Ocean SAR altimetry

from SIRAL2 on CryoSat2 to Poseidon-4 on Jason-CS

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SAR Altimetry EGM
NOC, Southampton, 26 June 2013

History of SAR altimetry over open ocean

- K. Raney 1998
  - SAR mode improves range noise : heuristic assessment based on « rule of thumb ».
  - But ! nobody knew how to re-track the data - with a good accuracy !
- 2000-2006 many unformal discussions between Thales and radar altimeter scientists and engineers to convince them to look at numerical re-tracking (even for LRM !)
- 2007 : Phalippou and Enjolras : « Re-tracking of SAR altimeter ocean power-waveforms and related accuracies of the retrieved sea surface height, significant wave height and wind speed, IGARSS 2007 Barcelona”. Theory and simulation using numerical re-tracking and retrieval error estimation.

  ~ 0.8 cm range noise accuracy is expected over ocean for SIRAL
- 2010 Launch of CryoSat 2 : 3 months later we knew internally in Thales that numerical re-tracking over ocean in SAR Mode was not just theory.
- 2012 : OSTST and 20 YPRA in Venice, CP4O : Similar findings by several groups

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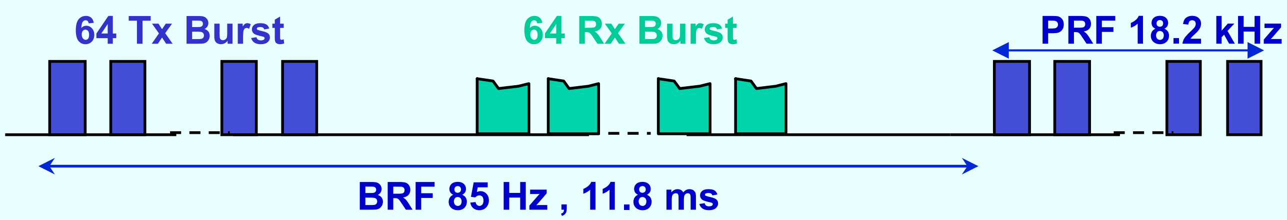
SIRAL SAR MODE

- SIRAL on CryoSat
  - **Altitude** **720 km**
  - **Antenna** **~1.2 m**
  - **Radar Frequency** **13.575 GHz**
  - **Chirp (FM) Bandwidth** **320 MHz**
  - **Time resolution** **3.125 ns**
  - **SNR (σ_0=15 dB)** **37 dB** (after SAR filtering)

SIRAL SAR- MODE TIMING



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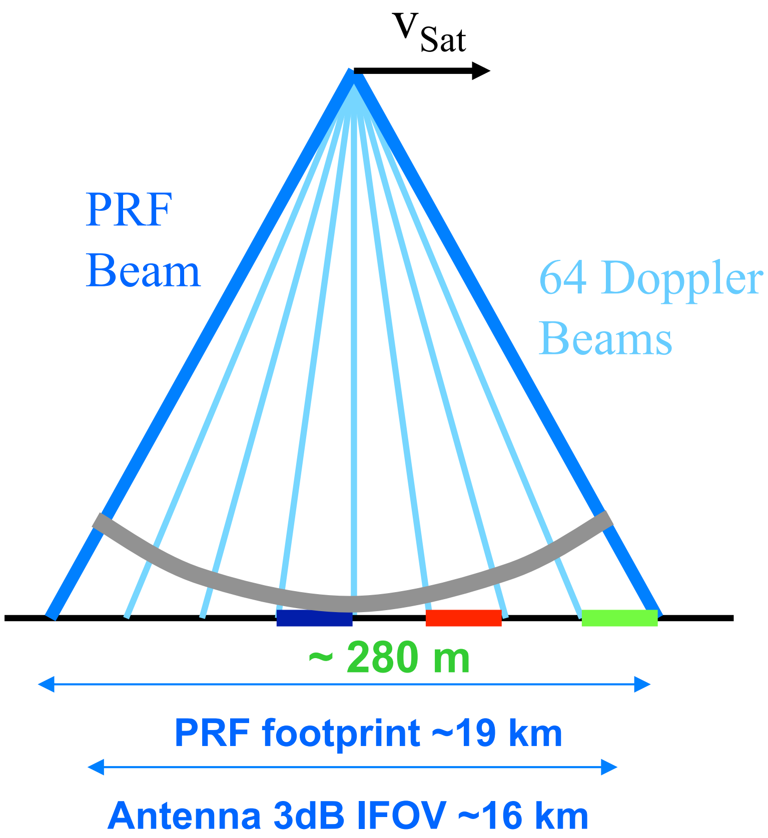
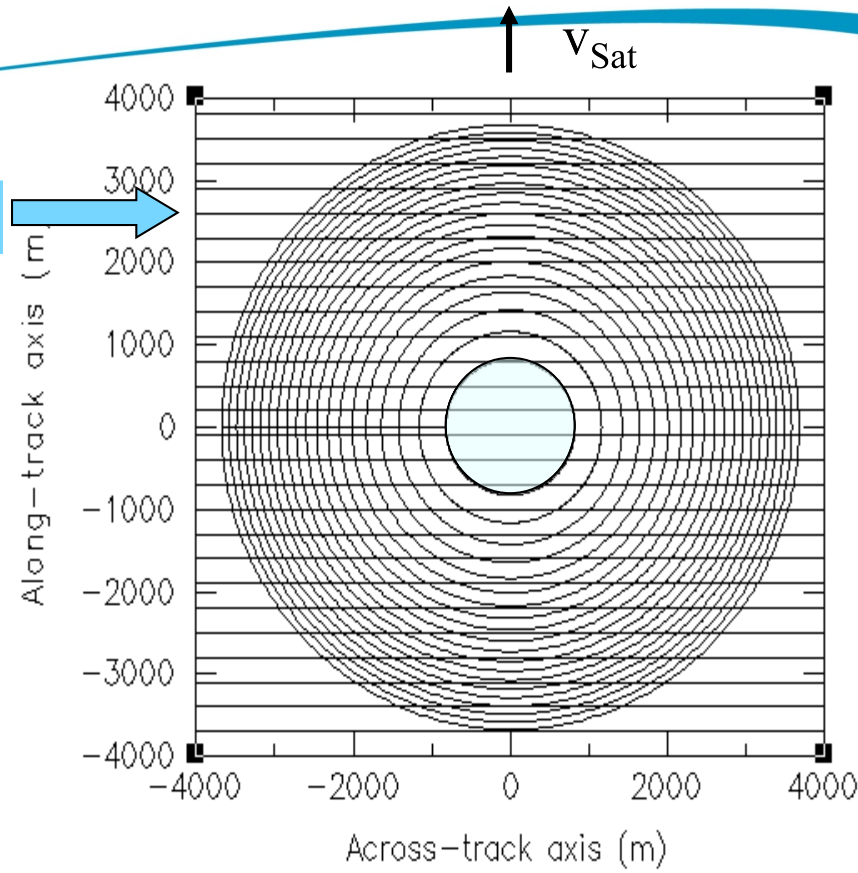
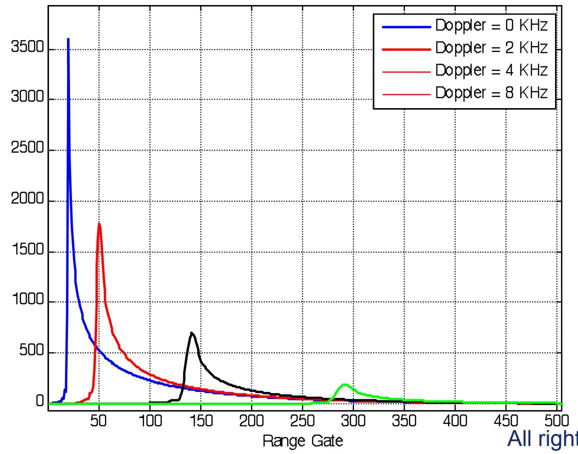
ThalesAlenia Space
A Thales / Finmeccanica Company

SIRAL FLAT SURFACE RESPONSE

For Top Hat Azimuth & Range Impulse Responses







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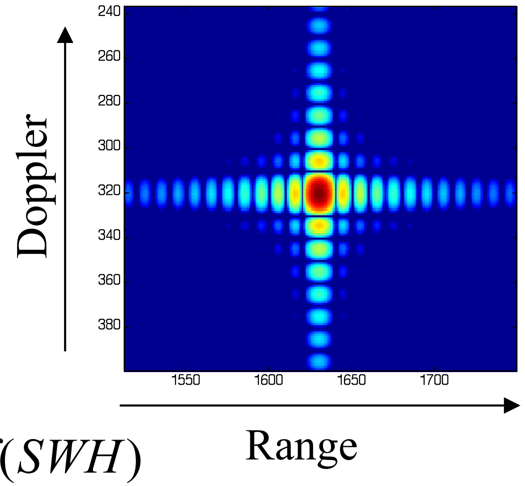
WAVEFORMS MODEL



- **The Point Target Response of 2D Impulse Response**
  - Product of 2 sinc function (Deramp in time, FFT in azimuth)

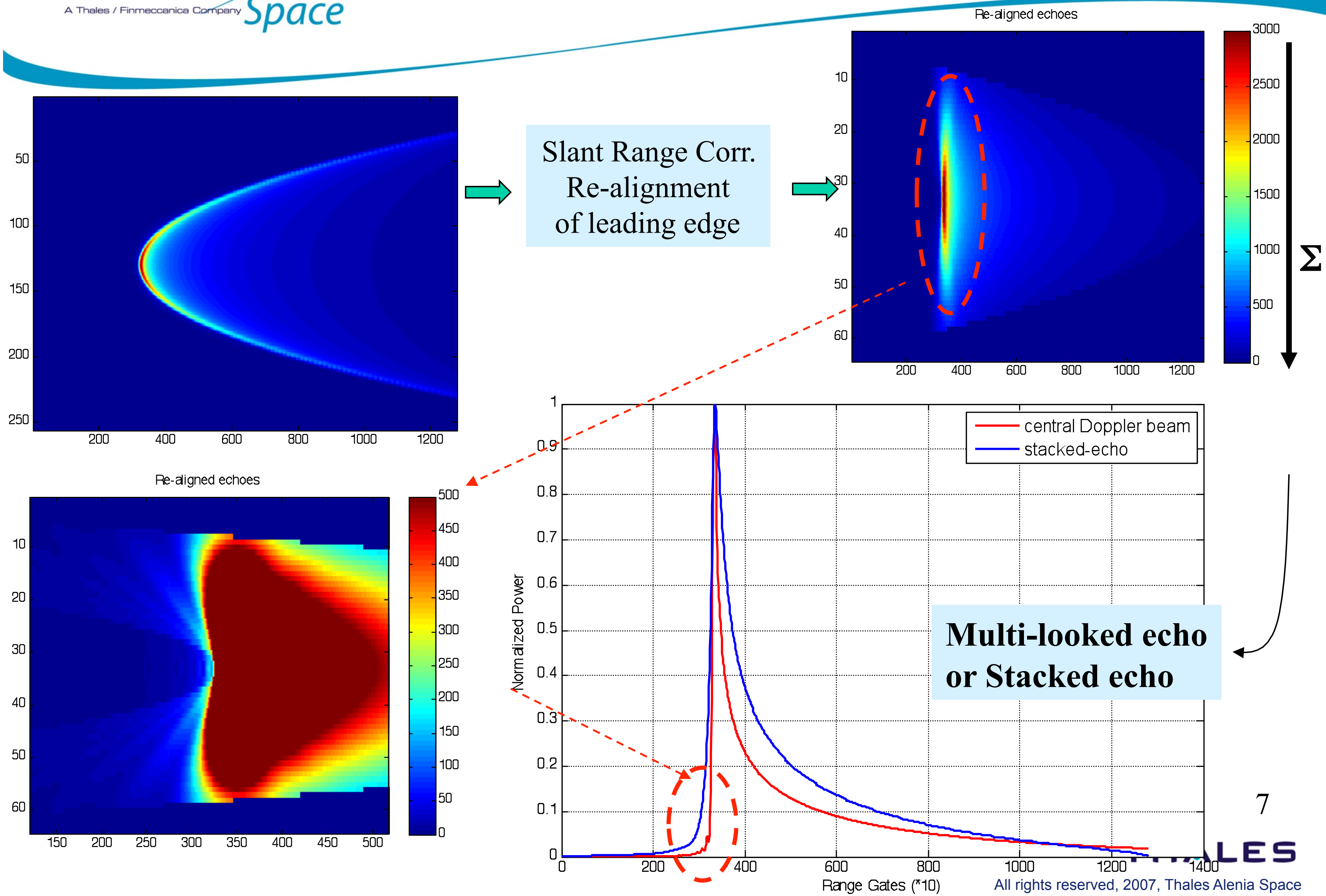
- **Mean Waveform, a function of Doppler x_i and time t**

$$P(x_i,t) = cte\ sigma0\ G^2(x_i,t)P_{f\,lat}(x_i,t) * RIR(t) * AIR(x) * sea\_pdf(SWH)$$

- **Geophysical Variables : unknown to be retrieved**
  - Range, Wave Height H1/3, sigma0

- **The a priori information – i.e. information known with “sufficient” accuracy**
  - Geometry (orbit, ellipsoid / geoid , sat velocity vector …)
  - Antenna : fine characterization on ground, pointing (star tracker)
  - Range and Azimuth impulse responses : calibration in flight
  - Receive chain transfer function CAL2 filter
  - Sea state height pdf (gaussian, or skewed …) driven by H1/3
  - Model (pdf) of speckle and thermal noise

Stacking for 1D re-tracking



WHAT WE NEED FOR RE - TRACKING

- **AN ACCURATE UN-BIASED FORWARD MODEL**
  - Any systematic error in the model will be mapped into « non-random errors » in the retrieved geophysical products
  - The model must re-produce the physics of the measurements including the instrument characteristics and the data processing as accurately as possible
  - The model must be free from systematic error
  - No specific need for analytical modeling (adjoint technique to be explored)

- **MODEL OF THE MEASUREMENT ERRORS STATISTICS**
  - Noise source : Thermal noise and speckle noise
  - Multilooking different mean power wavefoms shall be accounted for

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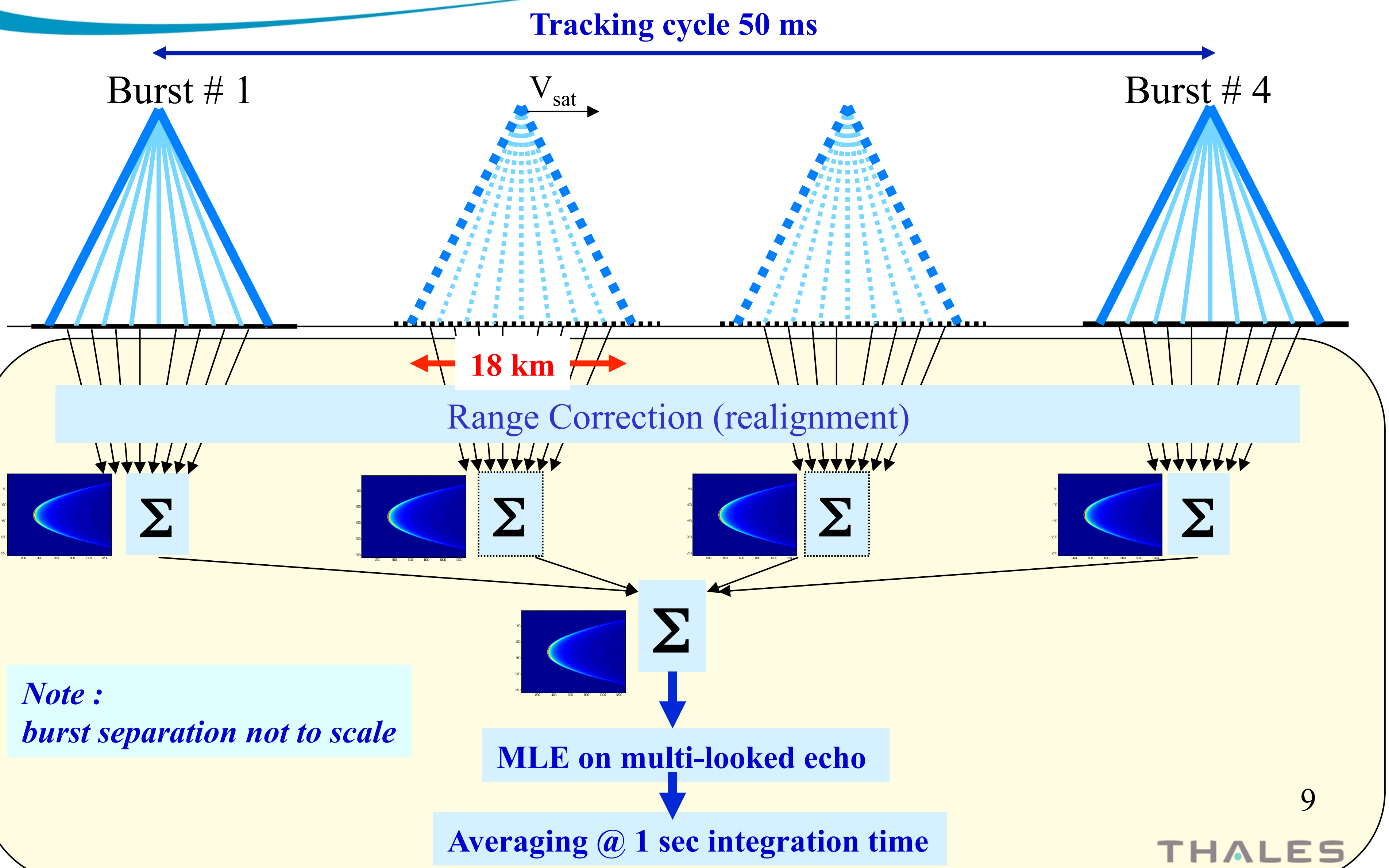
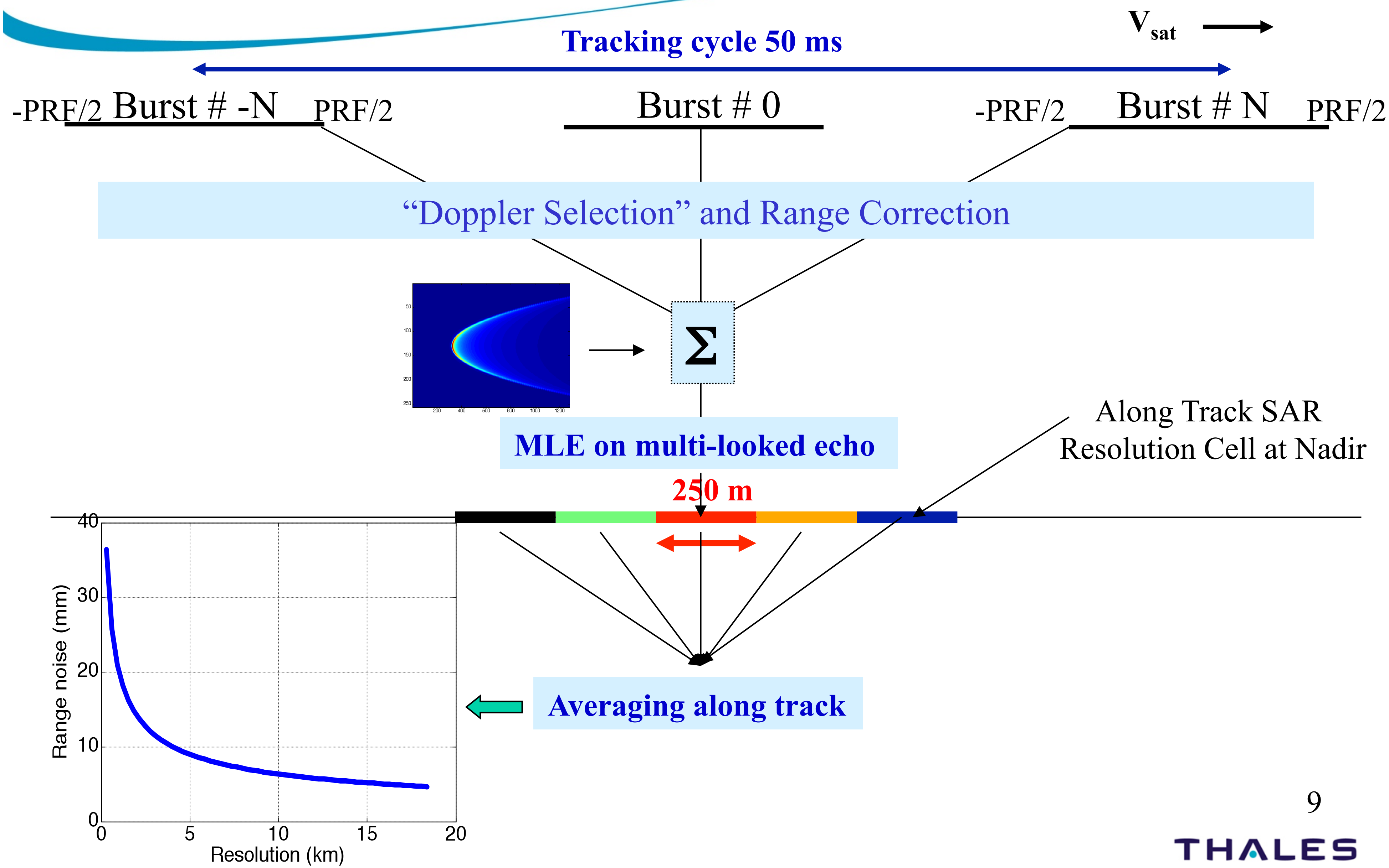
MULTI-LOOK SAR-1 Type



Note :
burst separation not to scale

MULTI-LOOK SAR-2 Type : Full-resolution



OPTIMAL RE-TRACKING

OPTIMAL “the best solution in a statistical sense”=> MLE

Model of Waveforms
Forward Model

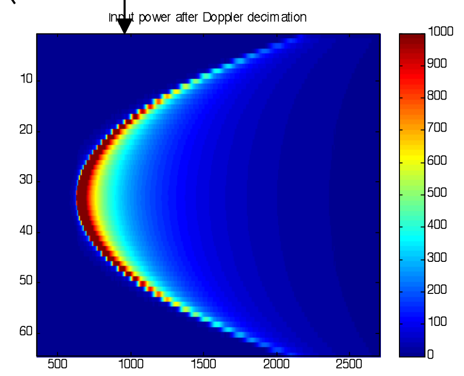
Parameters to retrieve
Range, sigma0, SWH, + …

Constraint Relaxation

Measured Waveforms

Measurement noise Covariance Matrix Speckle + Thermal

+ Noise



Noise in the retrieval of α : Cramer-Rao bound

$$\mathbf{C}_{\boldsymbol{\alpha}} = \left[\mathbf{K}^{T}\ \mathbf{C}_{n_o}^{-1}\ \mathbf{K}\right]^{-1}$$

Key for Information Content Analysis

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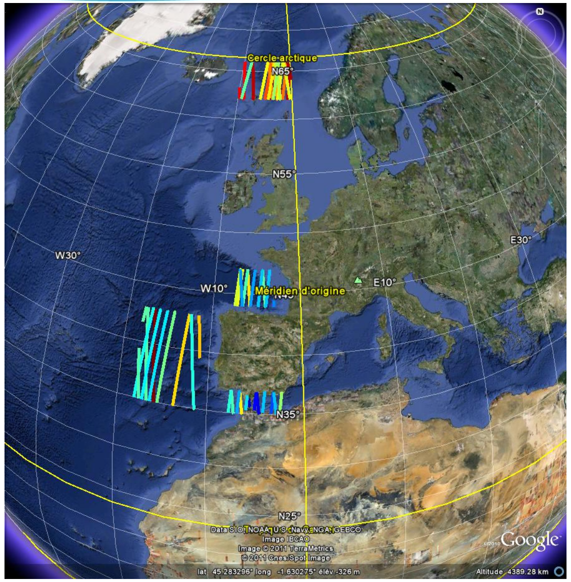
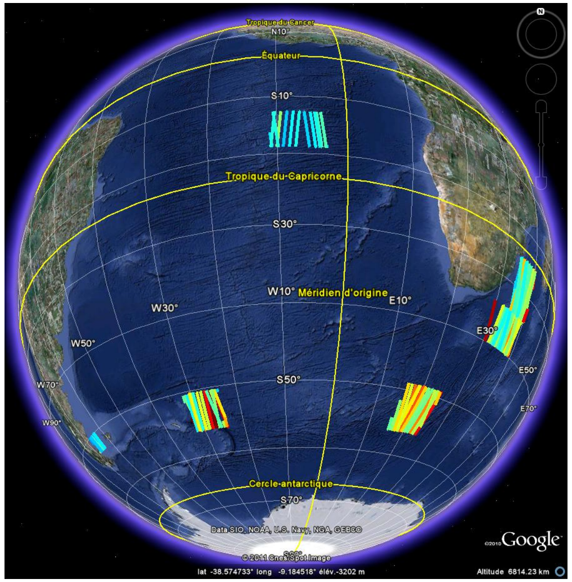




- **147 orbit sections**
- **12 000 s, 90 000 km, 240 000 tracking cycles**

- **Takes : March 2011**

- **Full Bit Rate (FBR). I/Q data.**

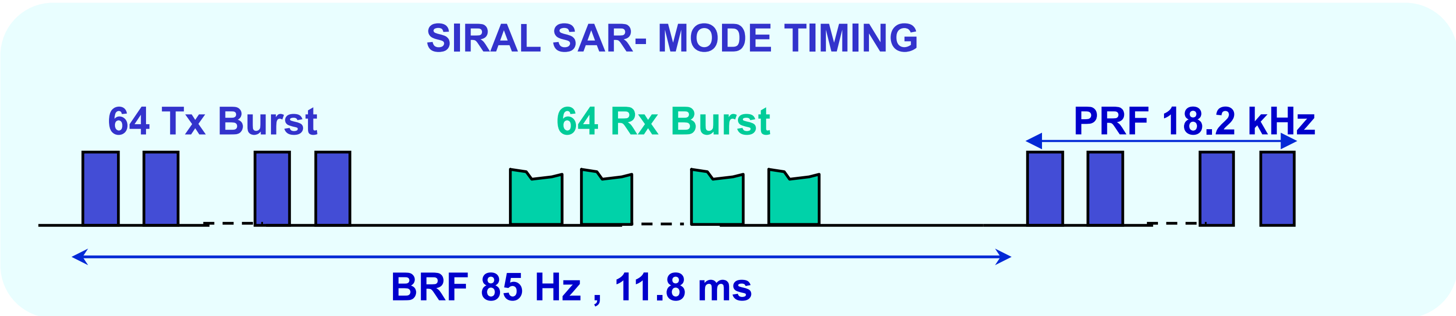
- **10 zones sampling various sea state SWH [0 - 10 m]**

- **Re-tracking of SAR acquired data**
  - SAR re-tracking
  - “LRM” re-tracking for relative comparisons

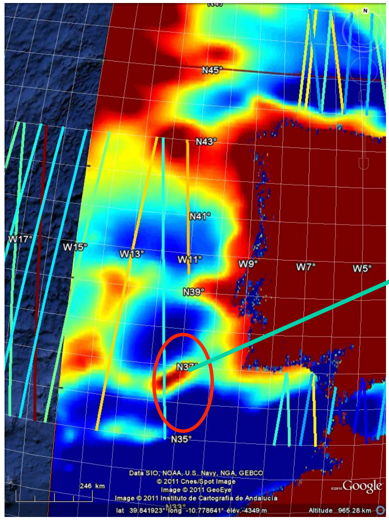
- **Mean Sea Surface : ACE2 dataset**

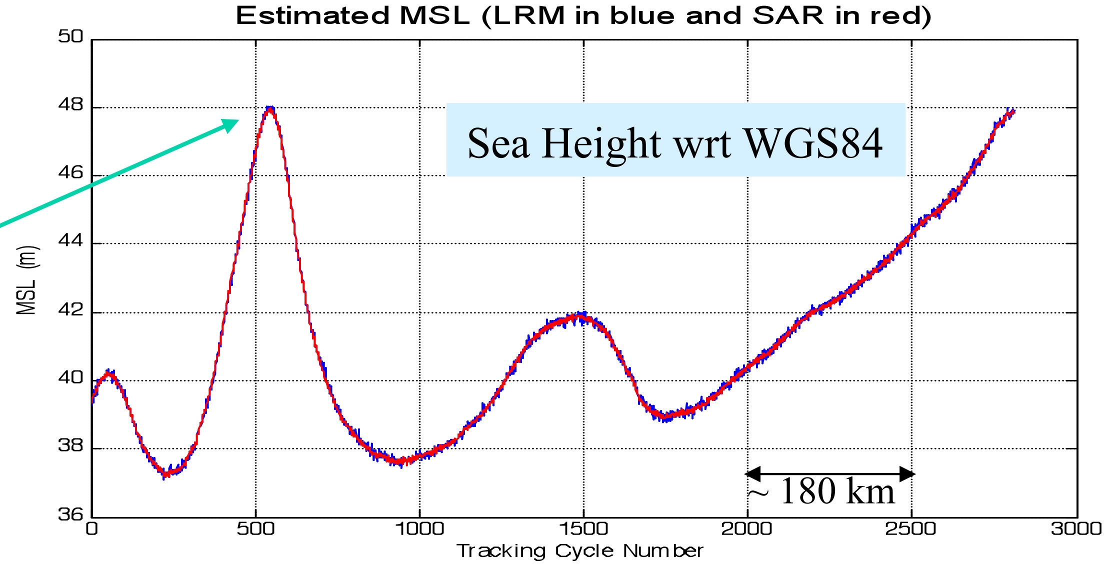
NUMBER OF LOOKS (NL)

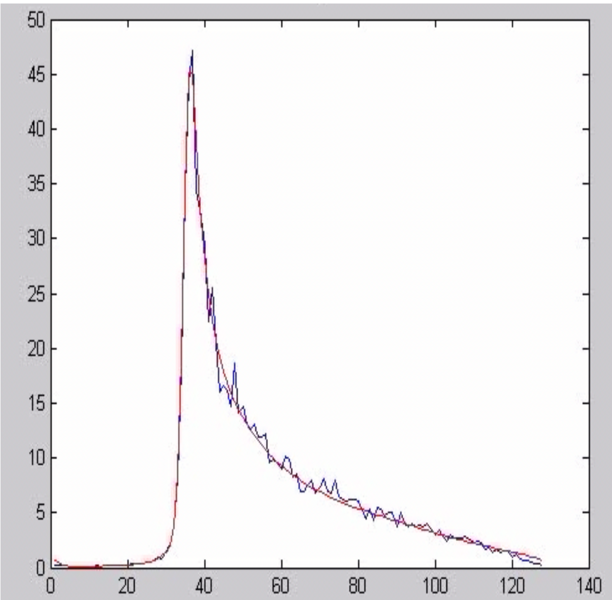
- **SAR DATA WITHOUT SAR PROCESSING (LRM re-tracking)**
  - For SIRAL for **NL in "LRM like" is ~ 760 @ 1 sec** due to closed burst mode (18 kHz / 2 kHz / 11.8 ms=760)
- **SAR DATA WITH SAR PROCESSING**
  - Doppler filtering de-correlates the Doppler beams.
  - 32 central Doppler bins per burst are kept (minor changes with 64 bins)
  - 32 bins / 11.8 ms. **ENL SAR (max) = 2700 / sec**
  - Ratio (NL SAR / NL LRM)$^{1/2}$ = 1,88 (for high SNR …)
  - Note : variation of the mean power waveforms with Doppler bin must be accounted for computing the Effective Number of Looks (ENL)

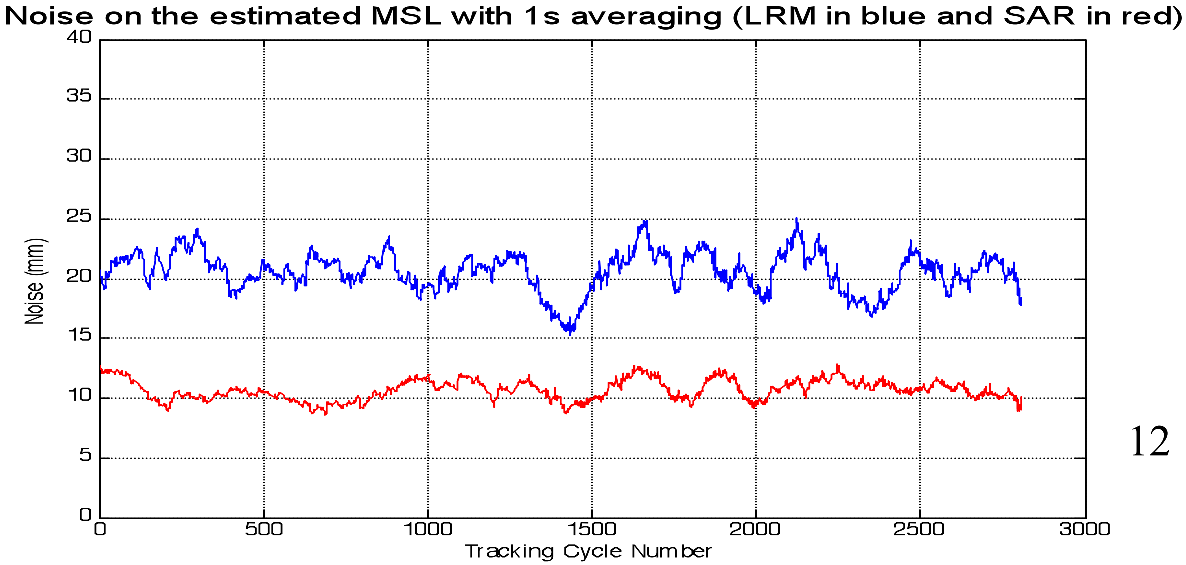


SAR VS LRM PROCESSED AND MSL





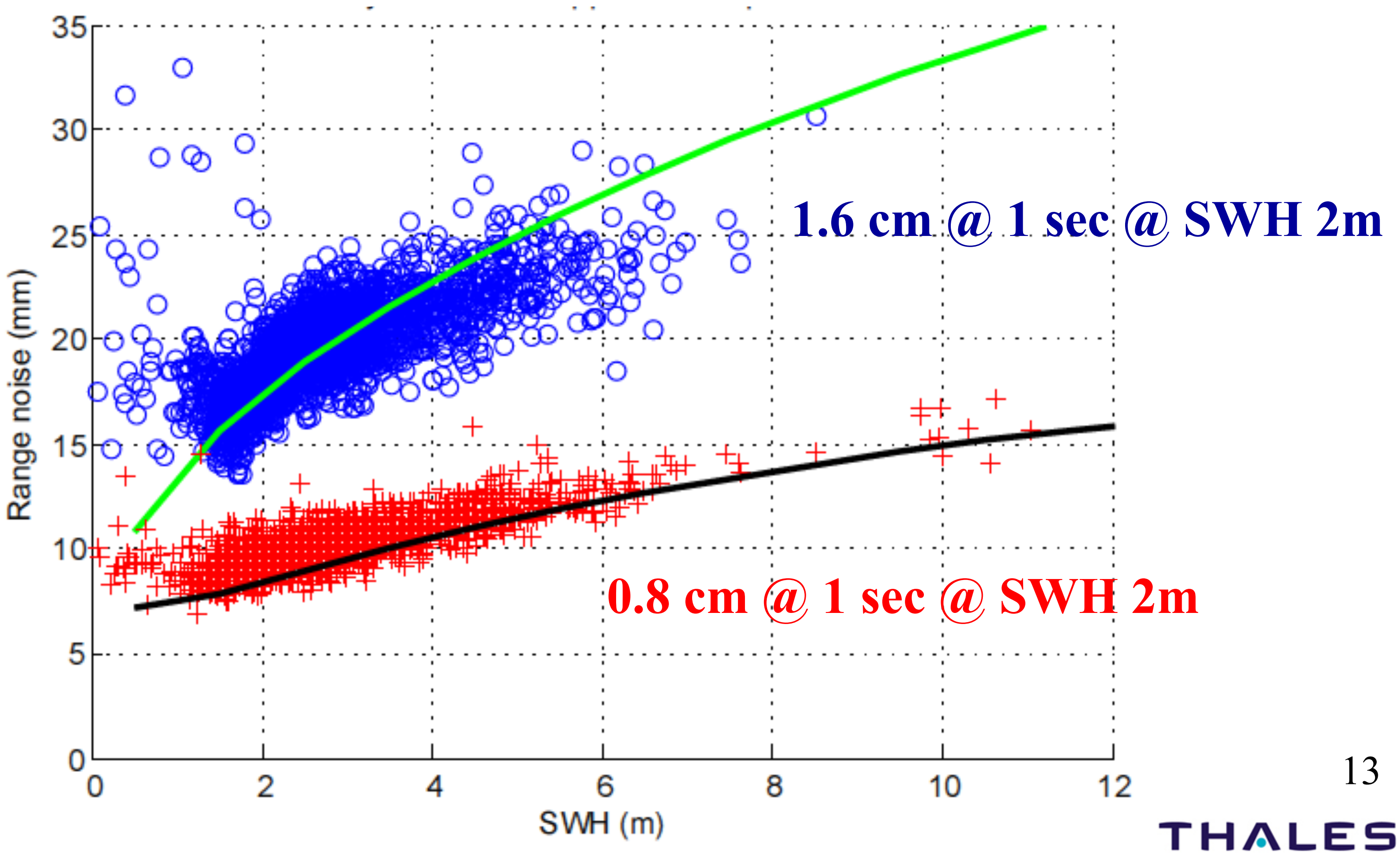




SAR mode acquired data

without SAR processing “LRM like” (blue), with SAR processing (red)

12 000 s, 90 000 km, 240 000 tracking cycles

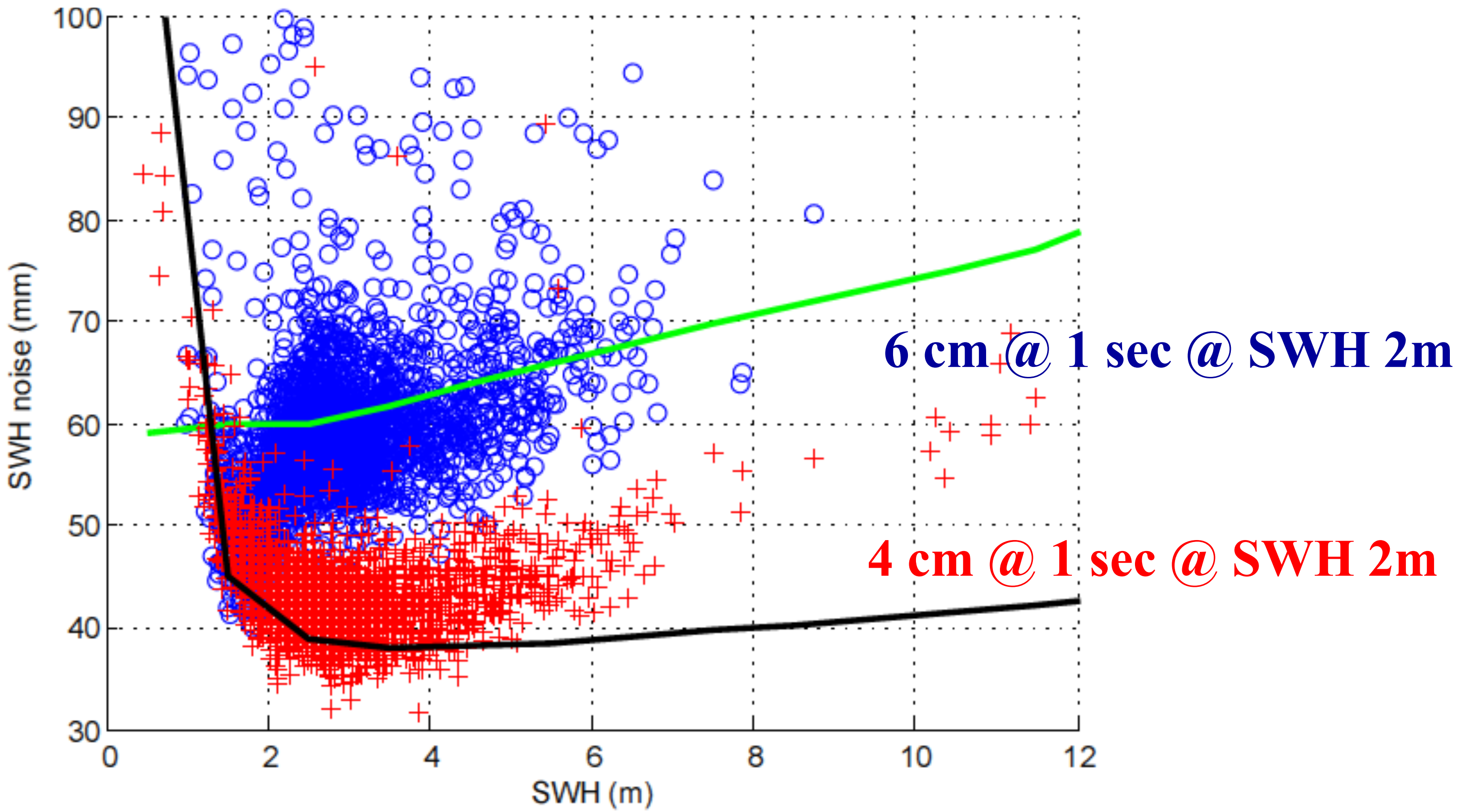


SWH NOISE

SAR mode acquired data

without SAR processing "LRM like" (blue), with SAR processing (red)

12 000 s, 90 000 km, 240 000 tracking cycles



SIRAL FINDINGS

- **SIRAL/SAR capability to improve ocean range noise**
  - **~0.8 cm @ 2 m SWH @ 1 sec is now demonstrated on real data by several groups**

- **SAR echoes re-tracking with accurate numerical modeling of the waveforms is the way forward (even for LRM)**

- **The results can be used for supporting new missions (Jason-CS)**

NEXT, FOR SIRAL …

- **Validation against independent measurements for assessing non-random noise (“biases”) is needed**

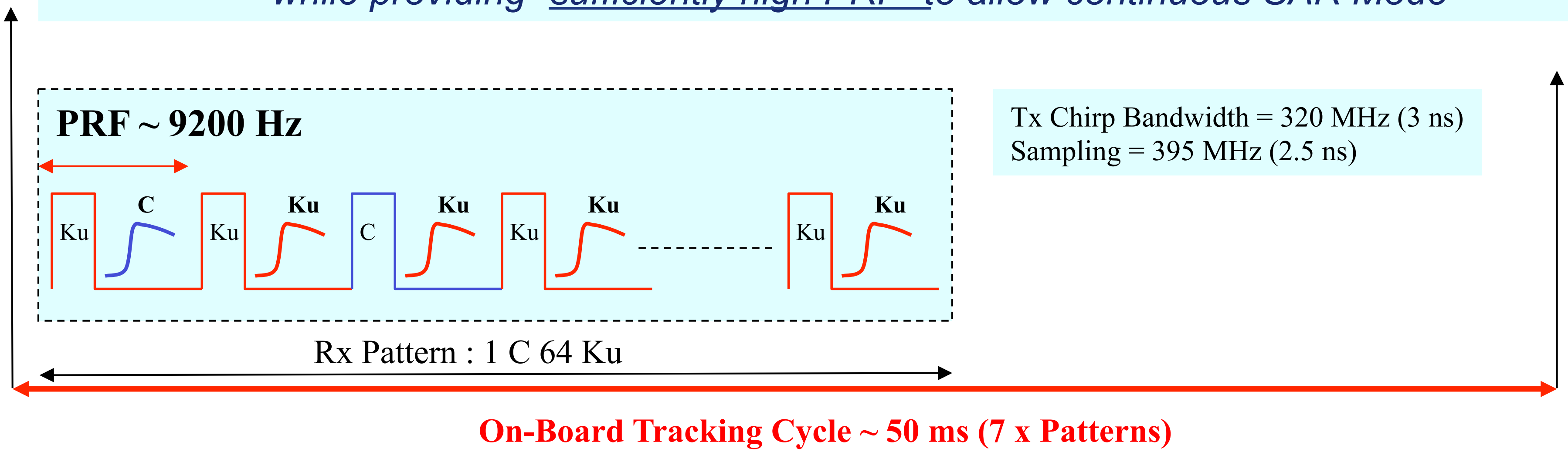
- **BIASES**
  - Non random component in the differences (spectrum) between two data set

- **Potential non-random signature**
  - **Altimeter hardware**
    - **Internal / External Calibration shall help in assessing / removing most of the internal variability of the altimeter**
  - **LRM mode versus SAR mode : the geometry is very different !**
    - **LRM and SAR mode smooth (average) and sample the ocean surface in a different manner**
    - **When multilooking the data, the ocean cells are averaged in a different manner in LRM and in SAR**
  - **Antenna pointing : to be included in the retrieval**
  - **Non-Gaussian Sea effect (e.g swell) are projected differently in SAR and LRM due to the geometry.**

POSEIDON 4 On Jason-CS

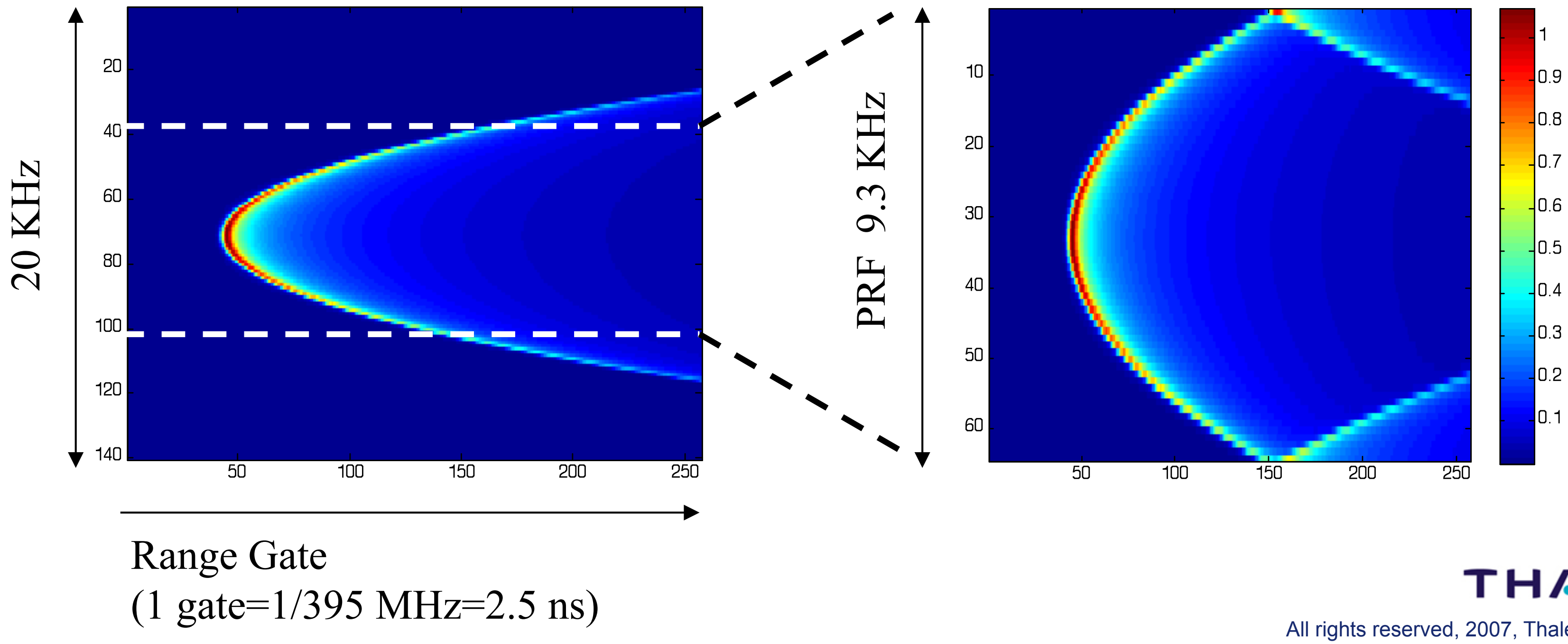
- Chronogram trade-off
  - POS4 altimeter data shall provide continuity of demonstrated Poseidon-2,3,3B performances
  - Closed burst SAR chronogram (SIRAL, S3 like) are exclusive of LRM mode 2KHz
  - Altimeter / satellite constraints shall be accounted for (power, downlink ...)

The "interleaved mode" fulfils Jason data continuity - Low Resolution Mode - while providing "sufficiently high PRF" to allow continuous SAR Mode

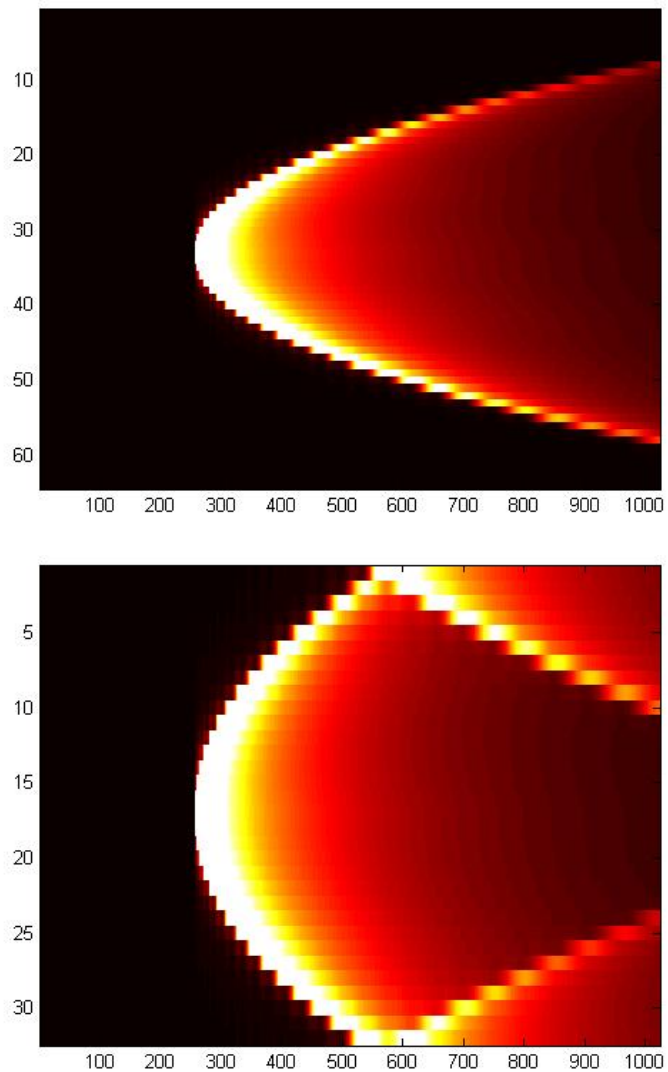


PRF & Doppler

- **PRF < Doppler bandwidth creates aliasing but …**
  - Doppler aliasing occurs at the « end » of the trailing edge of SAR processed echoes
  - Doppler aliasing can be accounted for in the re-tracking
  - PRF has been selected as a trade-off between performance and space segment contraints

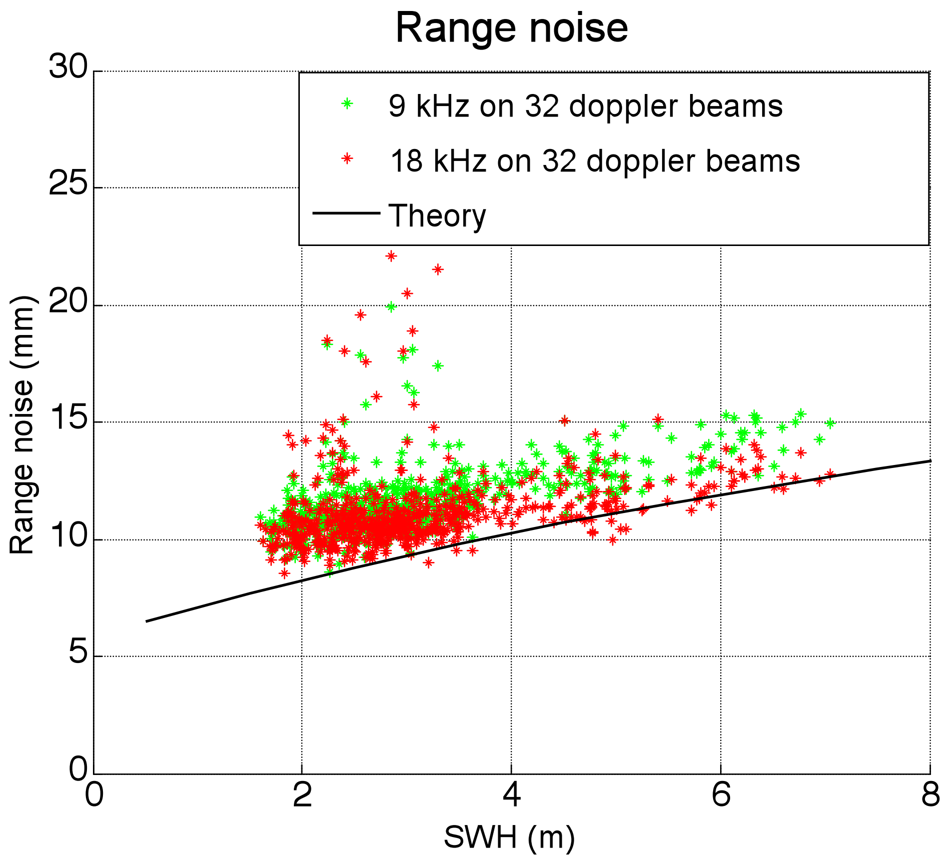


SIRAL re-tracking with aliasing



18 KHz data are undersampled at 9 KHz and re-tracked

Phalippou L. & Demeestere F. AGU 2011



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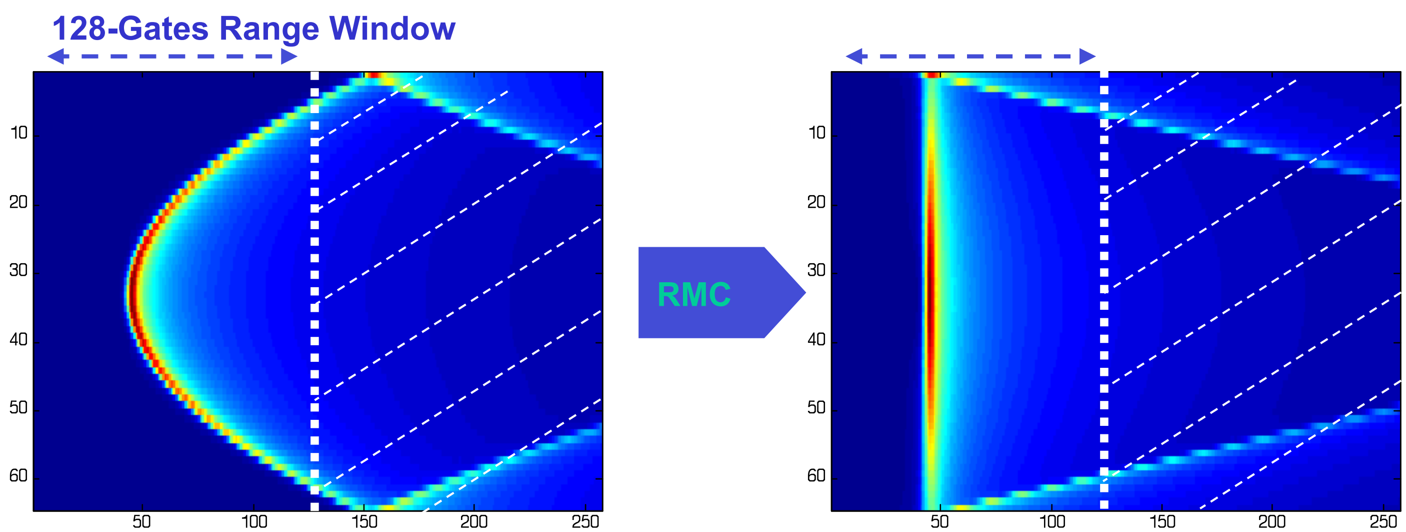
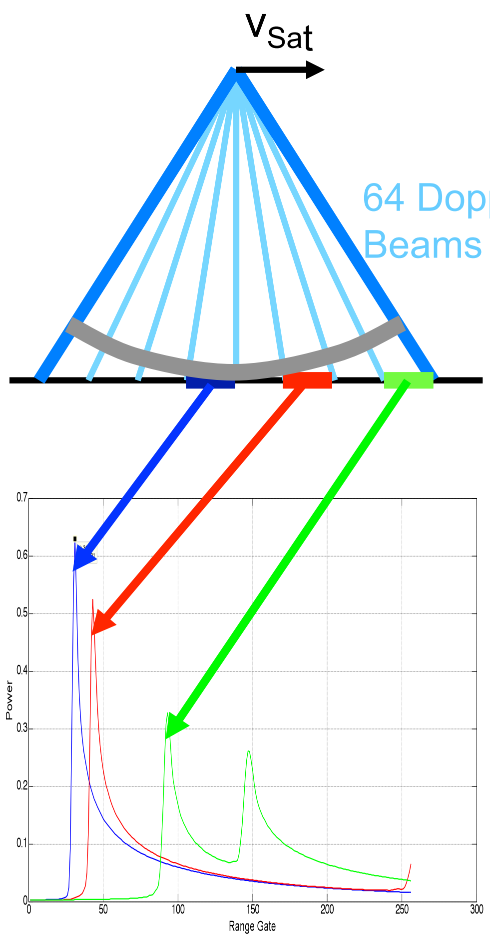
RMC processing principle for J-CS

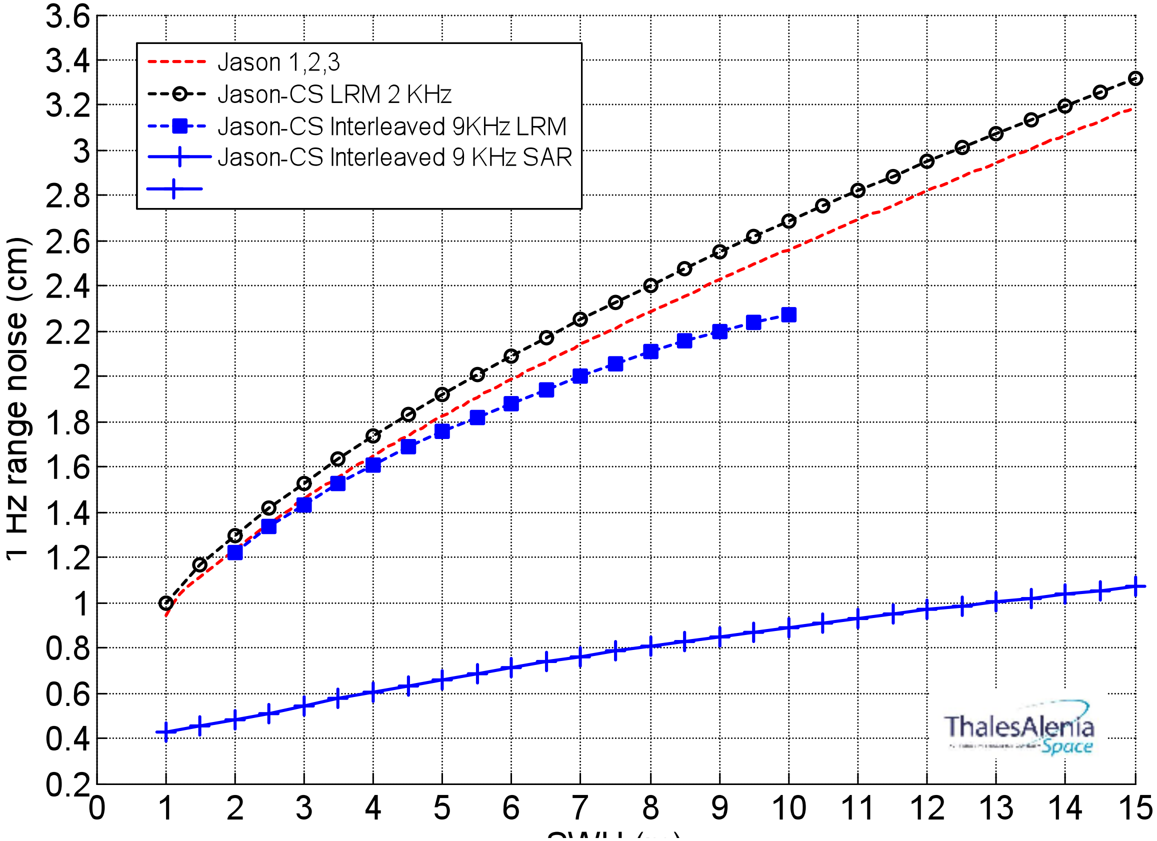
- **Range Migration Correction (RMC)**
  - On board re-alignement to compensate range migration ~120 gates, in order to keep the most informative data
  - RMC shall be “reversible” on-ground
  - Complex data (I & Q data) after RMC will be downlinked





J-CS POS-4 Range Noise

- **Range noise estimation**
  - Methodology and echo modeling validated against in flight SAR-SIRAL data
  - Numerical model of echoes including azimuth aliasing + speckle / thermal noise
  - RMC effect has also been assessed



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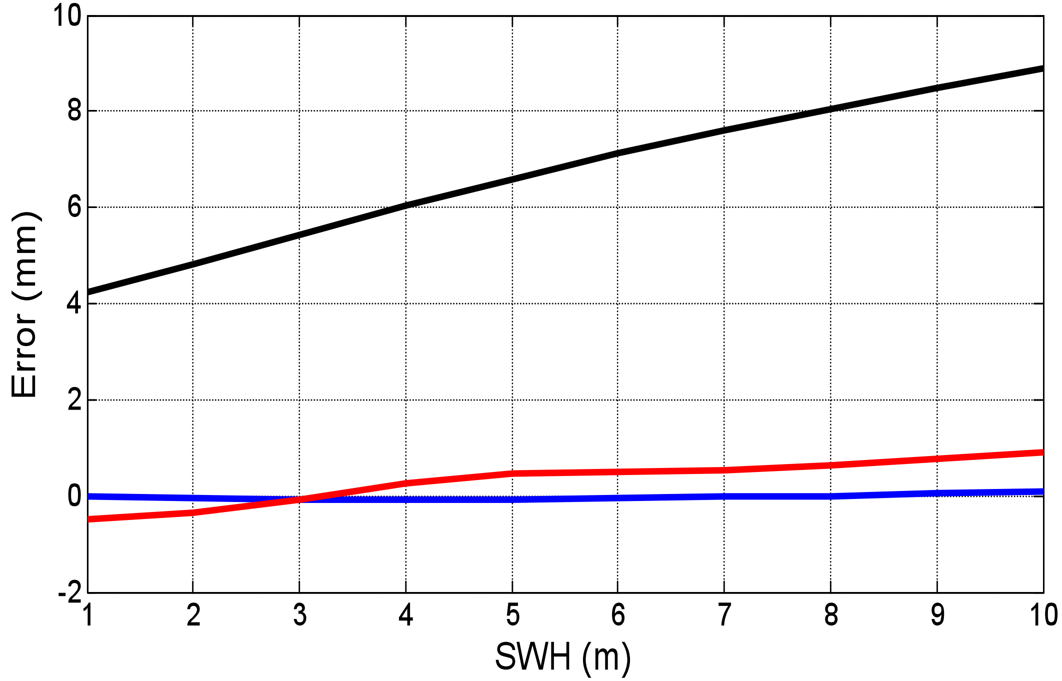
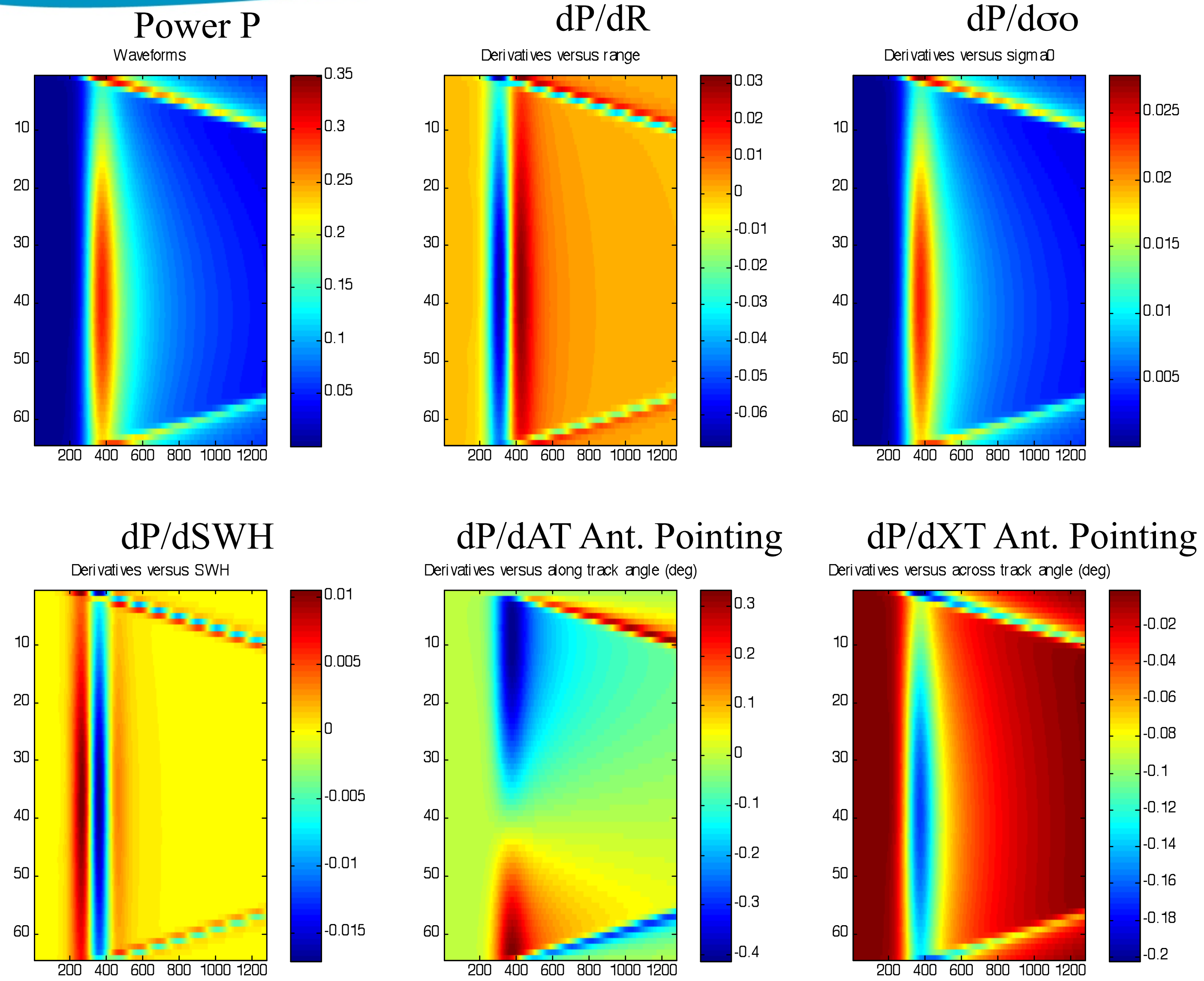
Impact of RMC



- Re-tracking simulation with / without RMC
- Max error due to the RMC truncation (for SAR type2 only) is less than 1mm [1-10 m] SWH
- Multi-looking strategy should reduce even further the RMC impact
- Keep in mind the residual of EMB correction !

The antenna pointing issue



Note correlations in the K matrix

2D re-tracking why ?

- Pointing estimation
- Validation of forward model (fine tuning & « biases » analysis)
- Investigation on SWELL

2D Re-tracking : Retrieval Noise

2D Retracking of :

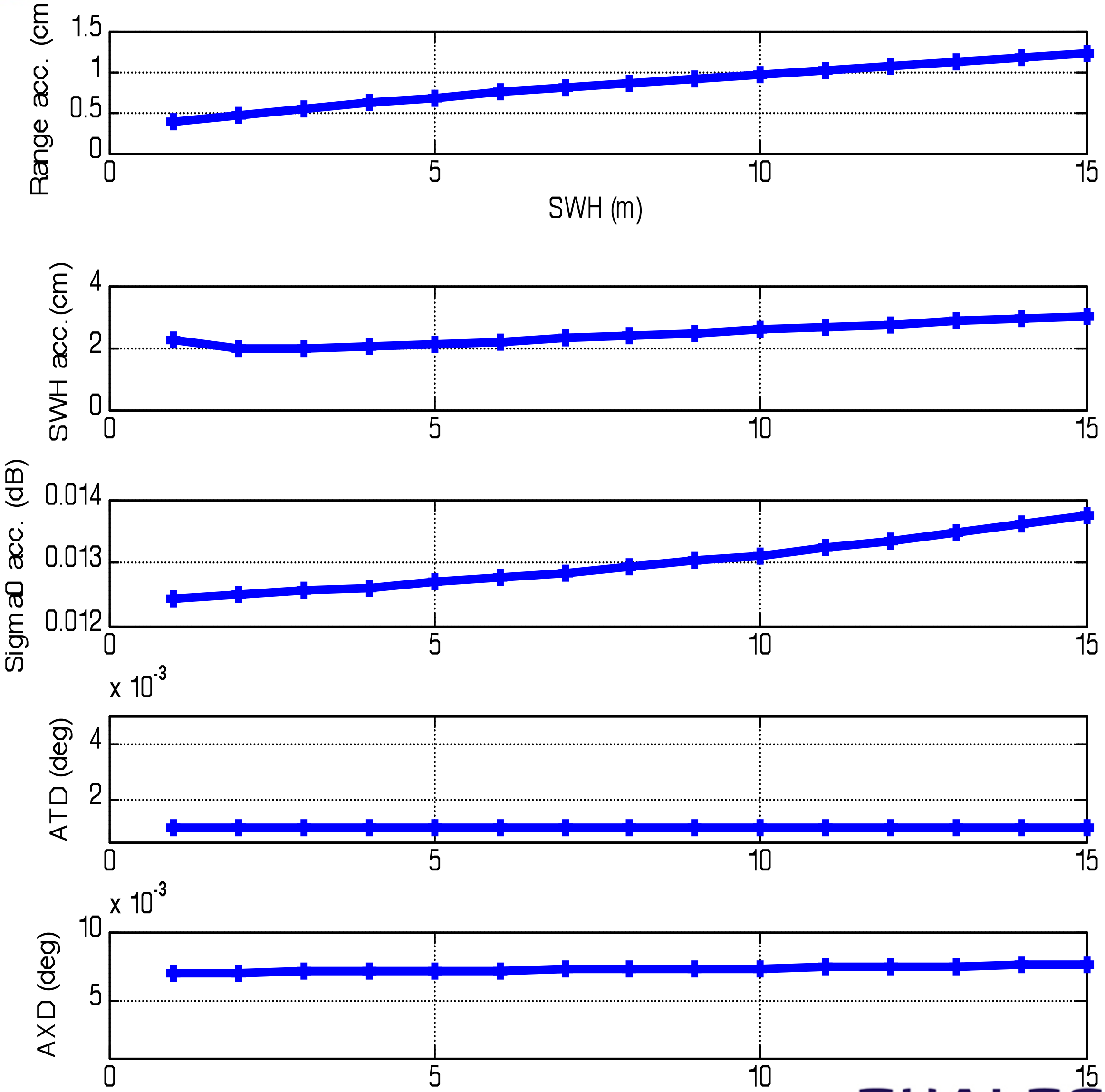
Range

SWH

Sigma0

Along Track Depointing (ATD)

Across Track Depointing (AXD)



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Conclusions

- Interleaved chronogram allows continuous data take over the ocean : data can be processed on ground either in the conventional LRM mode or in the SAR mode to improve significantly the range noise (factor 2-3)
- JCS : opportunity to compare and validate both mode against each other
- The Interleaved mode is well suited to the new hardware architecture of POS4 (range pulse compression instead of deramp)
- No risk : value for money !
- POS4 will pave the way to the future of <u>operational altimetry</u> with higher spatial resolution / smaller range noise
- 2D SAR data open a vast field of <u>research</u> for ocean / coastal / inland water