Atelier Glaciologie

Altimétrie Doppler sur glace continentale

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Introduction

- Ice-sheet surfaces (Antarctic & Greenland) have been monitored by radar altimeters since the launch of GEOS-3 (1975)

- Since then, several altimeter missions have provided a near-continuous survey of the ice-sheet topography, all of them using a conventional Low Resolution Mode (LRM)

- Surface topography mapping from conventional altimeters suffers from various sources of uncertainties :

  - Penetration of the Ku-band signal into the snowpack disrupts the measured waveform

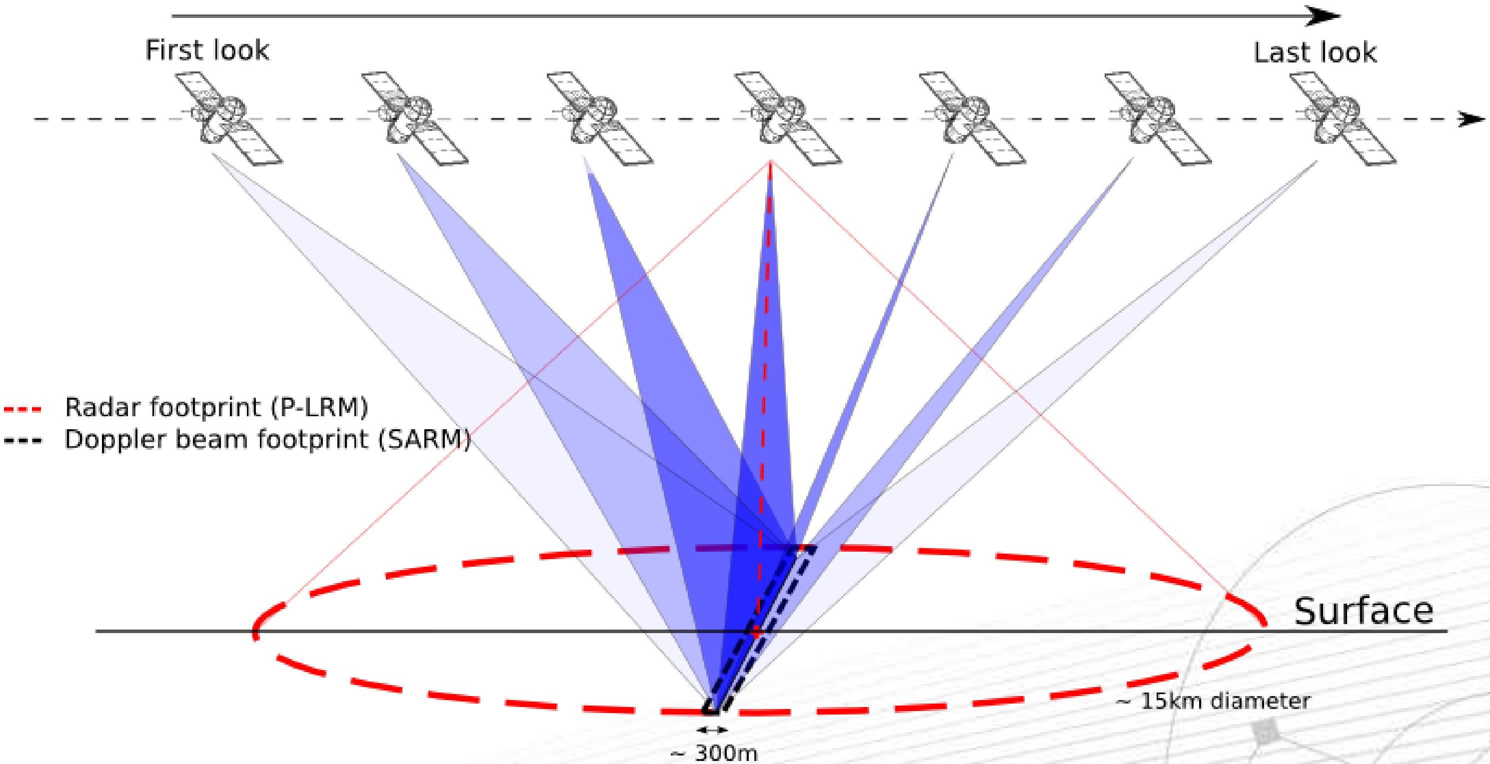
  - Inability to retrieve fine topographic variations due to the large radar footprint (12 to 20km diameter depending on mission)

  - Range estimation errors due to surface slopes (idem)

- **Sentinel-3A is the first altimetric mission operating on SARM over ice sheets (100%). Improvements regarding the conventional LRM are expected and will be investigated**.

Introduction

Résolution spatiale de la mesure SAR & (P)LRM

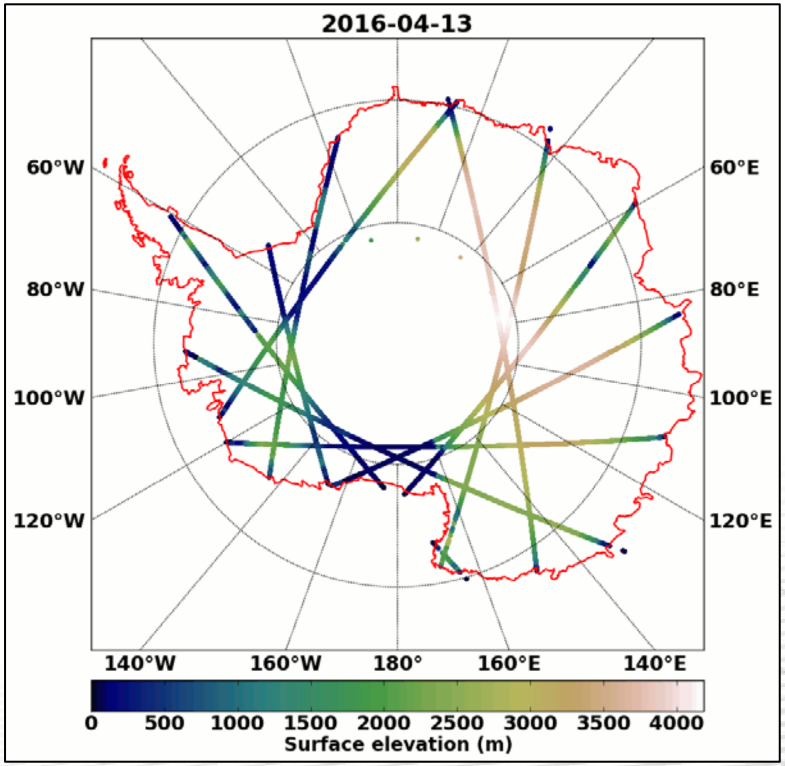


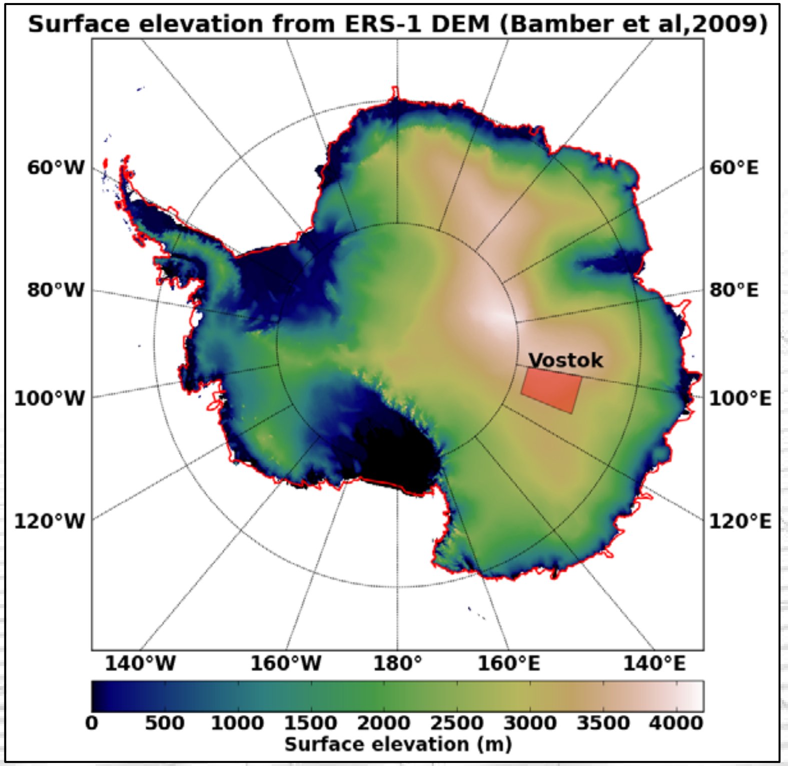
- Surface échantillonnée totale :
  - **P-LRM** : **175km2** au total
  - **SAR** : **4.5km2** au total
- Pas de recouvrement entre deux mesures successives 20Hz en SAR

Introduction

- Sentinel-3A measurements over Antarctica have been analysed from **April 13th 2016** to **May 9th 2016**. **(S3PP process)**
- The assessment is essentially done with measurements located over lake Vostok, where Cryosat-2 acquired 10 days of data in SARM on November 2014 **(CPP process)** .

Illustration of Sentinel-3a day-to-day acquisitions





Introduction

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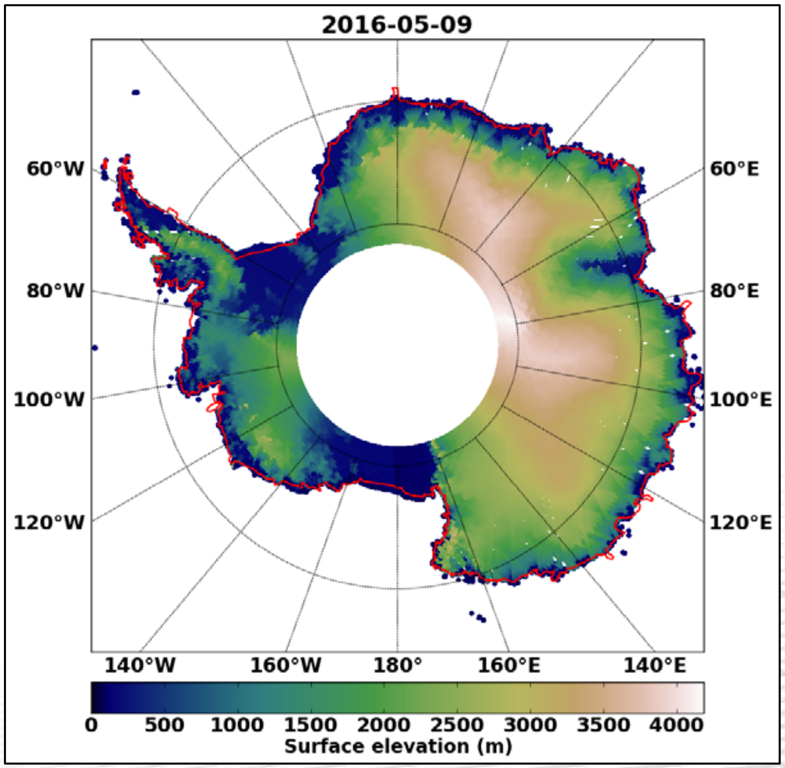
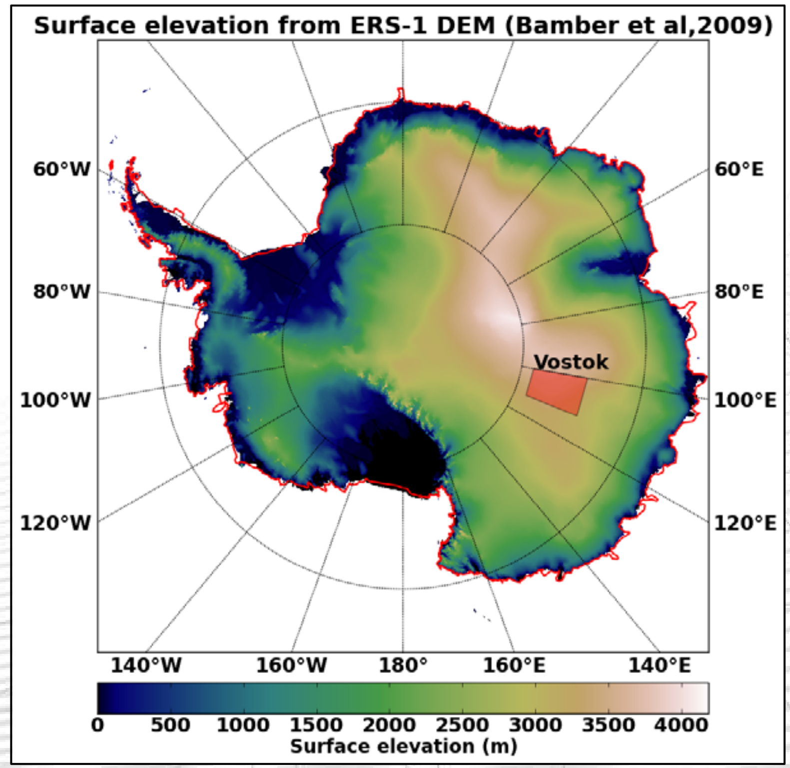
Illustration of Sentinel-3A acquisitions





Presentation content

1) Penetration effect on the alimeter measurements
2) Surface elevation assessment over lake Vostok
3) Impact of the surface slope on the surface elevation
4) Results over fine-scale topographic variations

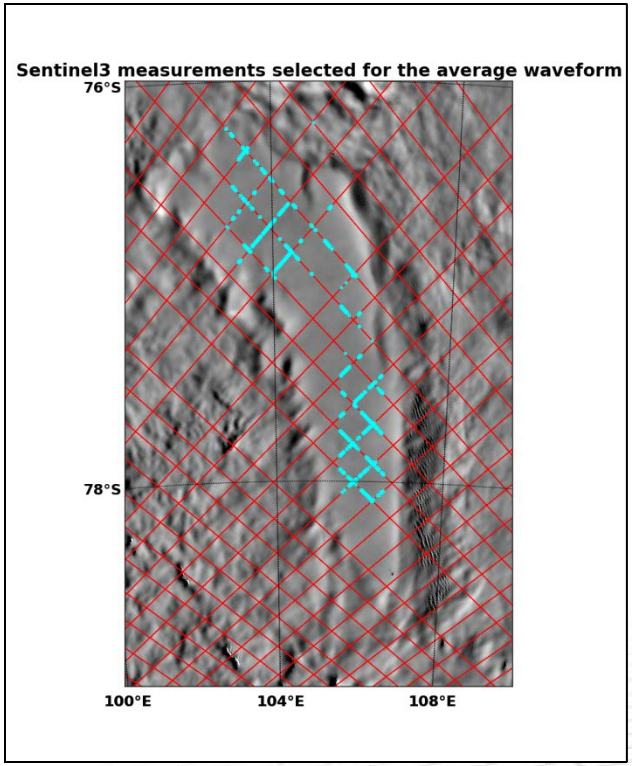
Waveform analysis

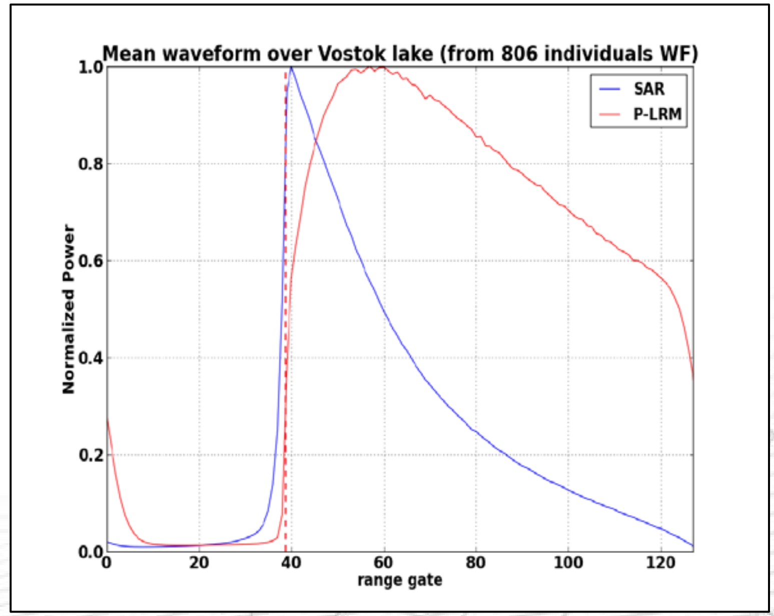
Surface elevation assessment

Surface slope effect

Fine scale topography

Computation of mean SARM and P-LRM waveforms over lake Vostok





Waveform analysis over lake Vostok

Waveform analysis

Surface elevation assessment

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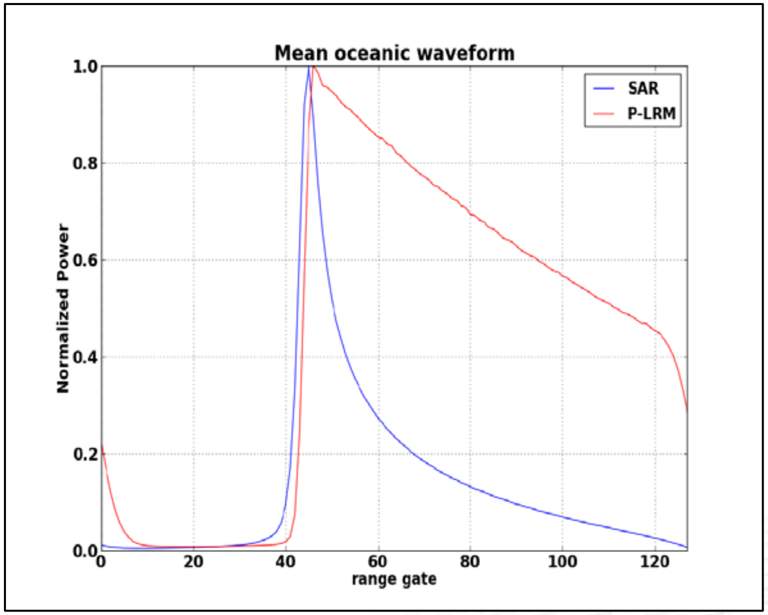
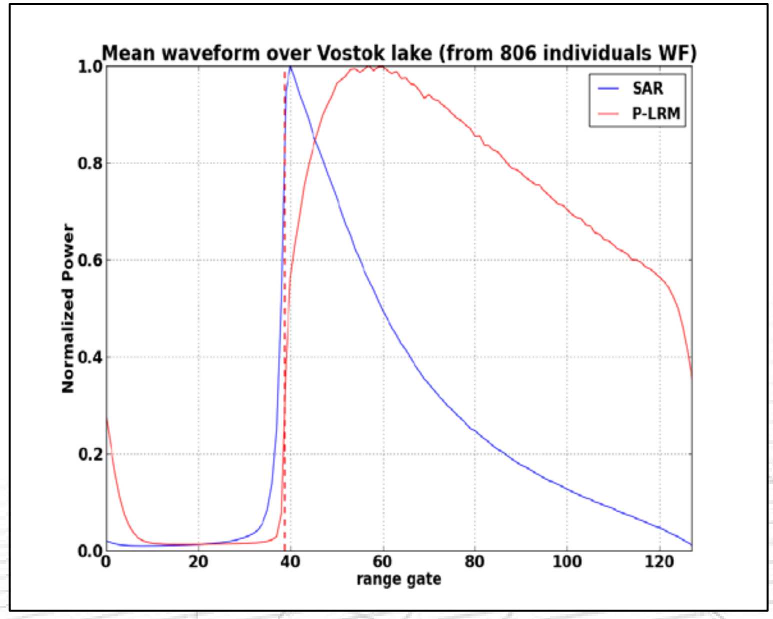
Fine scale topography

Comparison with oceanic waveforms (east Pacific)

Oceanic waveforms ***: East Pacific***



Ice-sheet waveforms ***: lake Vostok***



➢ **Waveforms measured over ice-sheet surfaces are "volumetric" because of the penetration effect of the Ku-band signal into the snowpack**

Ice-sheet waveform simulation

Waveform analysis

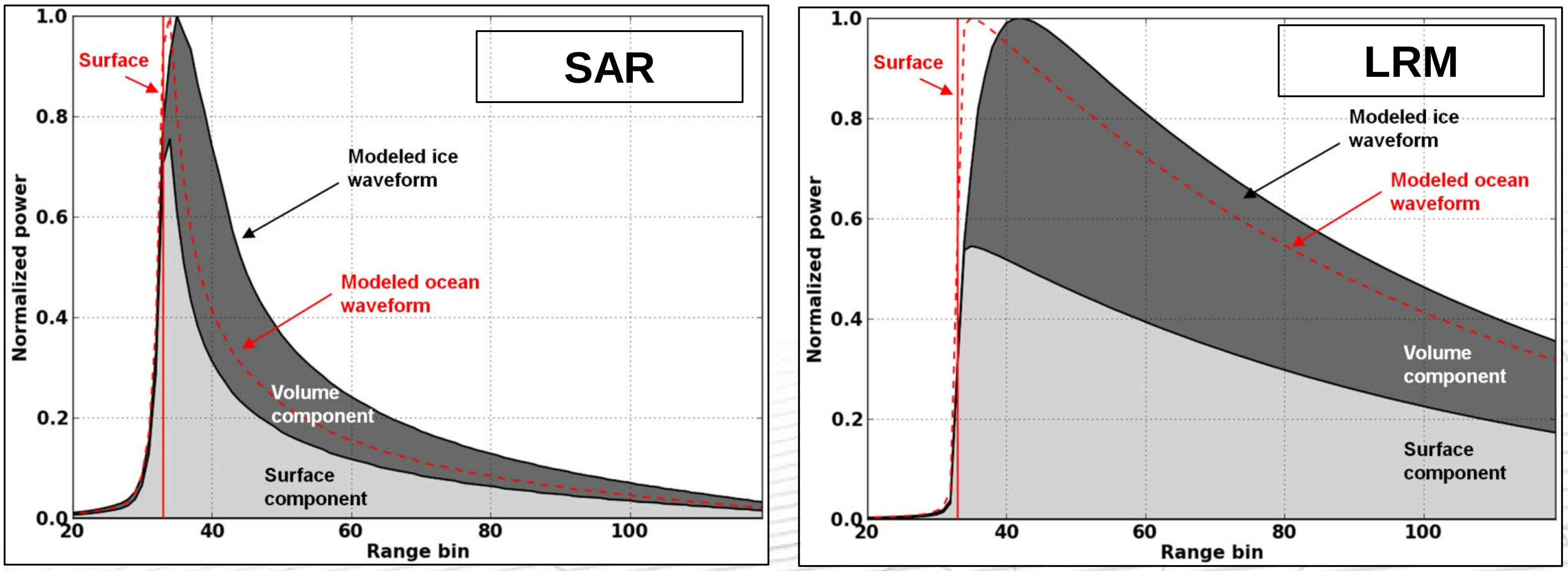
Surface elevation assessment

Surface slope effect

Fine scale topography

- Altimetric waveforms over ice-sheet surfaces are a sum of **a surface echo** and a **volume echo**

- **Important observation :** Instead of PLRM, SARM leading edge waveform is weakly impacted by the penetration effect
  => Range measurement is more directly determined on SARM



Modeled ice-sheet waveforms in SAR and LRM modes with their two components : the surface echo (in light grey) and the volume echo (in dark grey). Modeled oceanic waveforms is superimposed (dotted red line)

Surface elevation estimation

Waveform analysis

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Fine scale topography

➢ Altimetric distance is computed from the waveforms with a threshold retracker dedicated to the ice-sheet surfaces.

➢ Computation of the surface elevation :
H = Orbit - altimetric_distance - internal path delay - Σ (geophysical corrections)

➢ Surface elevation estimated from Sentinel-3A data on SAR and P-LRM modes is compared with three DEM available over Antarctica :

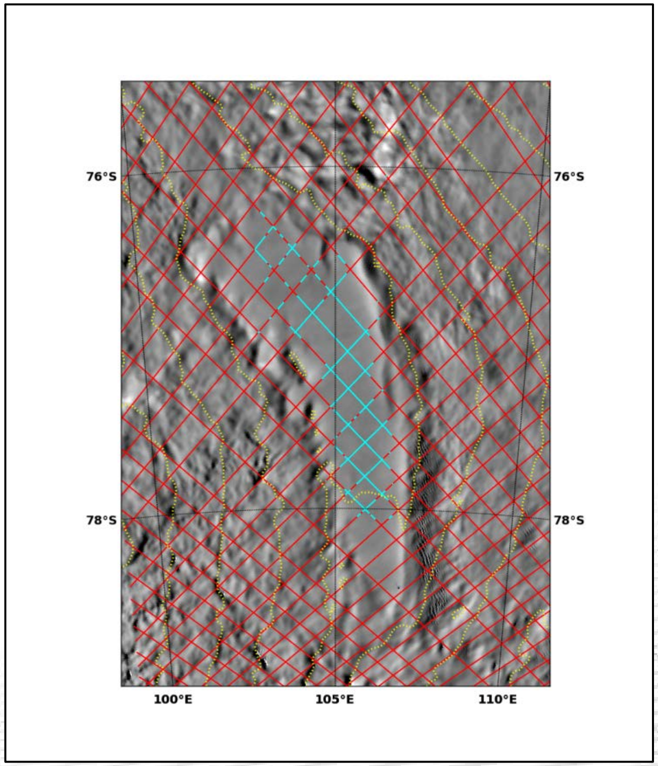
- ❑ **ERS-1 DEM** (Bamber et al, 2009) : Computed from ERS-1 and IceSAT data. Time Stamp : 2004
- ❑ **Cryosat-2 DEM** (Helm et al, 2014) : Computed from Cryosat-2 data (LRM & inSAR modes). Time Stamp : 2014
- ❑ **IceSAT DEM** (DiMarzio et al,2007) : Computed from IceSAT data. Time Stamp : 2003 to 2005

Assessment over lake Vostok

➢ To avoid surface slope errors, an assessment has been made on measurements acquired over the flat surface of lake Vostok (surface slope < 0.025%).

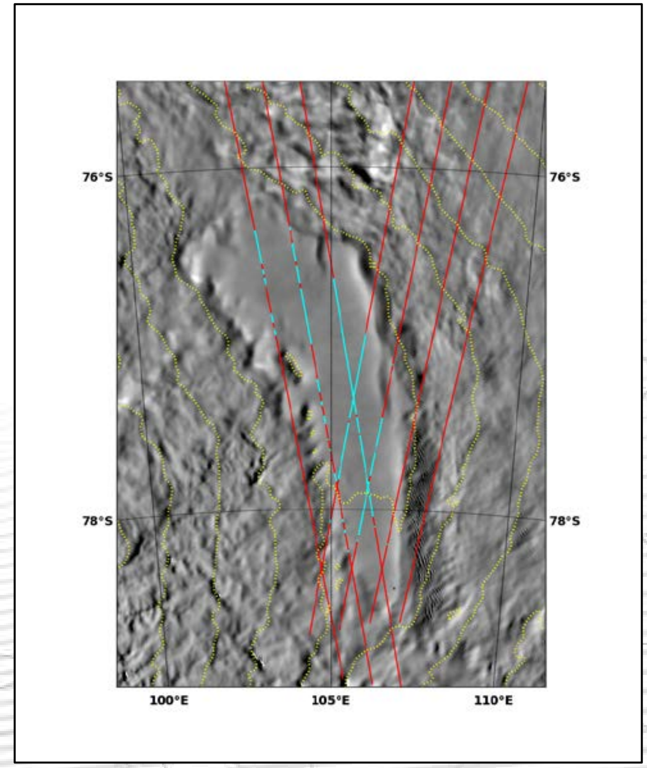
➢ Moreover, the surface height of the ice sheet over lake Vostok is very stable, with a height change rate as low as 1 ± 5 mm/yr [Richter et al, 2014].

Sentinel-3A measurements



April / May 2016, ~2000 measurements

Cryosat-2 measurements



Novembre 2014 ~1200 measurements

Assessment over lake Vostok

Waveform analysis

Surface elevation assessment

Surface slope effect

Fine scale topography

Comparison of the estimated elevation computed from colocated SARM and P-LRM

Cryosat-2 : mean bias (SARM – PLRM) : **+0.5cm** /// standard deviation : **17.2cm**

Sentinel-3A : mean bias (SARM – PLRM) : **+0.6cm** /// standard deviation : **13.6cm**

- Excellent agreement of SARM and P-LRM for both missions.

Assessment over lake Vostok

Waveform analysis

Surface elevation assessment

Surface slope effect

Fine scale topography

Mean biases between the surface elevation computed from Sentinel-3A & Cryosat-2 SARM and three DEM

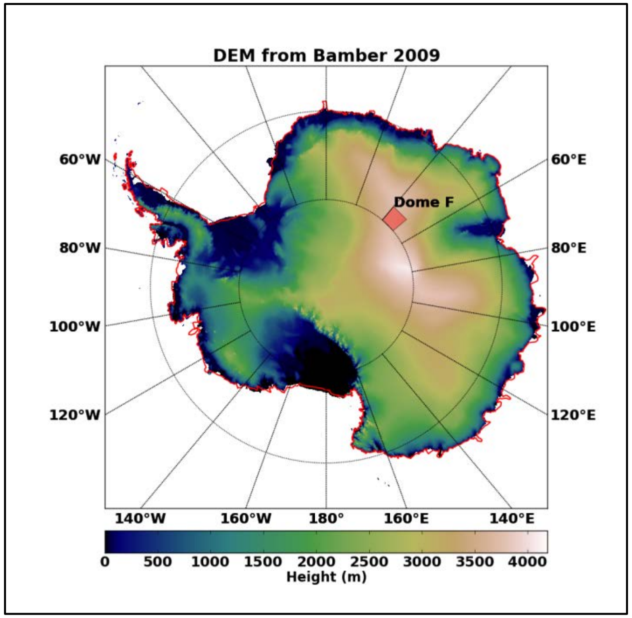
	Mean biases with DEM (cm)	
	S3A SAR autumn 2016	CS-2 SAR summer 2014
ERS1 DEM	+15.2	+3
CS-2 DEM	+12.6	+1.5
ICESat DEM	+2.4	-7.3

- Both missions very consistent with DEM.
- Cross-over analyses will permit to better compare altimeter missions. On-going study.
- Need in-situ measurements (GPS data) to perform a better assessment

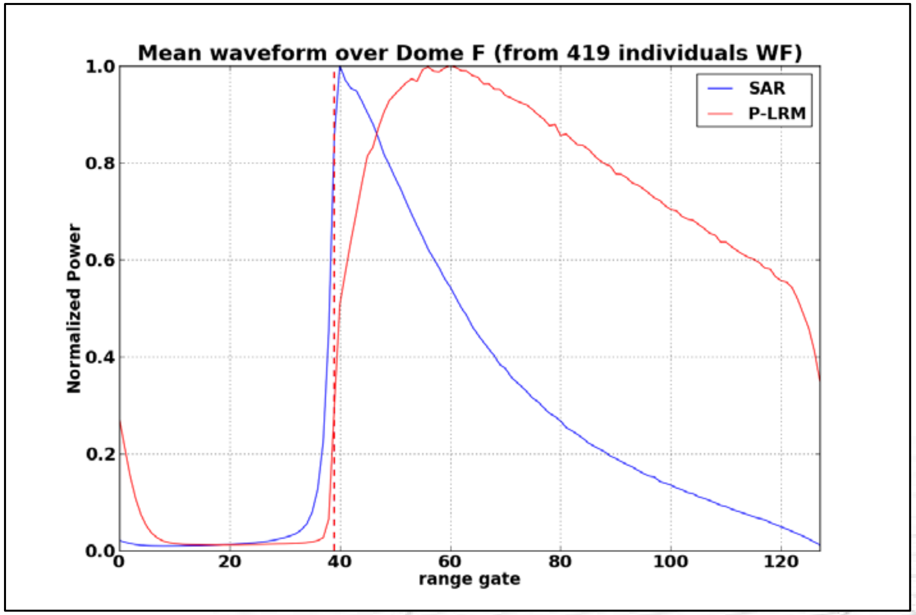
Good elevation accuracy computed from SAR data over lake Vostok

Assessment over DOME-F

Mean waveforms & median bias with DEMs over Dome-F area (flat surface analyses)



Location of Dome-F

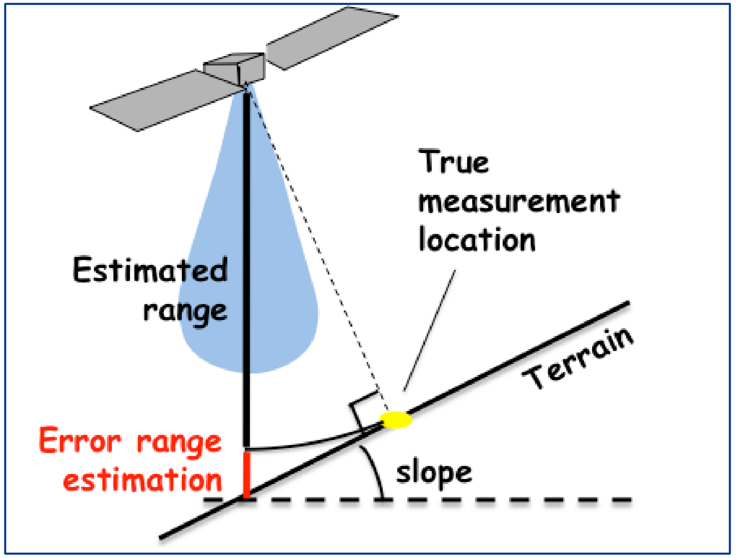


Aggregation of 419 individual waveforms & with surface slope < 0.05%

	S3A SAR	
	Median bias	Standard dev.
ERS1 DEM	+ 37.7	46.5
CS-2 DEM	+16.4	51.7
ICESat DEM	+8.9	72.8

Median bias between S3A SARM and DEMs. ~ 1500 Measures with surface slope < 0.025%

Slope induced error on altimeter measurements



- Slope induced error leads to an over estimation of the surface elevation.

  It is theoretically computed as : $\Delta h = (s^2 + He) / 2$
  with : **s =** surface slope
  He = effective altitude of satellite
  [Wingham et al., 2004; Sandwell and Smith, 2014]

- Range measurements need to be corrected for this error. On the following results, no corrections have been made to compare SARM and P-LRM errors.

Slope induced error on altimeter measurements

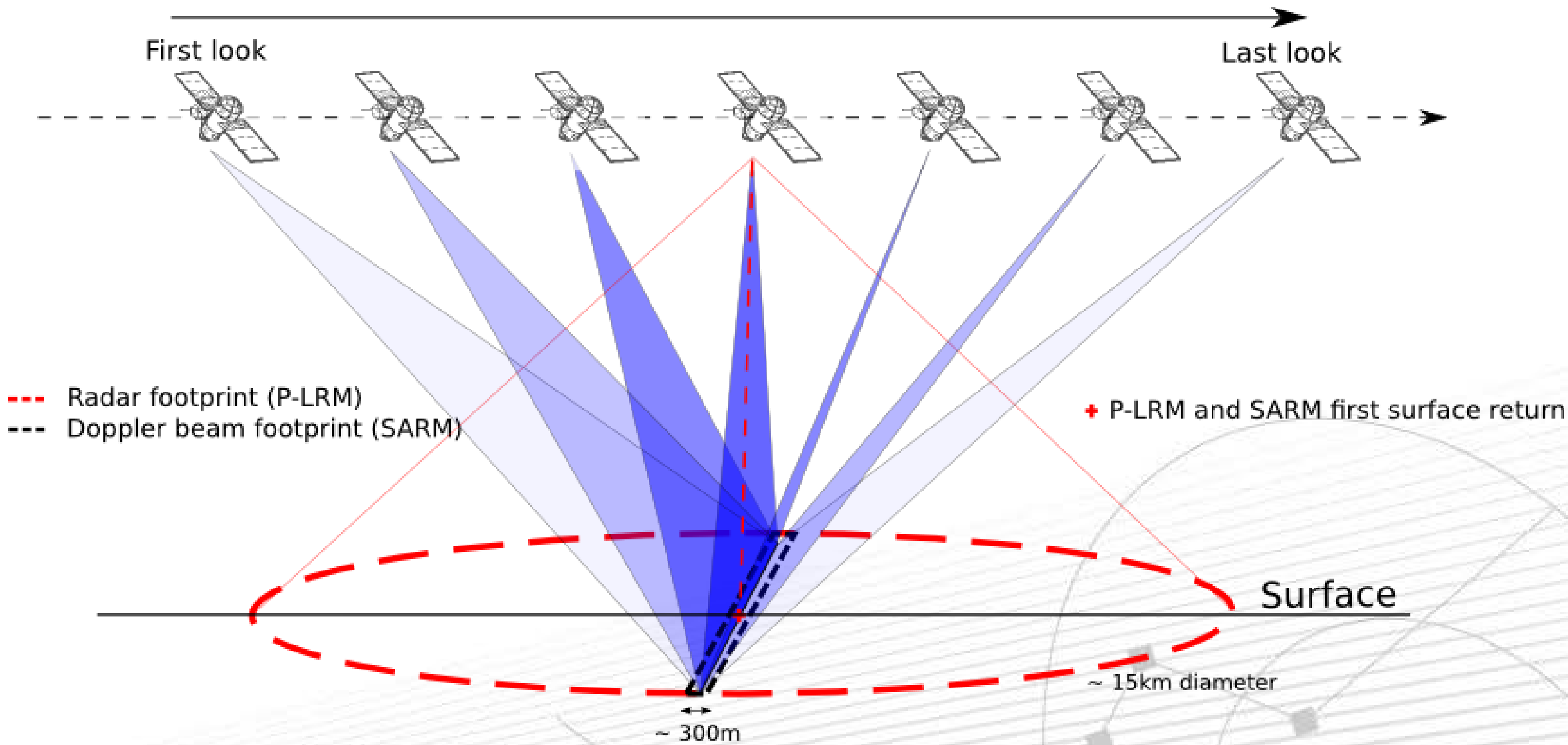
Waveform analysis

Surface elevation assessment

Surface slope effect

Fine scale topography

Illustration of the SARM and P-LRM footprints



LRM footprint *: a nearly 15 km circular area on a flat surface*

SARM footprint : *0.3km x 15 km (along-track / acros-track)*

Slope induced error on altimeter measurements

Waveform analysis

Surface elevation assessment

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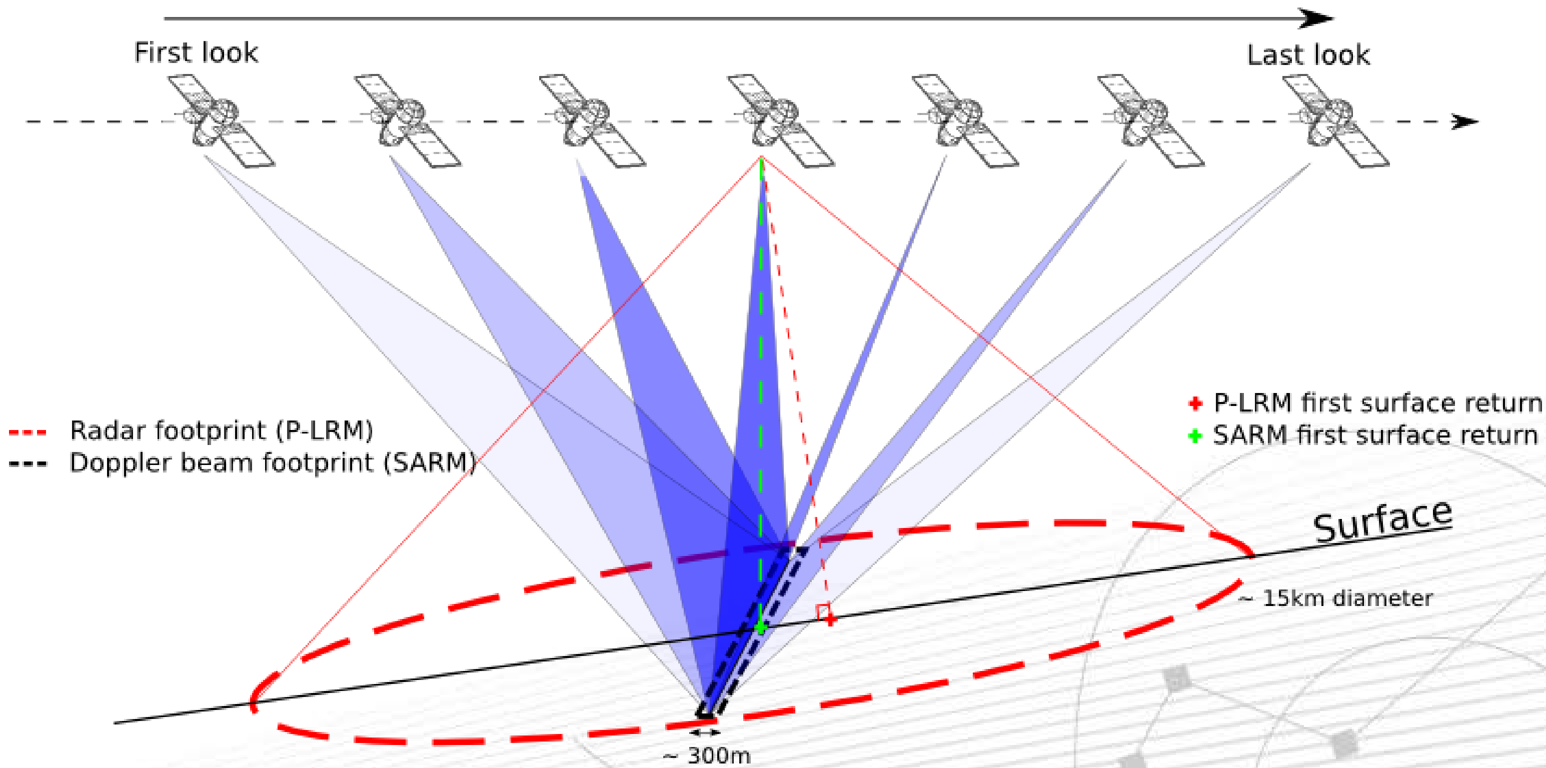
Fine scale topography

<u>Along-track</u> surface slope effect



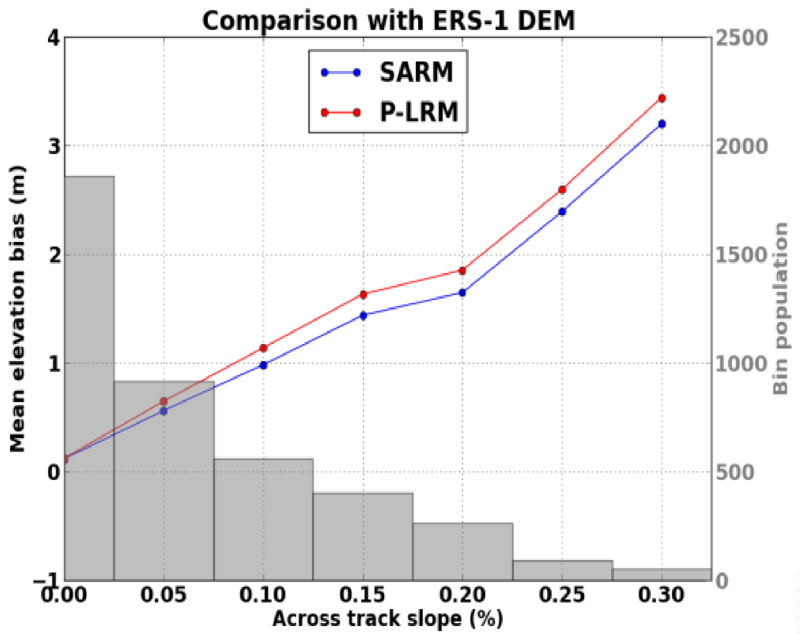
LRM* : *the closest point of the surface is shifted upslope (red mark)

SARM* : *the footprint limits this shift within the Doppler strip (green mark)

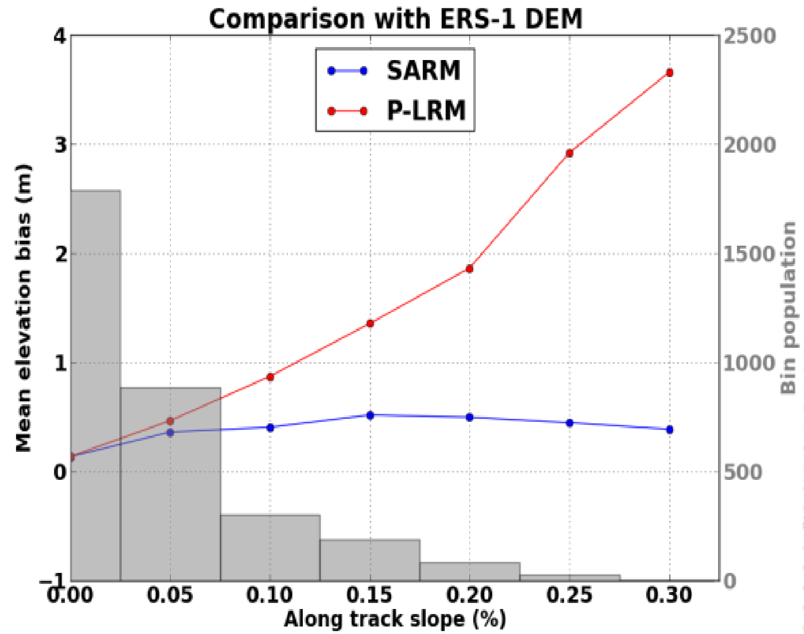
(However, the across-track slope has the same effect on both modes)

Cryosat-2 bias with DEM, function of surface slope

Cryosat-2 results, only over Vostok area (with 9000 overall measurements)



Bias function of across-track slope.
along-track slope < 0.05%



Bias function of along-track slope.
across-track slope < 0.05%

=> Negligible impact of the along-track slope on SARM (over small data population and limited slope range)

Sentinel-3A bias with DEM, function of across-track surface slope

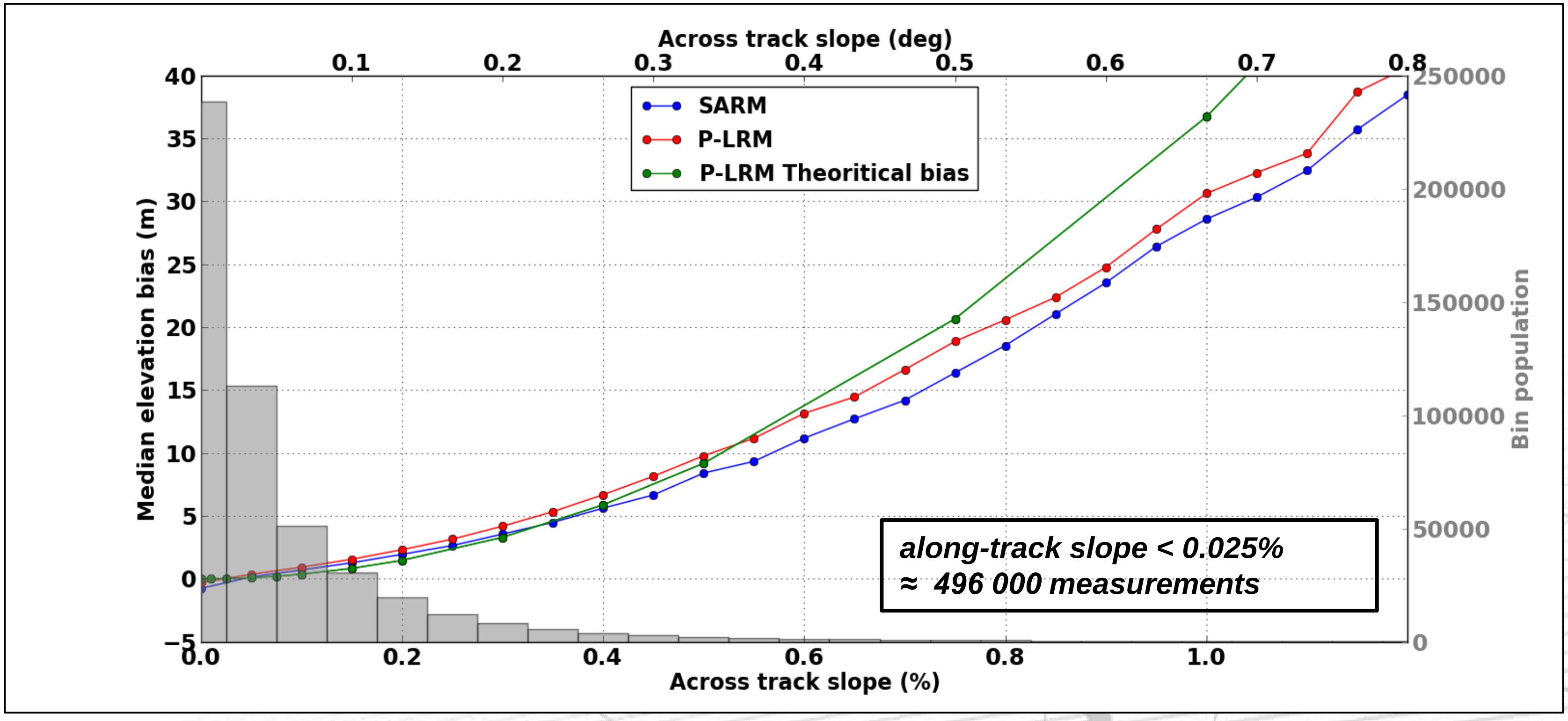
Waveform analysis

Surface elevation assessment

Surface slope effect

Fine scale topography

Sentinel 3A results with measurements located over the whole continent. Across-track slope effect.



=> SARM and P-LRM have the same sensitivity to across-track slope.

Sentinel-3A bias with DEM, function of along-track surface slope

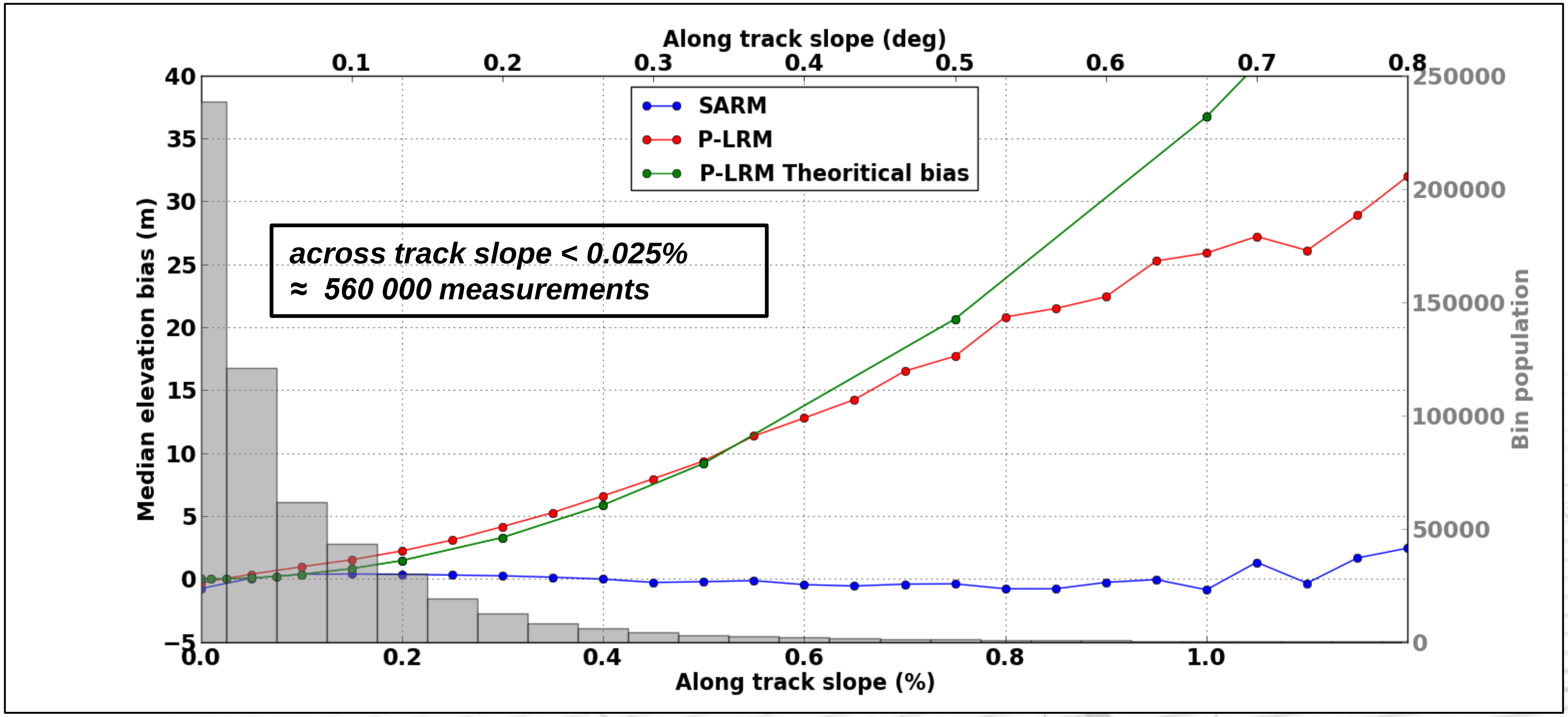
Waveform analysis

Surface elevation assessment

Surface slope effect

Fine scale topography

Sentinel 3A results with measurements located over the whole continent. Along-track slope effect.



=> Confirmation of the expected SARM no-dependency to the along-track slope. Very promising result for the SARM and its ability to map the surface topography

Cryosat-2 analysis over the margins

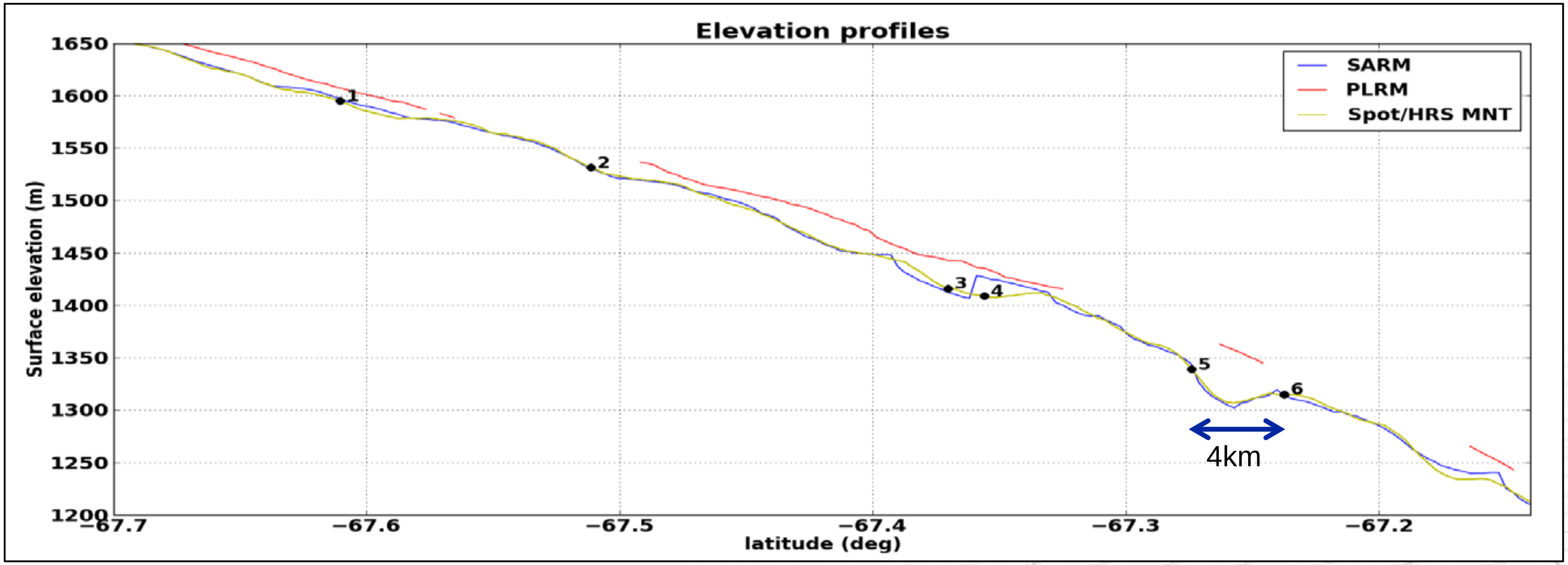
Waveform analysis

Surface elevation assessment

Surface slope effect

Fine scale topography

Cryosat-2 SARM and P-LRM elevation profiles over Adelie land.
Surface elevations are compared with a Spot/HRS DEM (40m spatial resolution)



- ➢ On this example, Cryosat-2 SARM proves its ability to infer surface height measurements at small scales.
- ➢ However, over a complex topography surface, the elevation estimation process is challenging and sometimes leads to errors (see mark 4)

Future results soon with Sentinel-3A…

Conclusions

Promising first results of the Doppler altimetry over ice-sheets with both Cryosat-2 and Sentinel-3a missions :

- ❑ Elevations consistent with DEMs (slight bias under investigation)
- ❑ Waveform leading edge weakly impacted by volume scattering
- ❑ Negligible sensitivity to along-track slopes (as expected)
- ❑ Ability to retrieve fine scale topographic variations

⇨ **Scientific publication is currently being drafted with Cryosat-2 results**

Perspectives

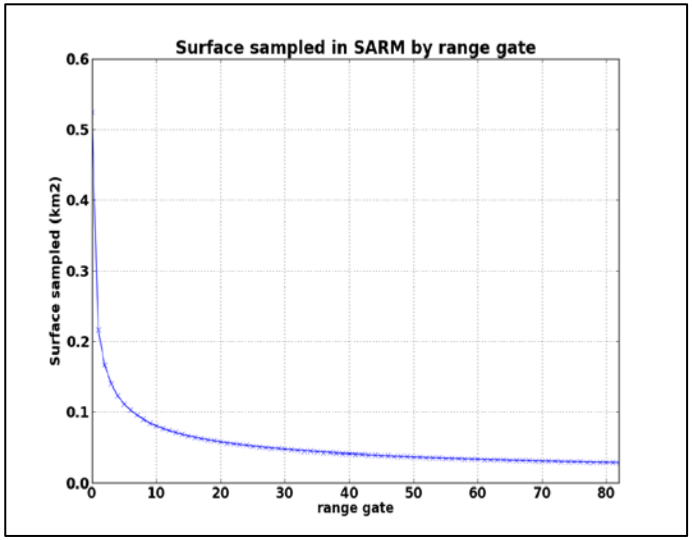
List of studies to complete the assessment of SARM over ice-sheets :

- ❑Cross-over analyses with Cryosat-2 SARM over Vostok lake (elevation bias, penetration & polarization effects)
- ❑Retracking improvement (estimation of the WF geometric parameters)
- ❑Study of the fine scale topography over the margins
- ❑Repeat-track analyses of Sentinel-3A
- ❑Multi-mission comparisons (in particular penetration effect in Ku / Ka)
- ❑Revisit of the historical data set (ERS, Envisat, Cryosat-2) accounting for penetration corrections
- ❑Elevation assessment by ICESat & GPS comparison (if obtention of GPS data…)
- ❑Analyses on Greenland

BONUS

Analyse des effets de pénétration sur les échos & justification des formes des fronts de montée

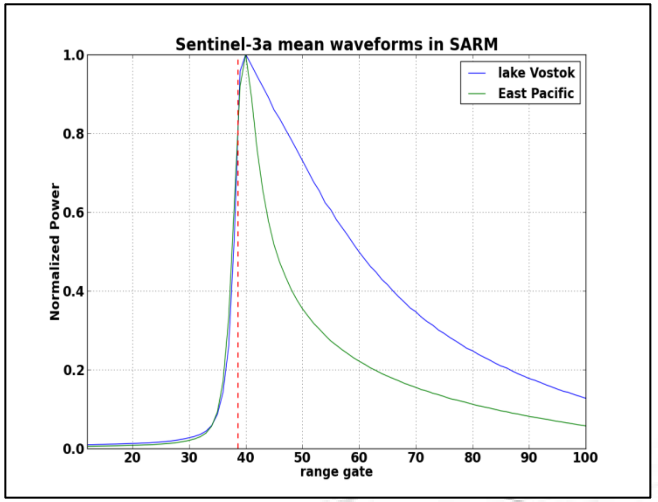
Surface échantillonée par porte distance

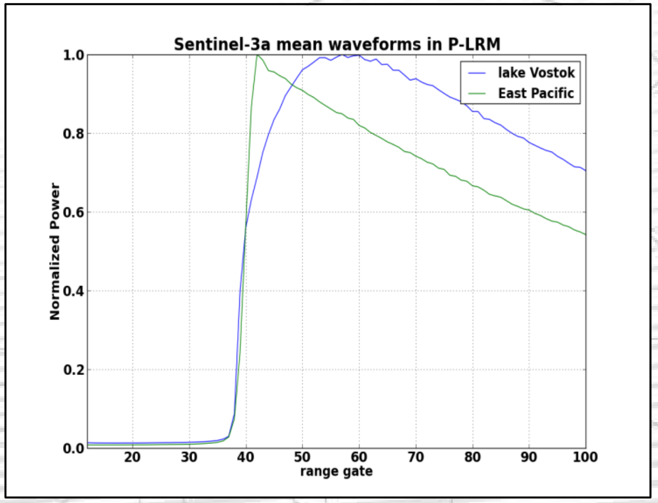


En P-LRM la surface échantillonée est constante : 2.4km2

⇒ En SAR, la surface échantillonnée par porte distance décroit très vite. Cela explique la forme très peaky de l'écho sur Océan (courbe verte, haut à droite). Par conséquent, sur les calottes polaires l'apport de la diffusion de volume sur les portes distance situées immédiatement après le front de montée ne déplace pas le point maximum d'énergie de l'écho. Le front de montée reste donc peaky, contrairement à ce que l'on observe en mode (P)LRM.

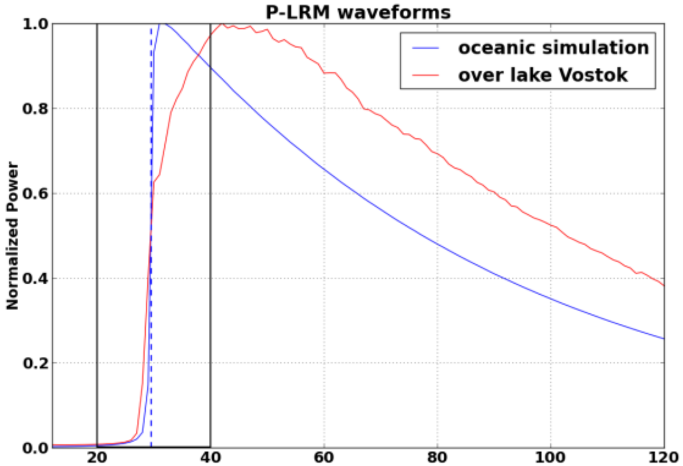
Comparaison échos Océan & Glace continentale

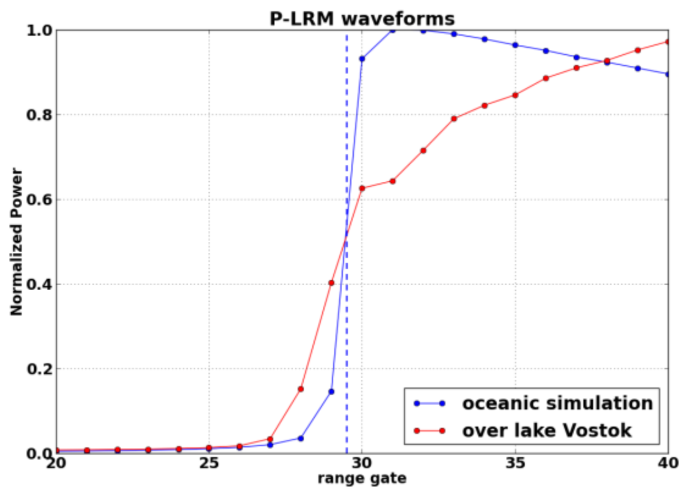




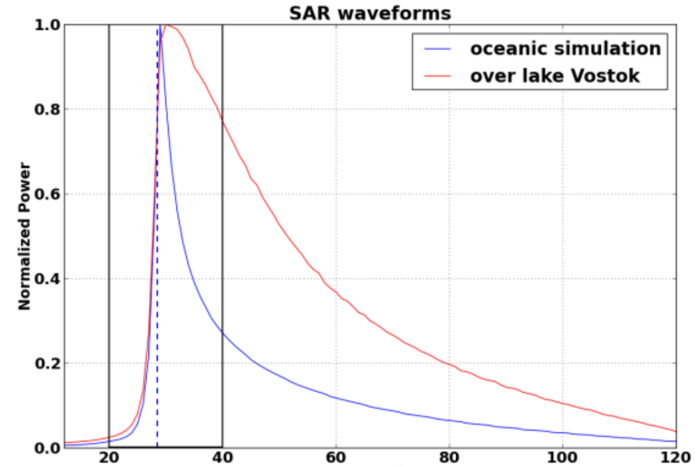
Comparaisons des WF PLRM / SAR de Cryosat-2, "Lake Vostok (rouge) vs Ocean (bleu)"

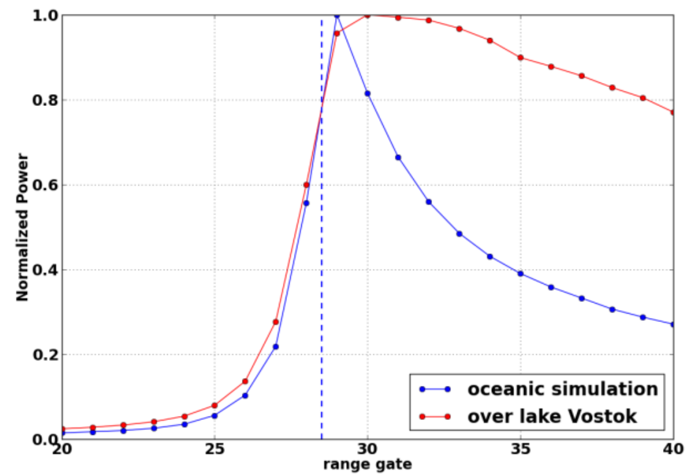
PLRM





SAR





Retracking TFMRA

Le retracking TFMRA (Threshold First Maximum Retracker Algorithm) est inspiré des travaux de Veit Helm [2014]. Il s'agit d'un retracking à seuil « amélioré ».

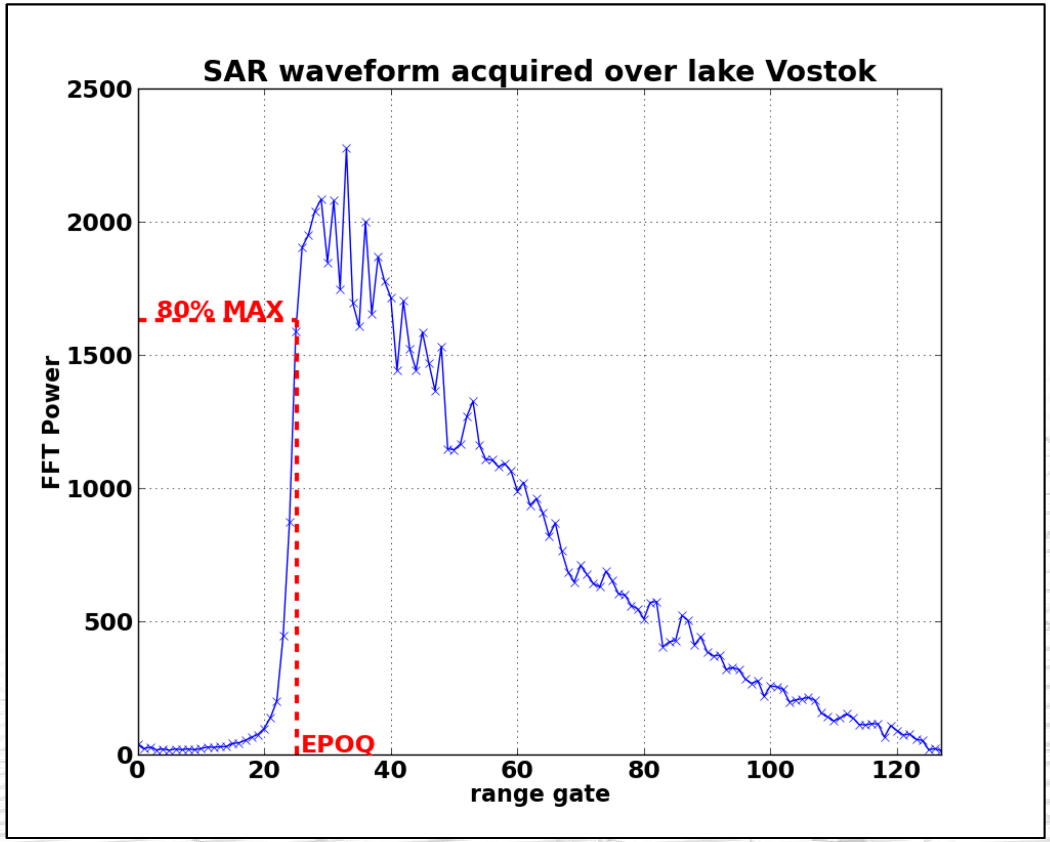
1 - Mesure à retracker

2 – Sur-échantillonnage x10

3 – Lissage

4 – Calcul de l'énergie max

5 – Position du point époque sur l'écho SAR initial à « MAX * threshold »

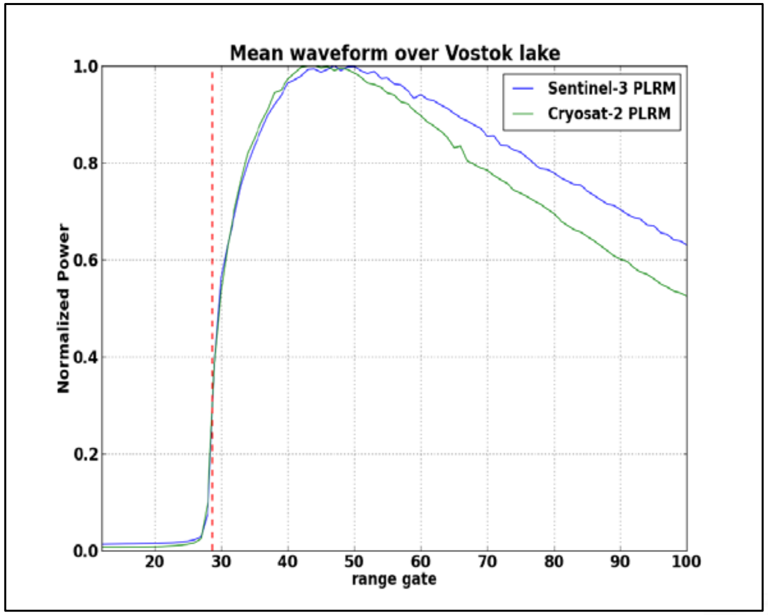


Le retracking TFMRA permet d'estimer deux paramètres :

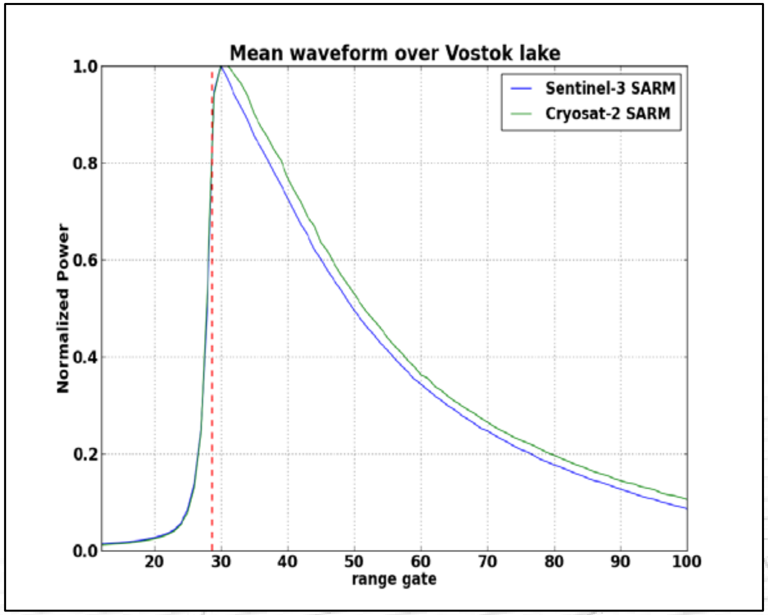
- un point époque
- un Sigma0 (max de l'écho lissé)

Waveform comparison with Cryosat-2

P-LRM



SARM



CS-2 and S3-a waveforms are "manually" superimposed. (10 range gates shift of the S3-a WF)

- In PLRM, trailing edge differences between Cryosat-2 and Sentinel-3A are mostly explained by the different antenna aperture.
- In SARM, Cryosat-2 mean waveform is slighty more volumetric ➔ to be investigated.

Assessment over lake Vostok

Waveform analysis

Surface elevation assessment

Surface slope effect

Fine scale topography

Mean biases between the surface elevation computed from Cryosat-2 LRM & Sentinel-3A SARM and three DEM.

➢ Biases between Cryosat-2 LRM and DEMs have been computed at the same time of year than the Sentinel-3a measurements (autumn 2014 & autumn 2015)

	Mean bias with DEM (cm)		
	S3A SAR autumn 2016	**CS-2 LRM autumn 2014**	**CS-2 LRM autumn 2015**
ERS1 DEM	**+15.2**	**+12.3**	**+20.4**
CS-2 DEM	**+12.6**	**+9.7**	**+14.3**
ICESat DEM	**+2.4**	**+8.4**	**+9.6**

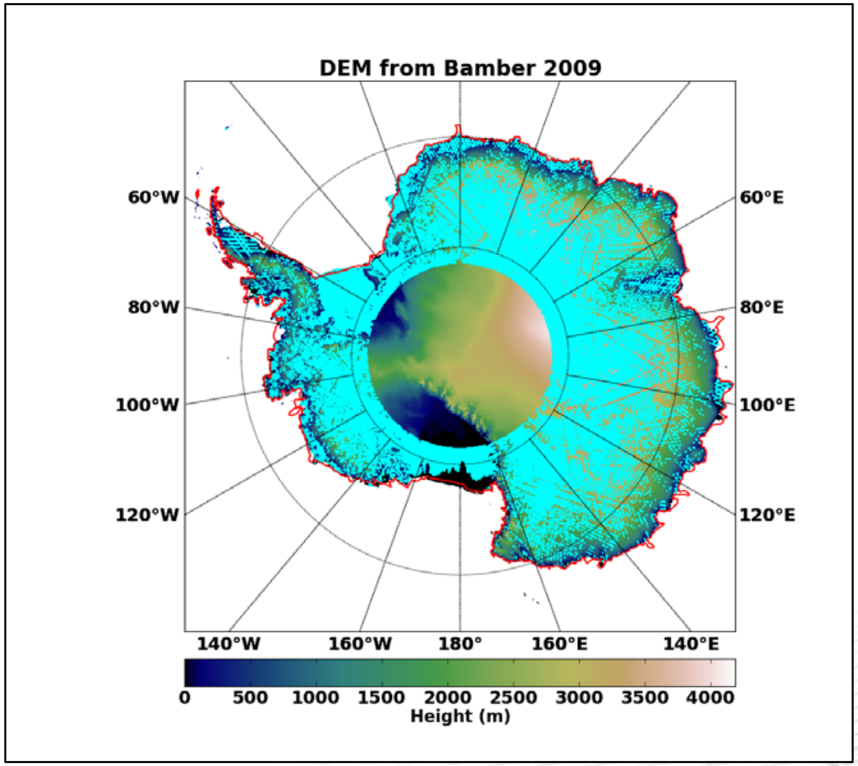
Biais moyens + écart type sur Vostok SAR & PLRM (complément diapo 14)

Mean biases between the surface elevation computed from Sentinel-3A SARM & Sentinel-3a PLRM and three DEM

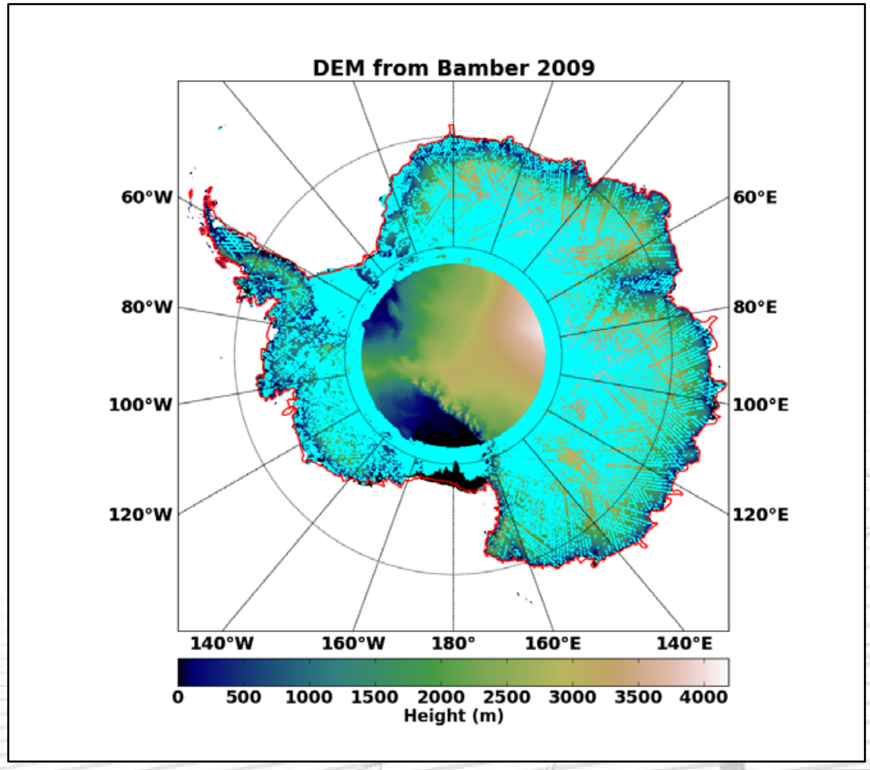
	S3A SAR		S3A PLRM	
	Mean bias	Standard dev.	Mean bias	Standard dev.
ERS1 DEM	+15.2	33.1	+14.7	33
CS-2 DEM	+12.5	16.8	+11.6	16.1
ICESat DEM	+2.4	36.4	+2	37.4

Mesures analysées pour les dépendances à la pente

Pente along-track < 0.025%

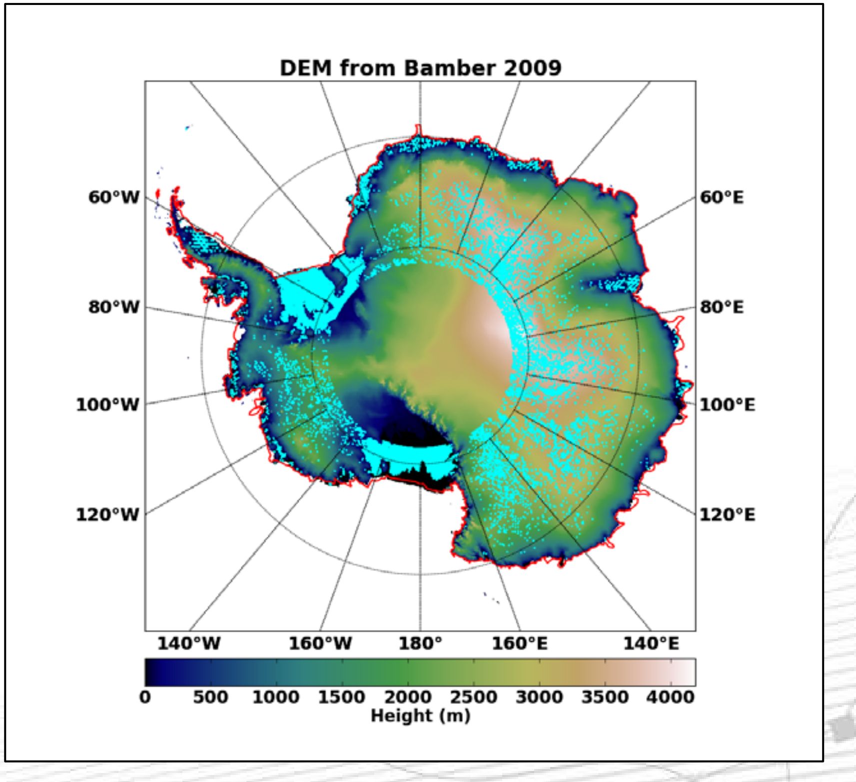


Pente across-track < 0.025%



Mesures analysées pour les dépendances à la pente

Pente along-track < 0.025% & Pente across-track < 0.025%



Biais théoriques en fct des pentes de surface

Pente (%) Pente (°)	0.01 0.0057	0.025 0.0143	0.05 0.0286	0.075 0.043	0.1 0.0572	0.15 0.086	0.2 0.115	0.25 0.143
simulation (m)	0.003	0.02	0.08	0.19	0.33	0.75	1.31	2.05
équation (m)	0.003	0.02	0.08	0.18	0.33	0.73	1.3	2.03
équation (m)	65	163	325	488	651	976	1302	1627

Pente (%) Pente (°)	0.3 0.172	0.4 0.229	0.5 0.286	0.75 0.43	1 0.573	1.25 0.716	1.5 0.859	2 1.146
simulation (m)	2.95	5.24	/	/	/	/	/	/
équation (m)	2.93	5.21	8.14	18.31	32.55	50.85	73.23	130.17
équation (m)	1953	2604	3255	4882	6510	8137	9764	13018