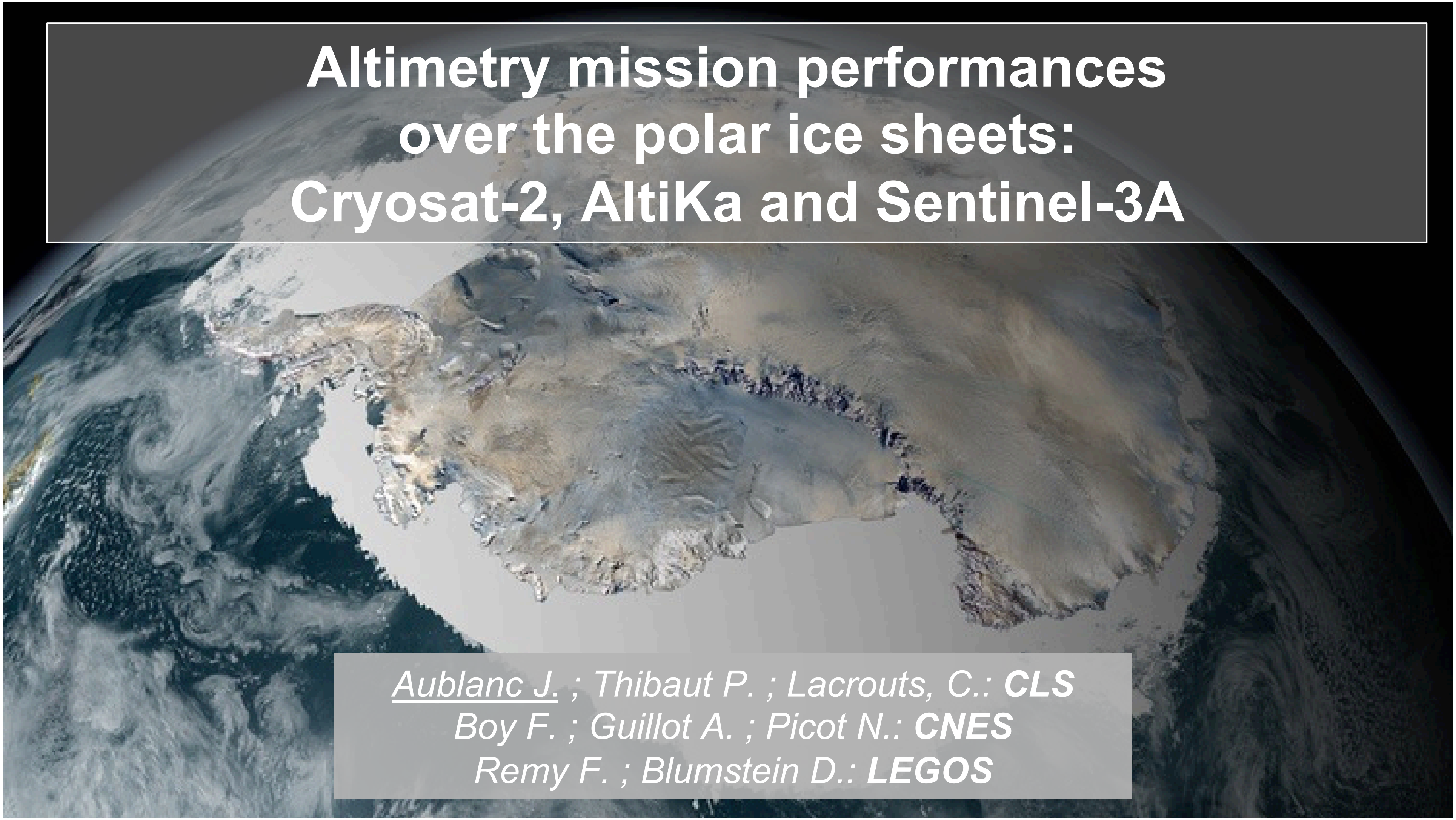


Altimetry mission performances over the polar ice sheets: Cryosat-2, AltiKa and Sentinel-3A

Aublanc J. ; Thibaut P. ; Lacrouts, C.: ***CLS***
Boy F. ; Guillot A. ; Picot N.: ***CNES***
Remy F. ; Blumstein D.: ***LEGOS***

Introduction

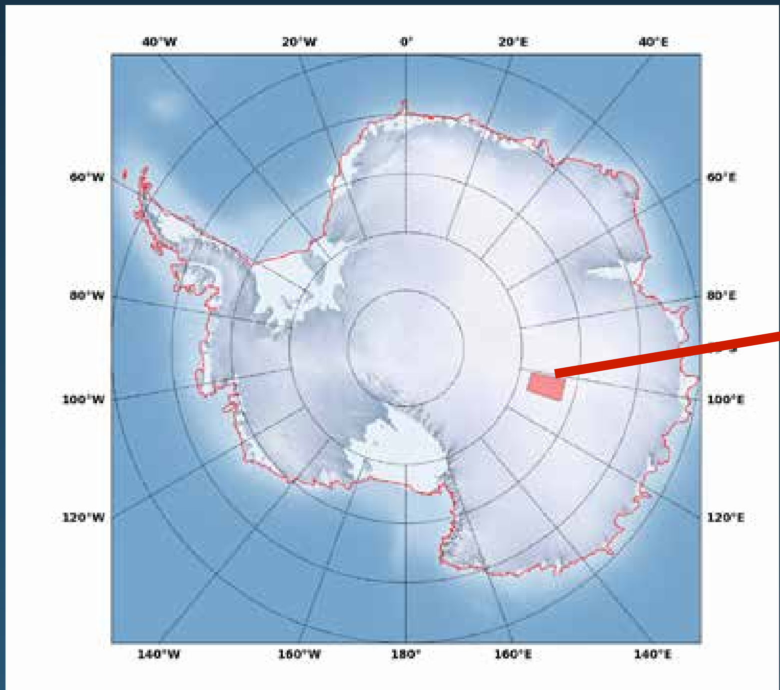
- Quantifying mass balance evolution of polar ice sheets is crucial for Sea Level Rise projection
- Three altimetry missions are currently observing polar ice sheets with different modes and frequency bands: **Cryosat-2 LRM & SARIn Ku** / **AltiKa LRM Ka** / **Sentinel-3A SAR Ku**
- **Ka band** should be much less sensitive to volume scattering than Ku band: penetration depth between 0.1 meter and 0.3 meter [Vincent et al., 2006]
- **The improved footprint of the SAR altimetry mode** should allow to retrieve fine topographic variations. The measure should be no, or weakly, sensitive to the along-track slope induced error.

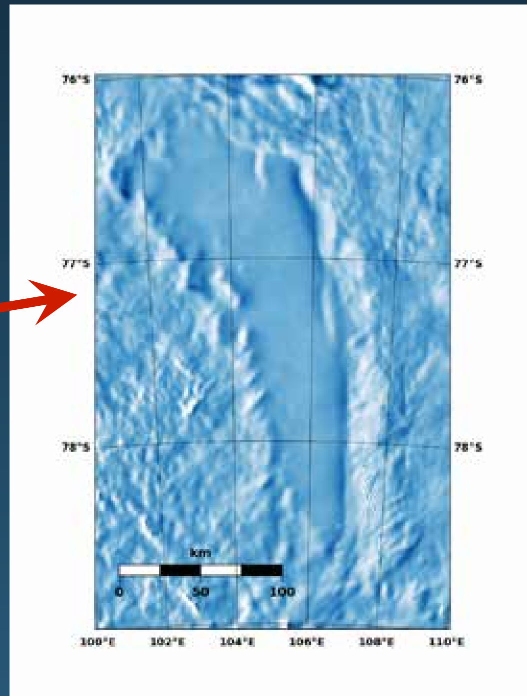
→ **This presentation gives an overview of the Cryosat-2, AltiKa and Sentinel-3A performances over Antarctica (studies funded by CNES)**

Altimetry data

- **AltiKa**: L1B waveforms from on-board processing => **LRM Ka band**
- **Cryosat-2**: L1B waveforms from CNES CPP => **LRM Ku band**
- **Sentinel-3A**: L1B waveforms from CNES S3PP => **SARM & P-LRM Ku band**

Lake Vostok calibration site





MODIS image of the lake Vostok

Lake Vostok calibration site

- **Extremely flat**

North-south slope tilting 60 m over ~250 km. Average slope is 0,025%. *[Siegert, 2005] ; [Ewert, 2012]*

- **Equilibrated local ice-mass balance**

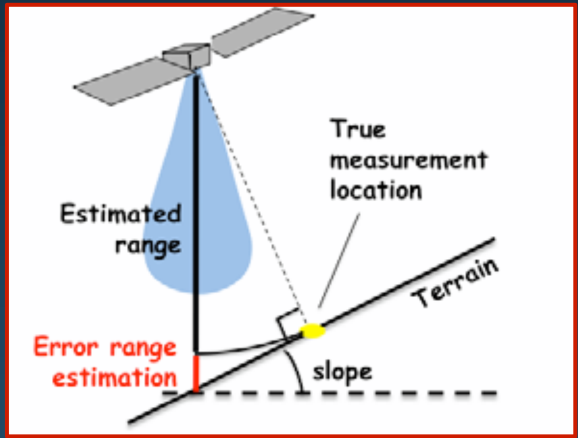
Mean snow accumulation: **6.24 cm/yr** *[Ekaykin et al., 2004].*
Mean vertical velocity of snow particle: **-6.17 cm/yr** *[Richter et al., 2014].*

- **Consequently, surface elevation is stable over time from GNSS studies**

From 2001 to 2013: +1mm/yr *[Richter, 2014]*
From 2001 to 2015: 0 mm/yr *[Schröder, 2017]*

Almost no slope induced error, surface stable over time: Lake Vostok is a perfect calibration site.

Altimetry slope-induced error

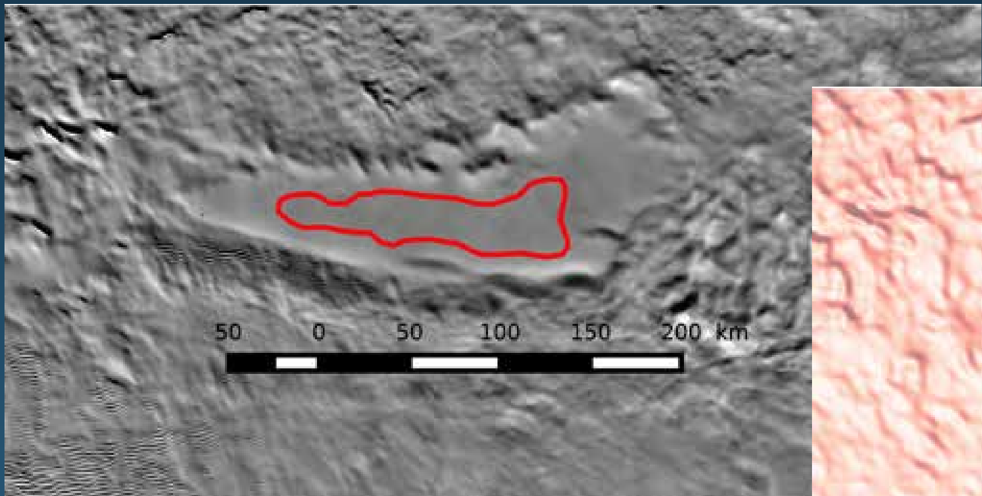


Slope induced error leads to an over estimation of the surface elevation.

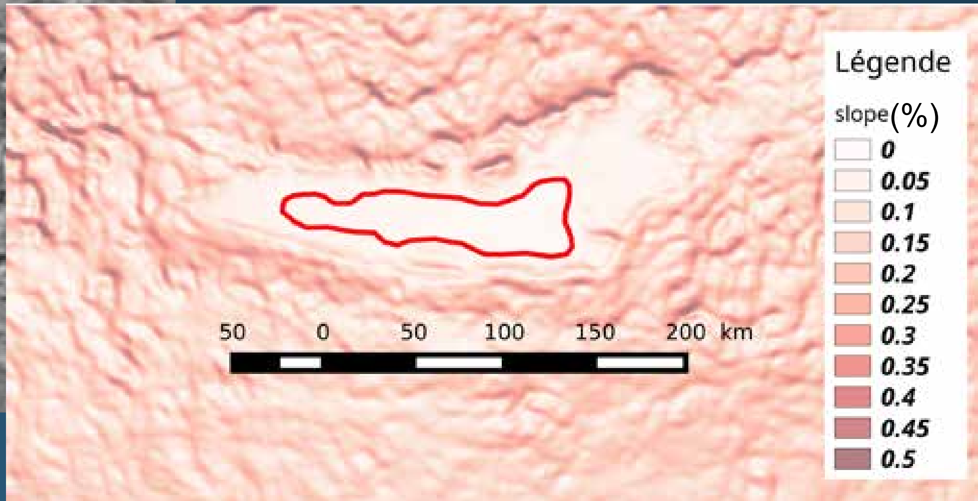
It is theoretically computed as: $\Delta h = (s^2 * He) / 2$
with : **s =** surface slope
He = effective altitude of satellite
[Wingham et al., 2004; Sandwell and Smith, 2014]

Definition of the study area (red line) thanks to a MODIS image (125m resolution) and the DEM from J.Bamber [2009].

*Surface slope on the area is in average 0.01%, this leads to theoretically bias the altimeter range of **~3mm** (displacement of surface return from nadir to POCA)*



MODIS image, 125m resolution

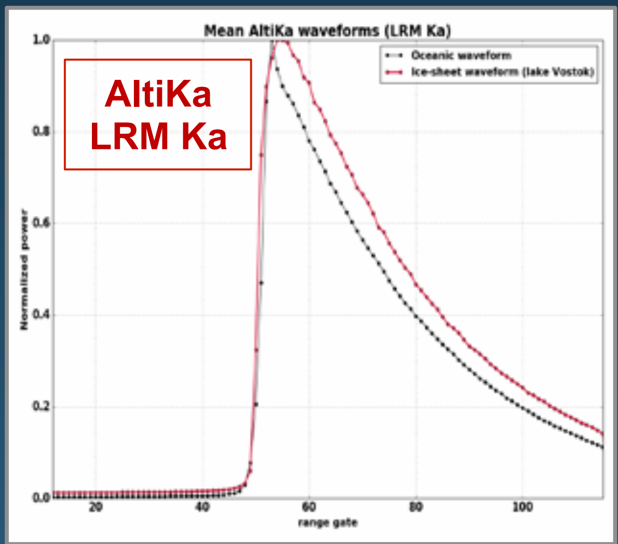


Surface slope derived from DEM of J.Bamber [2009]

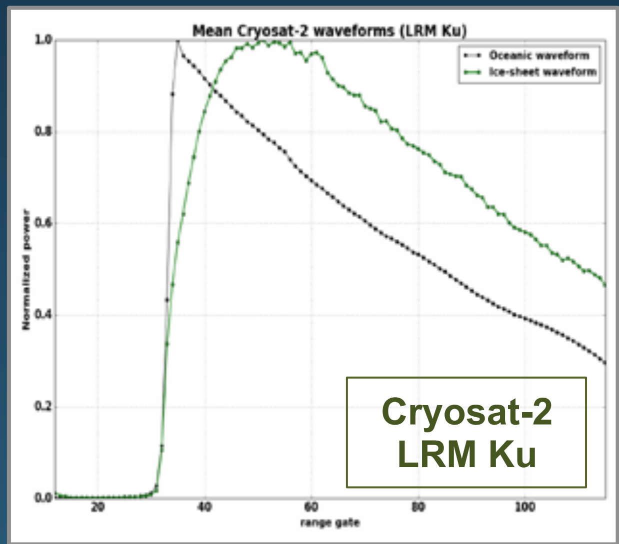
Comparison of mean Oceanic and LandIce waveforms (lake Vostok)

Methodology: Individual waveforms with a same epoch estimation are normalized and aggregated. For oceanic mean WFs, SWH estimation is 1 meter (+/- 20cm).

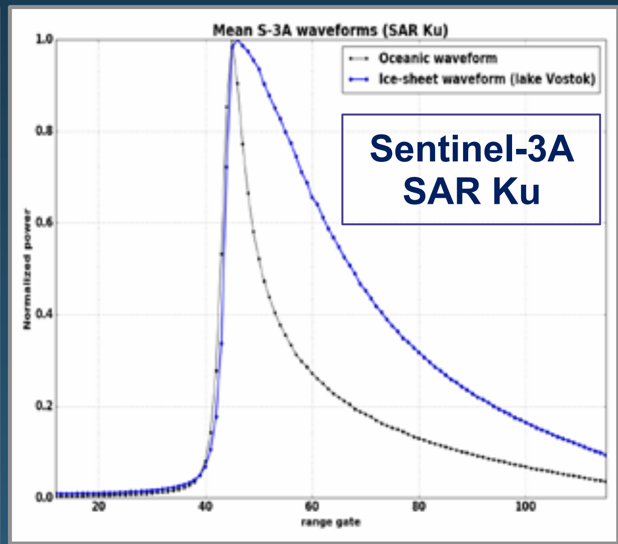
Oceanic and landice leading edge have been aligned on the window analysis.



518 WFs aggregated over LandIce



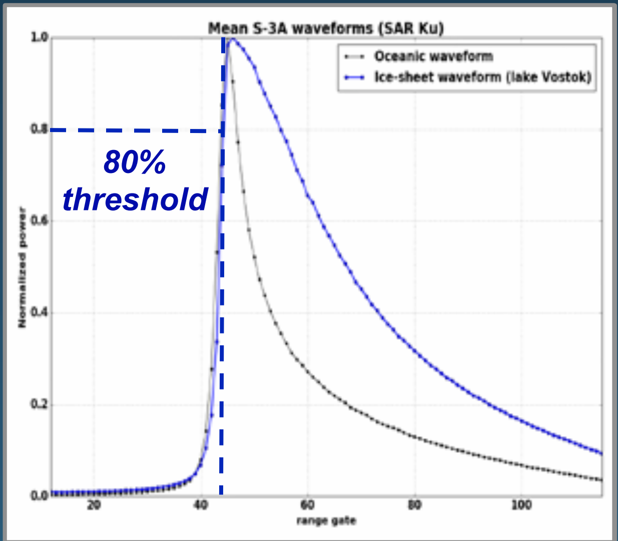
264 WFs aggregated over LandIce



874 WFs aggregated over LandIce

Waveform retracking & surface elevation estimation

- A **Threshold Peak Retracker (TPR)** is chosen to estimate the altimeter range (similar approach than Helm [2014]). In summary, retracking epoch is estimated at "*WF max * Threshold".*
- We choose the retracking threshold in order to estimate surface elevation at snow/air interface:



AltiKa LRM Ka: We make the assumption than volume scattering has no impact on the leading edge. Retracking point is positioned at mid-power (**50%**, same as ocean)

Cryosat-2 LRM Ku: We lower the threshold at **25%** to account for volume scattering, based on literature [Davis, 1997 ; Rémy, 2012]

Sentinel-3A SAR Ku: Leading edge looks non-sensitive to volume scattering, we choose **80%**, same threshold as Ocean. *We also estimate surface elevation from PLRM acquisitions with a* ***25%*** *threshold.*

Waveform retracking & surface elevation estimation

- Surface elevation is computed ad follow:

  H = Orbit – retracking range - Σ (instrumental corrections) - Σ (geophysical corrections)

- Same standard of geophysical corrections for all missions

- Surface elevation is calibrated on Jason-2 using oceanic CalVal studies performed at CLS (several cm of calibration)

- Jason-2 surface elevation estimation is supposed to be accurate in absolute elevation: **transponder bias is +1mm** in average [Mertikas, OSTST 2016], **SSH bias is +1.9cm** [Watson, OSTST 2016]

Mono-Mission Crossovers

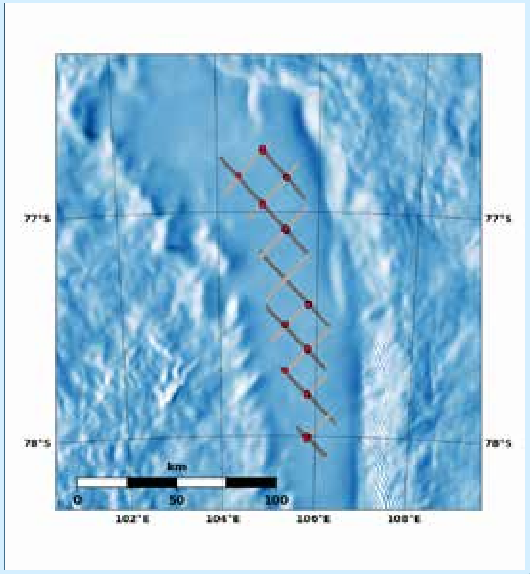
Methodology: Ascending / Descending measurements are directly compared when co-located in time and space: 10 days / 100 meters maximum.

Standard deviation at crossovers

AltiKa (Jan 2015 / Apr 2017): 85 crossovers
=> STD of Δh: 8.9cm

Cryosat-2 (Jan 2015 / Apr 2017): 94 crossovers
=> STD of Δh: 12.4cm

Sentinel-3A (Apr 2016 / Apr 2017): 35 crossovers
=> SAR STD of Δh: 17.7cm
=> PLRM STD of Δh: 14.3cm

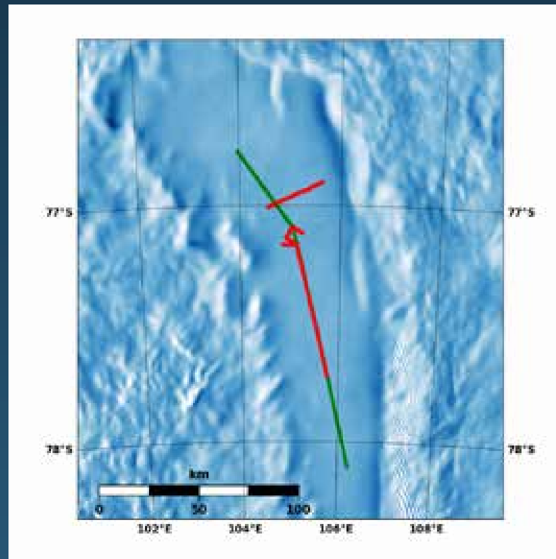


Comparison to GNSS acquisitions

Between 2001 and 2015 several kinematic GNSS profiles have been measured in the area of lake Vostok. GNSS data have been processed by the Technische Universität Dresden and are available for download. Courtesy to Schröder et al., [2017].

Two GNSS profiles have been measured in January 2011 & 2013:

- **2011 GNSS data:** **3374** measurements over the study area
- **2013 GNSS data:** **6880** measurements over the study area



Location of the GNSS acquisitions. 2011 (green) ; 2013 (red)

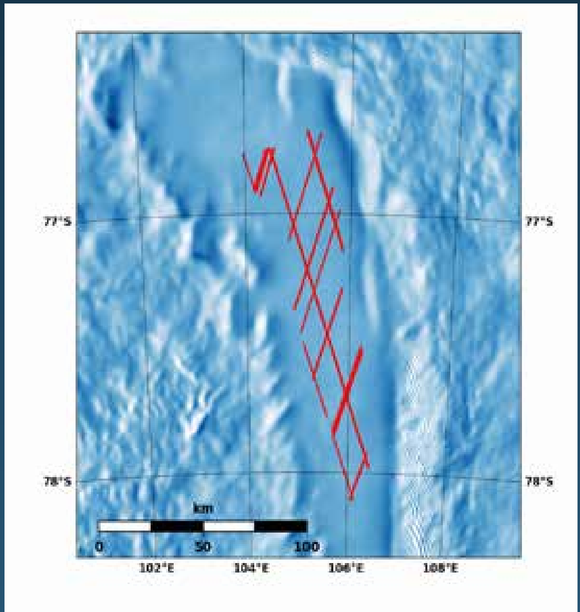
Comparison to ICESat acquisitions

- Comparison with ICESat elevations (GLAH12 v34) at crossovers (ICESat acquisitions between 2003 and 2009)

- ICESat brings two major advantages:
  1) No signal penetration into the snowpack. Surface elevation is estimated at snow/air interface.

  2) Footprint is 35 meters radius. No slope-induced error. *POCA = nadir.*

- Uncertainty of only several centimeters over lake Vostok [Ewert, 2012]



Location of the ICESat tracks on the study area (red)

Median bias and STD between altimetry and GNSS/ICESat at crossovers

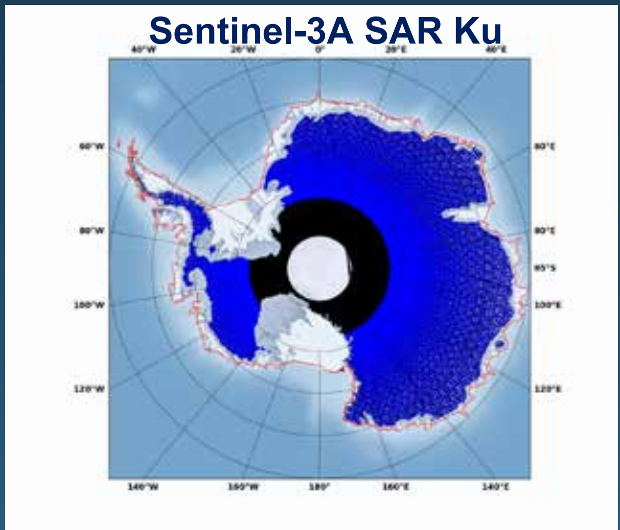
		Altika LRM Ka	Cryosat-2 LRM Ku	Sentinel-3A PLRM Ku	Sentinel-3A SAR Ku
GNSS (~200 Xovers)	Median bias (cm)	-22.6	-27.6	-22.2	-21.1
	STD (cm)	*13.2*	*16.3*	*17.3*	*22.6*
ICESat (~400 Xovers)	Median bias (cm)	-25.2	-24.7	-20.8	-18.9
	STD (cm)	*8.4*	*14.3*	*15.2*	*19.9*

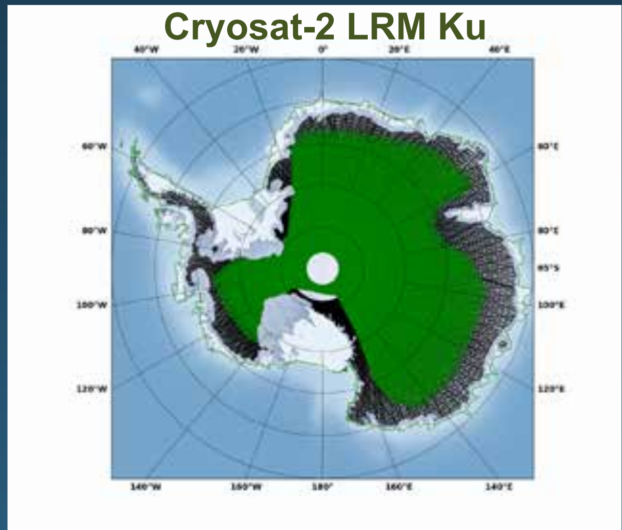
Altimetry data are acquired on a same period, from May 2016 to April 2017.

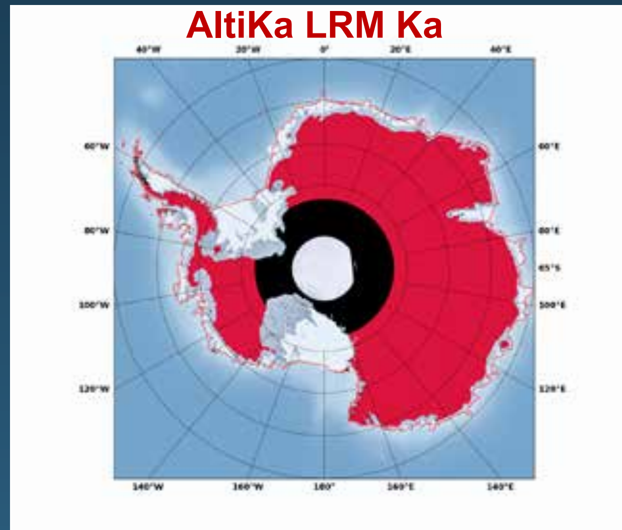
- The retracking thresholds provide overall a good alignment of the surface elevation between 3 missions.
- Altimetry underestimates surface elevation from 20cm to 25cm compared to GNSS and ICESat estimations.
  => Signal penetration into the snowpack
- Sentinel-3A SAR mode has the higher STD due to the high retracking threshold position on the leading edge: 80% (more sensitive to speckle noise and volume scattering).
- AltiKa measure is the most precise. High seasonal surface elevation variations have been noticed in Ku band. They should be related to snowpack properties (not real change of surface elevation) as described by Lacroix [2009], and need to be investigated/characterized.

Bias with ICESat acquisitions at crossovers

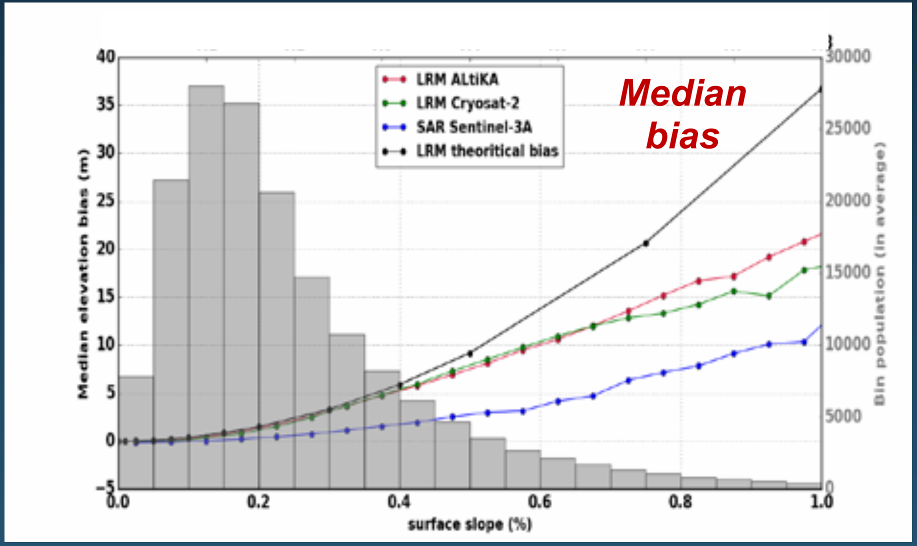
- Crossovers computed over the whole continent (surface elevation > 1000m). Direct crossovers: spatial co-location distance of 25 meters maximum.
- Altimetry measurements are not corrected for the slope-induced error and are acquired between September 2016 and April 2017. Bad waveforms are edited.

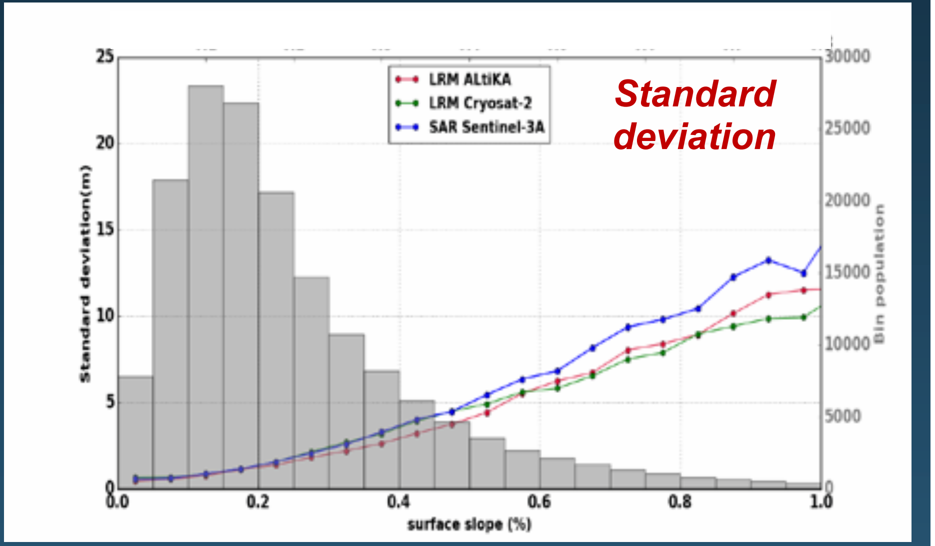






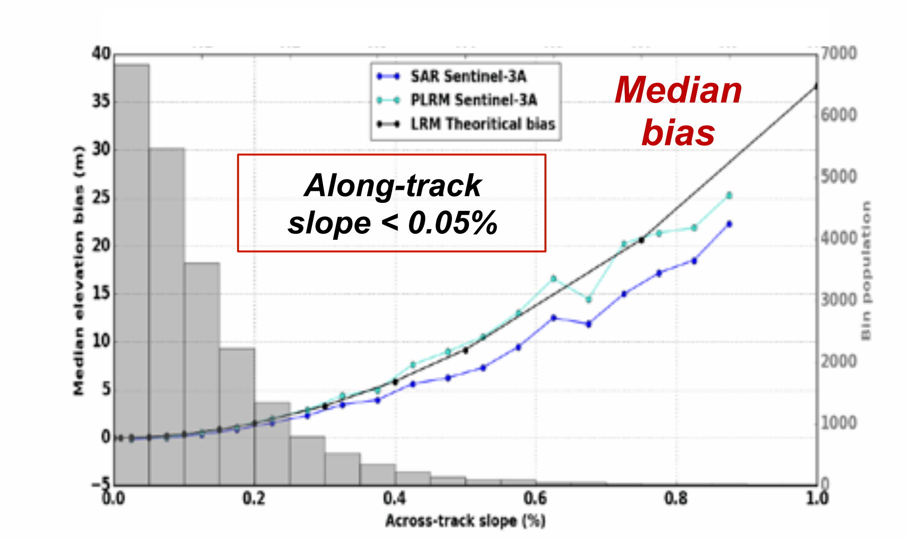
Bias with ICESat acquisitions at crossovers function of estimated surface slope (Bamber DEM)



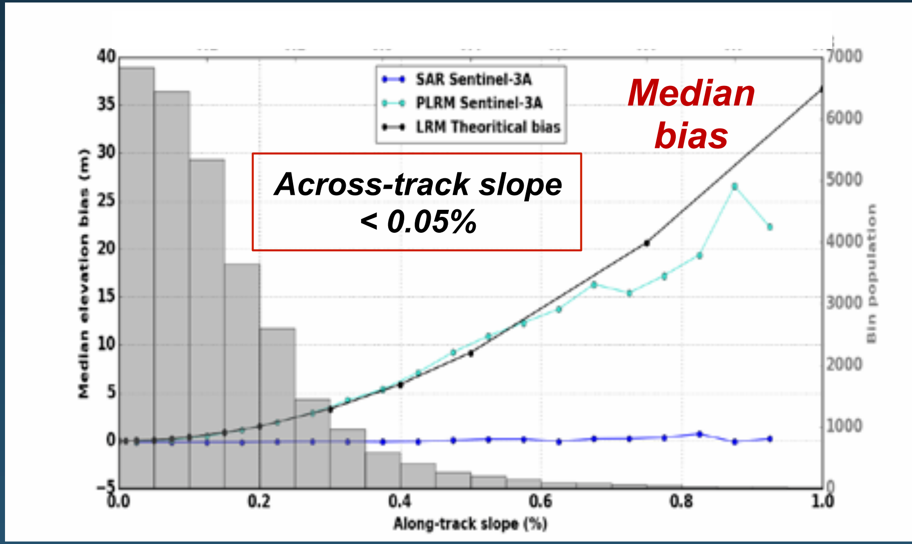


Similar bias and precision for both LRM missions (Cryosat-2 / AltiKA).
Lower bias in SAR mode due to the 300m along-track footprint.

ICESat bias function of surface slope: direct comparison of Sentinel-3A SAR and PLRM



Median bias function of across-track slope. Measurement acquired over along-track slopes < 0.05%

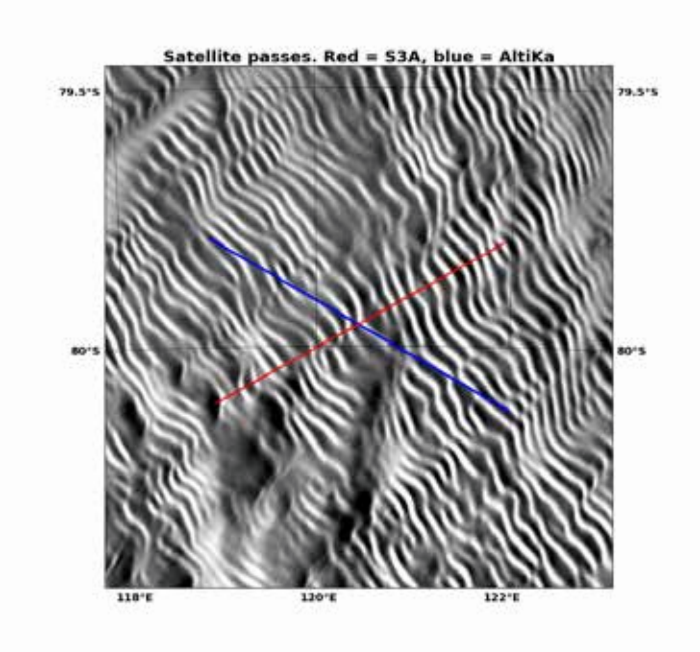


Median bias function of along-track slope. Measurement acquired over across-track slopes < 0.05%

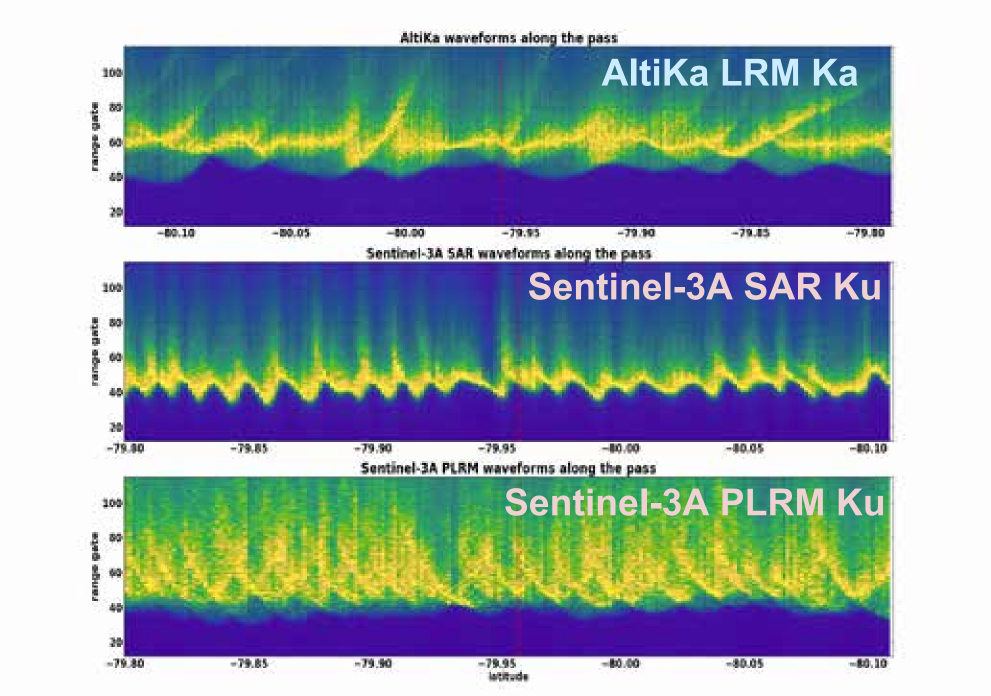
SAR mode has no sensitivity to along-track slope

Observations of megadunes by Sentinel-3A

meagadunes are surface oscillations from 2 to 8 meters in amplitude and 2 to 5 kilometers in wavelength [Ekaykin et al., 2016]



Sentinel-3A track (red) / AltiKa track (blue)



Observations of megadunes by Sentinel-3A

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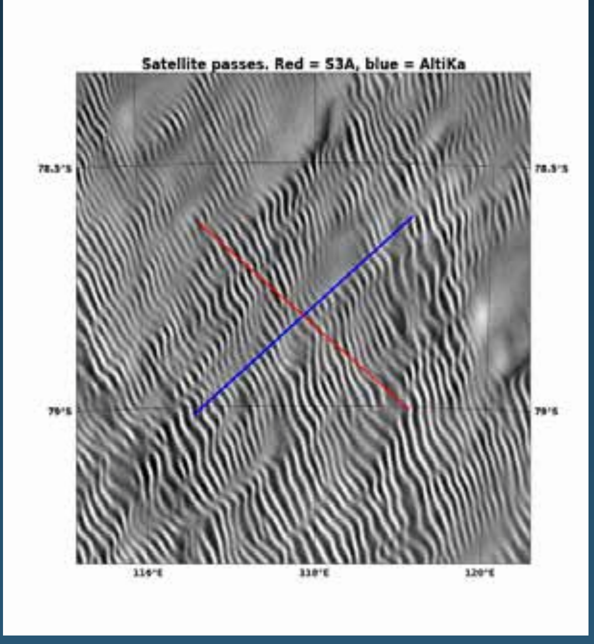
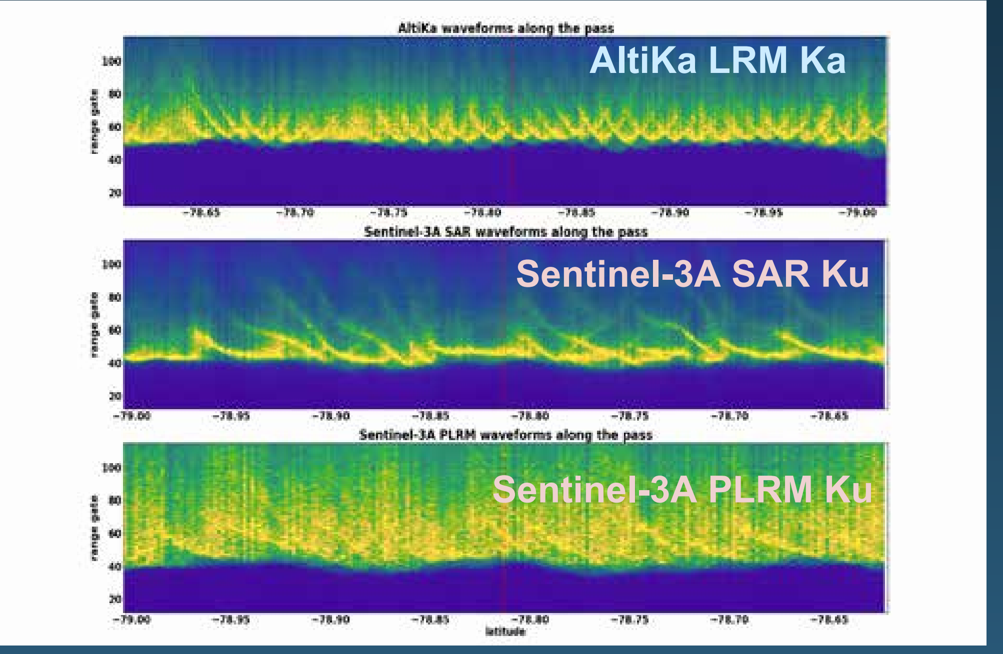




Sentinel-3A track (red) / AltiKa track (blue)

Conclusions

Assessment of the surface elevation over lake Vostok.

- The chosen retracking thresholds provide a good alignment of the absolute surface elevation estimated by the 3 missions.
- Surface elevation is underestimated by 20 to 25 cm compared to GNSS and ICESat acquistions. Most probably due to signal penetration into the snowpack.
- The retracking algorithm is empirical and the thresholds are arbitrary. The estimated surface elevation is very sensitive to these thresholds. Preliminary results show that the estimated elevation in Ku band can change by few decimeters because of variation of the snow properties, independently from surface height.

Conclusions

Comparison to ICESat over the whole continent

- LRM missions (Cryosat-2 & AltiKa) have overall similar performances. Precision gets worse with the surface slope intensity.

- **SAR mode proves to be non sensitive to the along-track slope and is able to retrieve fine scale topographic variations such as megadunes.**

Perspectives to this study

- To characterize precisely the effect of snow properties variations on the altimetry estimations (Ku/Ka bands) and develop retracking solutions to account for.

- To assess other areas than lake Vostok, with different surface roughness and snow properties.

Perspectives

On going studies at CLS

- Analysis of SARIn baseline C data (from L1B) over the margins steep surfaces
- Developing methods for generating a Digital Elevation Model over Antarctica combining Cryosat-2, AltiKa and Sentinel-3A data.

Future missions

The current altimetry missions and the future launches of Sentinel-3B and ICESat-2 (2018 both) will provide an opportuniy to improve existing DEMs

Cryosat-3 / Sentinel-9 mission: Potentially implementing dual Ku/Ka bands altimeter.

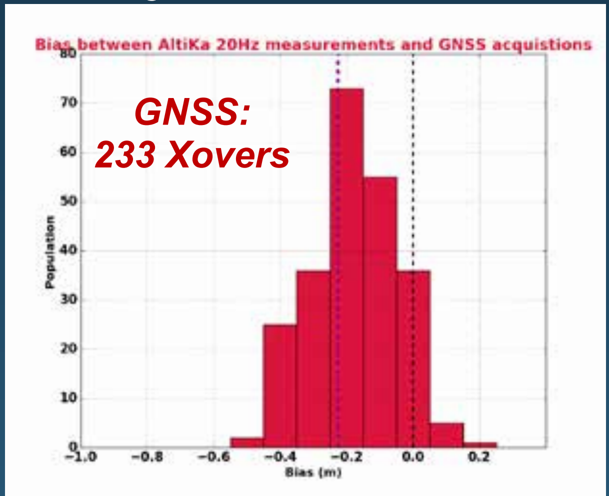
Backup slides

Bias with GNSS acquisitions and ICESat at crossovers

Methodology: 20Hz Altimetry and GNSS/ICESat measurements are directly compared if they are co-located in space (50 meters maximum). Altimetry data are acquired on a same period, from May 2016 to April 2017

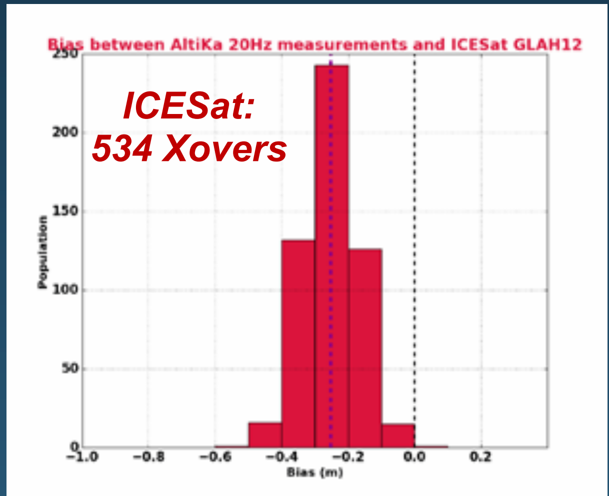
Altika LRM Ka

Histogram of bias with ***GNSS***



Median bias : -22.6cm
Standard deviation : 13.2cm

Histogram of bias with ***ICESat***



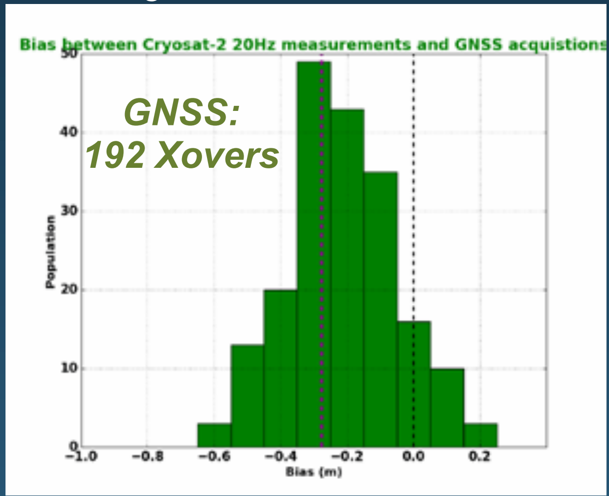
Median bias : -25.2cm
Standard deviation : 8.4cm

Bias with GNSS acquisitions and ICESat at crossovers

Methodology: 20Hz Altimetry and GNSS/ICESat measurements are directly compared if they are co-located in space (50 meters maximum). Altimetry data are acquired on a same period, from May 2016 to April 2017.

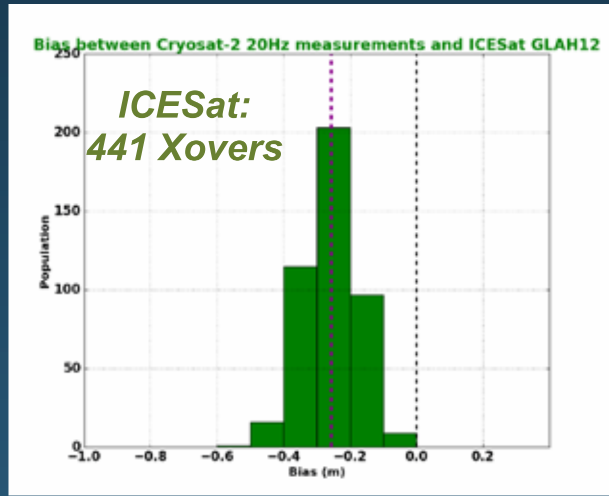
Cryosat-2 LRM Ku

*Histogram of bias with **GNSS***



Median bias : -27.6cm
Standard deviation : 16.3cm

*Histogram of bias with **ICESat***



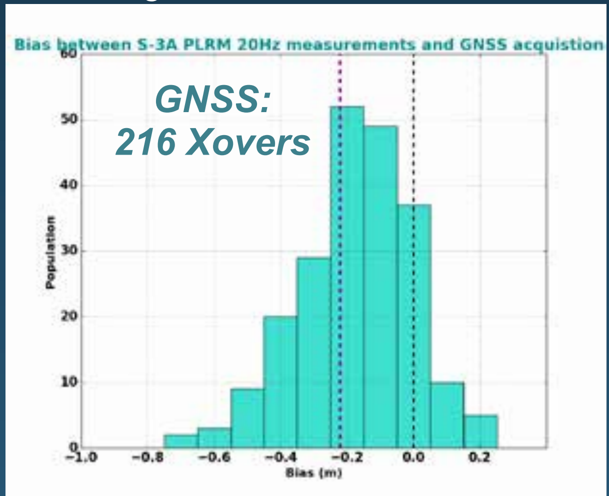
Median bias : -24.7cm
Standard deviation : 14.3cm

Bias with GNSS acquisitions and ICESat at crossovers

Methodology: 20Hz Altimetry and GNSS/ICESat measurements are directly compared if they are co-located in space (50 meters maximum). Altimetry data are acquired on a same period, from May 2016 to April 2017.

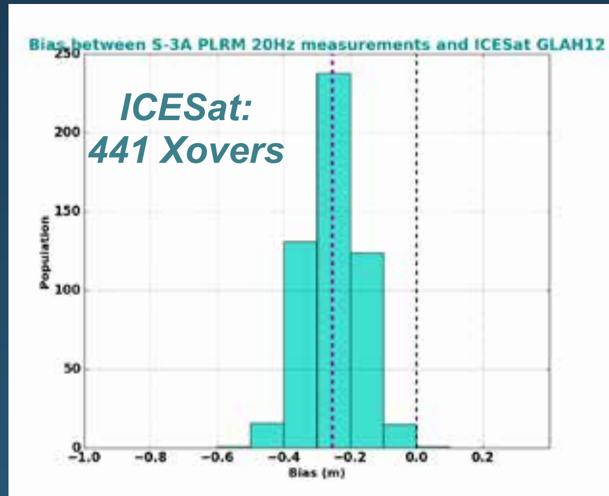
Sentinel-3A P-LRM Ku

Histogram of bias with ***GNSS***



Median bias : -22.2cm
Standard deviation : 17.3cm

Histogram of bias with ***ICESat***



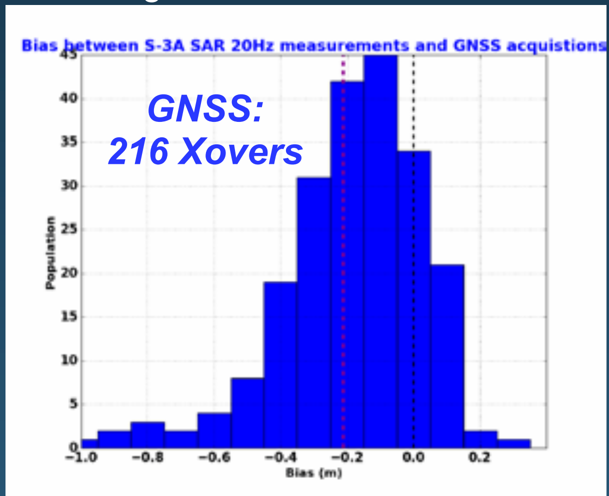
Median bias : -20.8cm
Standard deviation : 15.2cm

Bias with GNSS acquisitions and ICESat at crossovers

Methodology: 20Hz Altimetry and GNSS/ICESat measurements are directly compared if they are co-located in space (50 meters maximum). Altimetry data are acquired on a same period, from May 2016 to April 2017

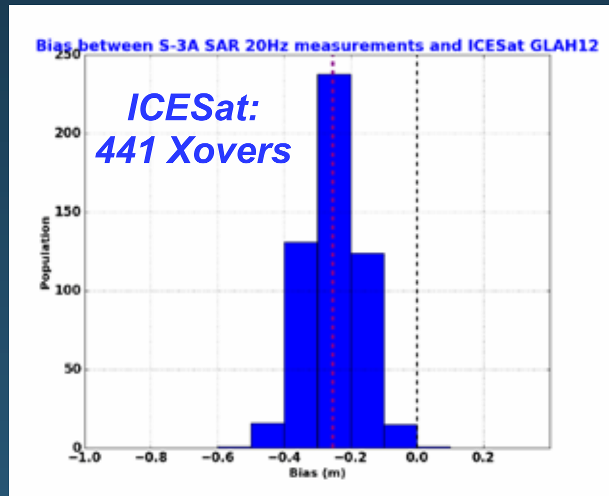
Sentinel-3A SAR Ku

Histogram of bias with ***GNSS***



Median bias : -21.1cm
Standard deviation : 22.6cm

Histogram of bias with ***ICESat***

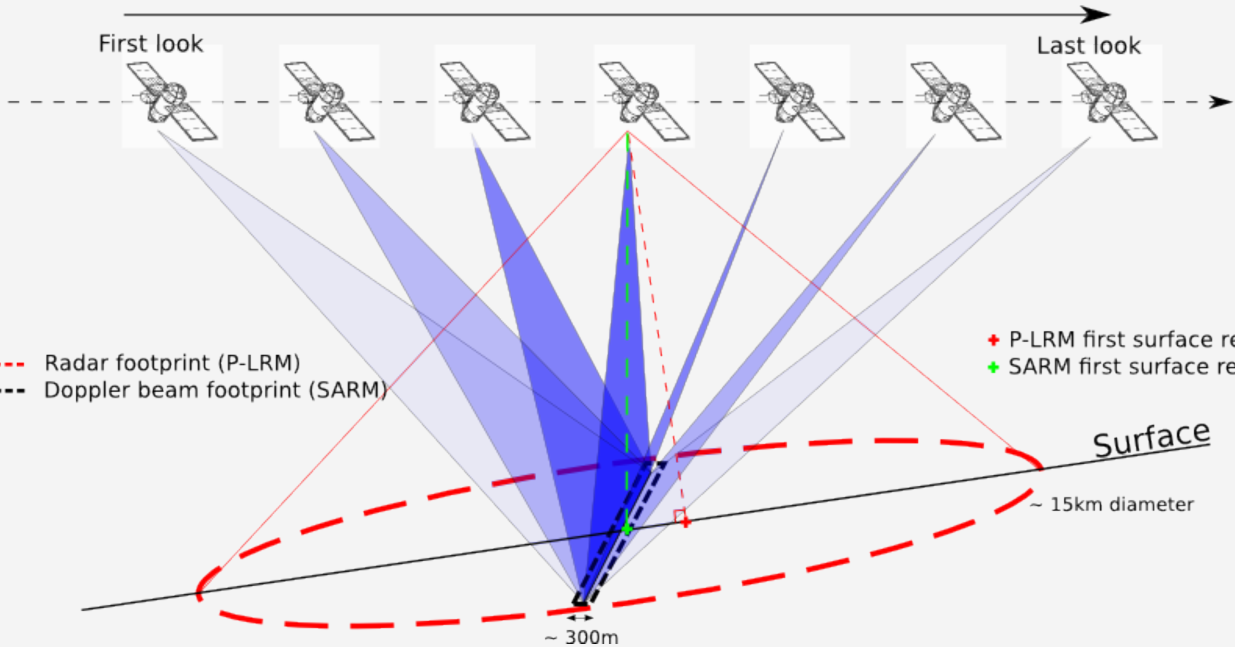


Median bias : -18.8cm
Standard deviation : 17.9cm

Geophysical corrections standards

- Dry & Wet tropospheric correction from **ECMWF**
- Ionospheric correction from the **Global Ionospheric Map (GIM)**
- Solid Earth Tide from **Cartwright model**
- Ocean Loading Tide from **GOT4v8**
- Geocentric Polar Tide from **Wahr [1985]**

Along-track surface slope effect (Cryosat-2 illustration)



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

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