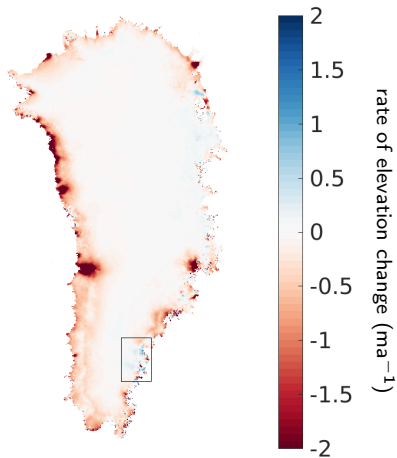
.

$$-2.18 \times 10^{11} \text{ m}^3 \text{ a}^{-1}$$

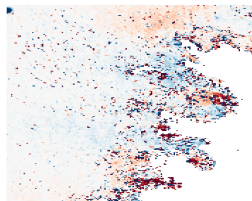


## Results

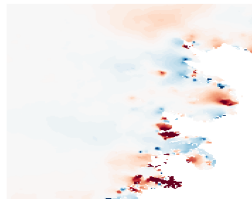
2010-2017



Input :

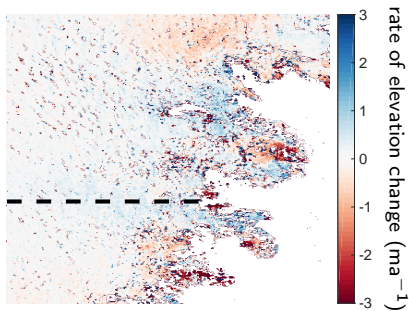


Output :

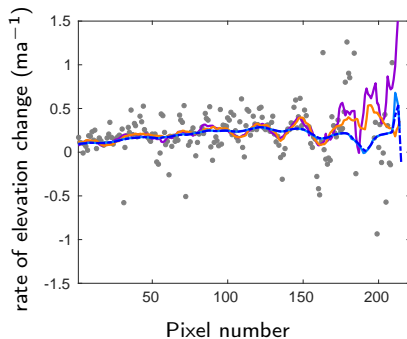


## Comparison with other denoising method

2010-2017



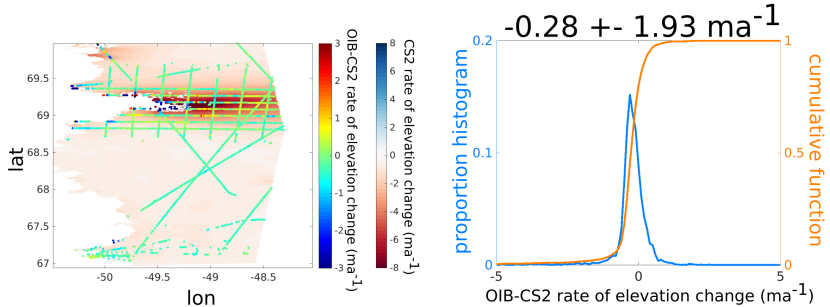
Cross section



- Proposed filter
- Mean filter
- Median filter

○ Oscillation due to penetration are reduced

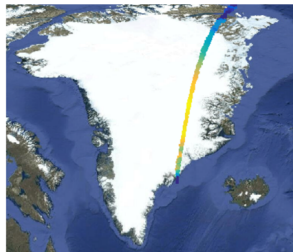
## Validation with OIB data



- No outliers compared to OIB data
- 99% of the rates have a difference smaller than  $2\text{ma}^{-1}$

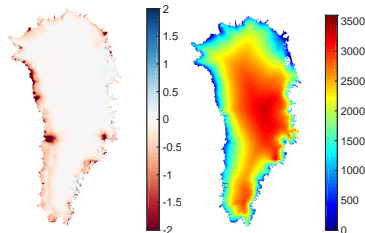
## Swath elevation

- $6 \times 10^9$  swath elevation points
  - Validated against OIB data
- Refine the resolution of gridded product



## Gridded products

- Grid of  $500\text{m} \times 500\text{m}$
  - Good agreement with OIB lidar data
- Better insight at glacial processes



→ Data available