Capitalizing on the experience of iceberg studies from classical, SAR and interferometric altimeter for the CRISTAL mission

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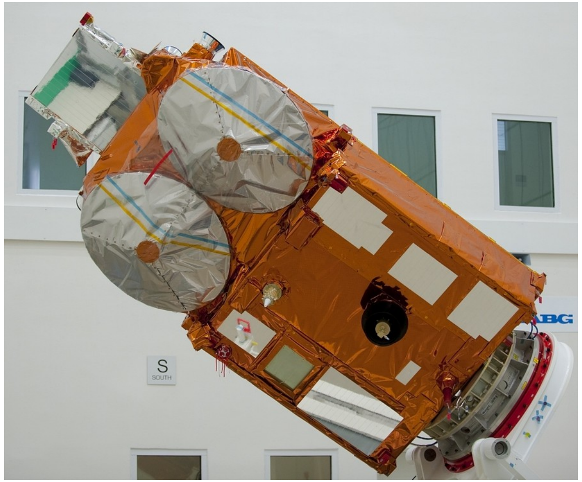
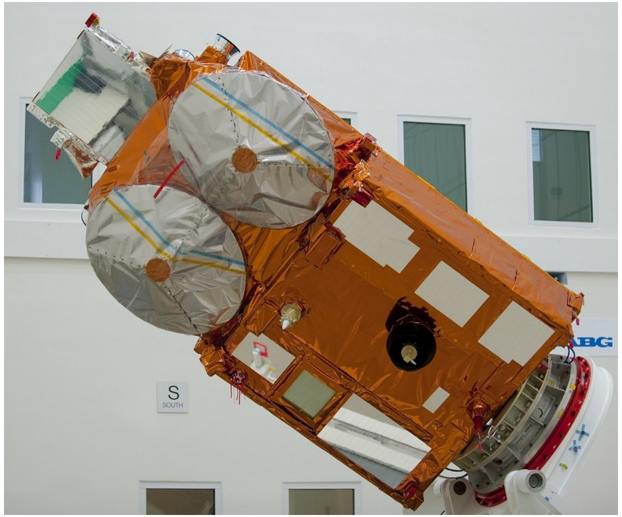


SENTINEL-9 CRISTAL

- Future CRISTAL (Copernicus Polar Ice and Snow Topography Altimeter) also SENTINEL-9 to be launched in 2027
- Main missions : monitoring critical climate signals
  - Sea_Ice thickness
  - Sea-ice snow loading
  - ice sheet,
  - ice cap melting and sea level,
  - Arctic and Southern Ocean sea-ice
  - **Icebergs**.
- Heritage of CRYOSAT-2



Cristal Cryosat heritage

Cryosat-2

SIRAL, *Synthetic Aperture Interferometric Radar Altimeter*

Ku band 3 modes LRM SAR SARInterferometry

Key instrument parameters for the SIRAL in each mode.

	LRM	SAR	SARIn
Receive chain[1]	left	left	left and right
Centre frequency	13.575 GHz		
Bandwidth	350 MHz		
Transmit power	25 W		
Noise figure	1.9 dB at duplexer output		
Antenna gain	42 dB		
Antenna 3 dB beamwidth (along-track)	1.0766°		
Antenna 3 dB beamwidth (across-track)	1.2016°		
Interferometer baseline	-	-	1.172 m
Samples per echo[2]	128	128	512
Sample interval	0.47 m		
Range window	60 m	60 m	240 m
PRF	1970 Hz	17.8 kHz	17.8 KHz
Transmit pulse length	49 μs		
Useful echo length	44.8 μs	44.8 μs	44.8 μs
Burst length	-	3.6 ms	3.6 ms
Pulses per burst	-	64	64
Burst repetition interval	-	11.7 ms	46.7 ms
Azimuth looks (46.7 ms)	91	240	60
Tracking pulse bandwidth	350 MHz	350 MHz	40 MHz
Samples per tracking echo	128		
Tracking sample interval	0.47 m	0.47 m	3.75 m
Size of tracking window	60 m	60 m	480 m
Averaged tracking pulses (46.7 ms)	92	32	24
Data rate	51 kbps	11.3 Mbps	2 x 11.3 Mbps
Power consumption	95.5 W	127.5 W	123.5 W
Mass	62 kg		

		Sea ice and icebergs		Land ice		
	Open and coastal ocean	Sea ice	Icebergs	Ice sheet interior (ice sheet/ice caps)	Ice margin	Glaciers
σ_0 range in Ku-band	6 to 25 dB	0 to 55 dB		0 to +40 dB	−10 to +40 dB	−10 to +40 dB
σ_0 range in Ka-band	+8 to +27 dB	+2 to +57 dB		2 to +42 dB	−8 to +42 dB	−8 to +42 dB
Measurement mode in Ku-band	SAR closed-burst	SARIn interleaved		SARIn closed-burst		
Measurement mode in Ka-band	SAR closed-burst	SAR interleaved		SAR closed-burst		
Range window size	256 points	256 points	256 points	1024 points	1024 points	1024 points
Tracking window size	256 points	256 points	256 points	2048 points	n/a	n/a
Range window size	64 m	64 m	64 m	256 m	256 m	256 m
Tracking window size	64 m	64 m	64 m	512 m	n/a	n/a
Tracking mode	Closed-loop	Closed-loop	Closed-loop	Closed-loop	Open-loop	Open-loop
On-board processing	RMC	RMC	n/a	n/a	n/a	n/a
Optional on-board processing	Yes	n/a	n/a	n/a	n/a	n/a

CRISTAL

IRIS *(Interferometric Radar altimeter for Ice and Snow)*

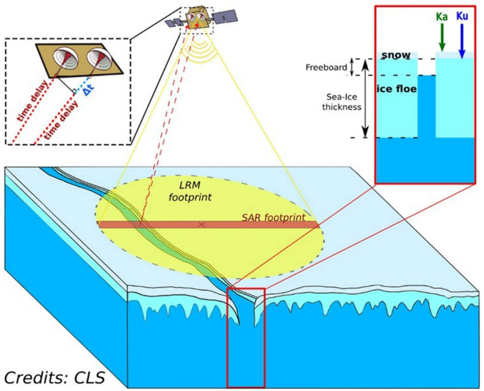
Ku Ka Band Delay Doppler SAR + Ku band Interferometry, Full focused SAR

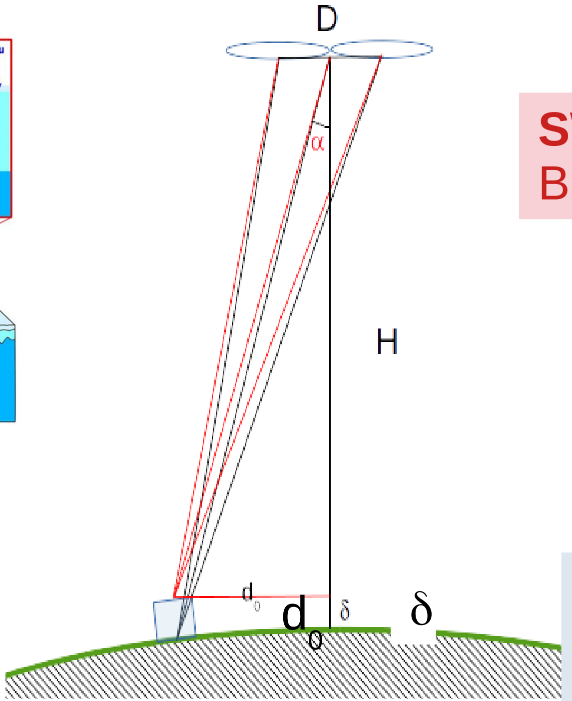
Altimeters icebergs detection

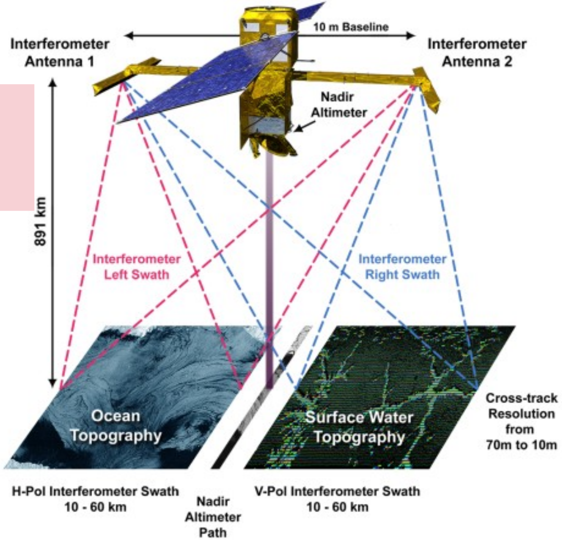
Previous studies (Tournadre et al, 2007, 2008, 2012, 2015, 2017,2018)

- In LRM or PLRM mode icebergs signature in the noise part of the HR waveforms is a parabola that can be easily detected
- In SAR mode signature reduces to a bright spot and can also easily be detected
- In LRM and SAR modes detection is only possible in open water
- Estimation of the icebergs area and volume only possible with assumptions on ice backscatter and iceberg's freeboard
- SAR interferometry allows to detect icebergs in sea ice, to measure the icebergs elevation and area at high resolution
- The presentation focuses on SARIn

SAR Interferometry for icebergs and sea ice







SWOT Karin
Baseline 10 m

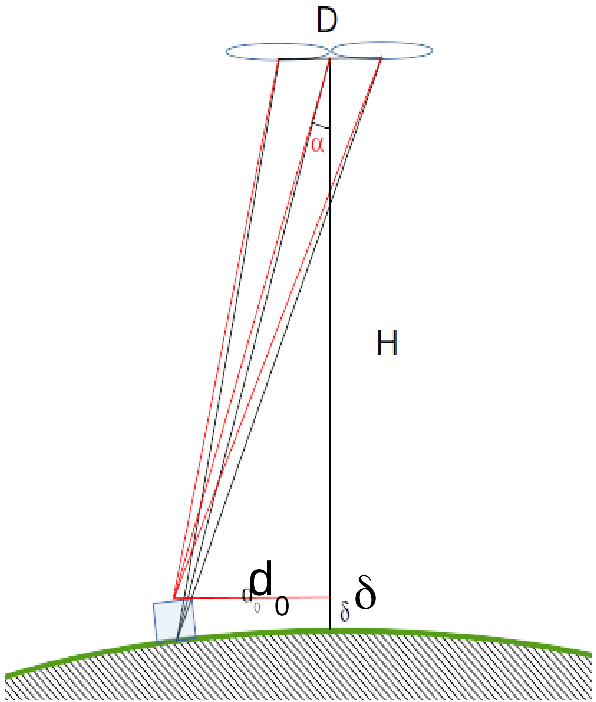
CRISTAL - IRIS
Cryosat-2 SIRAL
baseline of 1.2 m

1 antenna emitting two receiving:
difference in receiving time (range) for points off-nadir,
This time implies difference in phase (ΔΨ)
In practice, cross-product $\Phi_1\Phi_2^*$ of complex echoes from antenna 1 and 2 ,

- argument= phase difference
- module ~ coherence

Same principle but very different phase difference variability with elevation

Interferometry on icebergs Use of coherence and phase difference



Phase difference between the signals from the 2 antennas

$$\Delta\Phi = \frac{2\pi D}{\lambda}\sin(\alpha)$$

Off-nadir angle gives the position of the scatterer

$$\alpha = \frac{\Delta\Phi\lambda}{2\pi D}$$

Distance from nadir (small angle appoximation)

$$d_0 = H\alpha$$

From waveform range bin t_0 of signature

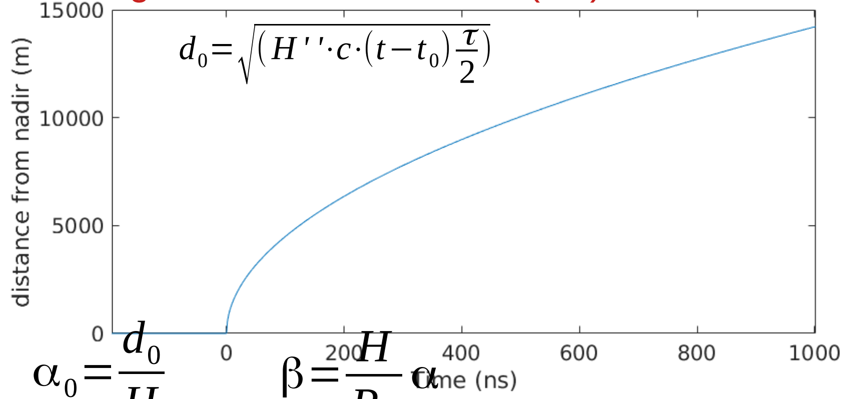
$$\frac{ct_0}{2} = -\delta + \frac{d_0^2}{2H''}$$

$$\delta = \frac{d_0^2}{2H''} - \frac{ct_0}{2}$$

Above the sea surface the 2 signals are incoherent, high coherence results from the presence of scatterer

Range as a function of time (bin)

$$d_0 = \sqrt{\left(H''\cdot c\cdot(t-t_0)\frac{\tau}{2}\right)}$$

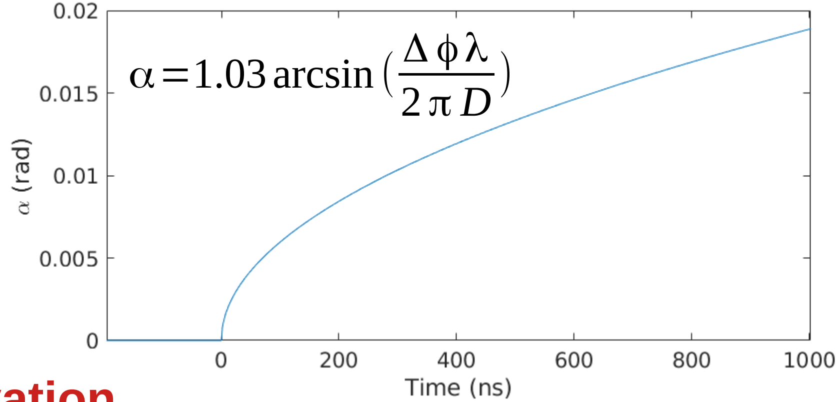


$$\alpha_0 = \frac{d_0}{H} \qquad \beta = \frac{H}{R_E}\alpha$$

Interferometry depends only Geometry : distance from nadir, off nadir angle and phase difference for Cryosat

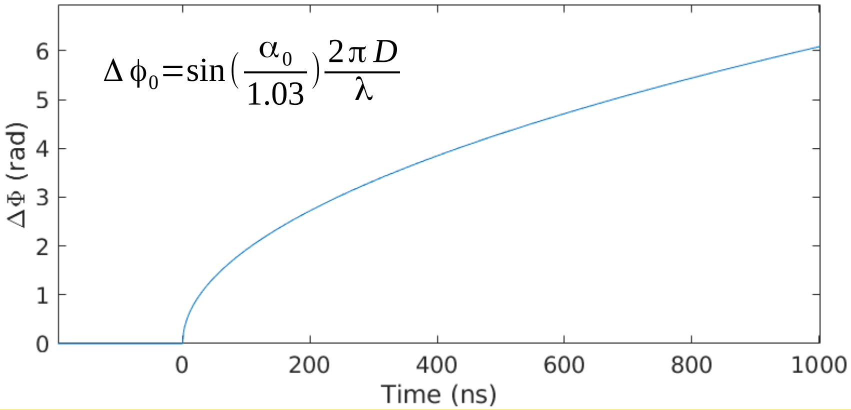
off-nadir as a function of time (bin)

$$\alpha = 1.03\arcsin\left(\frac{\Delta\phi\lambda}{2\pi D}\right)$$



Phase Diff as a function of time (bin)

$$\Delta\phi_0 = \sin\left(\frac{\alpha_0}{1.03}\right)\frac{2\pi D}{\lambda}$$

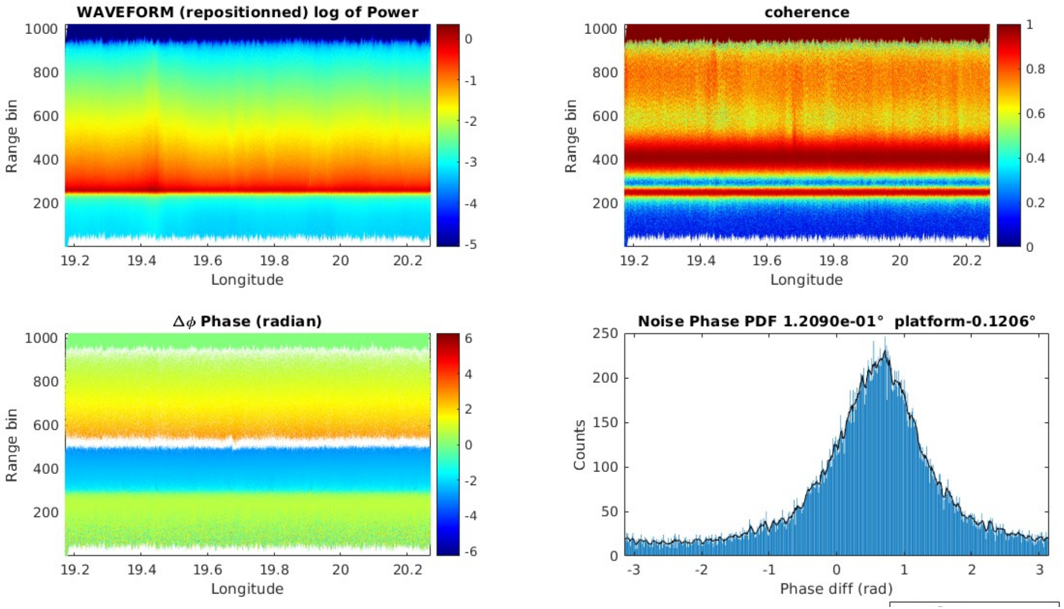


Elevation

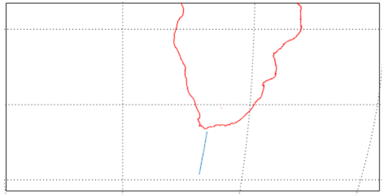
$$h = \frac{(\sin(\alpha)H)^2}{2H''} - c(t-t_0)\frac{\tau}{4}$$

$$h = \left(H - H(t-t_0)\frac{\tau}{4}\right)\cos(\alpha) + R_E(1-\cos(\beta))\cos(\beta)$$

However !!TEST OF CRYOSAT on flat sea surface



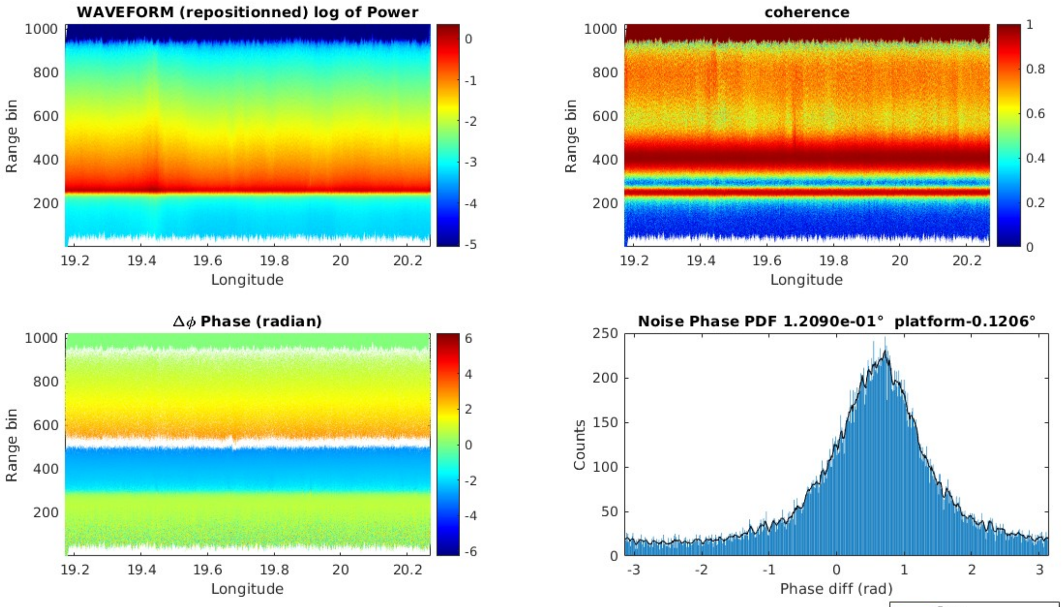
Pass across the Aghullas current



PDF of phase diff in the noise part of waveform
Maximum corresponds to the antennas bench roll angle

$$\alpha = \frac{\Delta \Phi \lambda}{2 \pi D}$$

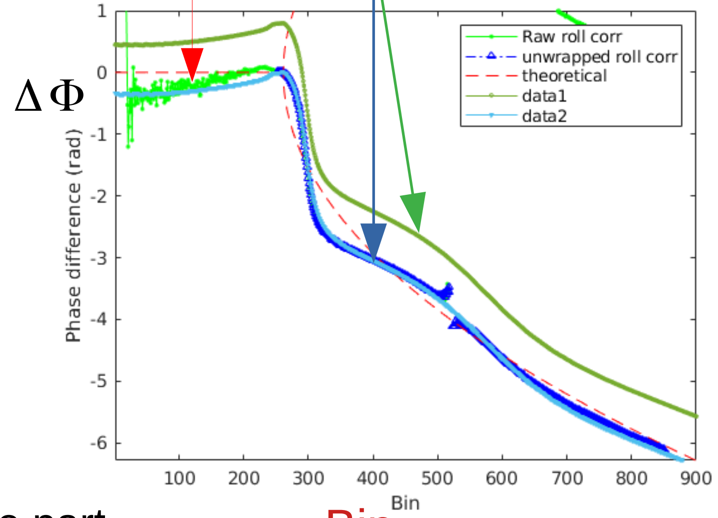
However !!TEST OF CRYOSAT on flat sea surface



Mean phase difference

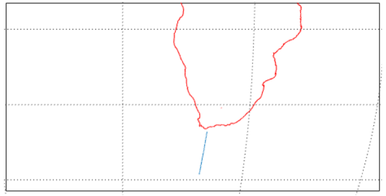
Theoretical geometric relation

Measured phase diff



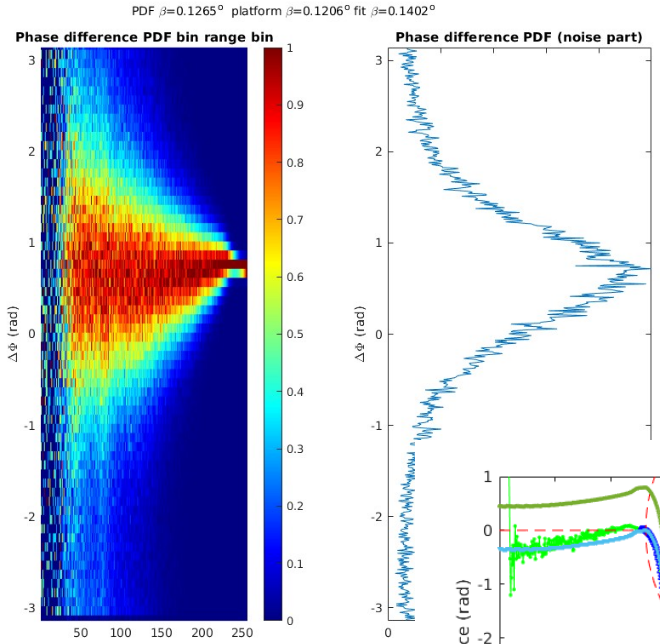
Bin

Pass across the Aghullas current

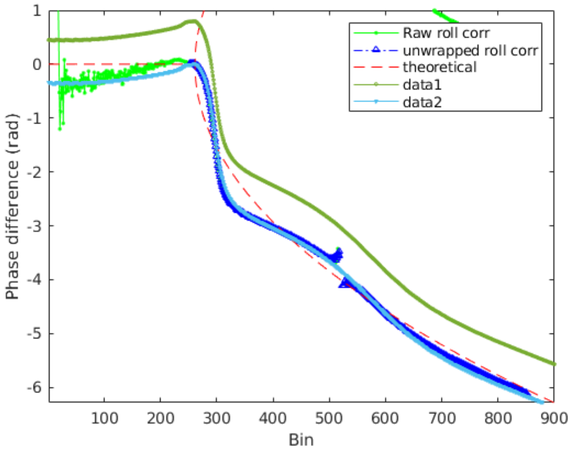


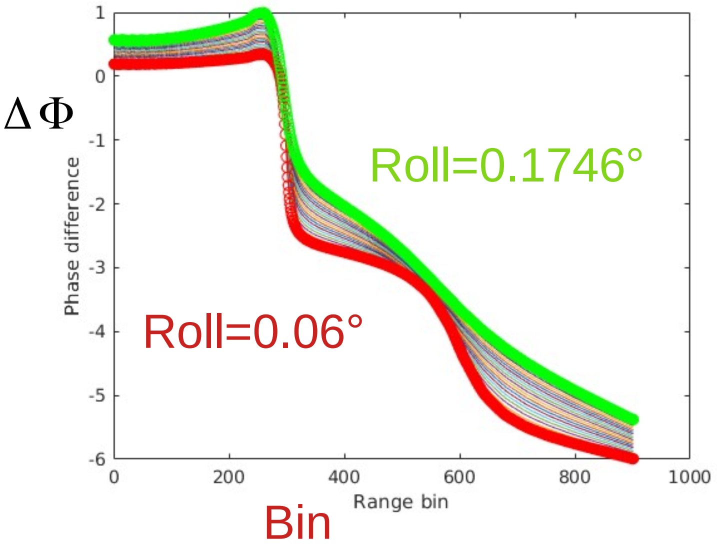
PDF of phase diff in the noise part of waveform
Maximum corresponds to the antennas bench roll angle

Impact of roll angle on phase difference



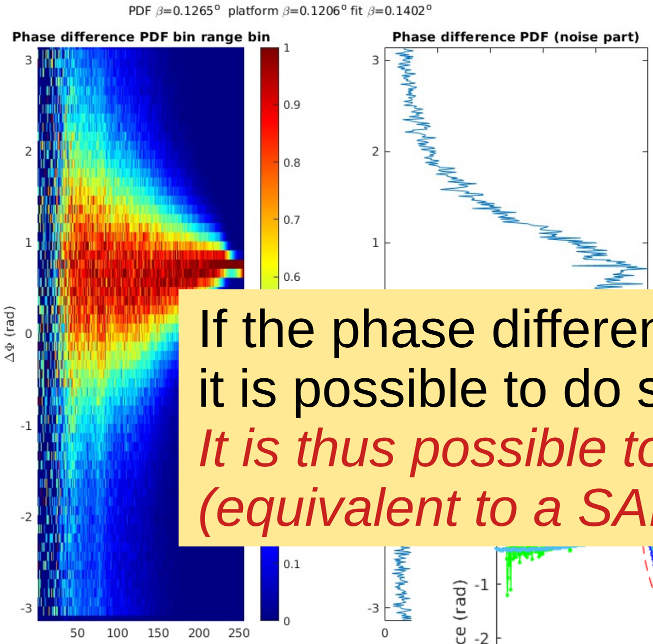
L. Recchia, M. Scagliola, D. Giudici and M. Kuschnerus, "An Accurate Semianalytical Waveform Model for Mispointed SAR Interferometric Altimeters," Geos. Rem. Sens. Let., 14, 9, pp. 1537-1541, 2017.





The larger the roll the smaller the impact.

Impact of roll angle on phase difference



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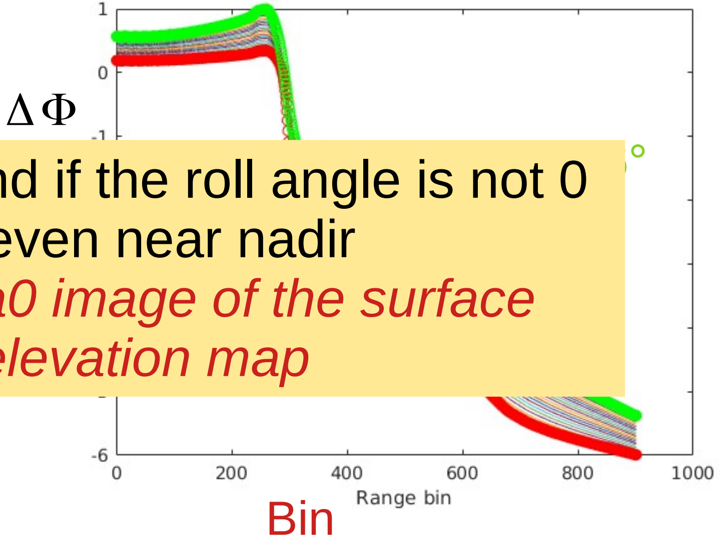
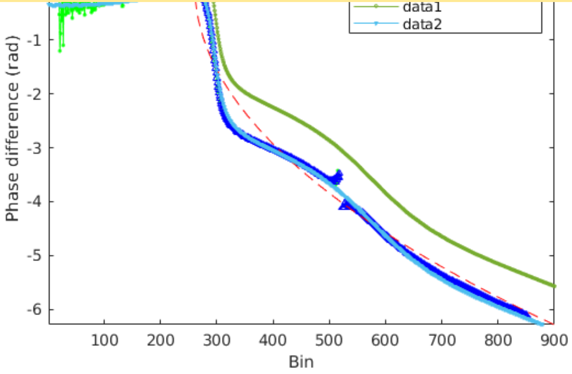


If the phase difference is corrected and if the roll angle is not 0 it is possible to do swath processing even near nadir

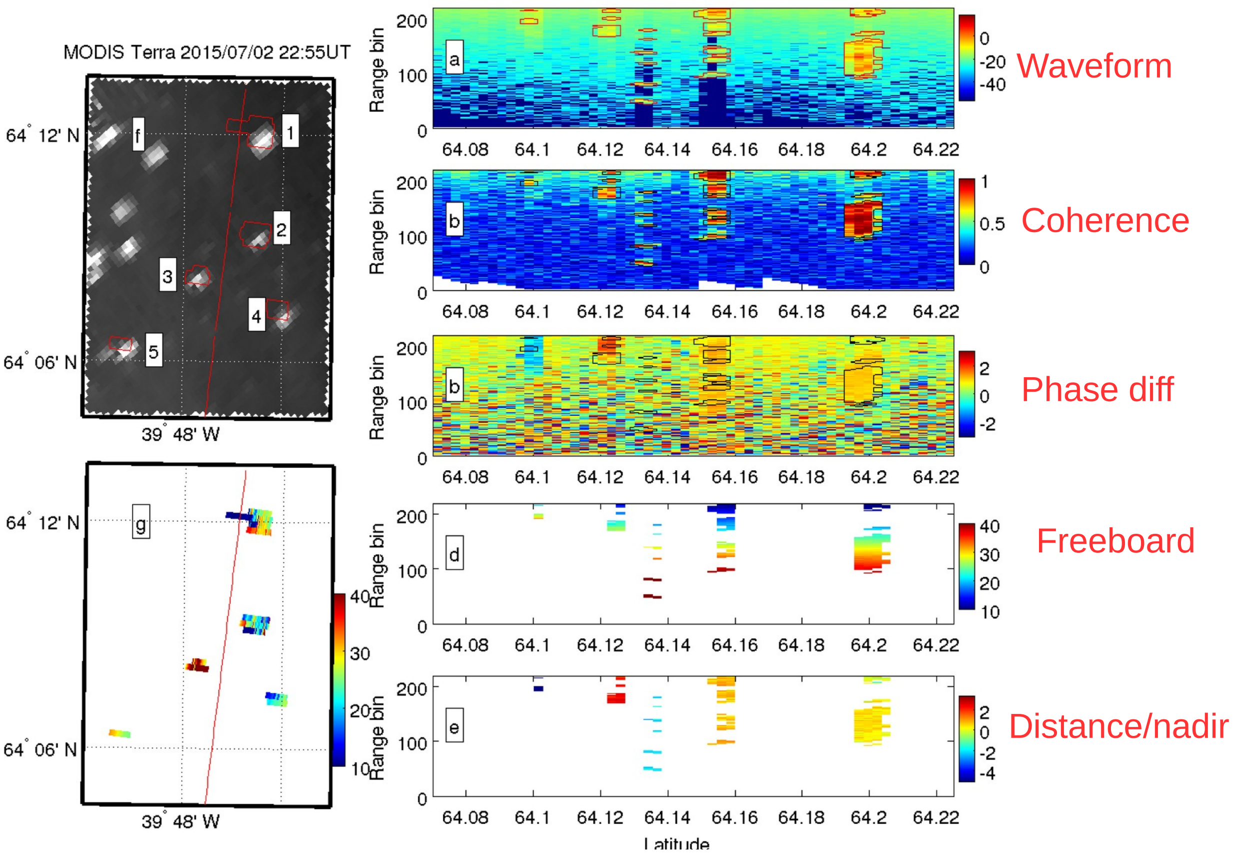
It is thus possible to compute a sigma0 image of the surface (equivalent to a SAR image) and an elevation map



The larger the roll the smaller the impact.

SAR interferometry detection in open water

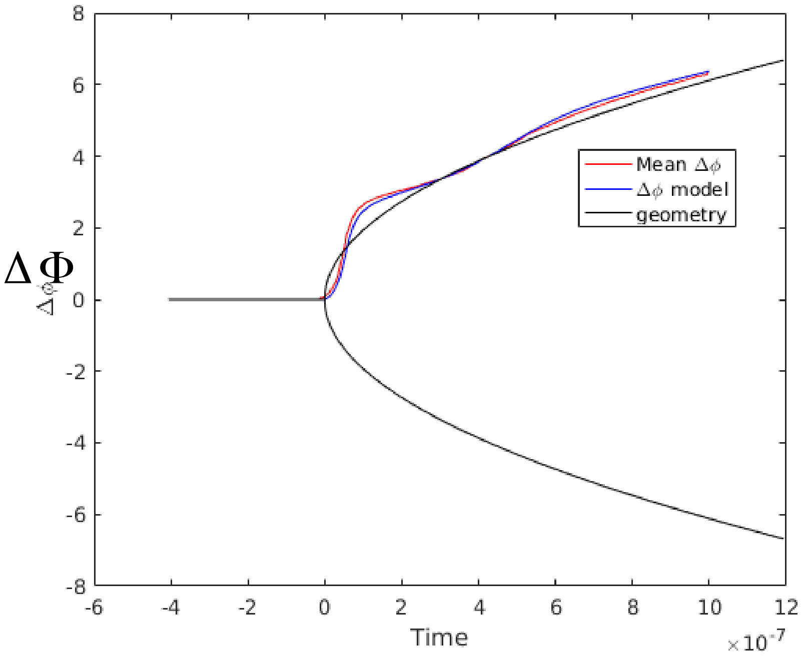
- Tournadre et al 2018
- Only the noise part of the waveforms considered
- Detection with SAR algo + condition of coherence >0.7
- Estimation of freeboard
- Remapping on a 300x50 m geographical grid
- Estimation of the iceberg characteristics (freeboard, sigma0, size)

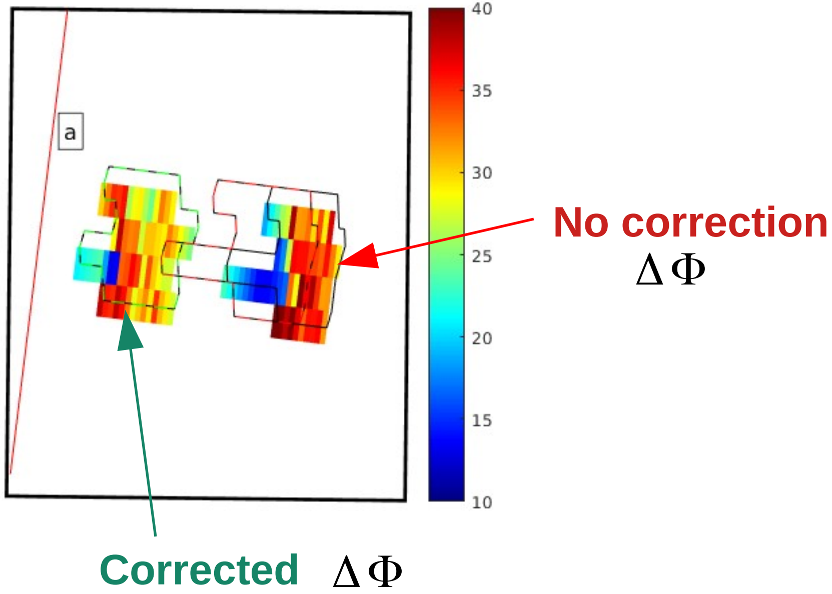


Ifremer

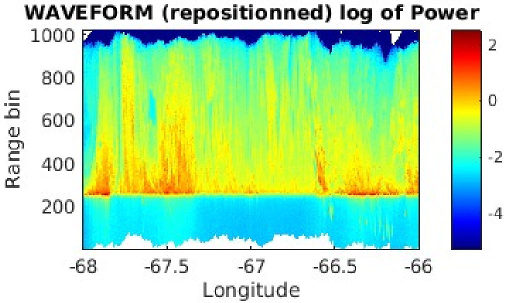
The phase difference can be corrected (calibrated) by using either

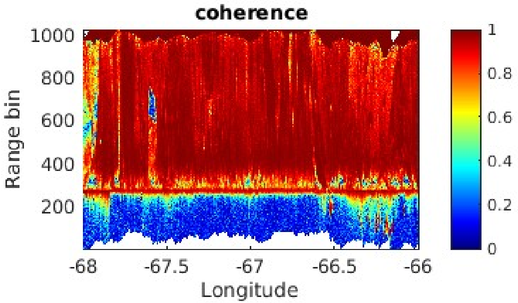
- the mean phase difference as a function of range or
- the Recchia model corresponding to the best fit of the mean phase difference (or the platform roll or the roll for the noise PDF)

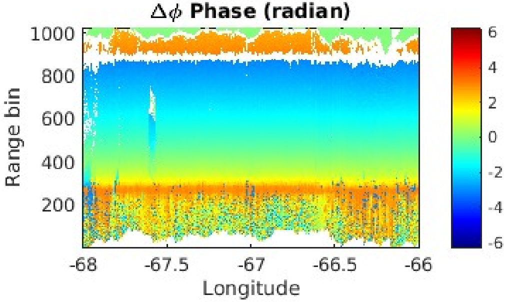


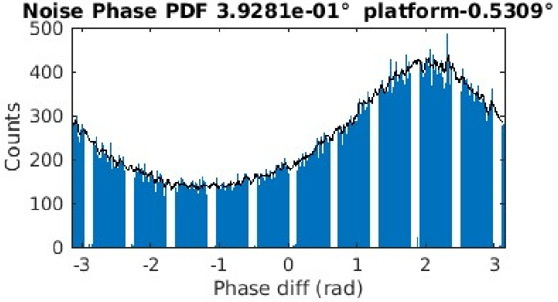


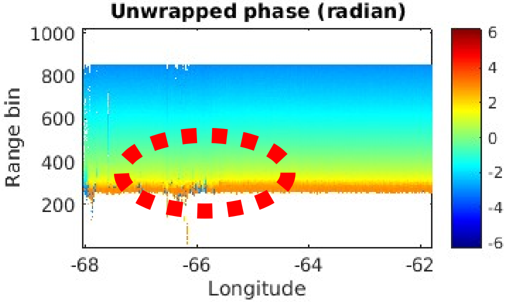
SWATH PROCESSING for icebergs and sea ice during roll campaign 11(0,4°)

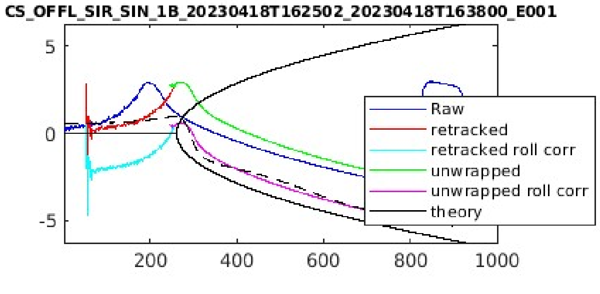




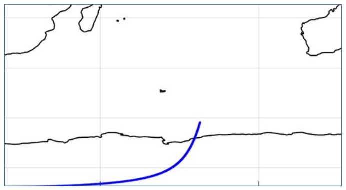






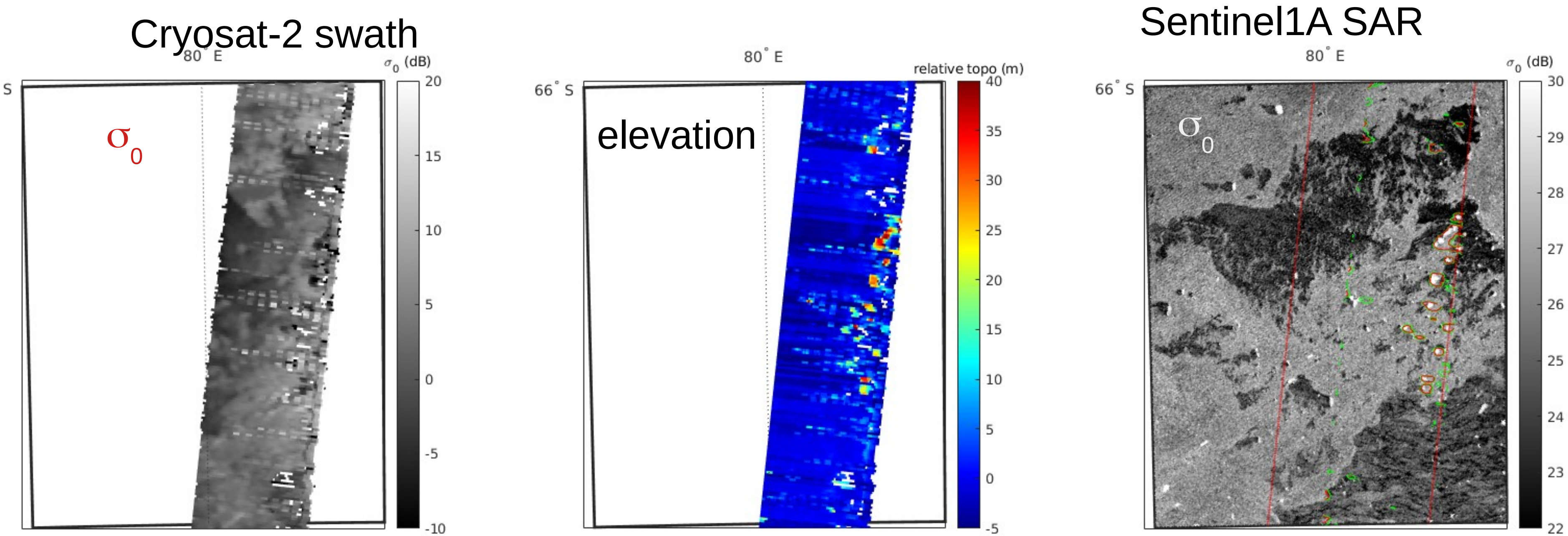


- Waveform, phase difference and coherence re-positioned with central gate at bin 261 (using tracker and range information)
- Check the roll angle using the noise PDF
- Keep the samples with coherence >0.7 in the WF noise part
- Compute mean phase difference in open water if available



Small iceberg in sea ice

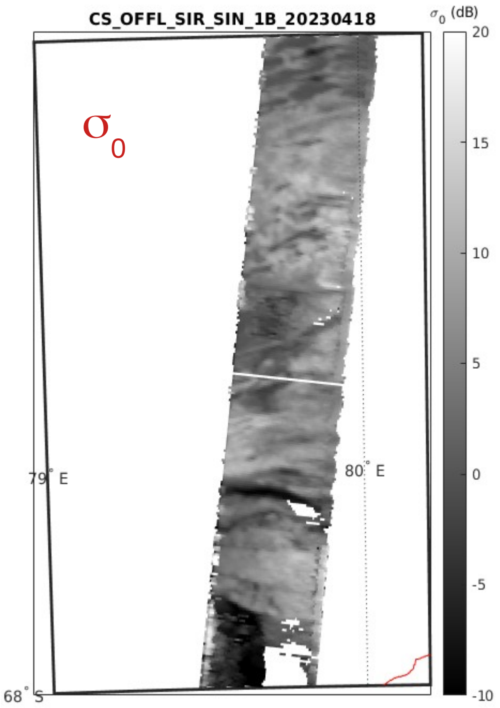
Signature in the noise part of the waveforms

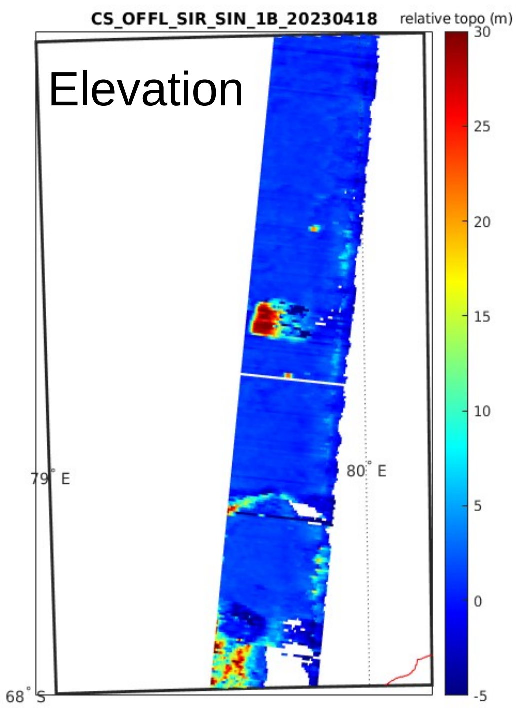


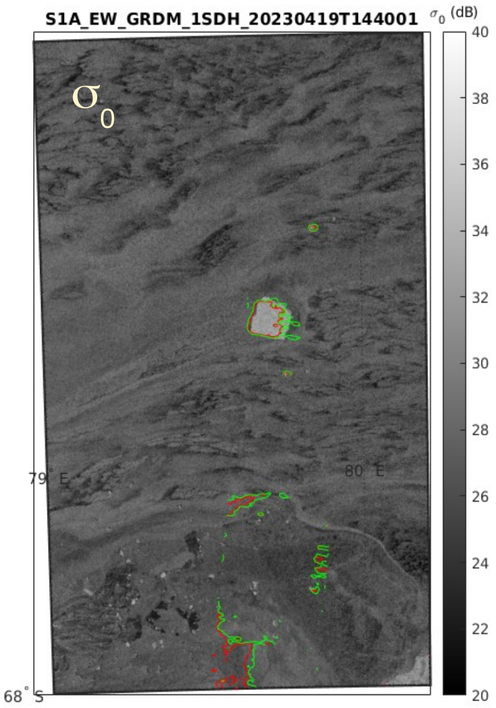
Example of medium size iceberg in sea ice

Cryosat-2 swath

Sentinel1A SAR



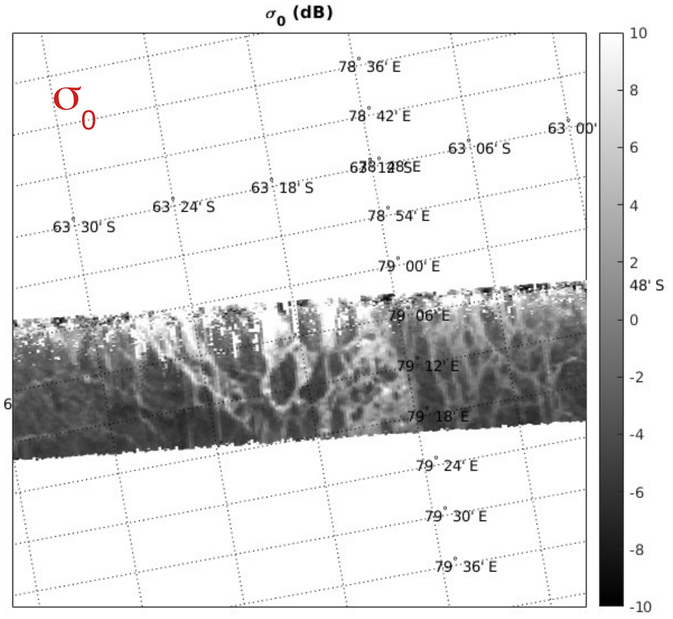


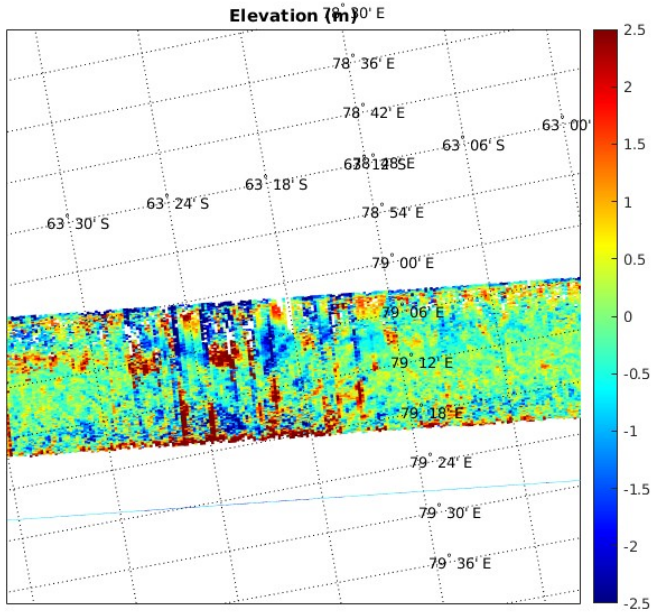


Signature in the plateau part of the waveforms

Example of sea ice

Cryosat-2 swath



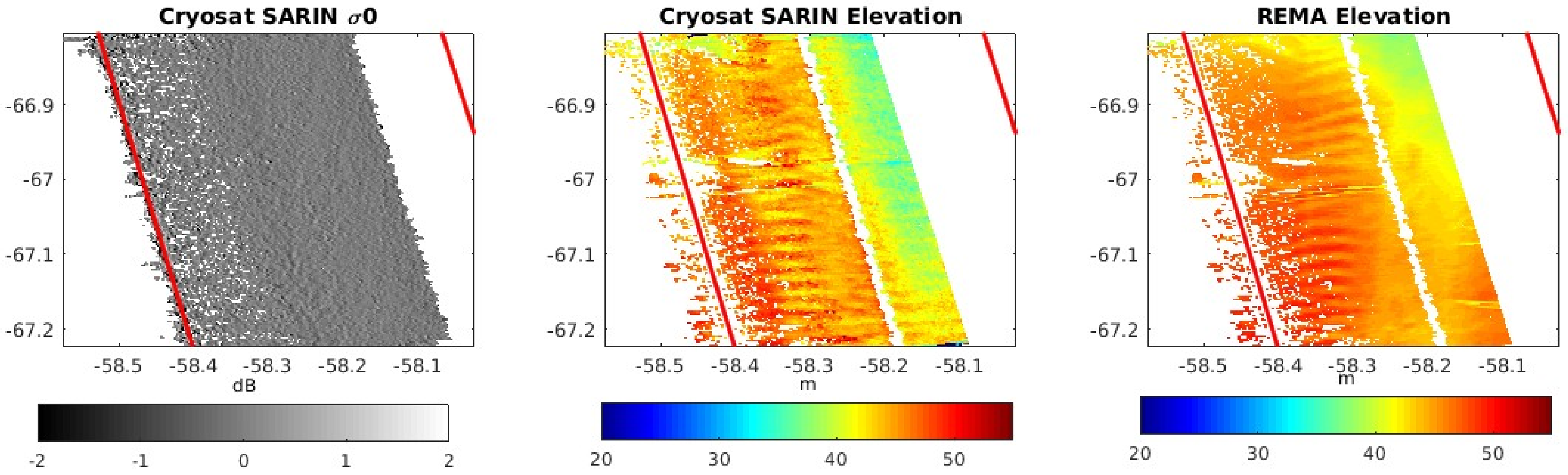


Clear leads, elevation shows that there is potential for estimate of sea ice freeboard elevation

Swath processing over A68 giant iceberg

CRYOSAT-2 swath

Elevation from stereo pairs of HR images

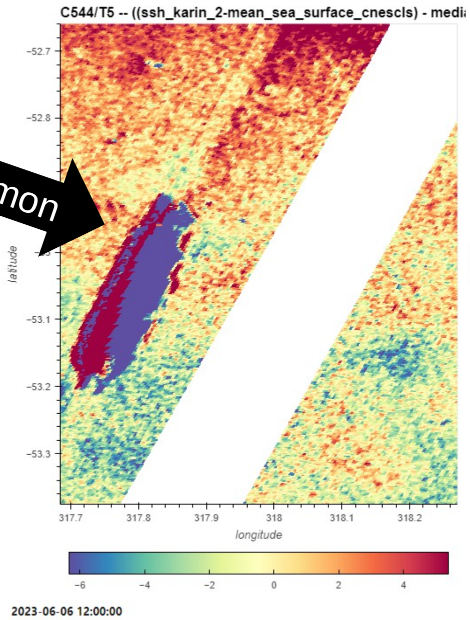


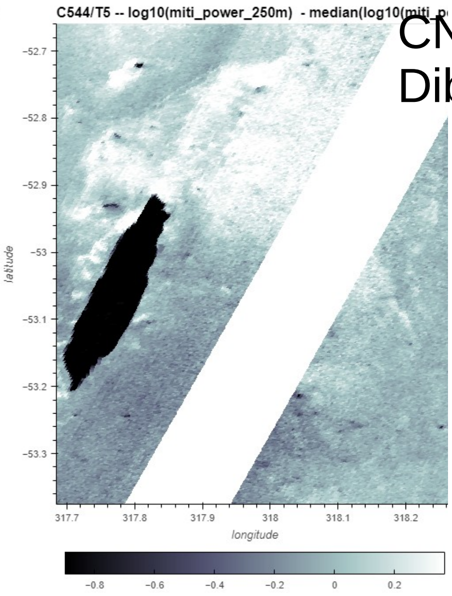
The iceberg is so high that KaRIn’s standard ocean processing does not work

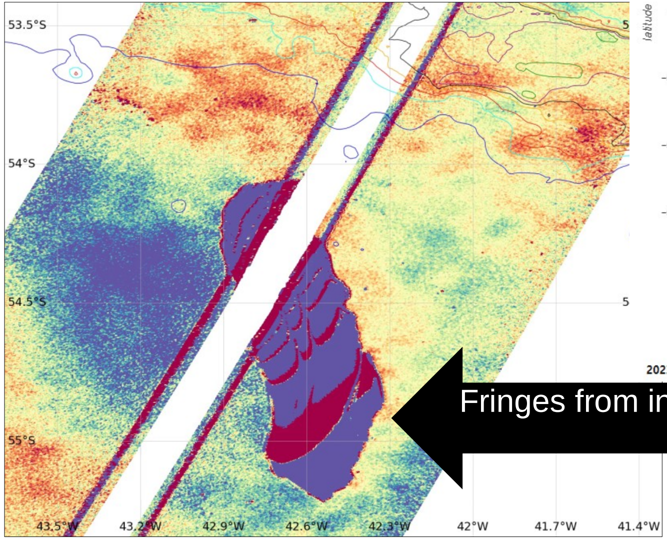
A product dedicated to sea-ice is needed (and in theory possible)

Courtesy CNES G. Dibarboure)

Ghost image are very common





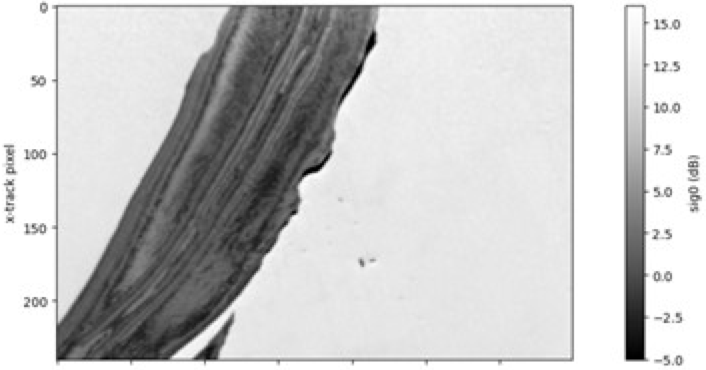


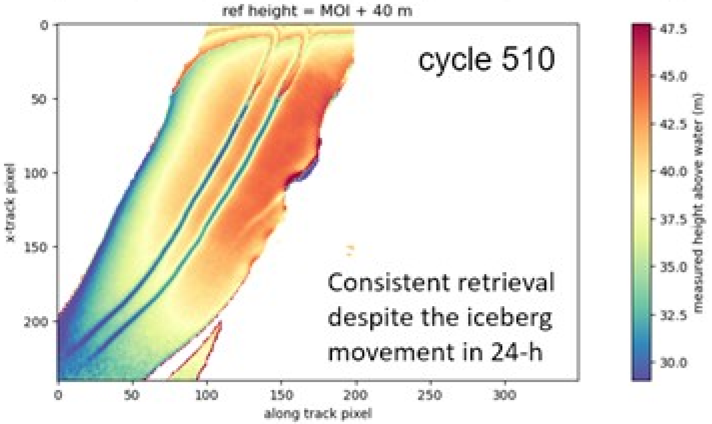
Fringes from interferometric phase wrap

These common artifacts originate in an ocean processor that make assumptions on a flat-ish ocean reference that are not valid for large icebergs (and sea-ice topography in general)

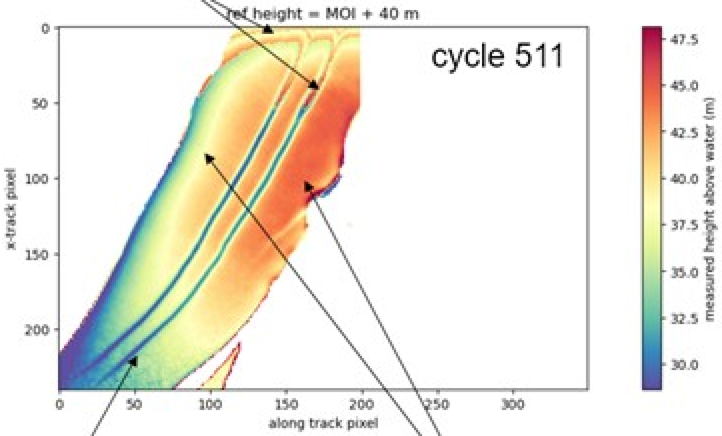
More work needed on the algorithm/product front

It is possible to retrieve a precise iceberg topography (w.r.t to the ocean surface) with a dedicated L2 processing





Residual phase wraps @ near range (constant ref surface used here cannot accommodate actual topography; for the very first pixels wraps will occur if actual surface differs from ref surface by more than 2-3 m; probably easy to get rid of with actual phase unwrapping)



deep fractures ?

topography gradient of a few meters over the width of the iceberg)

conclusion

- Keep working on interferometric altimetry
- 3D view of the surface instead of 2D.
- Perfect for sea ice, iceberg, land ice
- Experiences from CRYOSAT-2 and now SWOT/Karin are very complementary and fully demonstrate the interest of SARIn alt.


ありがとう
Merci
Thank you