COLLECTE LOCALISATION SATELLITES

SAR altimetry : a comprehensive approach from theoretical studies and instrument processing to geophysical validation

CONTEXT

- The SAR mode has been first designed for CryoSat mission to help along track resolution improvement for sea ice and ice sheet margins applications (including SARIn mode).
- This mode has been also proposed for Sentinel-3 mission for ice but also for coastal and inland water applications.
- From the beginning, one natural question has been raised on the usefulness of this mode for ocean applications. It was very difficult to answer this question without enough real data over ocean.
- Since CryoSat-2 launch and thanks to the operation of SAR mode over some ocean areas, it became possible to study and develop specific ocean processings and also to perform calval activities to assess this mode over ocean
- The first results are so promising that ocean users community is now interested in this mode and recent recommendations have been made to process Sentinel-3 in SAR mode everywhere over ocean in addition to coastal, inland water and ice surfaces.

The objective of this presentation is to give a status of the present S3 ground processing developments along with past, current and future studies, that have helped and will help to assess the SAR mode, improve the corresponding processing and solve the remaining issues.

This presentation will also present our recommendations for further tasks to support Sentinel-3 and by the same way Jason-CS missions .

SUMMARY

1. Sentinel-3 L1 and L2 Ground Processing Prototype (GPP) and Instrument Processing Facilities (IPF)
2. Theoretical studies including simulation activities
3. Validation activities using CryoSat-2 real data to help processing improvements
4. Conclusions and recommendations for Sentinel-3 and Jason-CS

1. Sentinel-3 SRAL Ground Processing

1. Sentinel-3 Ground Processing
SPS and GPP

In order to assess and control the expected Sentinel-3 Altimeter System Performance, a dedicated **System Performance Simulator (SPS)**, including a **Ground Processor Prototype (GPP)**, has been designed and developed for each instrument of the topography payload (SRAL, MWR and GNSS).

This activity has been performed by CLS (with a support of a consortium of several European companies: isardSAT, Deimos Portugal, GMV, MSSL/UCL and ACS) under a Thales Alenia Space contract for ESA (end customer) and an ESRIN/CNES contract.

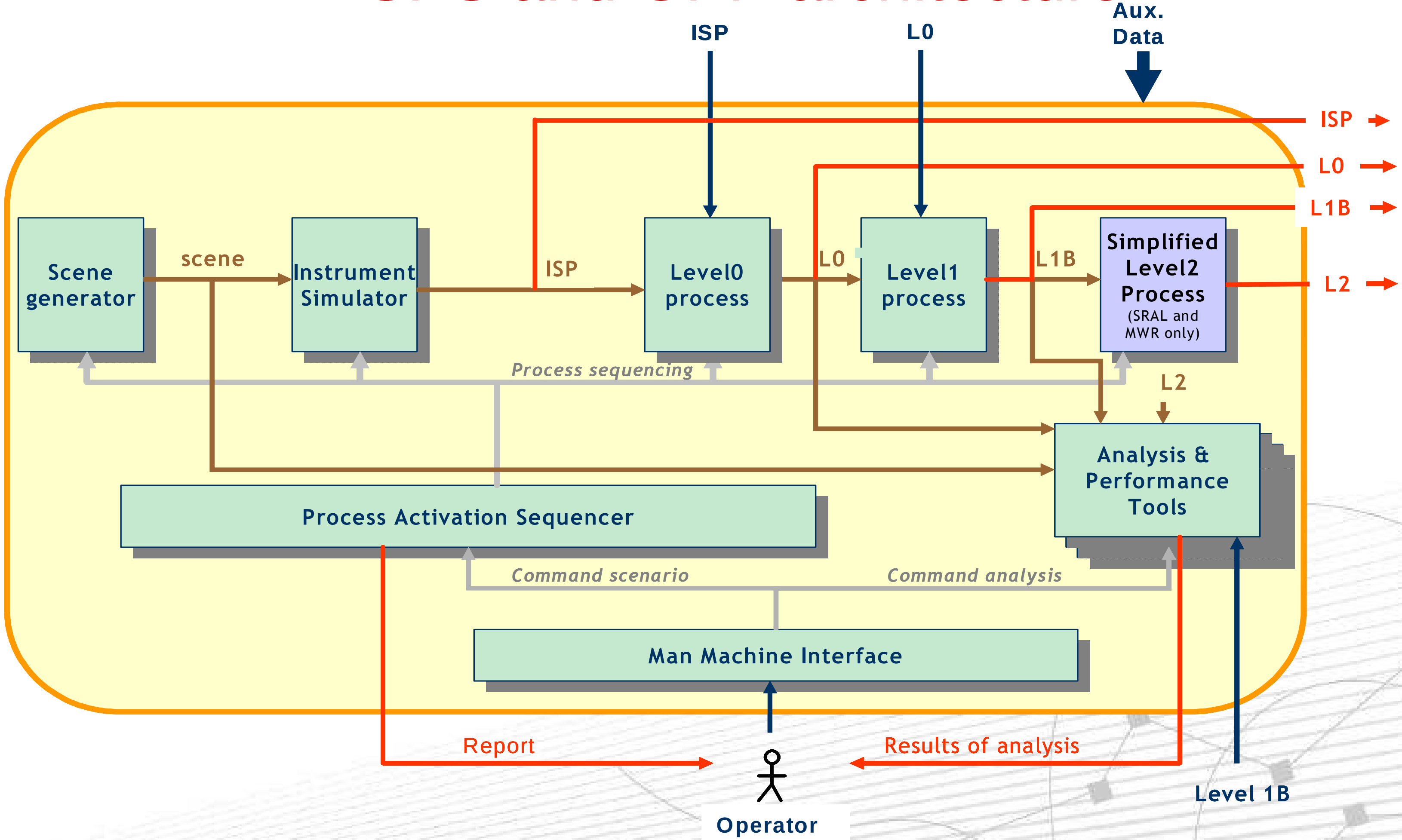
The objectives of SPS and GPP are:

- Support to the development and validation of the operational level 0, level 1b and level 2 processors by generating the reference TDS
- Pre launch activities
  - E2E performance verification with the SPS & GPP
  - Instruments validation by processing Instrument data with the GPP
- Post launch activities
  - Performance evaluation on real measured data along with GPP

The SPS and GPP can be easily adapted to Jason-CS.

1. Sentinel-3 Ground Processing

SPS and GPP architecture



Coupling of SRAL, MWR and GNSS has been simulated

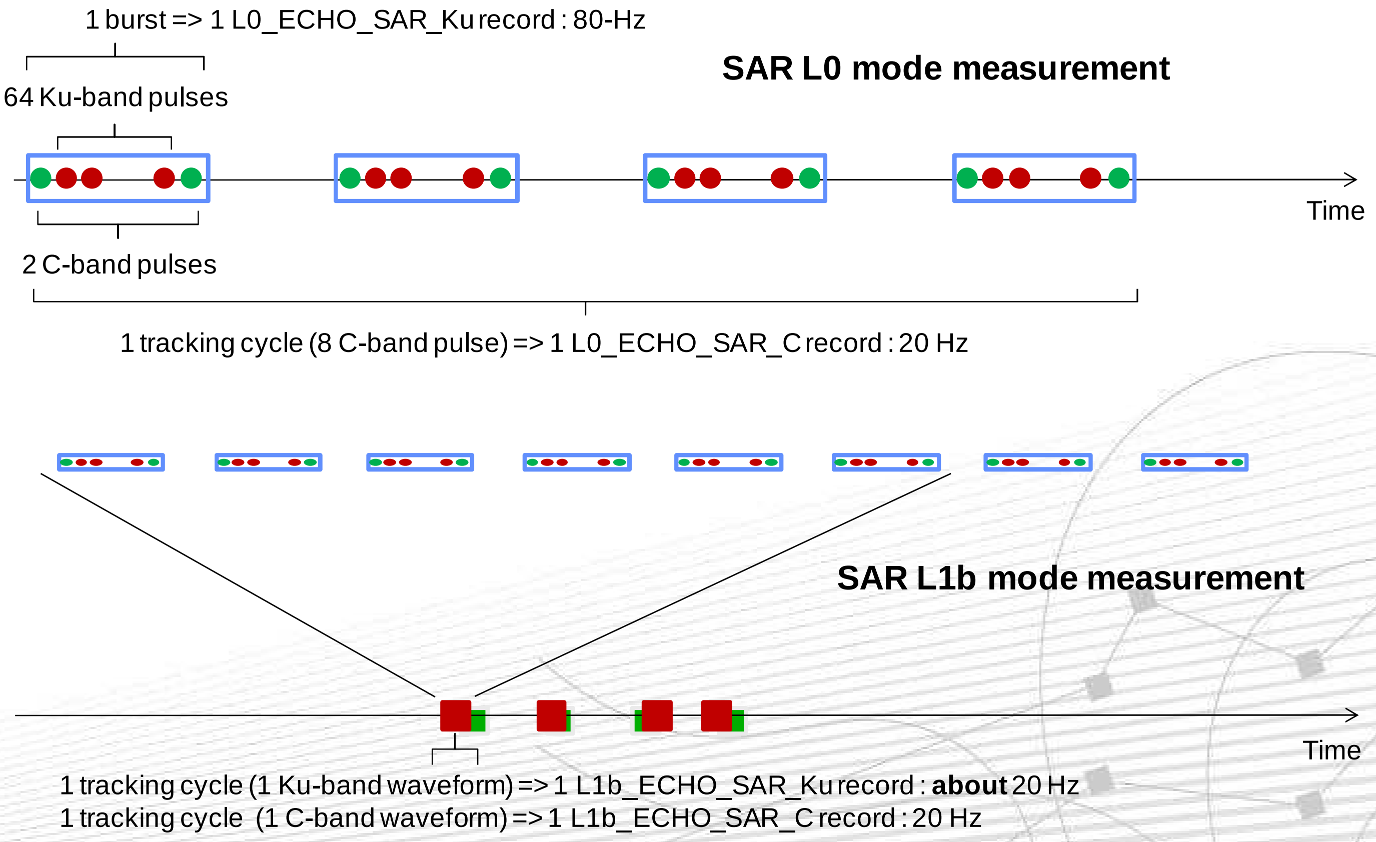
Simplified Level 2

SRAL / MWR Simplified L2 integrated in the SPS for verification purpose

Level 2 CFI for POD is out of scope of this activity

1. Sentinel-3 Ground Processing
SRAL Level 1b GPP

Version 1 of the SRAL L0/L1b Prototype has been delivered to TAS in 2011 and Version 2 is under validation and includes a new function: **Pseudo-LRM** processing in order to have LRM-Like echoes in **Ku and C bands** during SAR mode operation

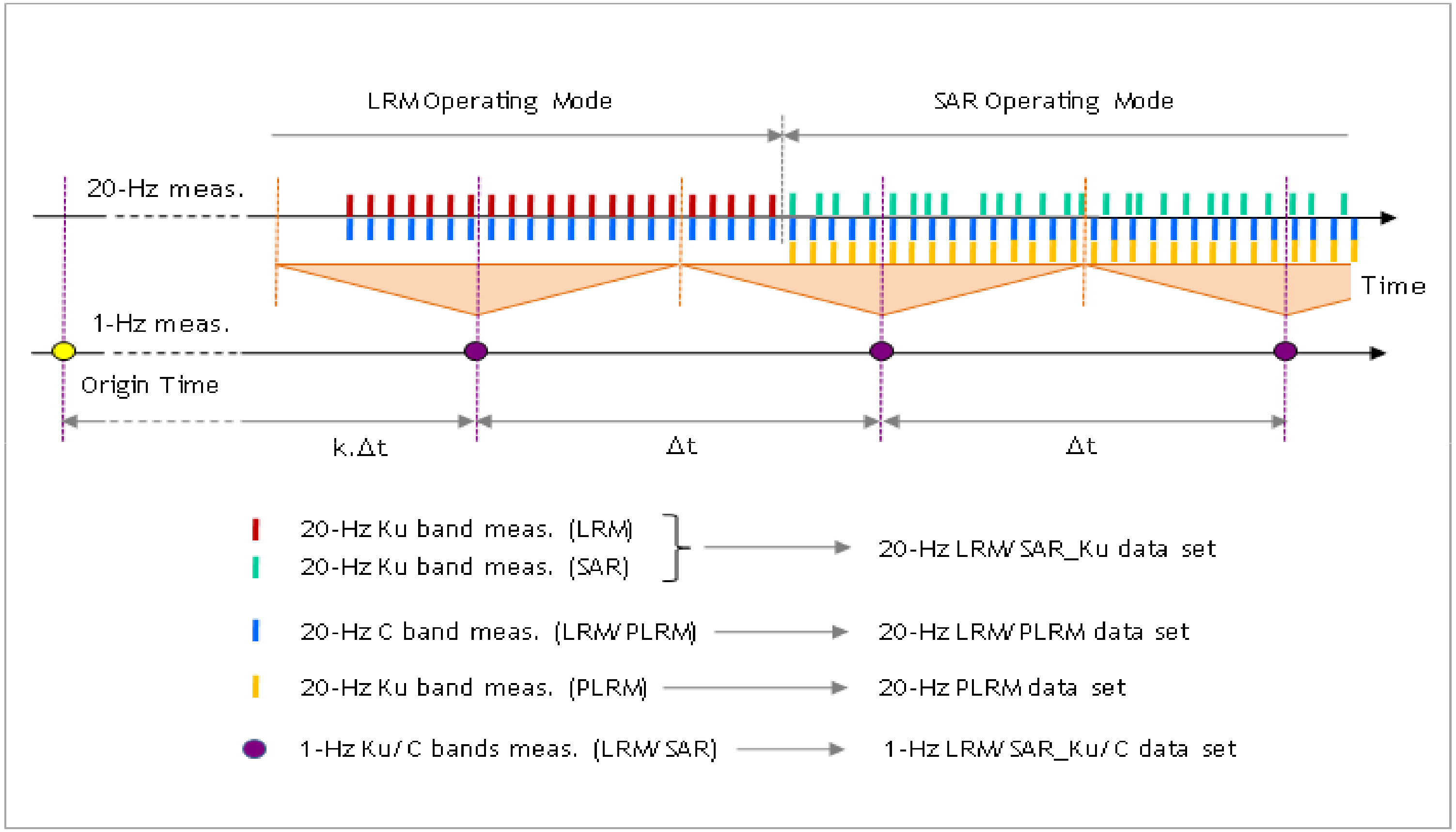


1. Sentinel-3 Ground Processing
GPP level 2 processing

- Algorithms heritage from ERS-1, T/P, ERS2, Jason-1, Envisat, CryoSat-2, Jason-2
- State of the art SAD and DAD files
- New innovative algorithms from independent ESA and CNES studies have been implemented:
  - Coastal composite wet tropospheric correction using ECMWF and MWR parameters
  - Enhanced ocean wet tropospheric correction using MWR data and Sea Surface Temperature
  - Model Dry and wet tropospheric corrections processed from 3 D meteo model parameters
  - Enhanced sea-ice flag and Continental ice classification
  - Rain rate
  - New land/sea mask from AltiKa derived from GlobeCover with 7 states

Parameter name in the product	Retracking algorithm	LRM mode Ku/C and PLRM mode Ku/C	SAR mode
Ocean retracking estimates	« ocean MLE4 »	X	
	« ocean/coastal SAMOSA »		X
OCOG retracking estimates:	« OCOG »	X	X
Ice sheet retracking estimates	« ice sheet »	X	
	« ice sheet marging »		X
Ice retracking estimates:	« ice erf » or Ice2	X	
Sea ice retracking estimates	« sea ice »		X

1. Sentinel-3 Ground Processing
GPP level 2 processing



1. Sentinel-3 Ground Processing
Operational processing

Current status

- The IPF (Instrument Processing Facility) for Sentinel-3 is being developed in the frame of an ESA/VEGA contrat within an ACRI consortium.
- CLS is responsible for the topography mission specifications (SRAL and MWR) and for the implementation of the SRAL L1b processing and SRAL/MWR L2 processing.
- The SRAL L1 processing passed the FAT v1 last week
- FAT v2 (including SRAL/MWR L2) is expected next september

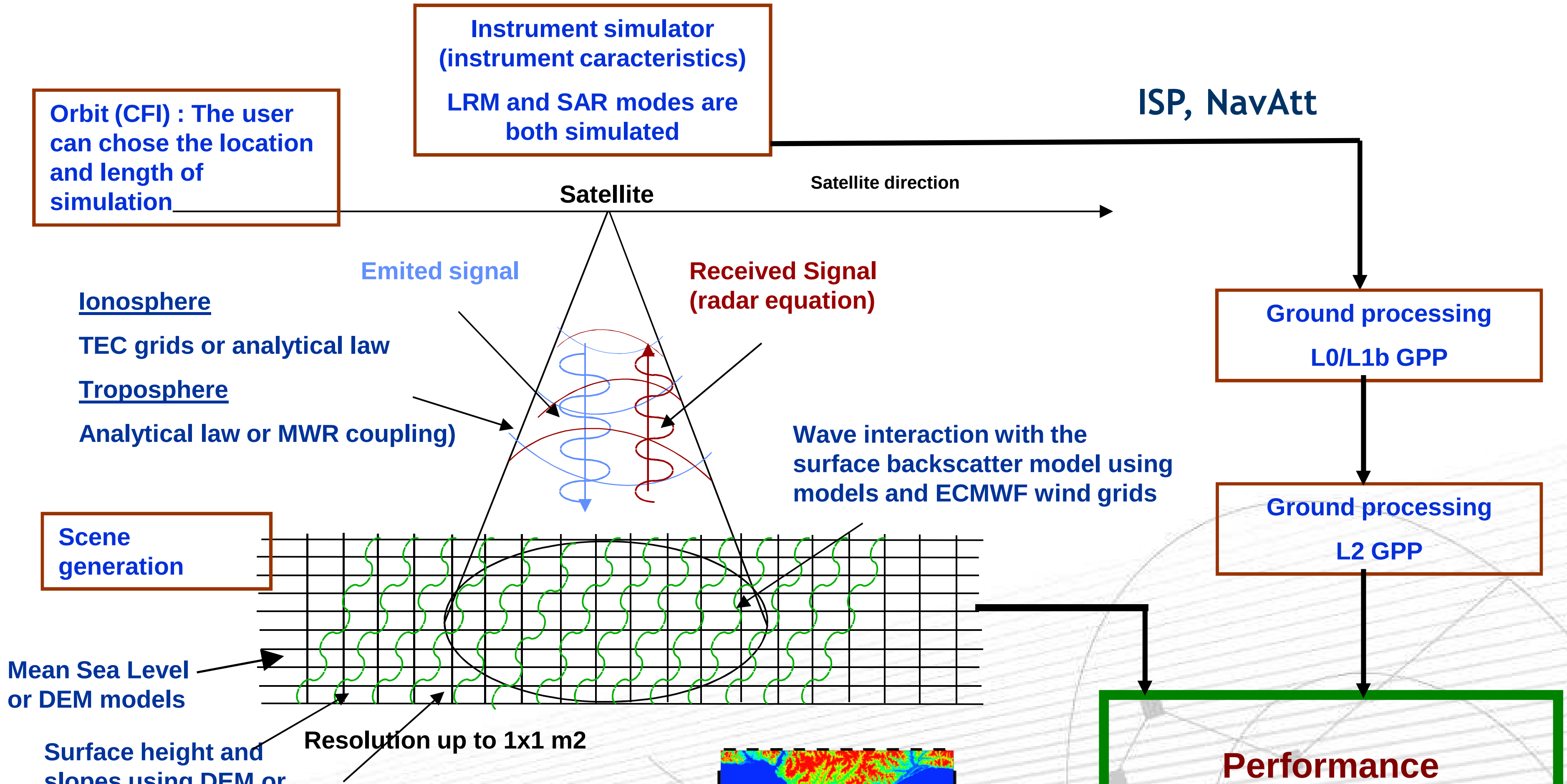
2. Theoretical Studies

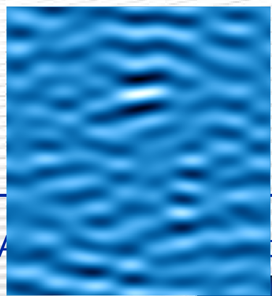
2. Theoretical studies
Simulation activities

- Since 2005, CLS has been conducting different studies, on ESA , CNES and CLS fundings, to understand the principle of the SAR processing
- Simulation tools have been developed to reproduce the raw complex echoes and the corresponding processing up to the retracking algorithm
- These studies allowed CLS specifying the Sentinel-3 SRAL L1b and L2 processings and also to develop the Sentinel-3 End-to-End System Performance Simulator
- End-to-End simulation activities have also been performed at CLS since years for conventional Ku band altimetry and for AltiKa, SWOT, CFOSAT missions
- These simulations have been first applied to the ocean surface and then extended to inland water, coastal and ice areas

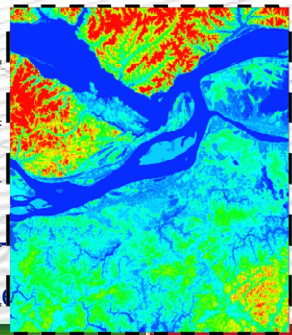
These simulators are very valuable tools allowing development of new algorithms, testing specific instrument parameters impact on the processing, testing specific geophysical effects on the performance …

2. Theoretical studies - Simulation activities





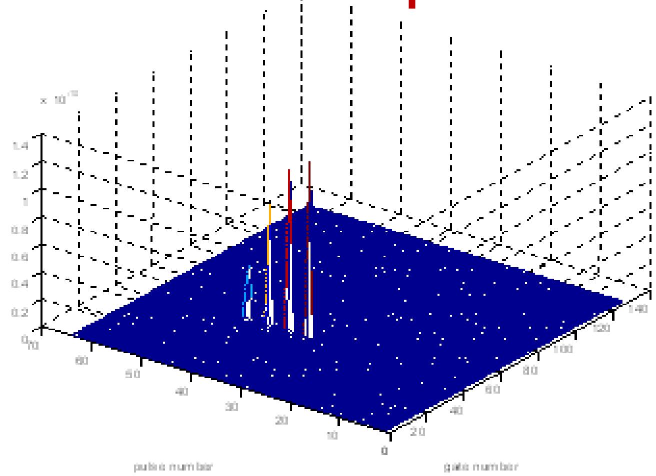
Sea Surface Elevation from a swell spectrum

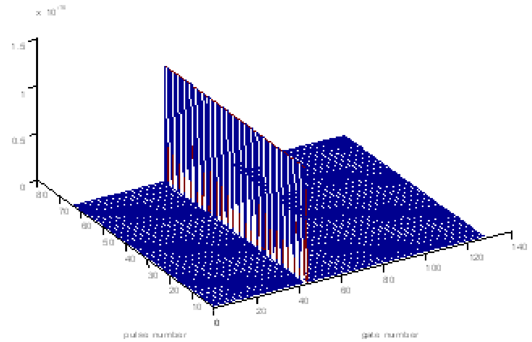


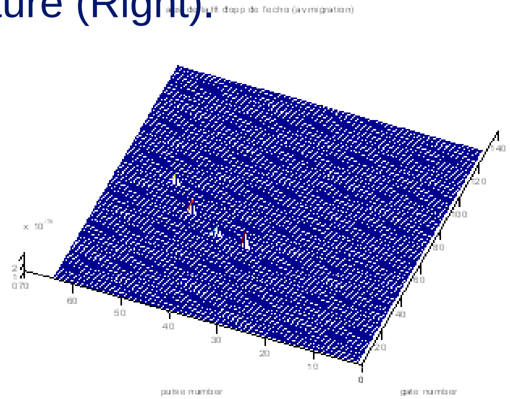
DEM elevations over hydrological target

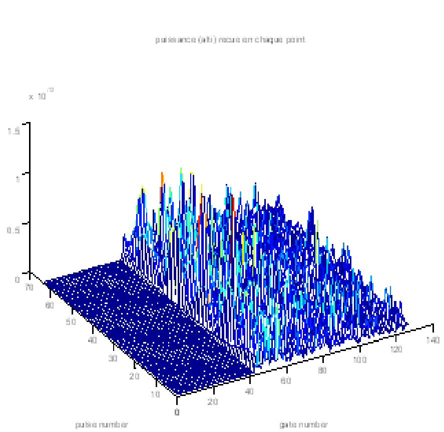
2. Theoretical studies - Simulation examples

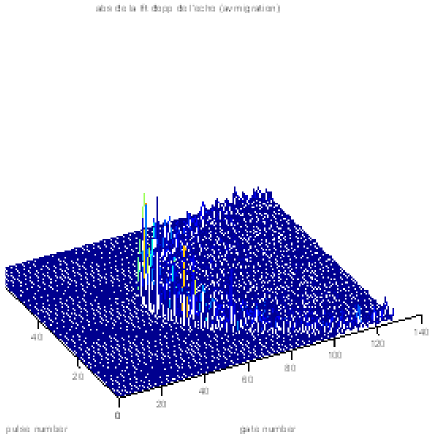
Conventional Altimetry Signal (Left) versus Doppler Altimetry Signal (Middle) using 4 scatterers on the sea surface aligned in the along track direction. After slant range correction we can correctly retrieve the four scatterers signature (Right).

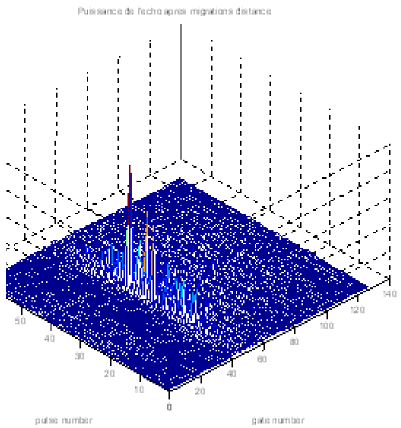




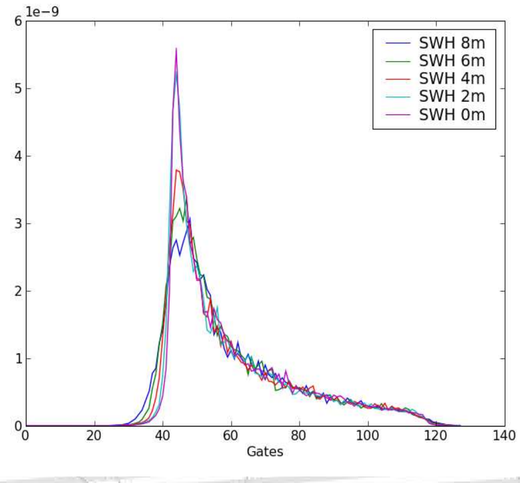






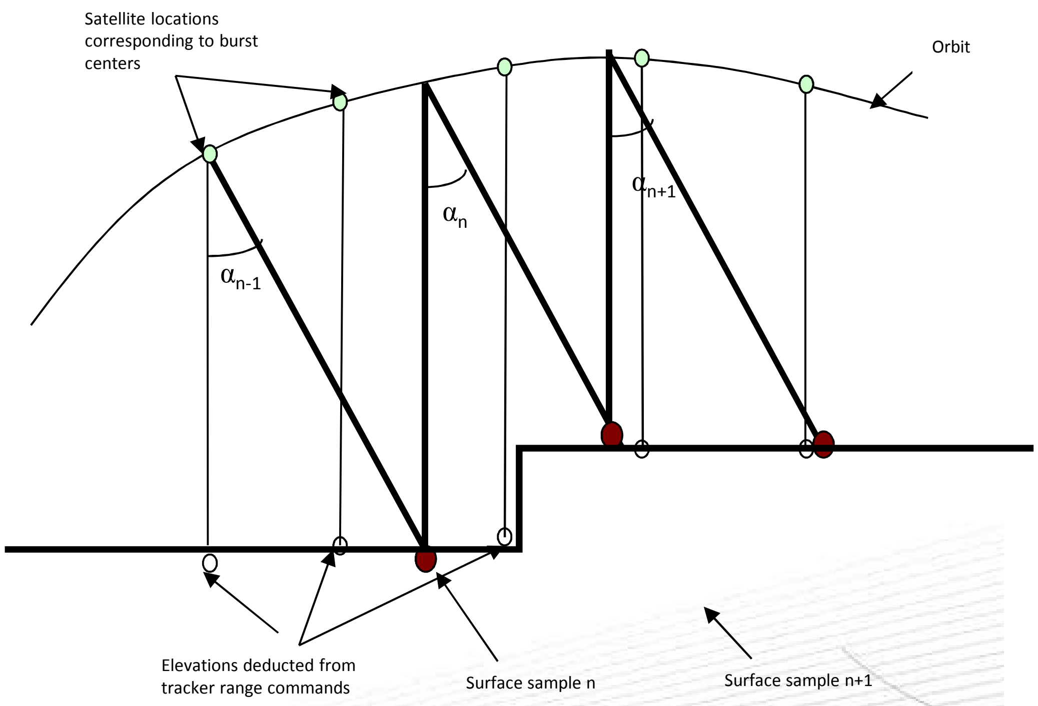


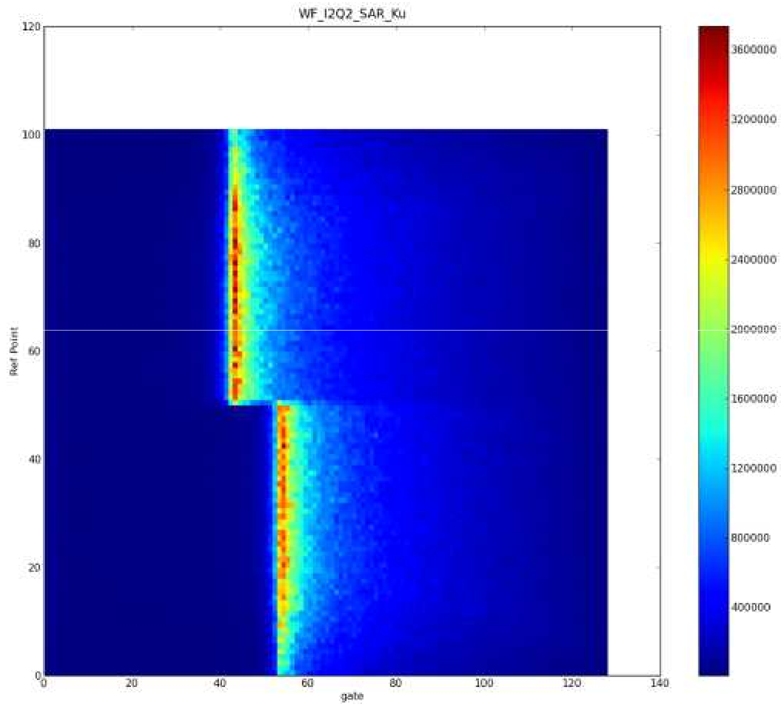
Simulated Doppler Echoes and Dependence with SWH



2. Theoretical studies - Simulation examples

This simulation case shows the high ability of the SAR mode to improve the resolution especially for coastal and inland water areas.

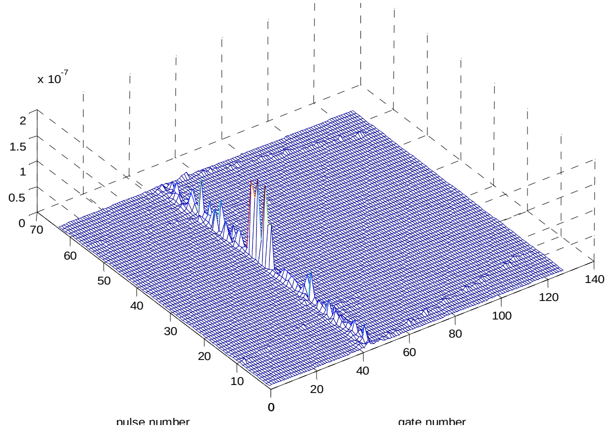




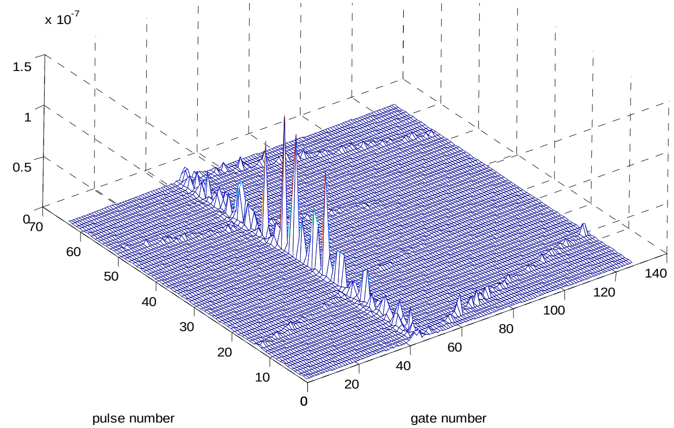
2. Theoretical studies - Simulation examples

This kind of simulation can be adapted for future instruments as Jason-CS.

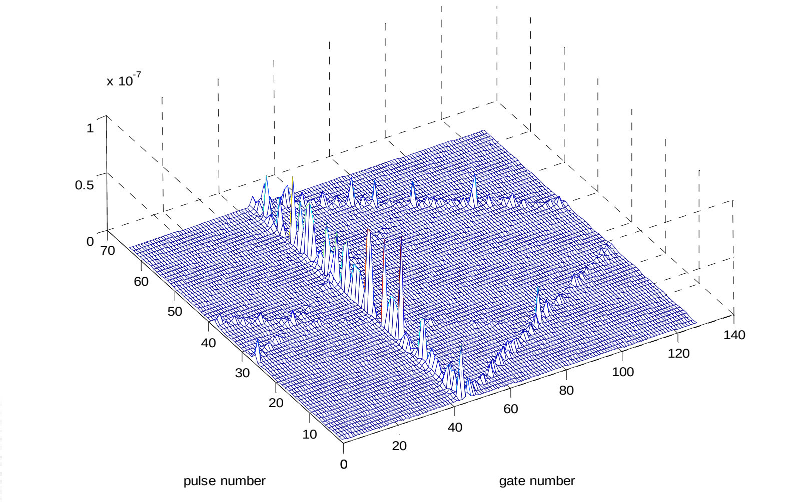
The spectral aliasing due to lower PRF is correctly simulated.



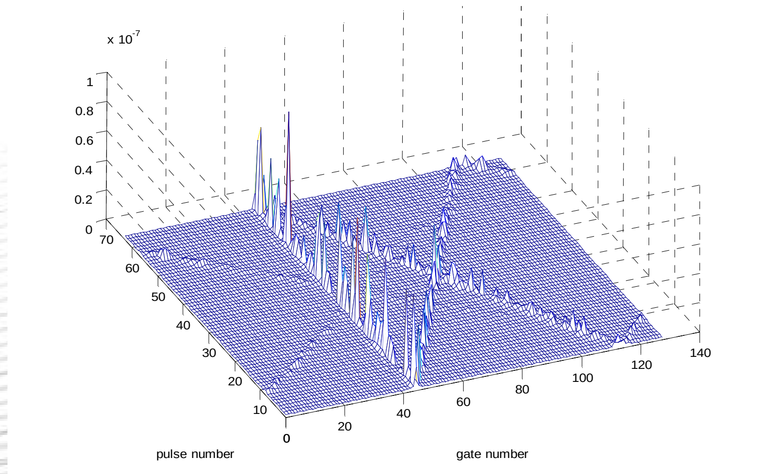
PRF =12000 Hz



PRF = 10000 Hz



PRF = 7000 Hz



PRF = 4000 Hz

2. Theoretical studies
Retracking algorithms

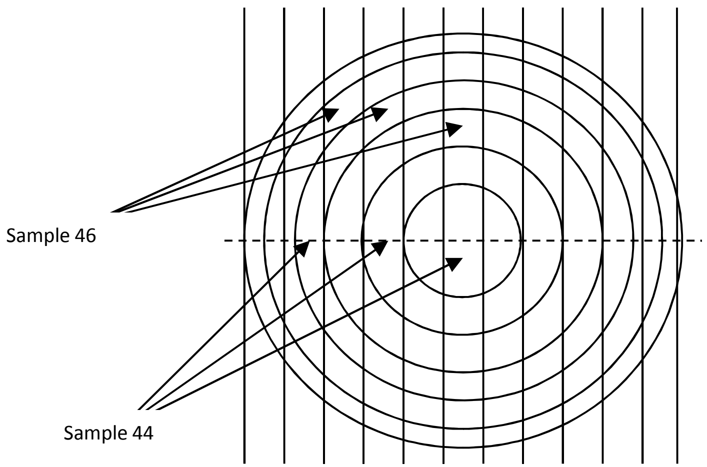
- **Numerical retracking algorithm using complex Doppler simulated data**
  - This algorithm including the true Doppler processing has been used as a reference, and has already provided a substantial support to the development of the CPP.
  - Some evolutions of the model are already planned to better account for the effects of new parameters (altitude and antenna mispointing angles).

- **Semi-Empirical Retracking**
  - Developed in the frame of a PHD thesis performed by A. Halimi and directed by CNES, CLS and the University of Toulouse
  - The FSSR function is modeled using an analytical formula and the double convolution with the ocean Power Density Function and Range and azimuth Impulse Responses is performed numerically.
  - The model accounts for 5-parameters, including mispointing angles in across and along-track directions is currently under investigation
  - The first results have been presented at the OSTST meeting of Venice in 2012: *An analytical model for Doppler altimetry and its estimation algorithm, by A. Halimi et al.*

2. Theoretical studies

Assessment of the SAR mode speckle noise

The theoretical noise presented in the literature is always based on the number of beams in the stack. Nevertheless, the observations are different.



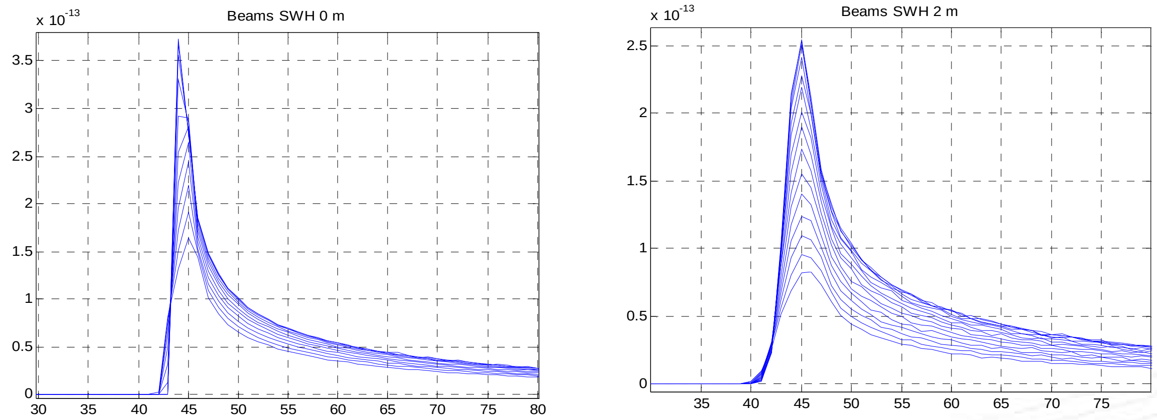


Illustration for different SWH values

When stacking the Doppler Beams, the power level for each sample depends on the beam angle

For conventional altimetry, the speckle standard deviation is equal to the waveform amplitude attenuated by the number of looks or the number of indivual echoes uncoherently accumulated.

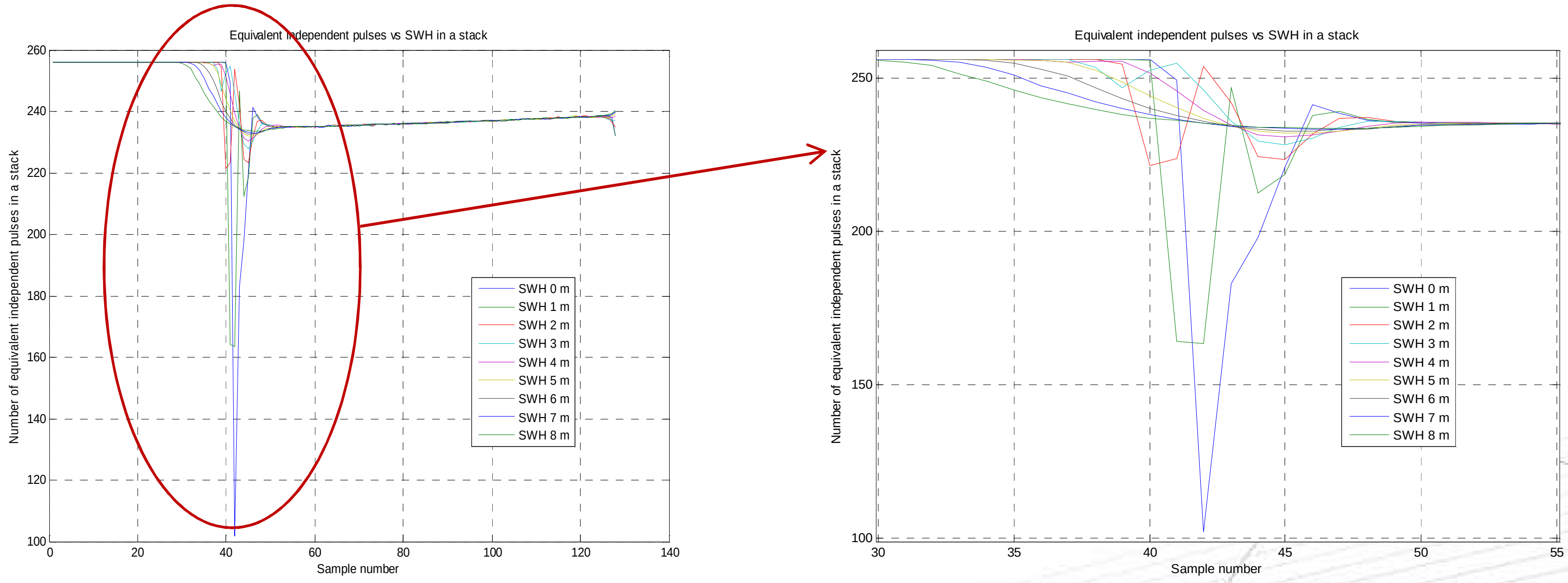
It has been shown using analytical calculation that for Doppler altimetry, the speckle noise level depends, for each sample, not only on the number of looks, but also on the mean power variations within the stacked beams.

$$\frac{a}{\sqrt{v}} = \frac{\sqrt{N}}{\sqrt{1 + \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\alpha_i}{a}\right)^2}}$$

2. Theoretical studies

Assessment of the SAR mode speckle noise

Using simulated data without speckle, we were able to apply the theoretical results to assess the equivalent speckle level versus SWH and waveform sample number.



The speckle reduction is not in agreement with the theory announcing a reduction directly related to the number of looks in a stack.

We analysed alternative beams weighting allowing us to optimise the speckle reduction but given the waveforms shapes it was not possible to find a best weighting applicable to all samples.

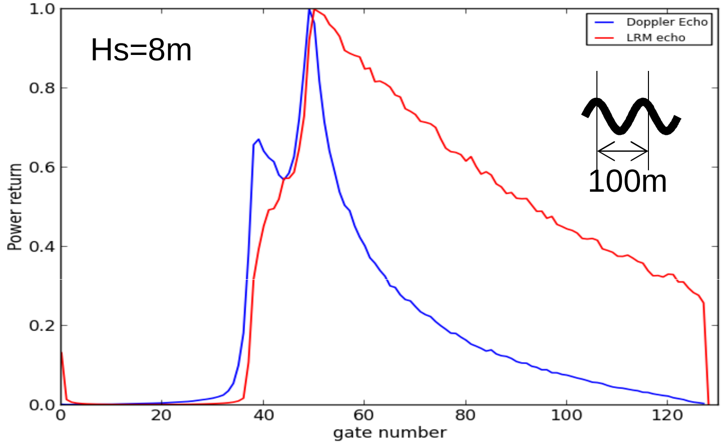
This first result will be confirmed in the near future using simulations and retracking algorithm.

2. Theoretical studies

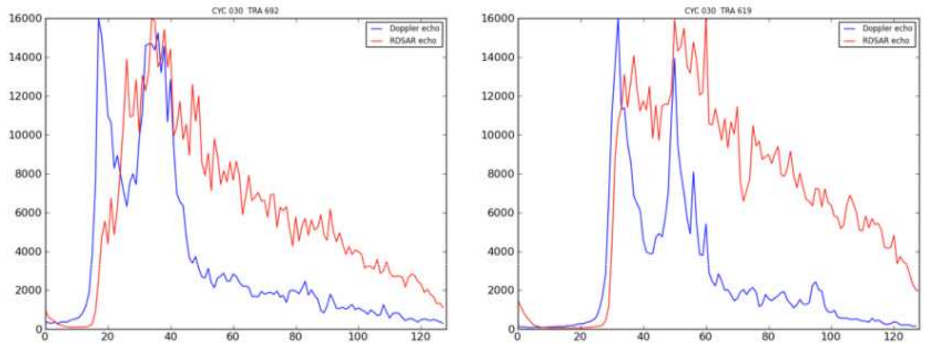
Sensitivity of the SAR mode to swell

Given the along track resolution of the SAR mode, long swell waves could affect the estimated geophysical parameters.

This is being investigated by CNES and CLS and the first results have been presented by *T. Moreau et al. at the Cryosat third User Workshop of Dresden of 12-14 march 2013.*



Simulated LRM and Doppler echo using CNES/CLS End-to-End simulator.



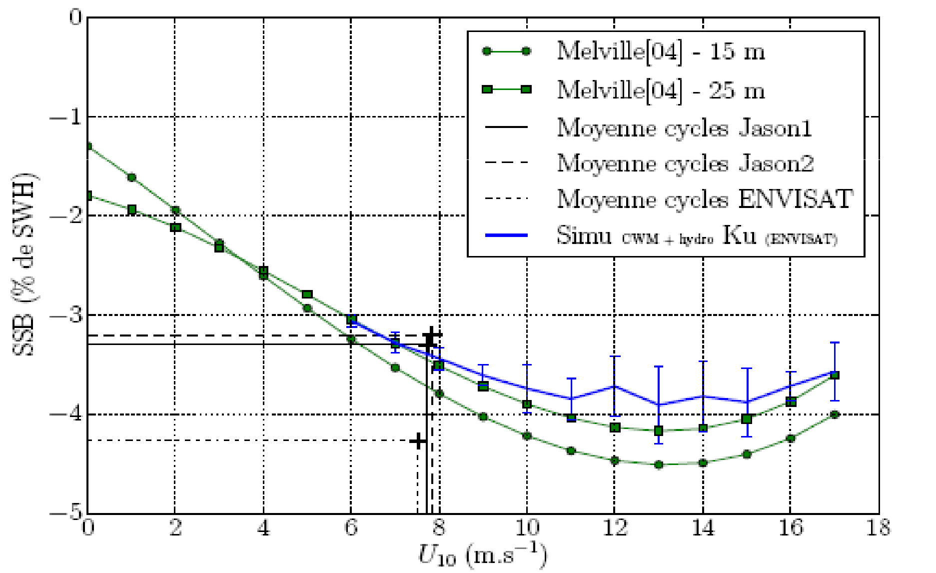
Example of detected PLRM and SAR CryoSat-2 Real Wavefoms with « no land in sight » but with shapes very similar to the simulated waveforms

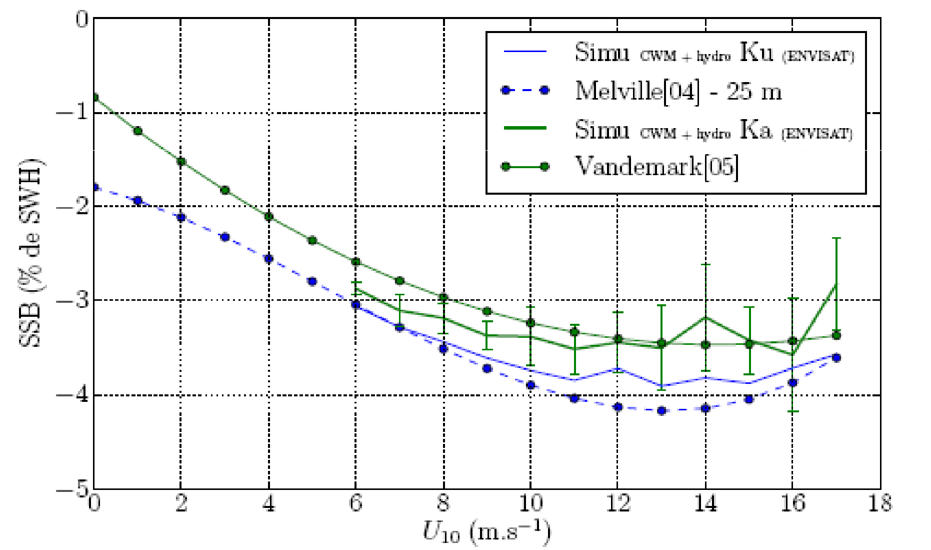
- These preliminary results show that SAR waveforms are sensitive to sub-mesoscale structures (below km)
- Other simulation activities are on-going using improved swell modelling
- It is also expected to use SAR images to help identifying ocean areas affected by swell to check that the observed waveforms shapes are due to swell.

2. Theoretical studies

Sea State Bias Analysis for new altimeter concepts

- In the frame of a PHD thesis directed by IFREMER, CNES and CLS, P. Dubois developed an end to end simulator for SWOT mission to assess the Sea State Bias for wide swath interferometry.
- The simulated sea surface simulation includes long waves non linear interactions and short scales hydrodynamic modulation by longer scales
- simulations for Ku and Ka nadir to help comparison with real data and validate the principle





Melville[04] : Plateform 15 or 25 m- Ku = 14 GHz Scatterometer - 16/06/92 to 26/09/92
Vandemark[05] : Airborne 15 m- Ka = 36.5 GHz Scatterometer - 1997 a 1999

2. Theoretical studies

Sea State Bias Analysis for new altimeter concepts

- Finally, SSB has been assessed theoretically and using simulations in SWOT configuration to show dependence with the angle of swath
- All these developments can be used for SAR nadir processing to have a first theoretical assessment of the SSB
- This can be done using the new surface developments in an end-to-end simulator

PHD thesis: *Impact de l'état de la mer sur la mesure d'élévation des futurs instruments altimétriques*, P. Dubois 2011
Corresponding publication
Design of a multi-configurations altimeter simulator for the study of the impact of the wind Sea State, P. Dubois et al., Submitted to IEEE

2. Theoretical studies

In a near future…

And Other RetD studies with CNES will start in 2013/2014

- **Analysis of SSB for SAR altimetry**
  - o Theoretical analysis of the SSB using the work performed in the frame of the SWOT PHd thesis of P. Dubois and adapting it to SAR nadir processing
  - o Empirical SSB computation using CryoSat-2 CPP data
- **High ResolutionTropospheric Correction**
  - o Analysis of a MWR processing to improve the resolution of the brigthness temperatures estimation in order to provide higher resolution estimates of the wet tropospheric corrections
  - o Thanks to S3 SPS coupling capabilities of SRAL and MWR, it is possible to assess the performance of such new algorithms in the case of the SAR mode
- **Analysis of the spectral « Hump »**
  - o Analysis of the SAR capabilities to resolve ocean short scales by injecting SLA real spectrum in and end-to-end simulaor and then by comparing geophysical estimates between SAR and LRM modes
  - o In the same simulation, rain cells and sigma bloom events will be introduced to assess the SAR expected improvements over these areas

3. Assessment/Validation Activities

3. Assessment/validation activities

The Validation activities are a necessary step to assess and constantly improve the performance of the system, and at the end the quality of the products disseminated to users

The objective of the validation (before and after launch, even after end of life to support reprocessing activities) are:

- To check the data availability and validity
- To estimate the system performances (instrument, ground processing)
- To analyze the physical content quality of product parameters
- To contribute to a better knowledge of the sea-level physical content
- To evaluate system upgrades
- To provide information for users and production center

Validation activities can be classified as follows:

- Global internal analyses
- Global multi-mission comparisons
- Global altimetry and In-situ data comparison

These activities have been developed at CLS since 1992 for the TOPEX/Poseidon mission, and are still on-going for Jason-1, Jason-2, Envisat and AltiKa missions in the frame of CNES and ESA contracts

3. Assessment/validation activities

- In CryoSat Quality Working Group, CLS is responsible for the CALVAL of ESA LRM ocean product
- Regarding the LRM CPP product:
  - First assessment of the quality has been performed in 2011 (presentation by S. Labroue et al. in the first Cryosat workshop in 2011)
  - Successful integration (LRM and PLRM) in DUACS/MyOcean altimetry products
- Concerning the SAR mode, the CNES CPP processing has been assessed and the first results have been shown in several meetings by CNES and CLS (Venice in 2012 for the 20 years of Altimetry meeting and Dresden 2013).
- CLS is responsible (with CNES contribution) of the assessment of the different SAR mode retrackings in the frame of CP4O project
- Thanks to the complementarity of Assessment/Validation with the L1b/L2 processing activities, several improvements have been introduced to the CNES SAR mode CPP as it has been shown in the presentation of F. Boy of yesterday.
- In this part of the presentation, some examples are shown, demonstrating the need and the potential of validation activities and also how they are complementary to ground processing developments and algorithms studies to ensure in the end high quality products for end users.

3. Assessment/validation activities
How to validate SAR processing?

- Objectives of this assessment for open ocean
  1. Detect correlated errors for large scales beyond 150 km
  2. Confirm that the SAR processing allows retrieving smallest spatial scales (20-70 km) thanks to 20 Hz noise and footprint reduction in the along track direction

20 Hz noise is not enough to demonstrate the performance of a processing

- Two different approaches
  - SAR validated versus Pseudo-LRM = Relative Validation
    - The most accurate method that allows checking the sensitivity to all parameters and detect possible long wavelength errors
  - SAR only = Absolute Validation
    - Analysis of Cryosat-2 data (Spectral analysis and crossovers)
    - Cross calibration with J2

The main limitation to these analyses is geographic coverage which makes difficult to separate the different effects that have spatial coverage varying in space and time

3. Assessment/validation activities

Spectral Analysis

An example, using CNES CPP L2 data, that have already presented in several meetings.

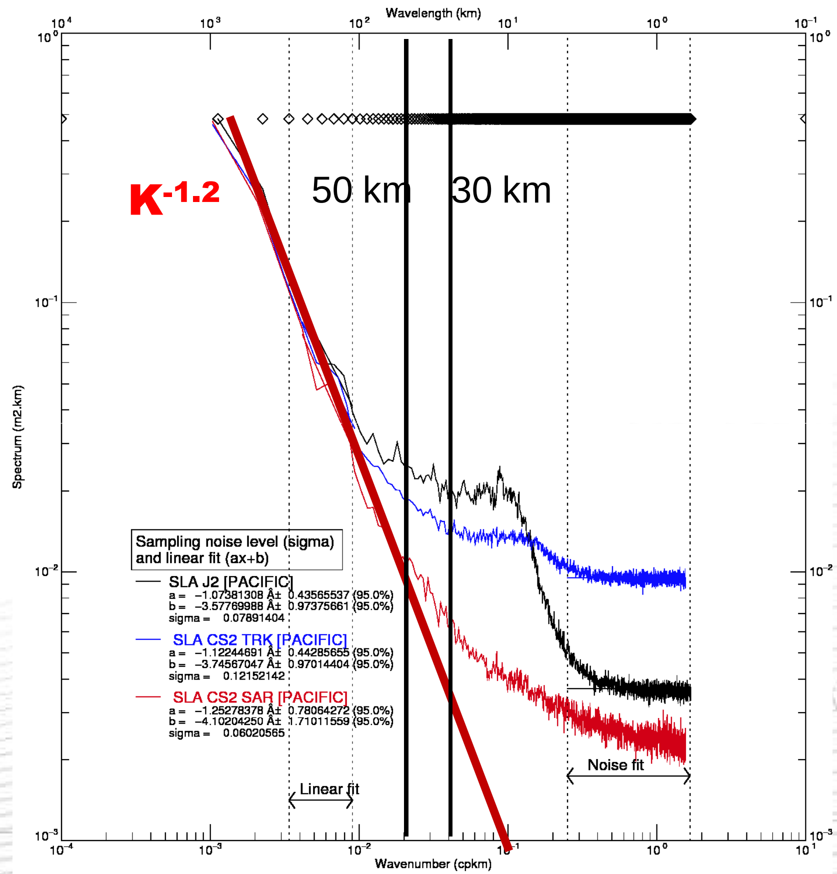
All existing altimeters present high spectral energy below 100 km which is assumed to be related to heterogeneous sea surface within the large LRM footprint

With SAR Mode :

- ✓ Clean SSHA spectrum down to 50 km
- ✓ Spatial limit (where error is 50% of the signal energy) seems to be close to 30 km compared to 70 km with LRM processing

SAR processing is very promising to improve the along track resolution of altimetry products and reduce estimation noise for high resolution altimetry

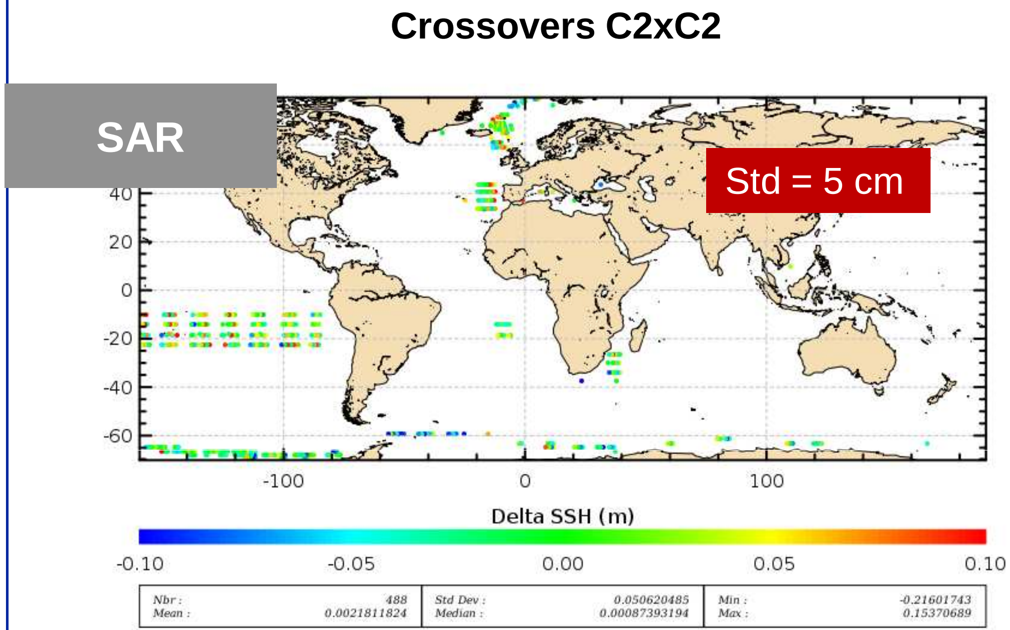
SLA Spectrum CRYOSAT [C30–32] J2 [C141–146] 20Hz

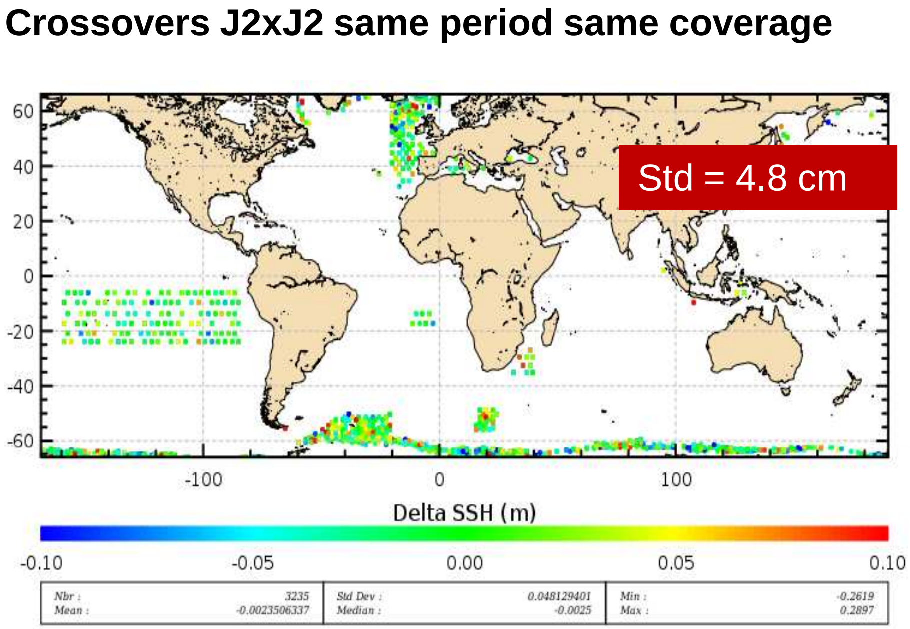


Wavenumber spectrum (m2.km)

3. Assessment/validation activities

Crossovers Analysis





Good performance of SAR at crossover 5 cms rms close to J2 performance (4.8 cm rms). The difference mainly comes from the crossover time lag which is larger for C2 vs J2 on SAR zones.

Mean = +2 mm

4. Conclusions and Recommendations

- A L0 to L2 Sentinel-3 prototype is today available and the operational IPF is under development and will be ready in the next months.
- As it has been shown, validation activities using real data are necessary to assess and improve the on ground processing and to evaluate the performance of the system.
- Given operational requirements for Sentinel-3 mission, it is necessary to have from launch the best available algorithms that have been fully validated with real data
- Prior to Sentinel-3 launch, It is then important to apply these processings to the only available SAR mode real data from CryoSat-2.
- For that, it is possible to recondition CryoSat-2 FBR data to Sentinel-3 L0 product format to allow their processing up to level 2 to perform validation activities as it has benn successfully done with CNES CPP.
- It is also of high importance to continue RetD efforts in different teams on the SAR mode to allow new algorithms development before injection and assessment in the Sentinel-3 processing and therefore help their improvements by allowing different users comparing them.
- Demonstrating the capabilities of the SAR mode over ocean will certainly help decisions on the instrument design of Jason-CS.

4. Conclusions and Recommendations