Impact of the range walk processing in the Sentinel-3A sea level trend

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OSTST 19-23 October 2020, virtual meeting

Context of the study: Sentinel-3A GMSL trend

From B.Meyssignac presentation at last Sentinel-3 ESL council meeting (September 2019)

- **SAR mode processing:** A strong drift has been detected on the **Sentinel-3A** GMSL:
  - **+1.7±1.2 mm/yr** by comparison to Jason-3
  - **+2.2±1.2 mm/yr** by comparison to AltiKa
- **PLRM processing:** S3A GMSL drift is reduced by ~1.4 mm/yr

estimations made on Sentinel-3A PDGS data

From JC.Poisson presentation at last OSTST (October 2019)

Sentinel-3A SAR PTR is drifting: a dissymmetry has been detected, not properly accounted for into the ground segment. The estimated impact on SSH from simulation (impact range + SSB) is:

- **SAR mode processing: ~ +0.28 mm/yr**
- **PLRM processing: ~ +0.32 mm/yr**

Even by correcting the **SAR Sentinel-3A range drift** by ~0.3mm/yr, the drift will remain above 1mm/year

Plan

1 – Starting point of the study: differences between S3PP v1.4 & v2.1

2 – The range walk correction

3 – Impact on real data

4 – Rationale for the range walk impact, from simulation analyzes

Starting point of the study

Evolution of the SAR/PLRM range bias from CLS CalVal analyses

- **S3PP: Sentinel-3 Processing Prototype developed at CNES** => a dedicated level-1 / level-2 processing chain of the Sentinel-3 data, fully validated.

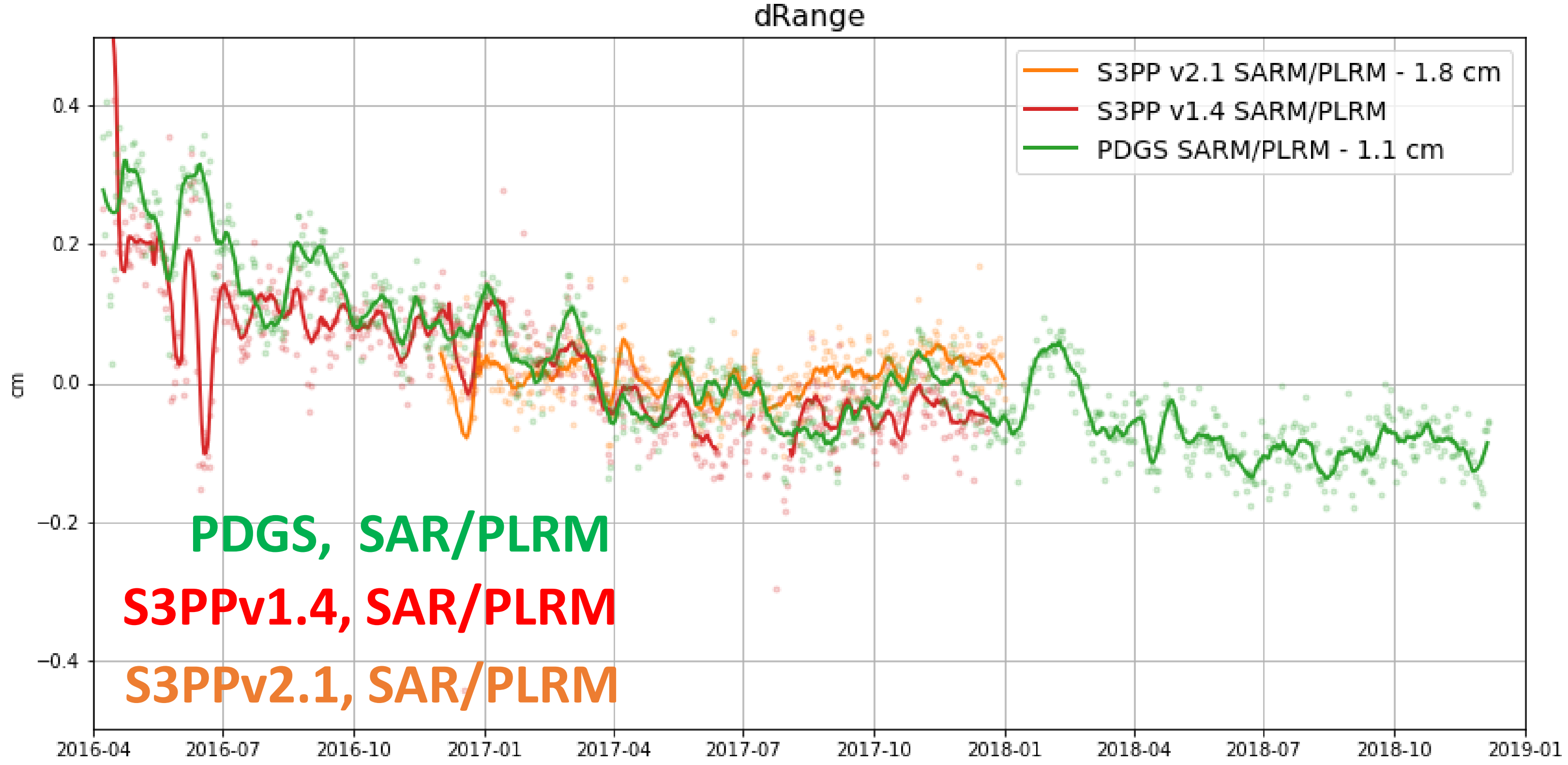
- **Directly inspired from the CryoSat-2 Processing Prototype:** *Boy et al. [2017] : « CryoSat-2 SAR-Mode over oceans: Processing methods, global assessment, and benefits »*

- **Three level-1 processing modes available:**
  - Conventional **Pseudo-LRM**
  - **SAR unfocused** mode
  - **LR-RMC:** Low Resolution with Range Migration Correction mode

  More details in Boy et al. "New stacking method for removing the SAR sensitivity to swell", OSTST Meeting 2017

Starting point of the study

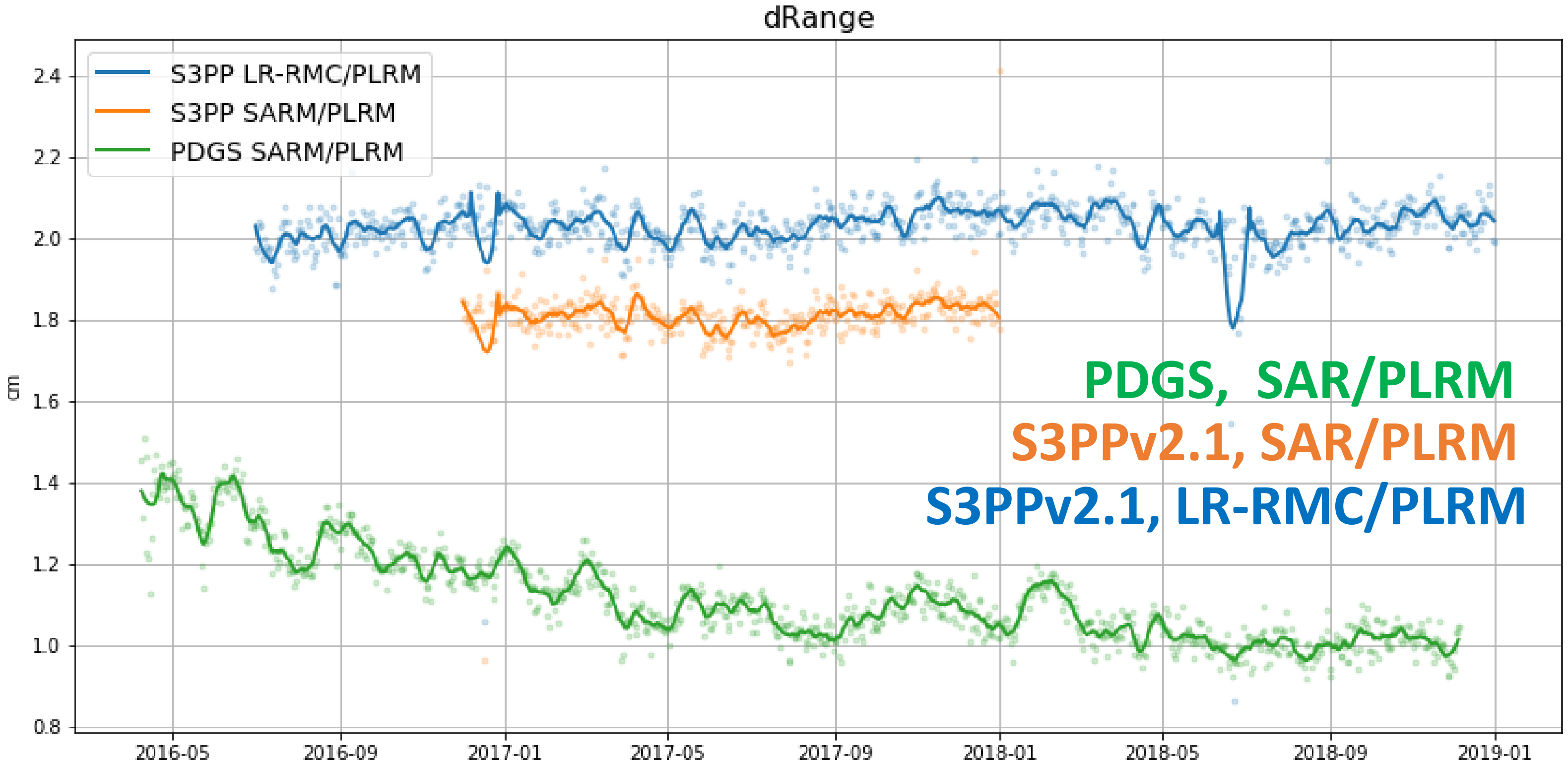
Evolution of the SAR/PLRM range bias from CalVal analyses



Only a single year processed in **S3PPv2.1**, but the SAR/PLRM range bias appears to be much more “stable” compared to **PDGS** & **S3PPv1.4**

Starting point of the study

In addition, evolution of the **LR-RMC/PLRM** range bias with **S3PPv2.1**



- **Over a 2 years period the S3PP LR-RMC/PLRM range bias is stable**
- Even if SAR unfocused & LR-RMC are two very different measures, they share many common processing at level-0/level-1 in the S3PP

What creates the different behavior between S3PP v1.4 & v2.1 ?

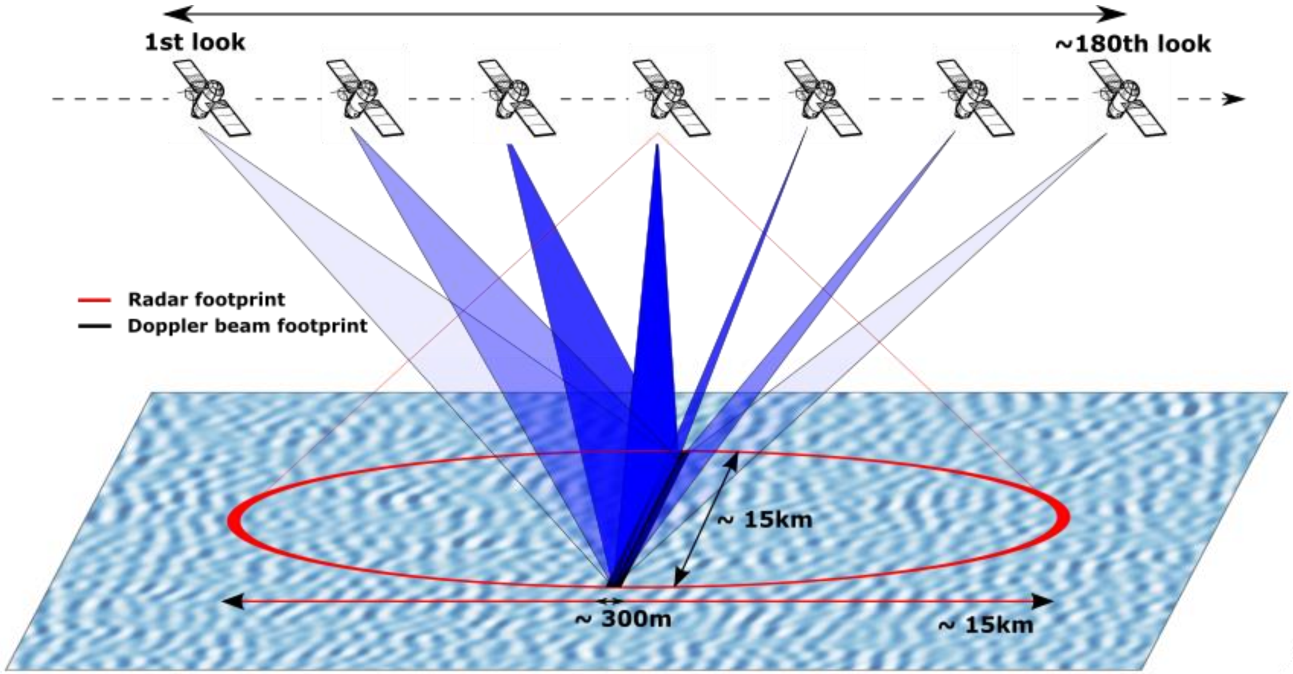
List of major/minor modifications between the 2 S3PP versions

- **Range walk implementation (SAR & LR-RMC)**
- When performing zero-masking at level-2, the « 0 » values brought back by migration are set to thermal noise to make better consistency between L2/L1
- The energy of the DDM beams is set to thermal noise for the gates [112-128], before range migrations, to avoid the shift of aliased er
- An anoma
- The tracke
- Phase var
- CAL-2 is applied at the beginning of level-0, not after burst alignment (using the FAI) (SAR & LR-RMC)
- In the level-2, FSSR are updated every seconds (SAR & LR-RMC)
- Thermal noise is adjusted in SAR mode to make it consistent wrt the number of looks (SAR mode only)
- New waveforms database (SAR mode only)
- Modification of the model waveform normalization in the level-2 retracking (SAR & LR-RMC)

Several modifications were analyzed, and we found that range walk was the only major modification acting on the range drift

Range walk correction principles

In introduction, reminder of the **SAR unfocused** concept: each 20Hz measurement corresponds to a Doppler band (~300m width) sampled at different satellite look angles



Range walk correction principles

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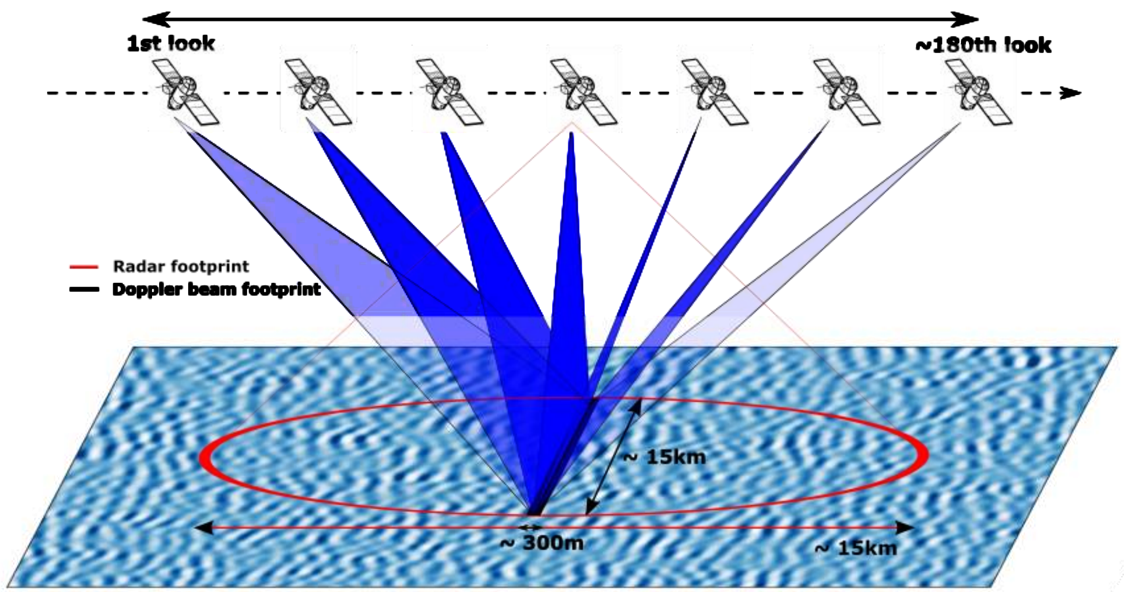
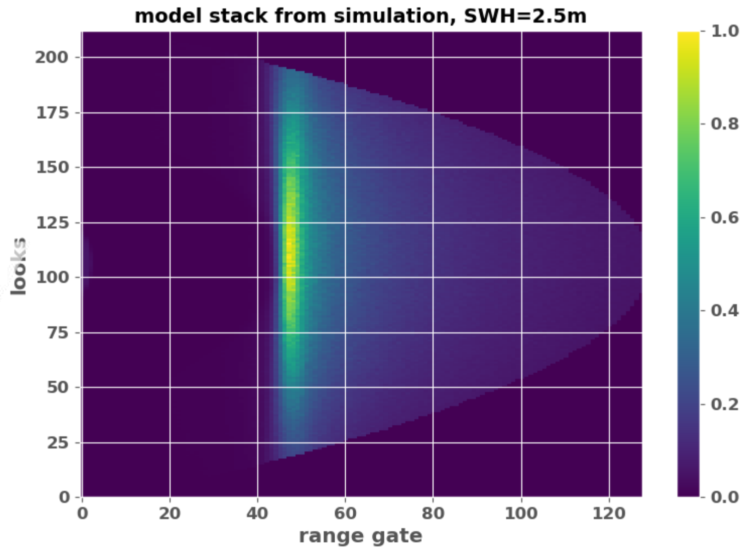
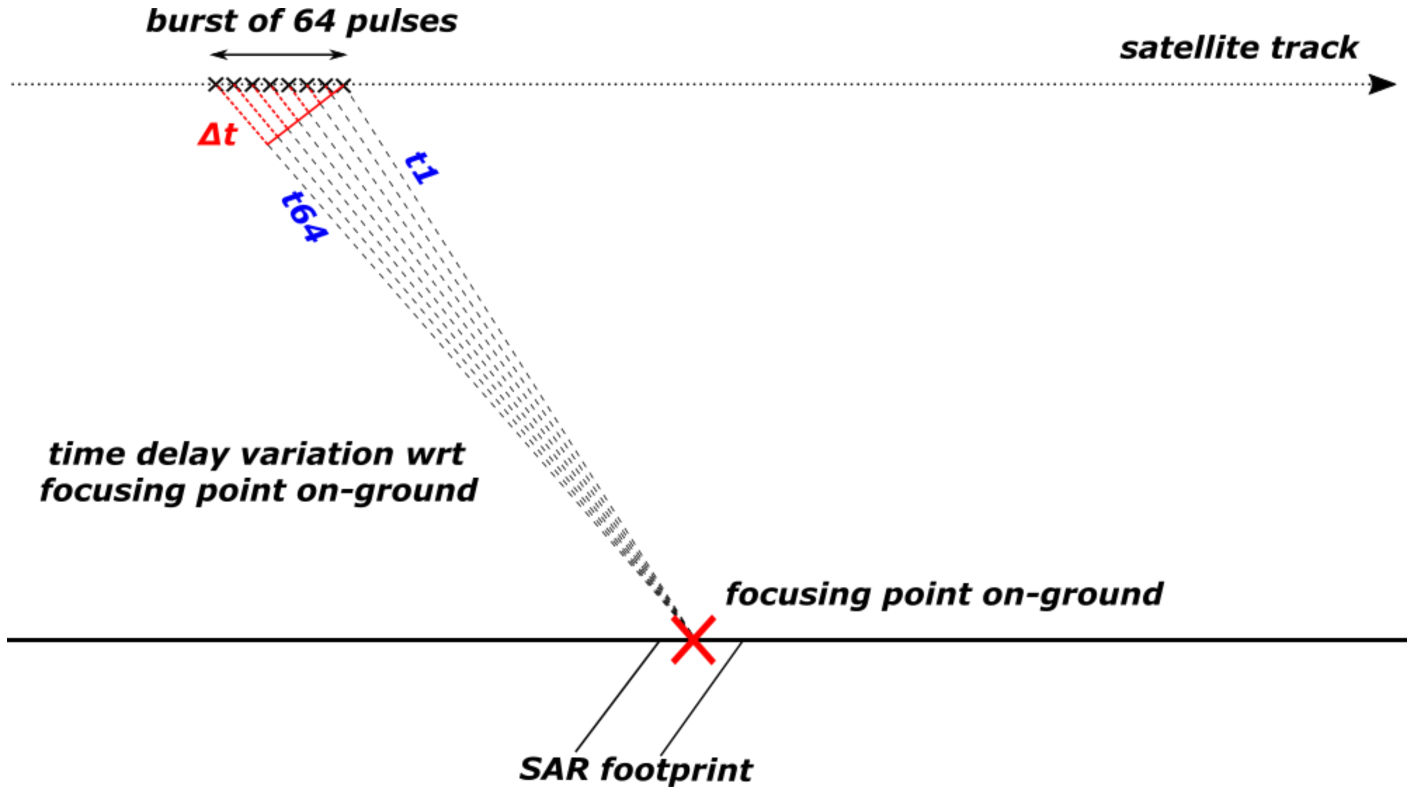


Stack after range migrations

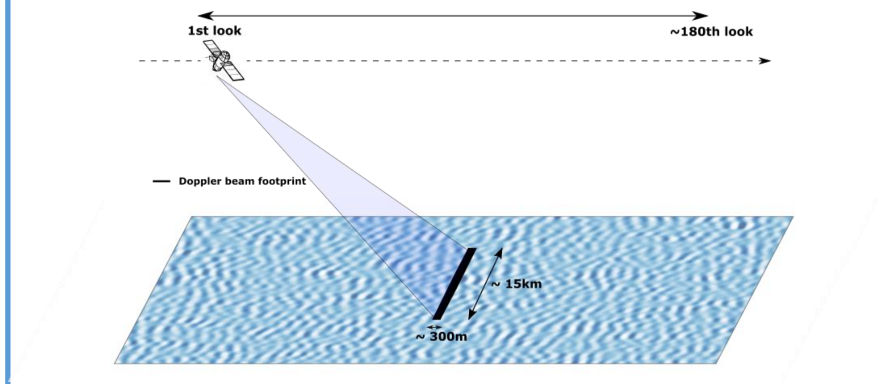


Range walk correction principles

Schematic illustration



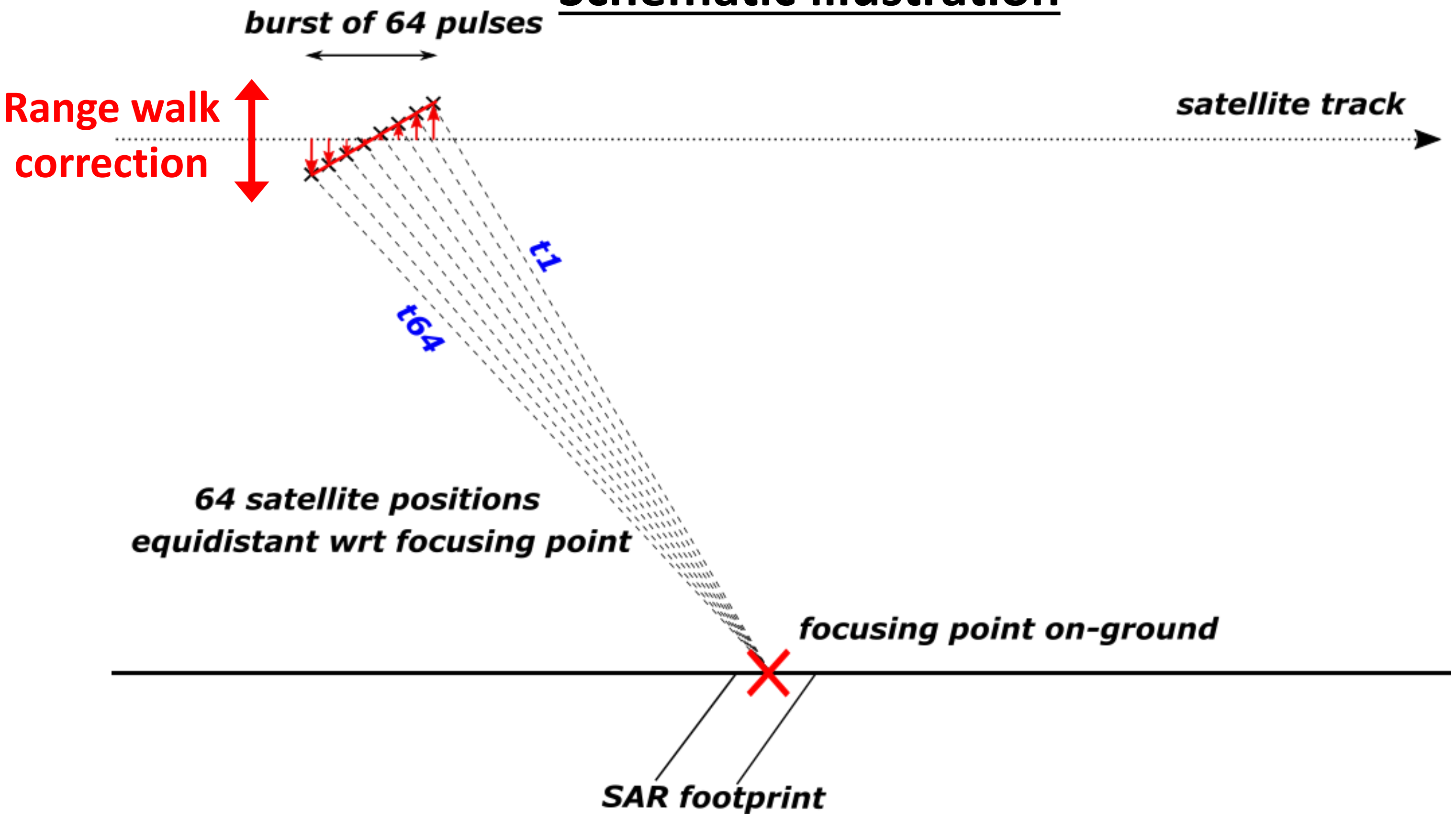
Note: to make the illustration, the scheme is out of scale. Spatial distance between two pulses is ~40cm. Horizontal distance between focusing point and center of burst can reach 8km



The 64 pulses of the burst do not see the focusing point at the same time delay

Range walk correction principles

Schematic illustration



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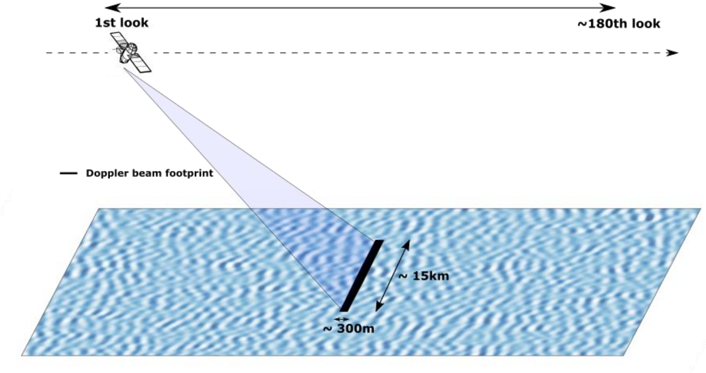


The range walk correction consists of applying range migrations to the 64 pulses, before azimuth FFT

This way, all pulses are equidistant wrt to the focusing point on-ground

The range walk correction in summary

- **<u>Objective</u>:** to compensate the range variation during the burst acquisition wrt focusing point
- The correction depends on the angle between satellite velocity vector & focusing point on ground. **Therefore the correction increases from central to lateral looks** (also depends on radial velocity)
- Because this correction is applied before azimuth FFT (beamforming), it has a direct impact on the 2D Pulse Target Response *(as seen later)*
- **Impacts on the level-2 estimates from recent studies**:

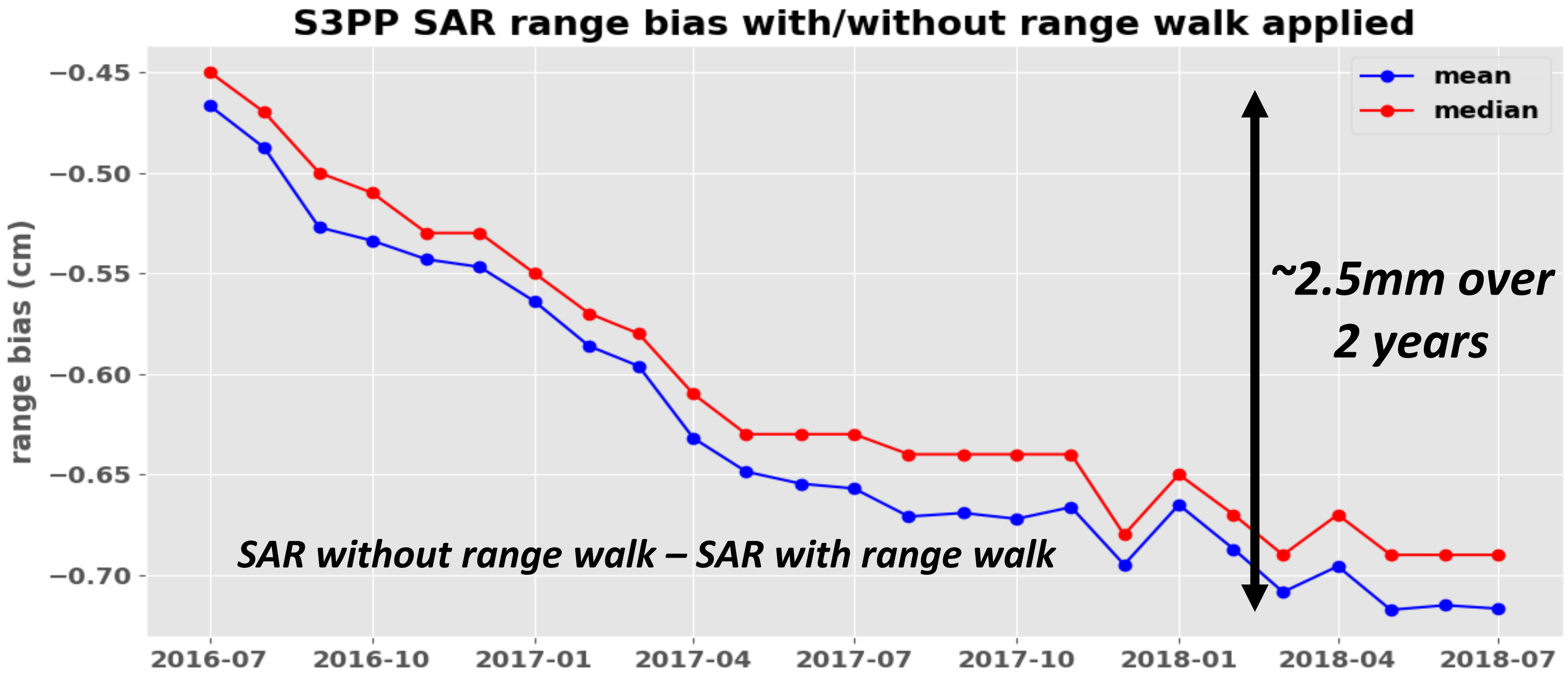
<u>ESA S3CD studies, T.Moreau [OSTST 2017], Sentinel-3A configuration:</u>

- **In average SWH is reduced by ~5cm,** *bringing SAR mode closer to PLRM*
- **A range shift of ~ +0.45cm** is observed in SAR mode *(computed at the beginning of the mission).*

<u>Scagliola et al.[2019], CryoSat-2 configuration:</u>

- **In average SWH is reduced by ~5cm,** *bringing SAR mode closer to PLRM*
- SSH difference between SAR unfocused and PLRM is reduced of about 1 mm

Impact on real data: comparison of SAR range with/without range walk



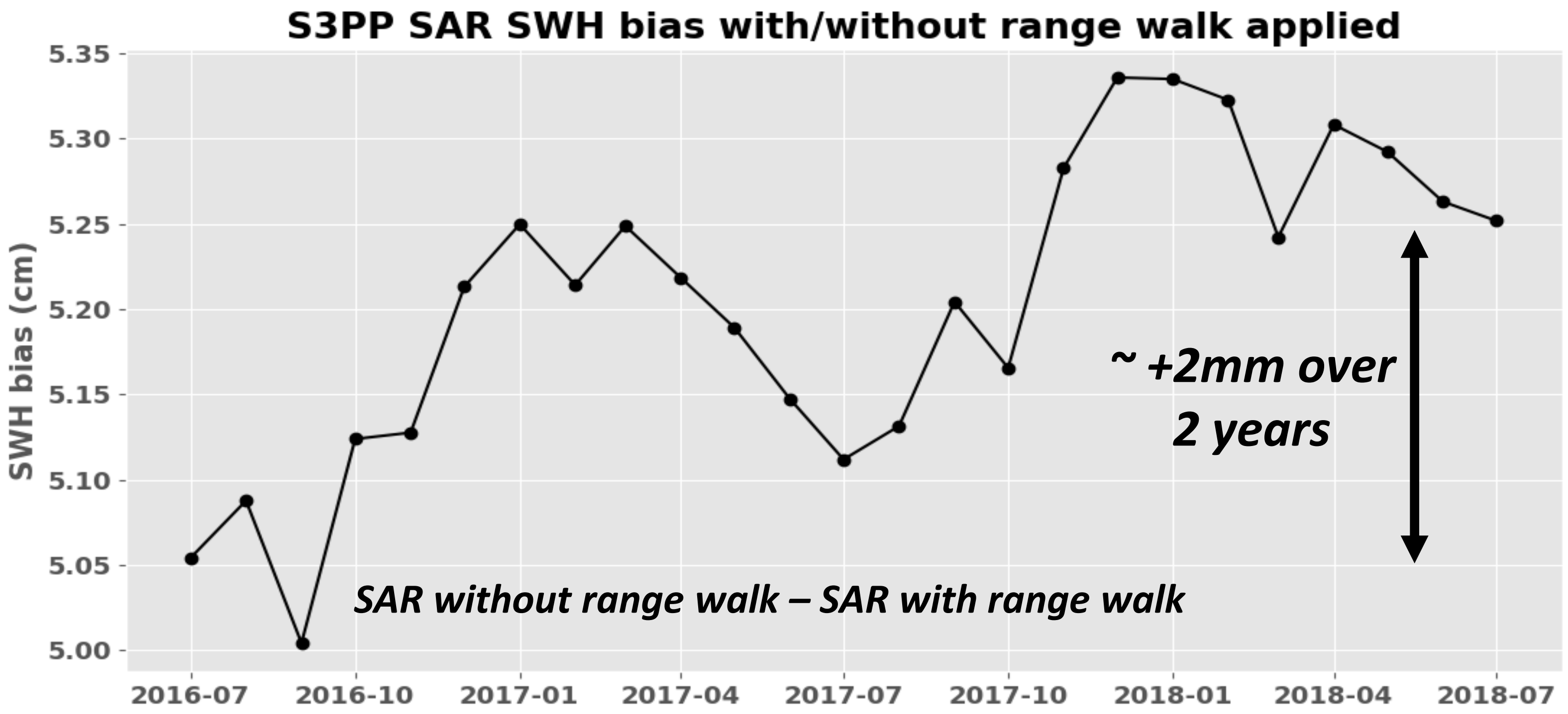
Methodology: *Over a 2 years time period, each first day of the month, a range bias is computed between S3PPv2.1 SAR unfocused measurements with & without range walk applied*

Approximately ~500 000 open ocean measurements (20Hz) integrated each day

Difference between SAR range estimates with/without range walk changes over time
Positive drift when range walk processing taken as reference

Range walk application reduces the SAR range drift of ~1.25mm/year

Impact on real data: same analysis with SWH



Methodology: *Over a 2 years time period, each first day of the month, a range bias is computed between S3PPv2.1 SAR unfocused measurements with & without range walk applied*

Approximately ~500 000 open ocean measurements (20Hz) integrated each day

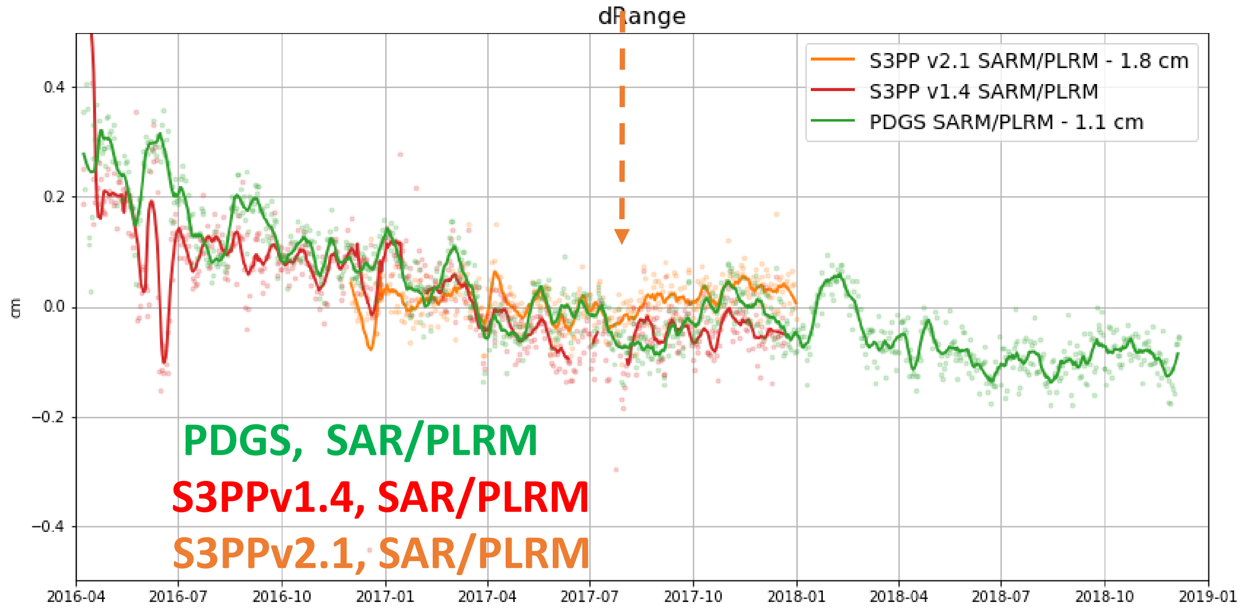
- ❑ **In SWH a ~5cm bias is found, as expected**
- ❑ **Evolution of this bias over the time is relatively limited, ~ +2mm over 2 years**.

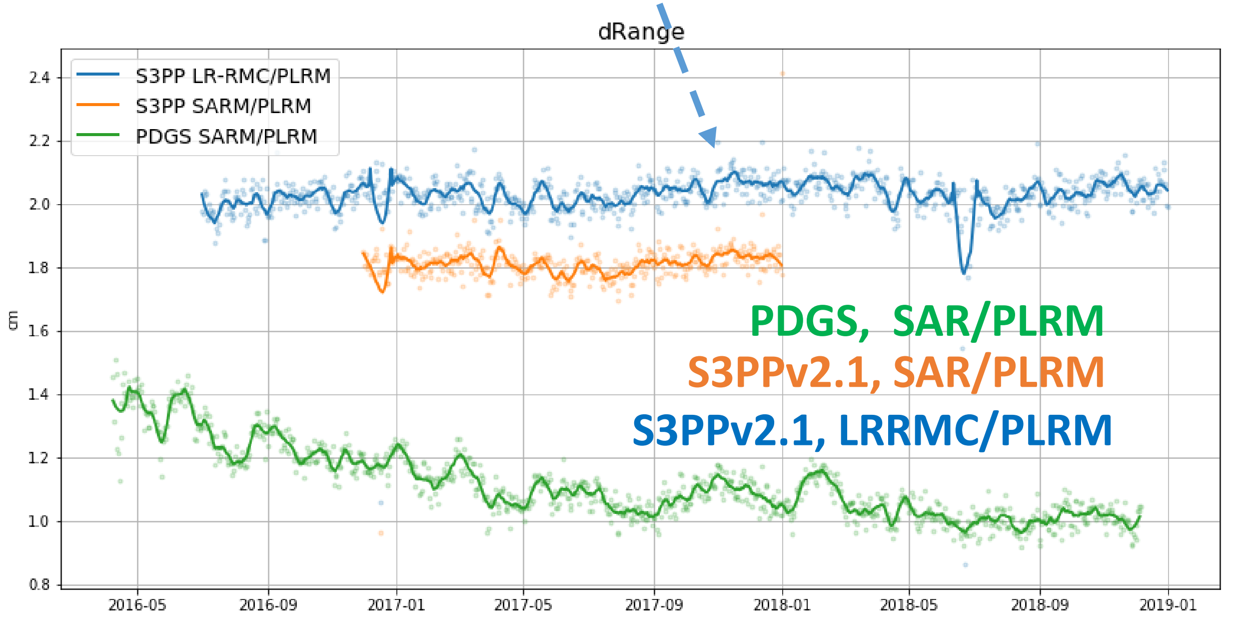
Theoretical Impact through SSB leads to a range drift reduction ~ ***-0.03mm/year*** *(3% of SWH at first order)*

First conclusions

By applying the range walk in the S3PP, results show that:

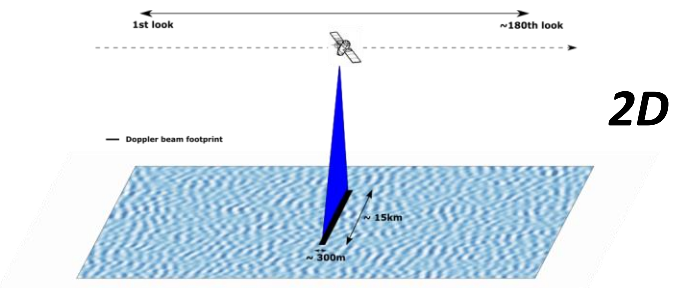
- **The range drift is reduced by ~1.25mm/year** *(not accounting for the additional 0.03mm/year through SSB)*
- It explains why the **SAR/PLRM range bias** apparently does not drift anymore in **S3PPv2.1**
- Other investigations show that **range walk has a very similar impact in LR-RMC mode** (wrt rang drift)



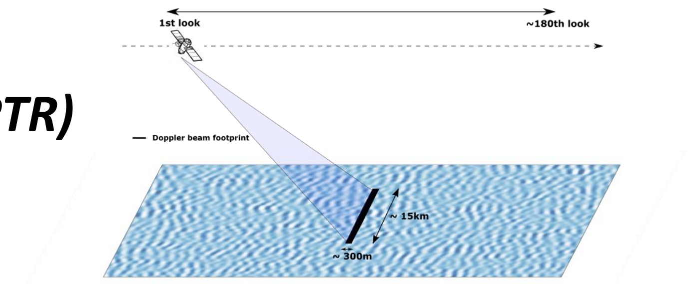


Origin of the drift when range walk is not applied

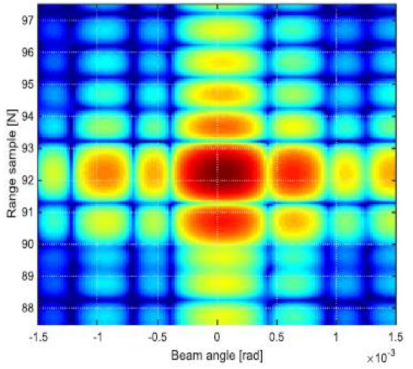
The range walk is not solely as a geometrical correction (such as slant range). Because it is applied before azimuth FFT, it has a direct impact on the **2D PTR**. *Demonstrated by F.Boy/P.Rieu (ESA – S3CD studies) & Scagliola et al. [2019]*



2D Pulse Target Responses (PTR)
From M.Scagliola paper

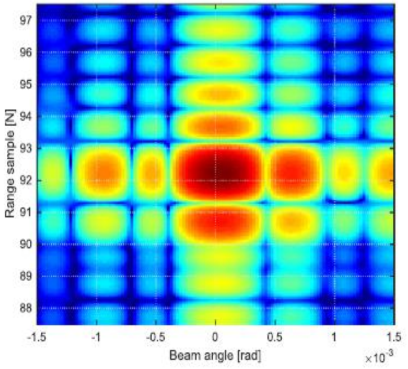


Without range walk



(c)

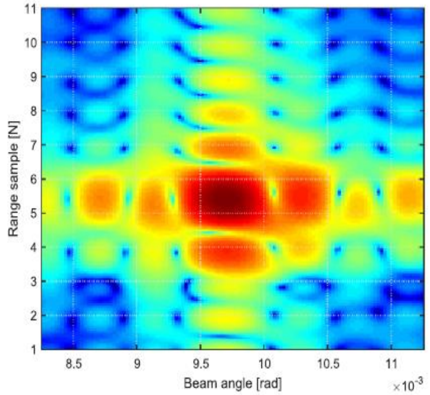
With range walk



(d)

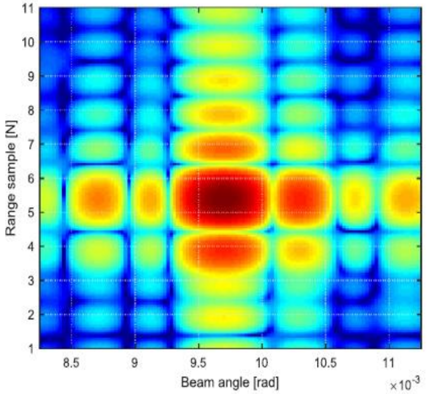
Focused burst over the transponder at beam angle near to zero, without range walk (left) ; with range walk (right)

Without range walk



(c)

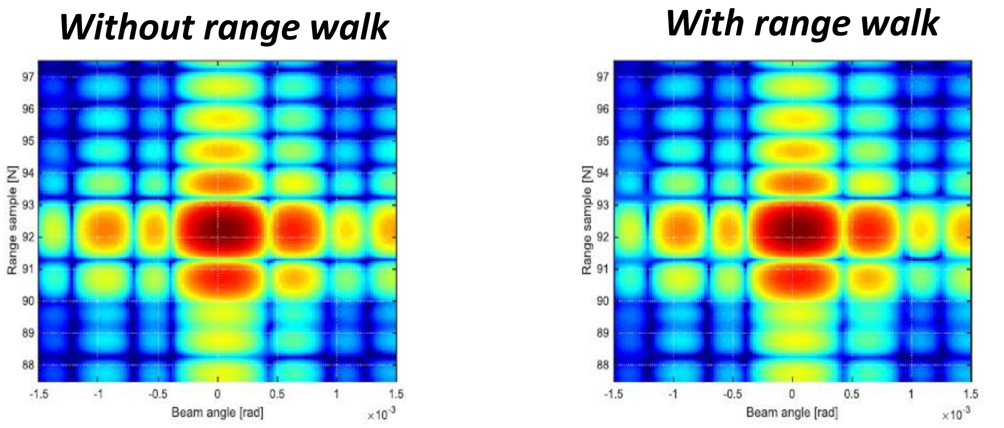
With range walk



(d)

Focused burst over the transponder at hight beam angle, without range walk (left) ; with range walk (right)

From M.Scagliola paper



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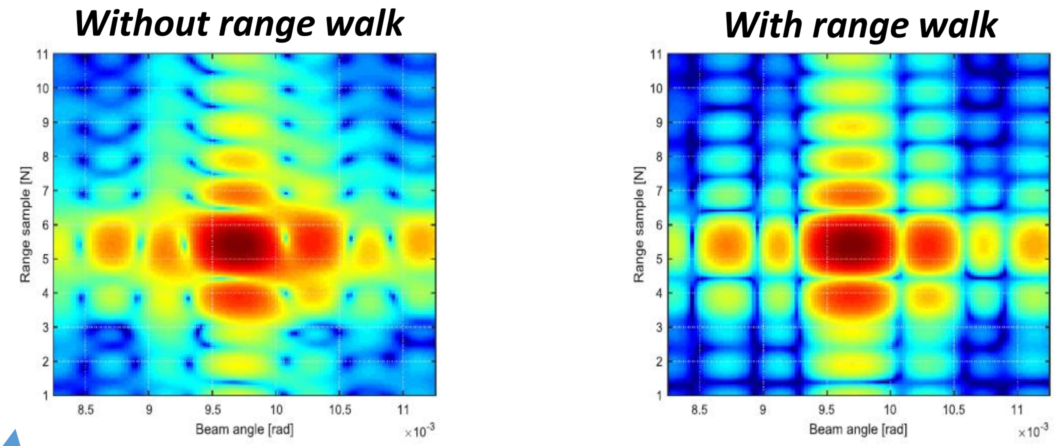


(c) (d)

Focused burst over the transponder at hight beam angle, without range walk (left) ; with range walk (right)

- 2D PTR shape directly depends on CAL1. **Subsequently 2D PTR stability over time directly linked to CAL1 variations** (width, dissymmetry, variations in a burst…)
- **The variation of the "distorted 2D PTR" over time** is not taking into account by the ground segment (internal path delay)

How to demonstrate & quantify the impact of the 2D PTR variations over time ?

- Not possible to directly assess the lateral looks 2D PTR using CAL1 measurements

- Difficult (impossible ?) to assess **precisely** the 2D PTR stability over time from real data. Transponder signals are not "clean" enough.

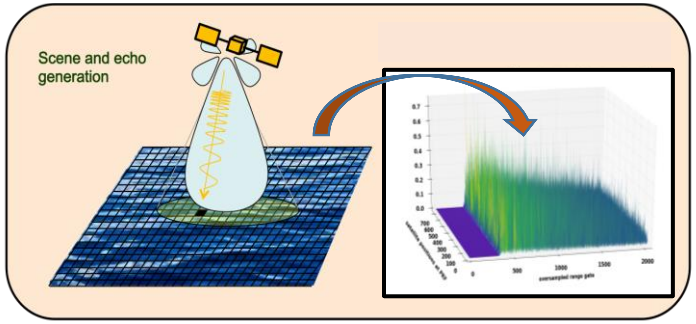
- **Remaining possibility is to use end-to-end simulator, to reproduce the whole altimetry processing from level-0 to level-2:**

  - **CNES/CLS developed a recent simulator for the Sentinel-6 mission preparation**: MADS (Multi-configuration Altimeter Data Simulator). Fully validated: sub-mm biases in range, cm biases in SWH. Fully adapted to S3.

  - In MADS the altimeter pulse compression (level-0) can be replicated using **real CAL1**. **Range walk** is also implemented in MADS, in the dedicated SAR unfocused & LR-RMC processing (level-1).

Multiconfiguration Altimeter Data Simulator (MADS), processing diagram

Level-0, raw data

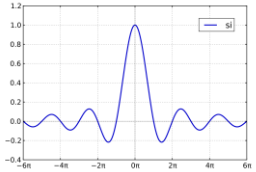


Simulation of complex pulses (I&Q) over a numerical scene

Scene/sea state fully customizable (windsea, swell…)

Level-0, pulse compression

CAL1



level-1

(P)LRM processing

SAR unfocused processing

LR-RMC processing

level-2

LRM numerical retracker & MLE4

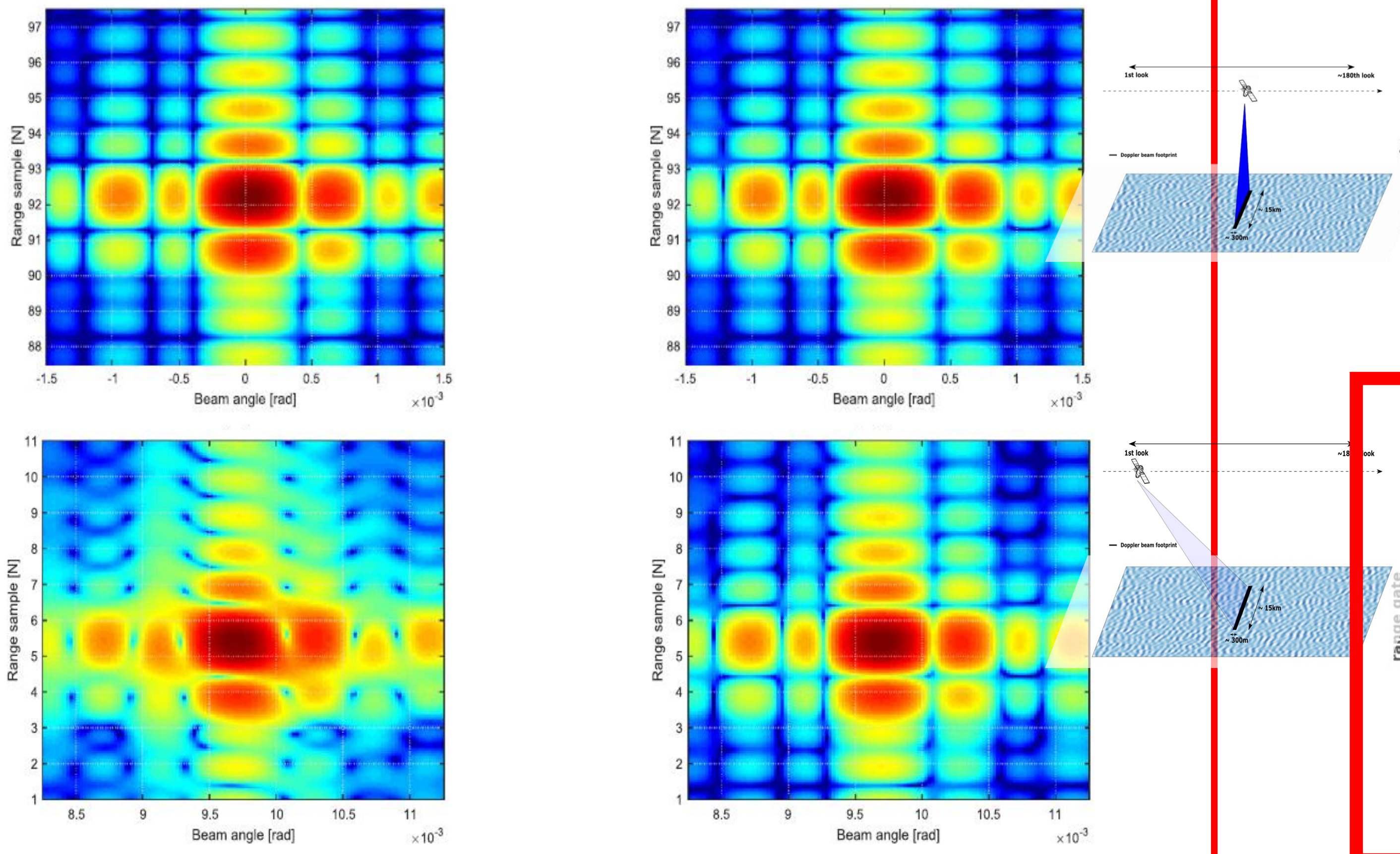
CNES SAR numerical retracker

CNES SAR numerical retracker

Preliminary result from a transponder simulation, using level-1 dedicated processing

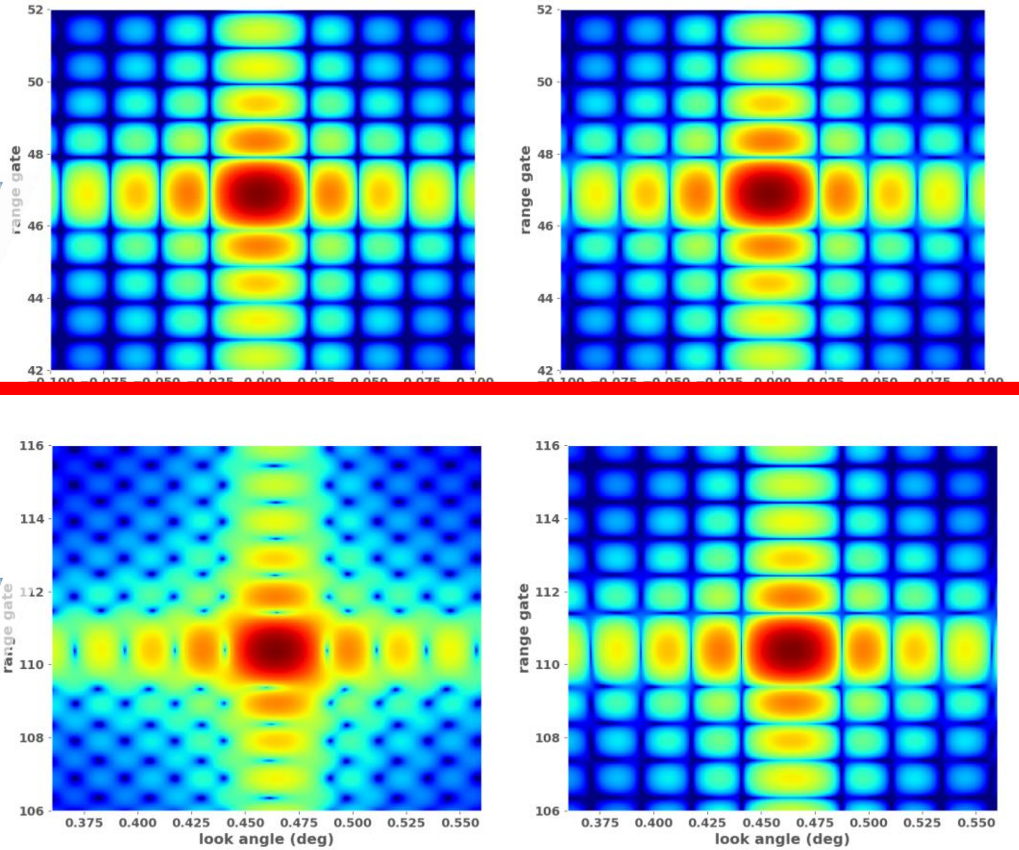
From Scagliola et al. [2019] CryoSat-2 2D PTR from real data (over transponder)

without range walk | **with range walk**



From MADS simulation, with Sentinel-3A real CAL1 (July 2016), using transponder processing

without range walk | **with range walk**

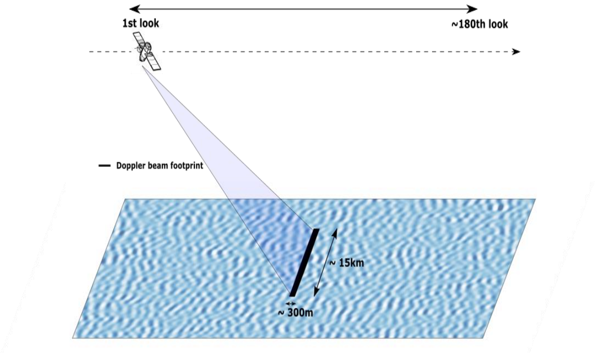


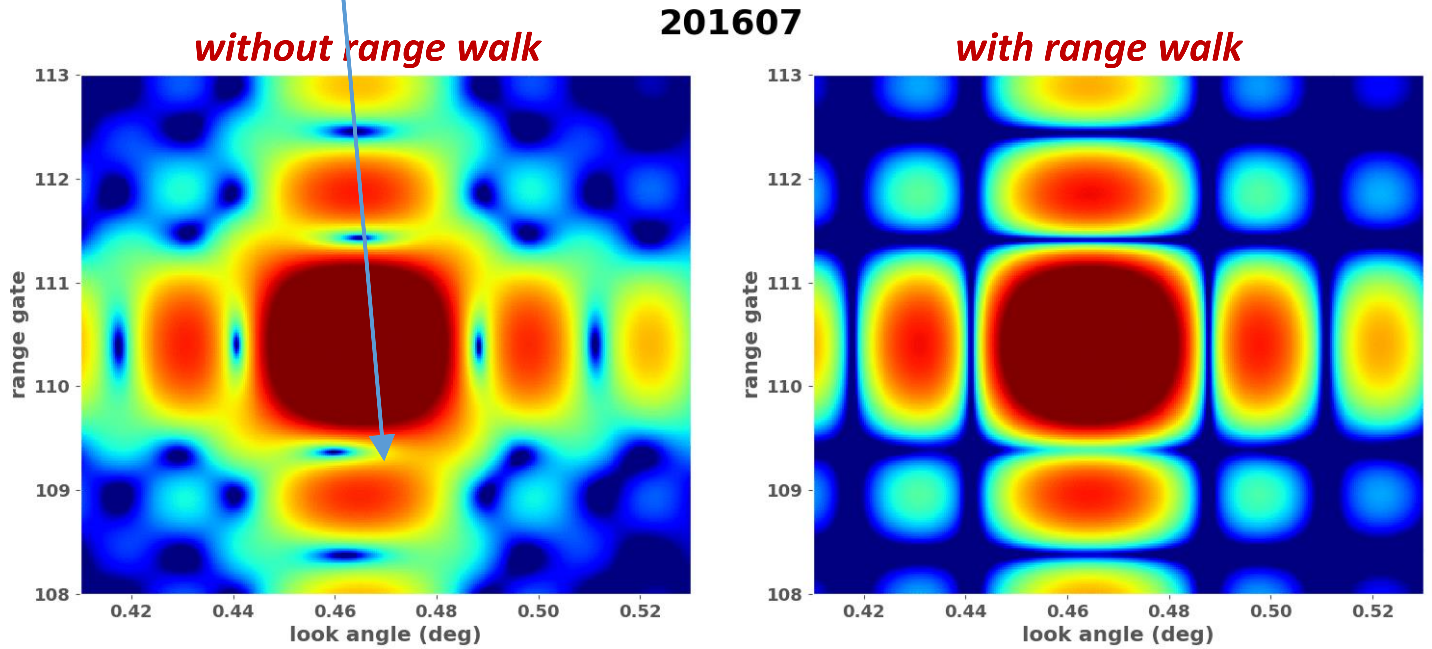
Preliminary result using transponder simulation

- 2D PTR from real data (Scagliola et al. [2019]) not completely symmetric because transponder backscattering changes the 2D PTR shape
- **Using simulation, it is possible to generate the theoretical 2D PTR, at different mission periods using corresponding CAL1 from telemetry**
- Without range walk, the shape of the 2D distorted PTR changes in the range dimension **=> This is neither taking into account by the ground segment and LUT**

2D PTR variation from simulation

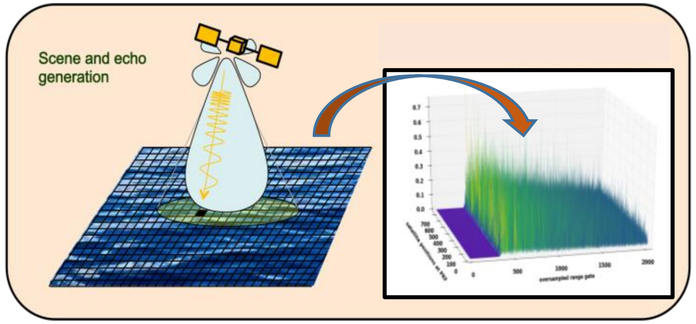
lateral look





Multiconfiguration Altimeter Data Simulator (MADS)
Settings for an oceanic case study

Level-0, raw data



*Complex pulses generated over a numerical scene (**SWH=2.5m**)*

~220 000 pulses generated at PRF

Level-0, pulse compression

Real complex S3A CAL1, from telemetry

Simulations run with different CAL1 measured along the mission

<u>=> to build a time serie</u>

level-1

PLRM processing

SAR unfocused processing

level-2

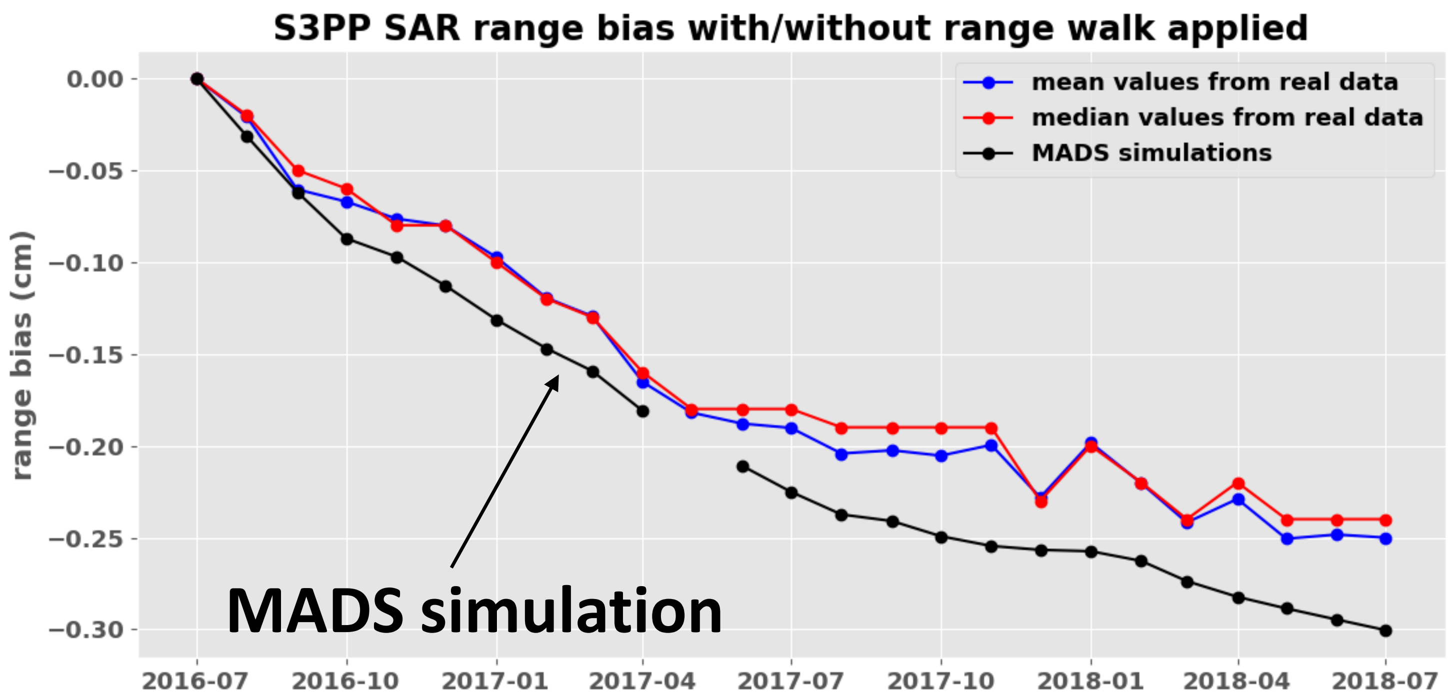
LRM numerical retracker

CNES SAR numerical retracker

Approximately 850 measurements simulated (20Hz)

*SAR unfocused waveforms are generated **with & without range walk***

Differences in SAR mode with/without range walk applied
real data & MADS simulation



Simulation results are close to the observation in real data:

~ **-1.5mm/year** drift in simulation
~ **-1.25mm/year** drift in real data

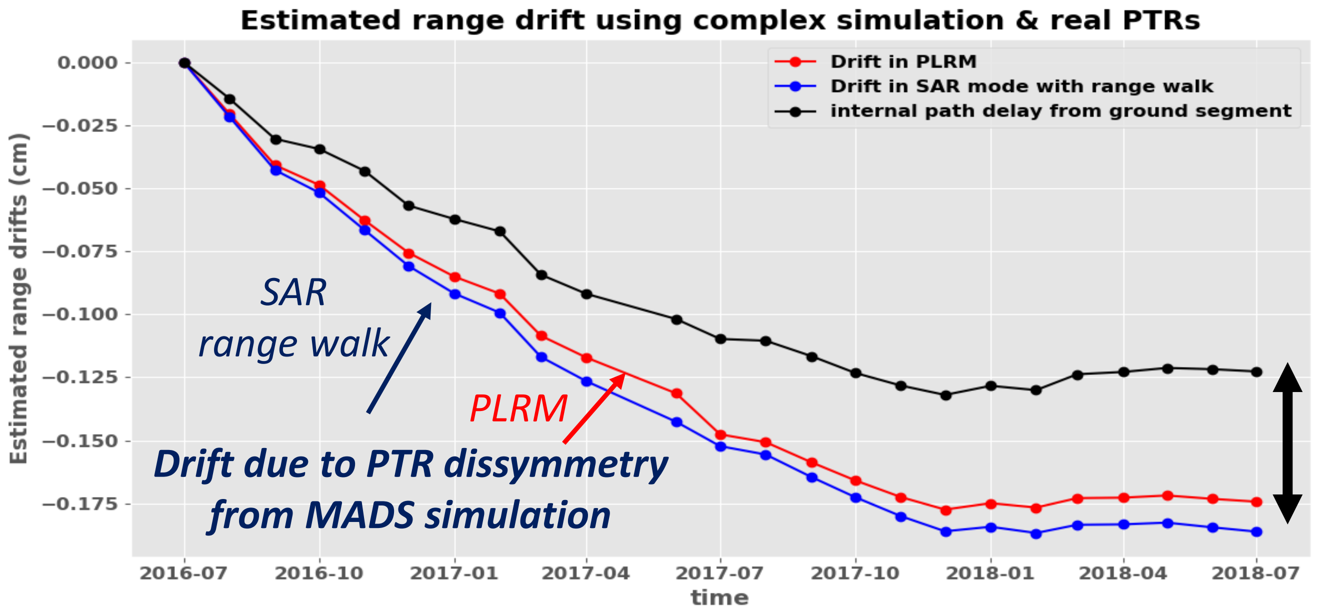
=> Confirming current drift is caused by a PTR effect

Simulations results not 100% in line with real data. But agreement very close regarding the drift we are seeking!

Several possible explanations:

- ❑ *pulse compression is done on analogic signals by the altimeter, on digital signal by the simulator (x64 oversampled signals)*
- ❑ *SNR evolution not taken into account in simulation*
- ❑ *….*

Remaining range drift in PLRM & SAR due to PTR dissymmetry evolution



Drift due to PTR dissymmetry

From JC.Poisson [OSTST 2019]
-0.28mm/yr in SAR
-0.32mm/yr in PLRM

From this simulation with MADS
~ -0.42 mm/year in SAR mode
(when range walk is applied)
~ -0.36 mm/year in PLRM

numbers also accounting for drift through SWH => SSB

- Range walk removes the distortion of the “2D PTR” for lateral looks, and subsequently **the waveforms generated are no longer sensitive to variations of the 2D distorted PTR**
- **But range walk does not correct the dissymmetry of the range PTR. And subsequently its evolutions over time.** This is why a remaining drift is measured in both PLRM & SAR in this simulation
- ***Note:*** *In this simulation this bias could have been corrected at level-2, by the numerical retrackers (LRM/SAR). But it was chosen to model the PTR as a sinc^2 (for the retrackers) to reproduce the current drifts of the ground segment.*

Conclusions

Outcomes

➢ **In the S3PP, the range walk application reduces the range drift observed in SAR mode by ~1.28mm/year**
(time period analysed: July 2016 / July 2018)

Explanation in a nutshell: *The level-1 range walk correction prevents from side-effects occurring to the stack lateral looks. These side-effects (2D PTR deformations) vary over time because CAL1 is not stable.*

=> Results confirmed recently using GPOD processing: *range walk application reduces range drift by ~0.9mm/year. Analysis made over a north-Atlantic patch, and a different time period (2016 – 2019)*

Most likely

➢ **In the PDGS, range walk implementation is expected to reduce the range drift at a similar magnitude.**
Along with a ~5cm reduction of SWH, bringing SAR closer to (P)LRM.

Perspectives

➢ **A range drift remains in SAR mode & PLRM due to the evolution of the PTR dissymmetry**
(~ -0.28 & -0.32mm/year respectively, from JC.Poisson presentation [OSTST 2019])

➢ **Studies still required to fully understand the 2D PTR distortion when range walk is not applied**

Status/recommendations for operational Sentinel missions

Sentinel-3

- **<u>Range walk implementation is planned for fall 2021</u>,** using a Chirp Z Transform (CZT). CPU time will be preliminary assessed.
- **Numerical retracker still recommended** to correct for the remaining drift in SAR mode & PLRM due to the evolution of the PTR dissymmetry

=> Both processing (level-1: range walk + CZT ; level-2: numerical retracking) will be implemented and evaluated in the upcoming CNES/CLS Sentinel-6 Processing Prototype (S6PP)

Sentinel-6

- **Matched filtering "should" provide a better PTR stability over time.** Nevertheless, range walk + numerical retracking highly recommended for cautiousness. In particular given the climatologic purposes of the Jason/Sentinel-6 serie. Moreover, range walk still has a positive impact on SWH.
- **Continuity/consistency with Sentinel-3 to be taken into account**

Status on the Sentinel-3A drift

Sentinel-3A SAR mode current GMSL trend: ~5.18 mm/year

(B.Meyssignac presentation at last Sentinel-3 ESL meeting using PDGS data)

- **Reduction of ~ -1.3 mm/year expected with range walk** ***=> magnitude to be refined with PDGS***
- **-0.28mm/year** due to the evolution of PTR dissymmetry *(JC.Poisson / S.Dinardo study)*

SAR GMSL value updated (projection): ~3.6mm/year

Sentinel-3A PLRM current GMSL trend: ~3.85 mm/year

(B.Meyssignac presentation at last Sentinel-3 ESL meeting using PDGS data)

- **-0.32 mm/year** due to the the evolution of PTR dissymmetry *(JC.Poisson / S.Dinardo study)*

PLRM GMSL value updated (projection): ~3.5mm/year (no change)

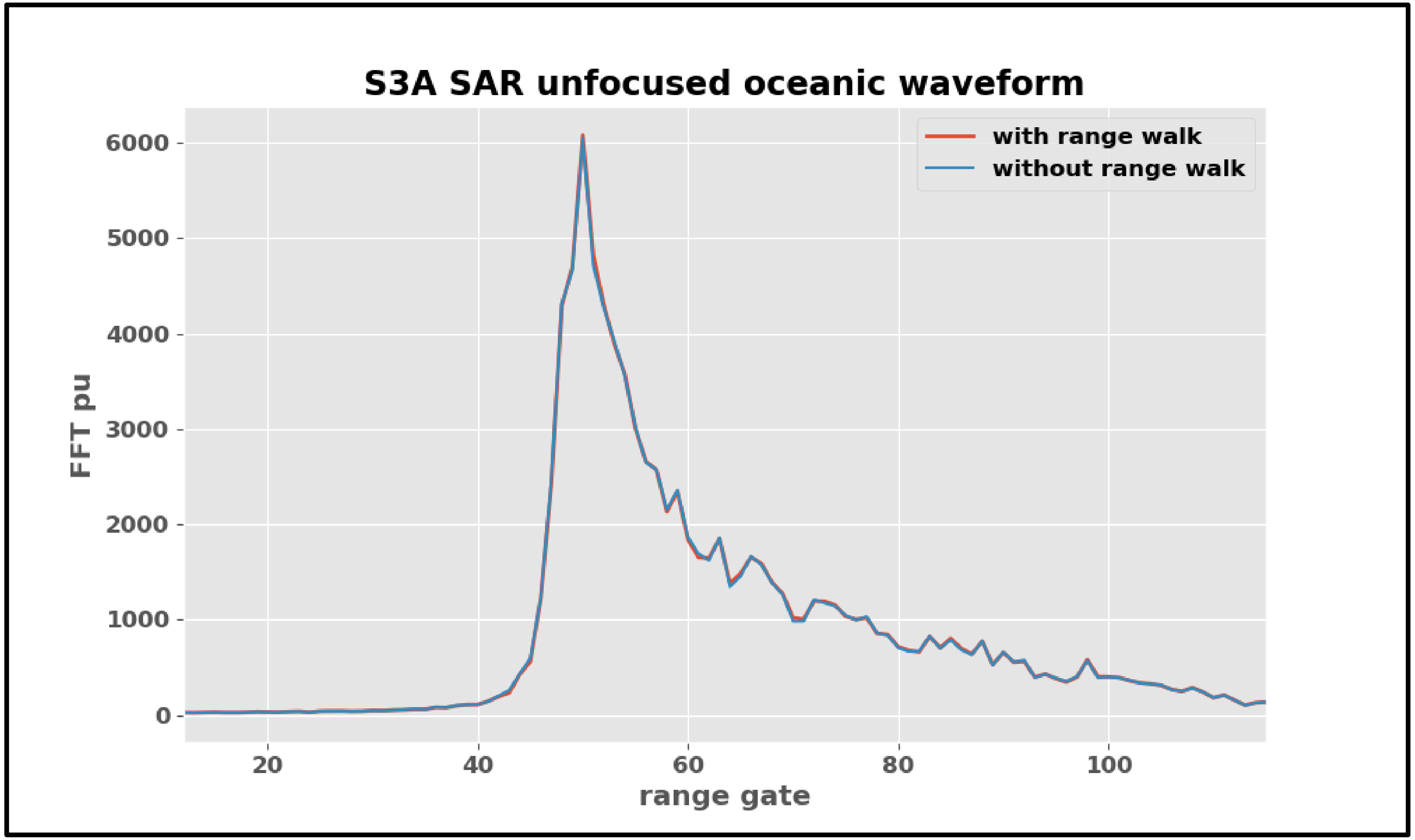
=> First projections, numbers to be taken with caution

=> To be compared with Jason-3 GMSL once range walk is applied to the PDGS data & PTR dissymmetry evolution effect is removed (using numerical retracker)

=> Values might also change with the PDGS reprocessing

BACKUP slides

Impact of range walk processing on a single oceanic measurement



How to implement range walk in the Sentinel-3 PDGS

IPF part of level-1 processing without range walk

IPF part of level-1 processing with range walk

- In the current IPF, the **Doppler beam steering & Doppler beam generation** are performed in two distinct operations. Directly on the 64x128 pulses matrix *(respectively phase shift + FFT)*

- In the proposed implementation, each **range bin is processed separately**. The CZT performs in a single operation: **Doppler beam steering + Range walk correction + Beam forming**

Efficient beam-forming with range-walk correction using the CZT

Using the first-order range walk correction, the beam-steering/beam-forming operation writes :

$$S_{k,j} = \sum_{i=0}^{63} s_{i,j}\, e^{-2\,j\,\pi\,(1-\underbrace{\frac{\alpha}{f_c}t_j}_{\text{range walk}})\,f_k\,\eta_i}$$

with :

$\eta_i = i * PRI$ (slow time)

$f_k = f_{dc} + \frac{k}{64} * PRF$ (Doppler frequencies)

Current IPF algorithm (ALT_COR_WAV_06) : use of the FFT

$$S_{k,j} = FFT(s_{i,j}\,\underbrace{e^{-2\,j\,\pi\,f_{dc}\,i\,PRI}}_{\text{phase shift}})$$

Computational complexity : O(N log N)

New proposed algorithm : use of the CZT

$$S_{k,j} = \sum_{i=0}^{63} s_{i,j}\, z_k^{-i} = CZT_{A,W}(s_{i,j})$$

with : $z_k = A\,W^{-k}$

Computational complexity : O(N log N)
(but still slower than FFT)

How to implement range walk in the Sentinel-3 PDGS

CPU time preliminary performances

Python-Numpy code, but Numpy functions used are written in C/C++

CPU time for the level-1 operations previously mentioned (Doppler centroid correction + Beam forming):

For a whole track (~200 000 bursts):

- **Current IPF:** 20 seconds
- **+ Range walk using CZT:** 12 minutes 45 seconds
- **+ Range walk using DFT (Scagiola et al., OSTST 2019):** 2 hours

With the proposed CZT approach CPU time will increase of ~12 minutes per track