Harmony Fine Time Synchronization: TRL6 test campaign results

MULTISTATIC RADAR WORKSHOP 2025

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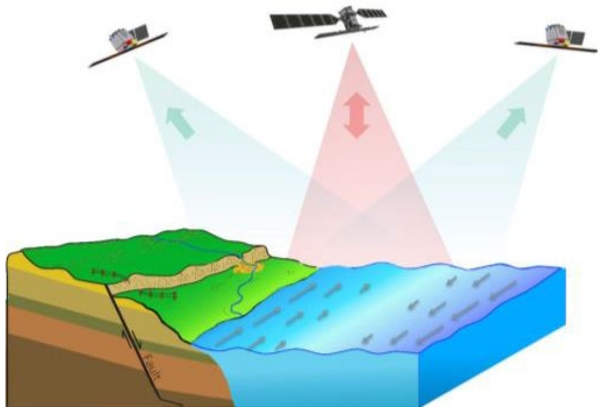
- Fine Time Synch. Algorithm
- TRL6 activities
- Conclusions

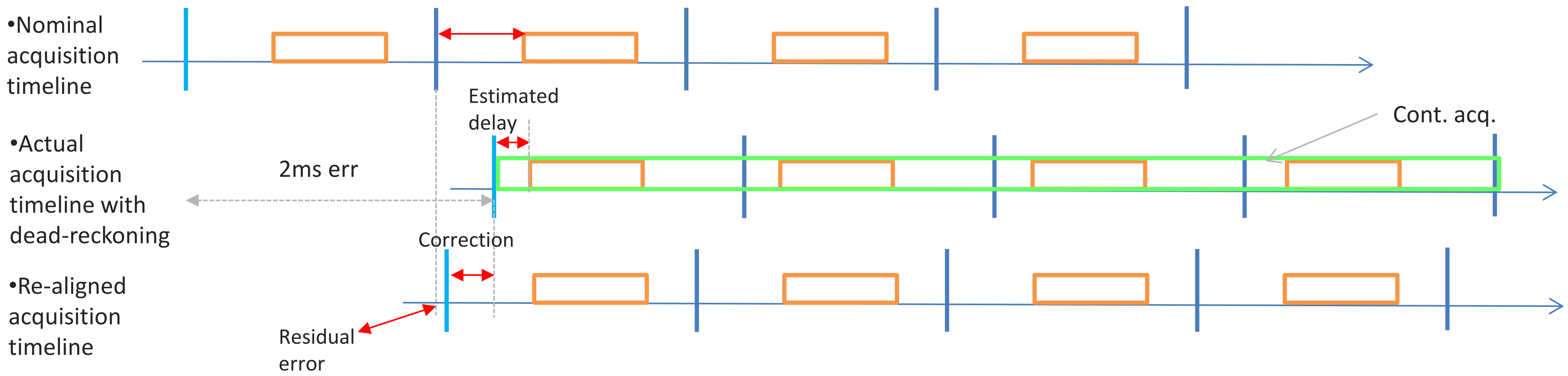
Introduction

- **HARMONY** is the 10th Earth Explorer Mission and it is envisaged as a mission with two passive SAR satellites that orbit in formation with one of the Copernicus Sentinel-1 (S-1), to address key scientific questions related to ocean, ice and land dynamics.
- As many **bistatic** SARs, also Harmony suffers from **synchronization** issues on both phase/frequency and on time
- Here we focus on the so called **Fine Time Synchronization** (FTS) problem, i.e.: the alignment Rx sampling windows.



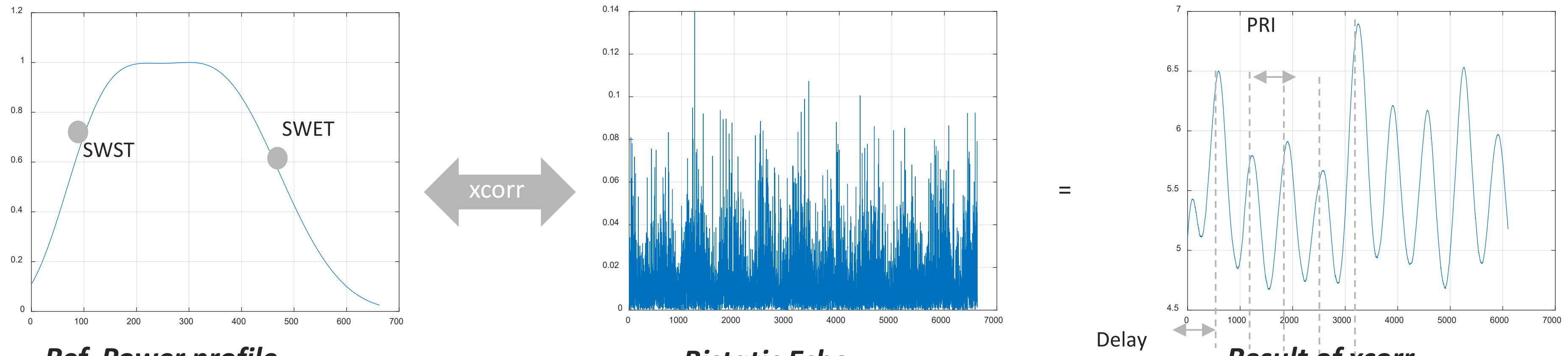
FTS: problem statement

- The time accuracy for the start acquisition of the data-take (Coarse Time) is required to be 2ms.
  - This requirement is accurate enough for the antenna steering (TOPS) synchronization, but
  - It does not ensure that the actual acquisition time of Harmony is a multiple of the PRI.
- The timeline of Harmony must be aligned to the one ruled by Sentinel 1 to correctly gather the echo signal:



FTSA: basic idea

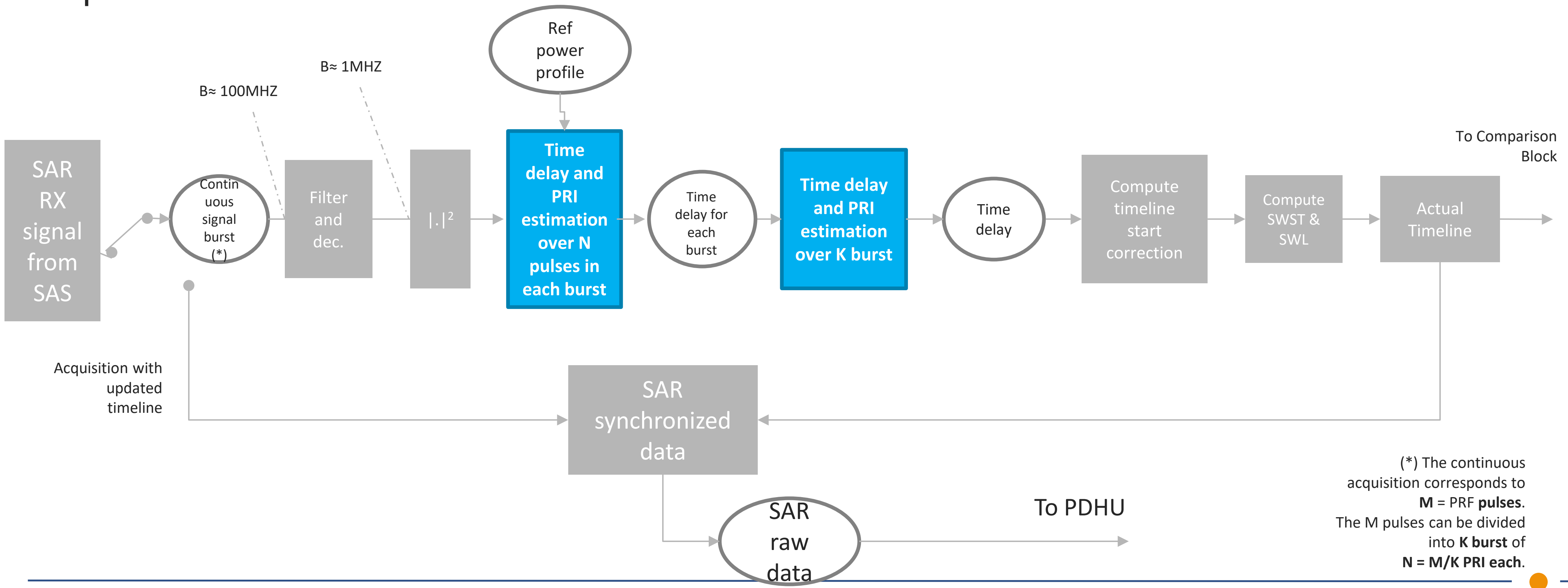
- Conversely to past methods, the algorithm we are proposing solves the FTS issue working only on **SAR bistatic echo** data by **fitting** (e.g.: via cross correlation) the theoretically-expected range power profile on the acquired bistatic echo.
- The result leads to estimate:
  - The difference between the actual start of the acquisition and the nearest multiple of PRI;
    - Correction of the start data-take time
  - The actual SWST and SWL (which are known on the theoretical echo profiles):
    - Fine time synchronization



Ref. Power profile ***Bistatic Echo*** ***Result of xcorr***

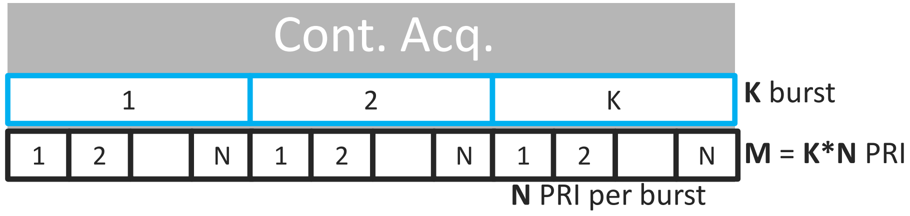
FTSA: overall Block diagram

- The following flow chart reports the block diagram of the FTSA.
- The Algorithm is supposed to be run on the three-assemblies coherently-summed data, single pol.



FTSA: steps description

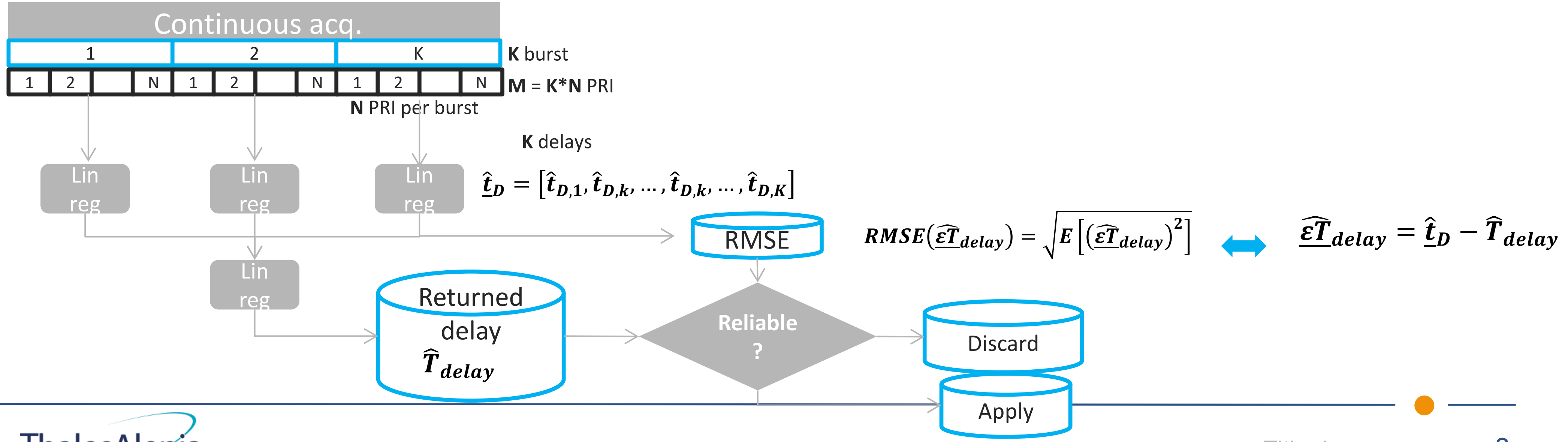
- In FTSA, the SAR echo signal is used to perform fine time synch
- **Continuous acquisition** of the echo signal for a set of initial **M PRIs** (e.g.: from warm up or from scientific datatake)
    - Max signal bandwidth: ~1MHz (i.e. echo signal to be filtered and used as input for the fine time algorithm)
- **The M PRI are divided into K bursts of N PRI each.**



- For each of the **K Bursts**, the following operations are performed:
    - **Cross correlation** between the power of the continuously recorded signal and the theoretical range power profile of the nominal radar signal within the PRI;
    - **Detection** and localization of the peaks of the cross correlation (with false alarm handling);
    - **Estimation** of the **offset** on the start time (and of the PRI) via linear regression over the detected peaks.
- Over the **K estimated** values of the offset start time, a **final regression** is done to make the estimation of the start time offset more robust.
- **Correction** of the timeline is done, i.e.: alignment of the start of the PRI and, consequently, of the sampling window.
- Nominal SAR acquisition with **updated** timeline.

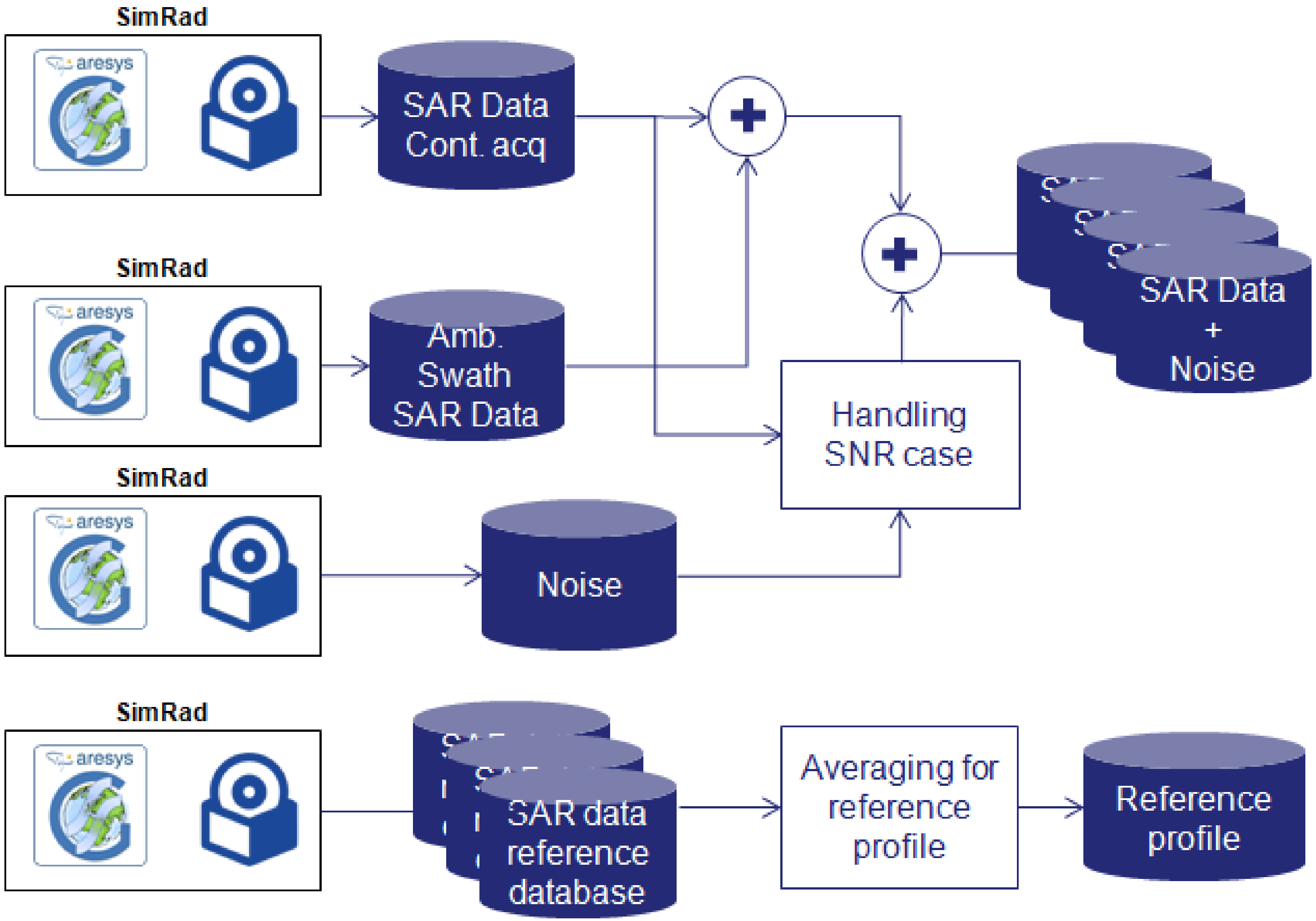
FTSA flagging of the results: basic idea

- To correctly detect the status of the algorithm is relevant to take the decision about using the updated timeline or switching to the back-up mode (continuous acquisition).
- The idea is to compute the RMSE of the estimation on each of the K Bursts:
  - within the time of the continuous acquisition, and
  - w.r.t. the offset returned by the FTSA.
- The block diagram is hereinafter reported including the math. quantities to be computed:



FTSA Testing: Scene simulation for testing

- According to the following block diagram, the simulation of the useful signal from the **distributed scene** (top branch) has been kept separated from the simulation of the **thermal noise**.
  - The advantage of this strategy is to have the maximum flexibility in simulating the combination of different scenes with different noise levels.
- The **IRF** of the **Rx** chain due to data sub-sampling to **1MHz**, for FTSA signal, has been included.

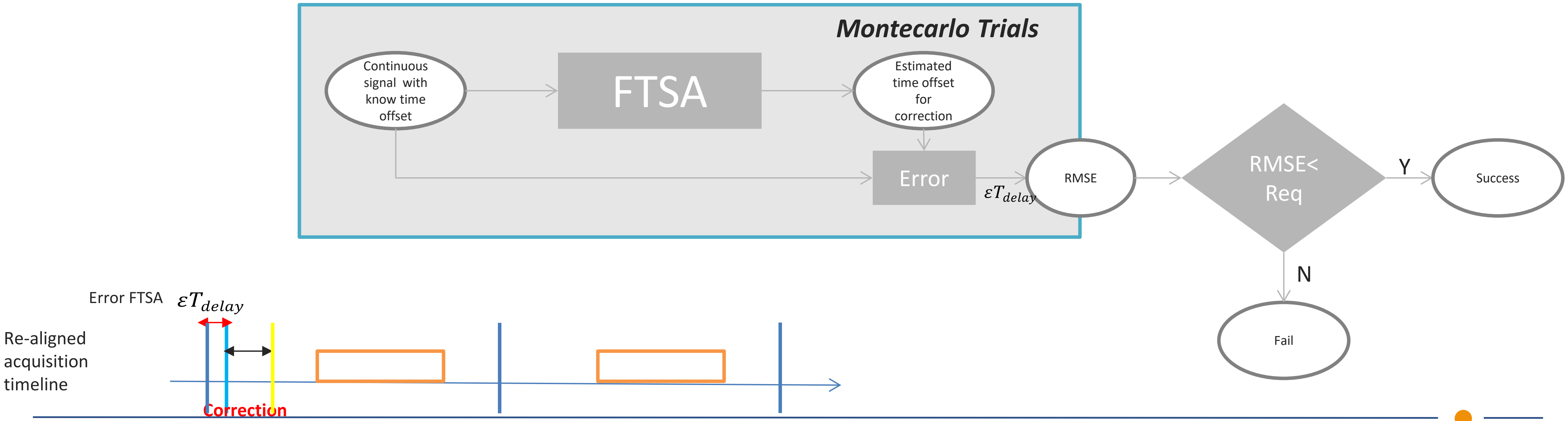


FTSA success/fail criteria

- The FTSA has been validated using a Montecarlo approach, simulating several acquisition start times (i.e.: delays of the waveforms) of the continuously acquired SAR raw data.
  - The quality of the estimated delay has been measured computing the Root Mean Square Error (RMSE).

$$RMSE(\varepsilon T_{delay}) = \sqrt{E\left[(\varepsilon T_{delay})^2\right]} = \sqrt{var[\varepsilon T_{delay}] + (E[\varepsilon T_{delay}])^2}$$

  - The requirement has been posed to 50us



Simulation cases for assumed for TRL6

- Test cases of major interest:
  - Real RCS maps
  - Extremely inhomogeneous scene
- For each of the cases we shall evaluate the success rate and the confusion matrix

Ocean

Acq. mode	Scene type	Remarks
WV1	Real S1 data over ocean	Real RCS case
WV2	Real S1 data over ocean	Real RCS case
WV1	Inhomogeneous - Collage of different ocean status	Extreme case for inhomogeneity
WV2	Inhomogeneous - Collage of different ocean status	Extreme case for inhomogeneity

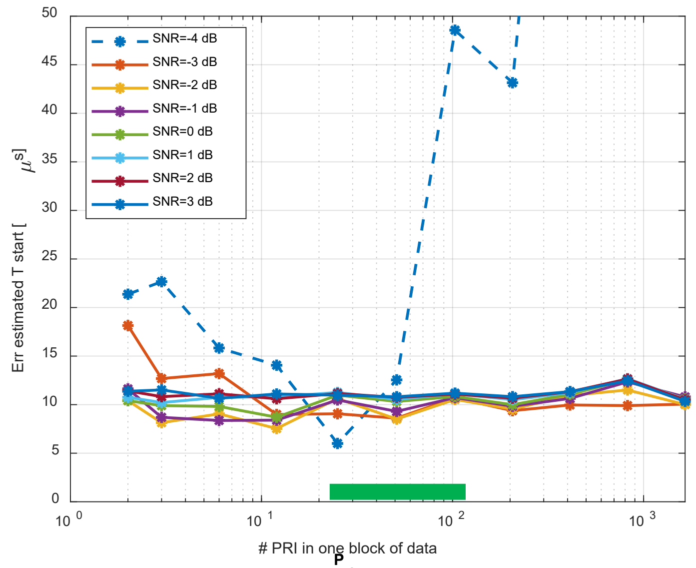
Land

Acq. mode	Scene type	Remarks
SS1	Real S1 data over land	Real RCS case
SS6	Real S1 data over land	Real RCS case
SS1	Inhomogeneous - Collage of different soil and ocean areas	Extreme case for inhomogeneity
SS6	Inhomogeneous - Collage of different soil and ocean areas	Extreme case for inhomogeneity

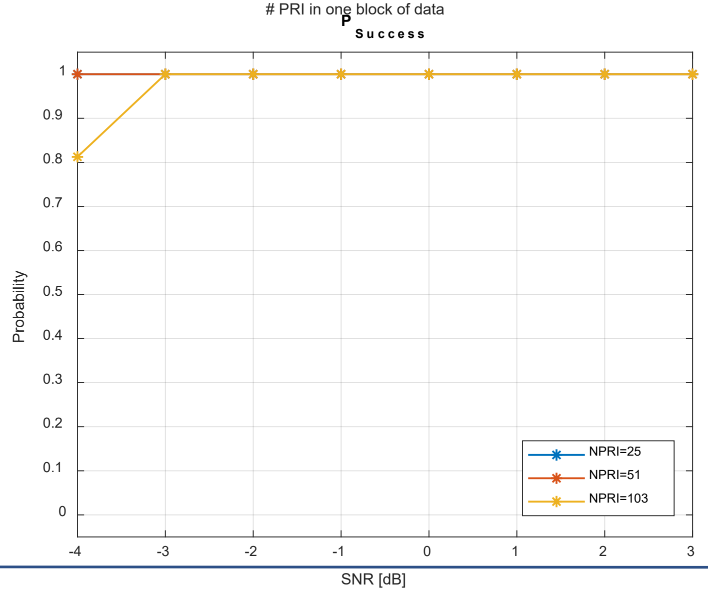
- Hereinafter we report the results for the sample but relevant case of WV1 mode for real Sentinel 1 data as RCS map

Test O_WV1_RealRCS: results

- **Top panel**: RMSE as a function of the number N of PRI in each of the K-bursts. Different lines are for different SNR (see the legend).
  - Y-axis's upper limit is the requirement.

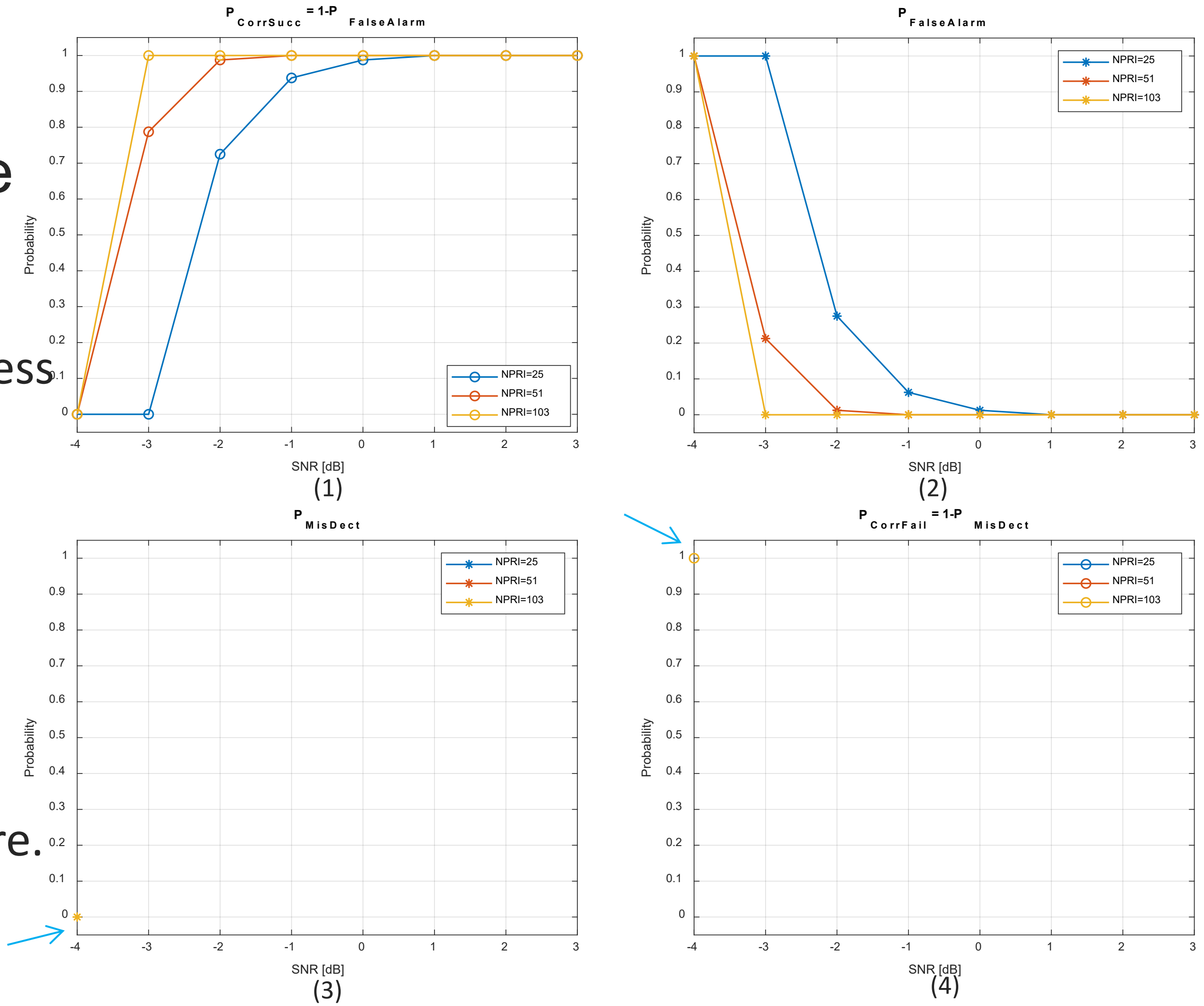


- **Bottom panel**: probability of success of FTSA as a function of the tested SNR values.
  - Different lines are for different values of N parameter.



Test O_WV1_RealRCS: confusion matrix

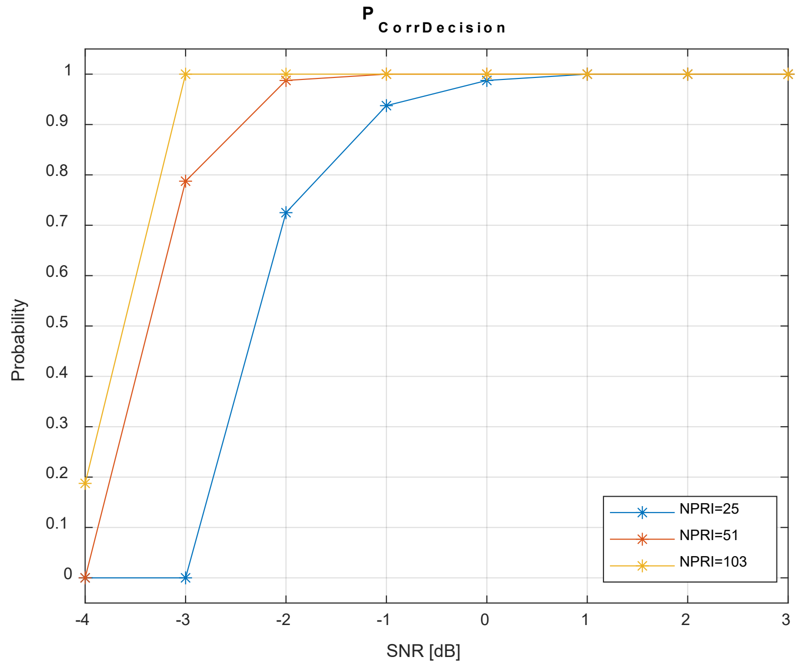
- Confusion matrix.
- The four figures refer to (in row-wise order):
  - 1) Probability of correctly predicted success
    - Desired value: 1
  - 2) Probability of False Alarm,
    - Desired value: 0
  - 3) Probability of Misdetection,
    - Desired value: 0
  - 4) Probability of correctly predicted failure.
    - Desired value: 1



Mis-detections seldom happen

Test O_WV1_RealRCS summary

- Probability of correct decision (i.e., “true success” or “true failure” of the FTSA) as a function of the tested SNR values.
  - Different lines are for different values of N parameter



Remarks

- In this presentation, it has been presented the FTSA based on the echo tracking technique.

- It has been reported the results from TRL6 activity which confirms that the algorithm is robust towards low SNR with an continuous acquisition based on Sentinel 1 warm-up pulses time duration (around 1s).

- TRL6 has been successfully achieved on Nov. 2024.

Acknowledgement

- This work has been developed in the framework of HARMONY SAR Payload contract with ESA within the consortium lead by Thales Alenia Space - Italia