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Airborne bistatic SAR clock synchronisation issues

Hubert Cantalloube
dept. of electromagnetism & radar, ONERA université Paris Saclay

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The 2023 bistatic campaign

2023 5th ONERA bistatic SAR campaign: high resolution (700 MHz bw at X-band) with circular and linear configurations.

This was the first operational (not experimental) acquisition campaign.

Requirement was to provide geocoded mono and bistatic SAR images, with assessment of radiometric accuracy, geometric accuracy and image quality parameters (resolution, PSLR, noise level).

Unlike previous campaigns with a handfull to a few tens of acquisitions, here we had 5033 images (1 km² each at 20 cm resolution) to produce on various clutters and ground features. Imaging conditions were 45° or 75° incident angle with 0 to 80° bistatic angle in heading.

However, the aim were beyond the performances attained during the previous experiments, hence redundant clock synchonisation capabilities were set up.

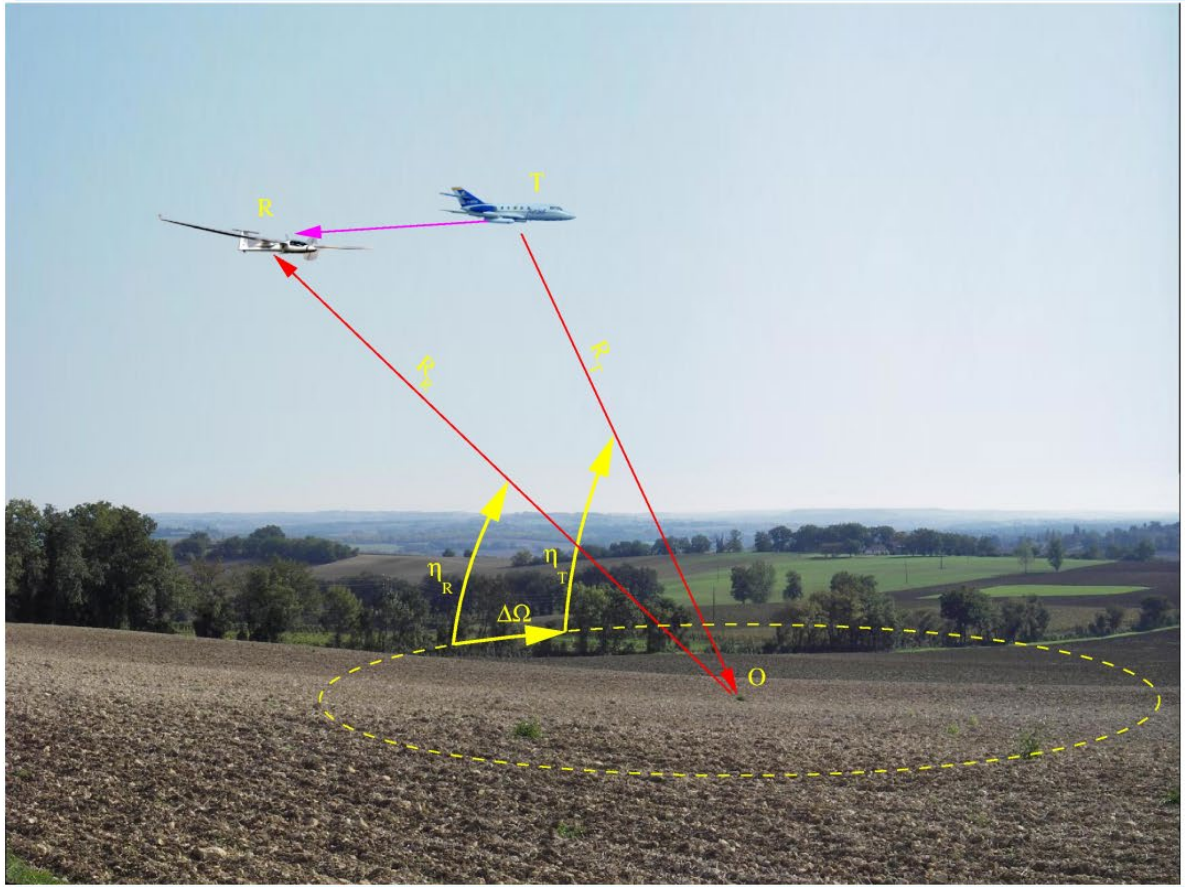
SAR systems

↑ Rx steered antenna (Tx not used)

↑ direct path omni & FLARM antennae

↑ Tx & monostatic Rx high-gain antennae

Acquisition geometry



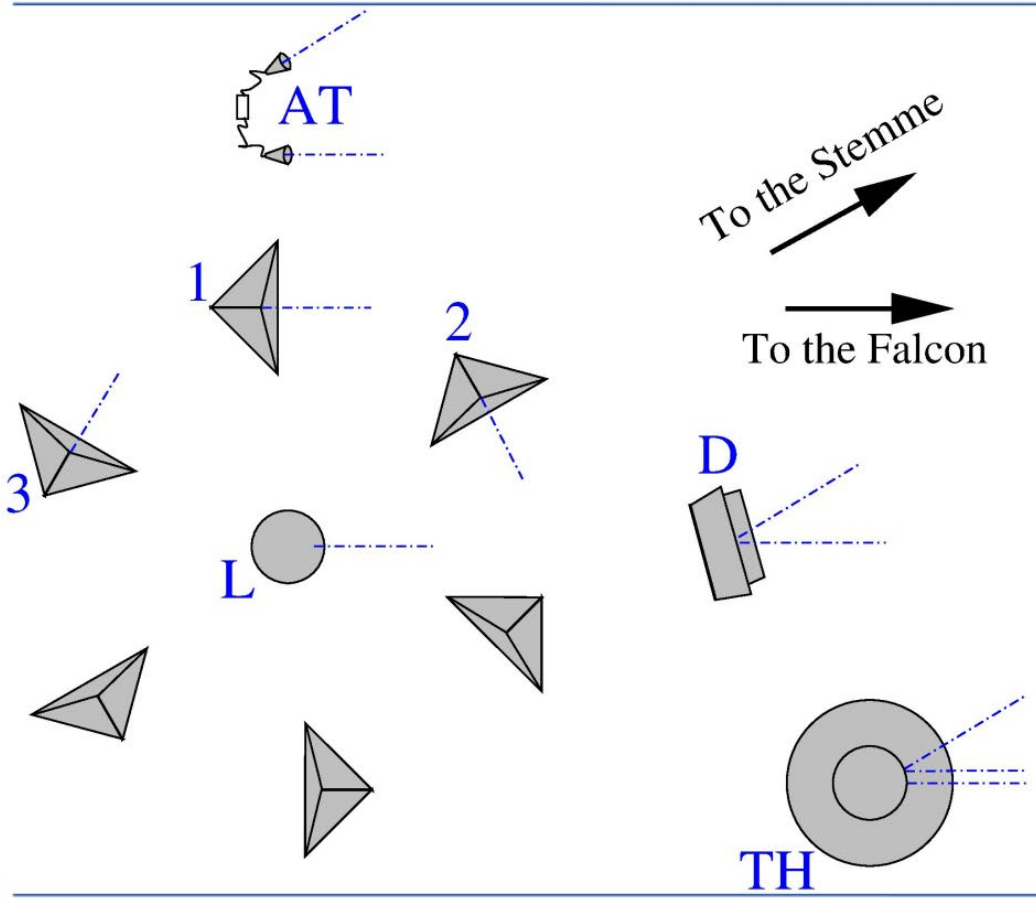
Circular trajectories around ROI centre O.
or
linear trajectories with antennae steered to O.

Same elevation η (15 or 45°) for both aircraft.

Aircraft velocities 3 to 1 (120 and 40 m/s resp.)
$R_T = 3 \times R_R \Rightarrow$ constant $\Delta\Omega$ (5, 10, 20, 30, 40 or 80° for circle, 0° for lines)

"Slow" Rx variant (with Stemme at 35 m/s) yielding $\Delta\Omega$ 0° $\rightarrow$ 20° during acquisition.
Antennae steering and swath width limits squint to ±40°.

Ground experimental setup



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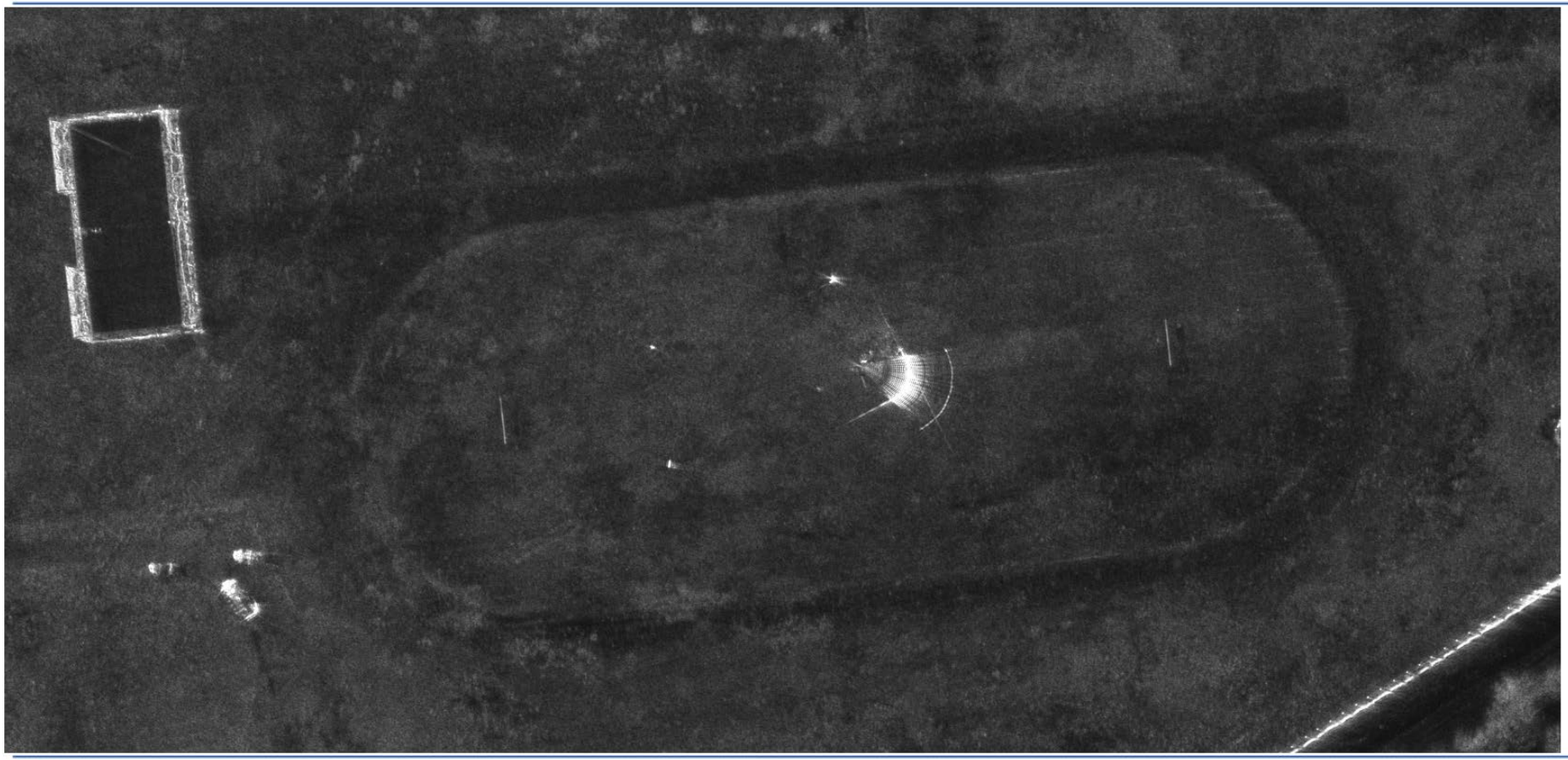

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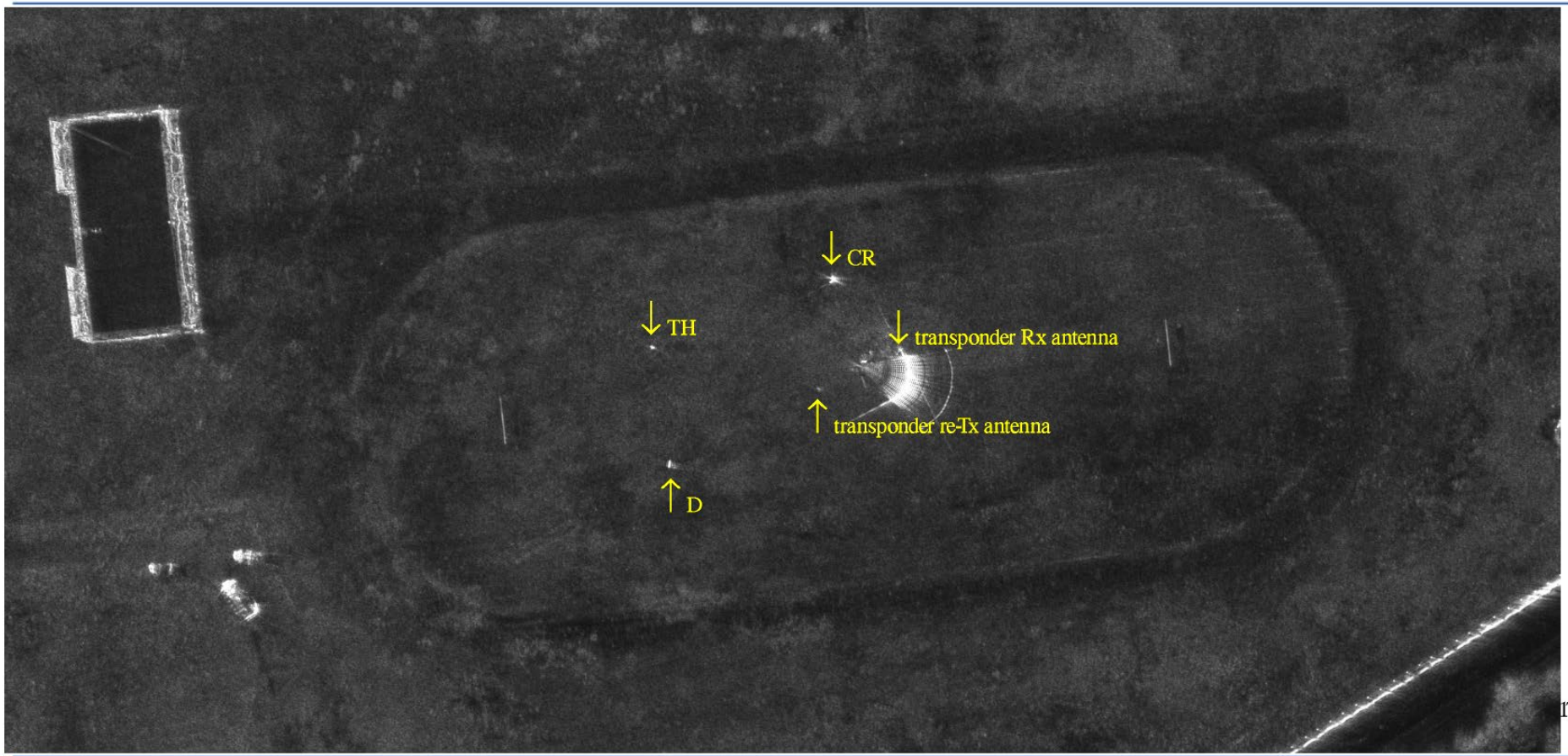
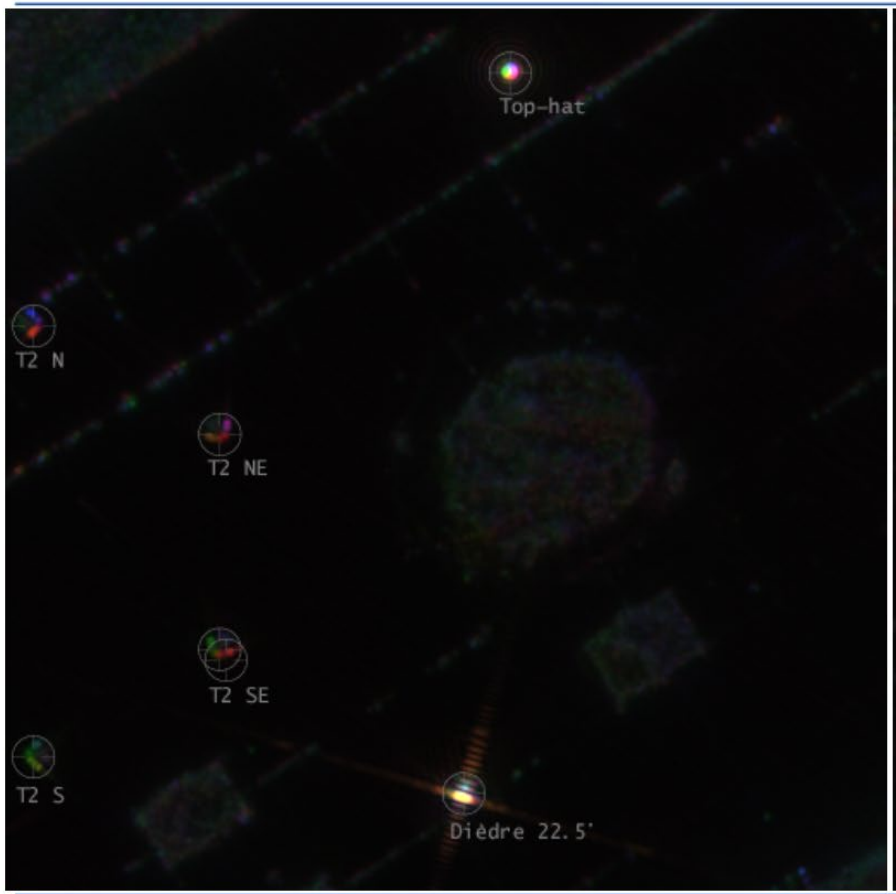
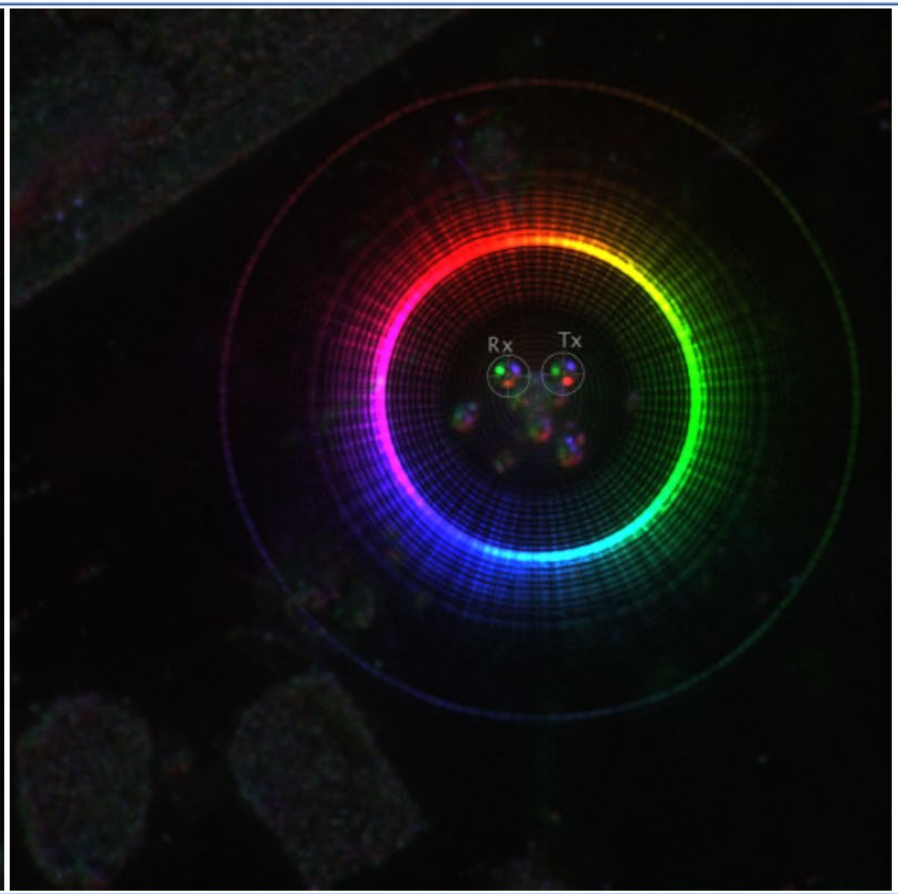


17-look bist. line “std”

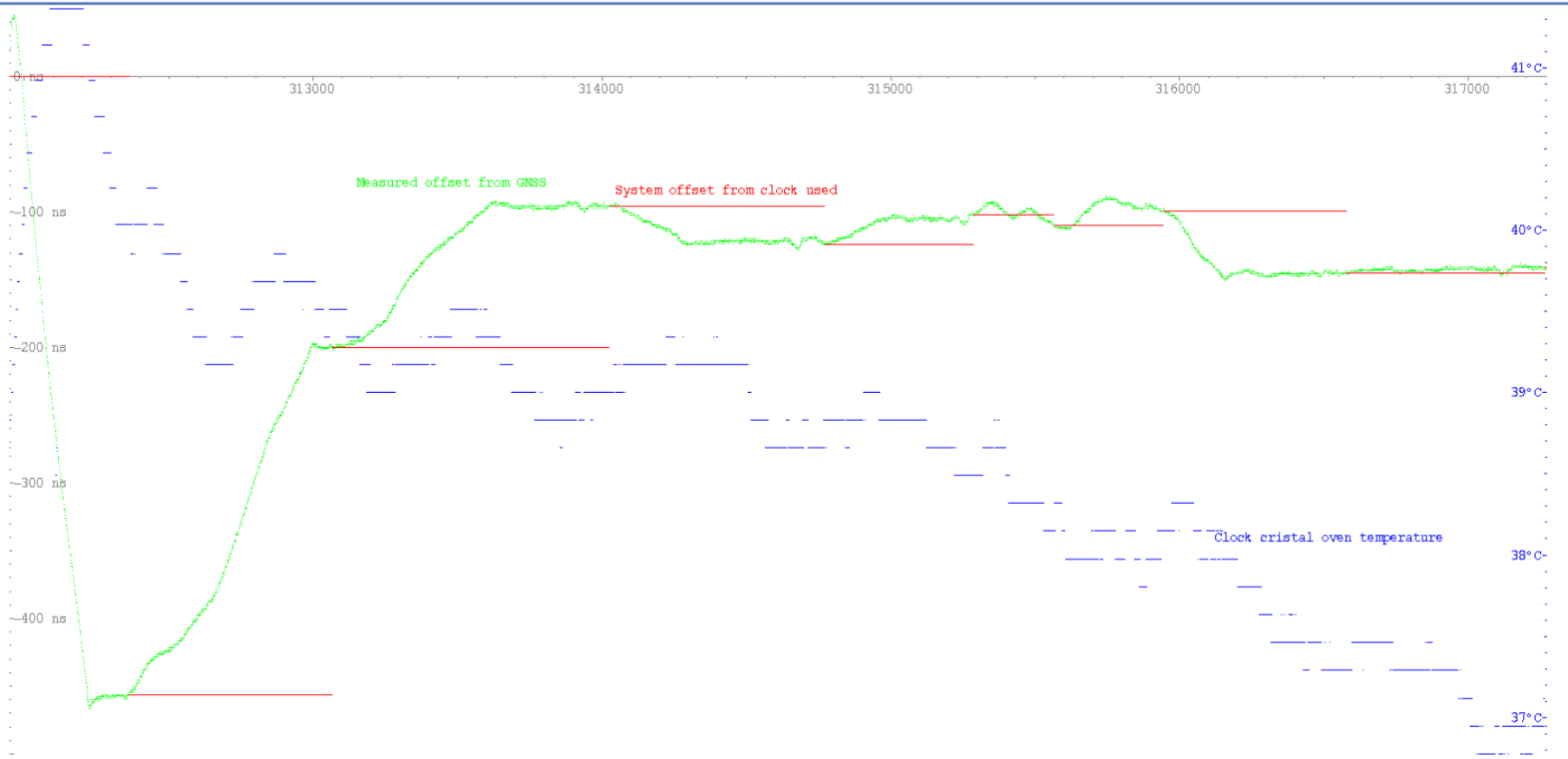
Ground experimental setup





72-look circle image
elevation=15°
bistatism=80°
colour-code=LOS heading

Synchronisation: GPS discipline



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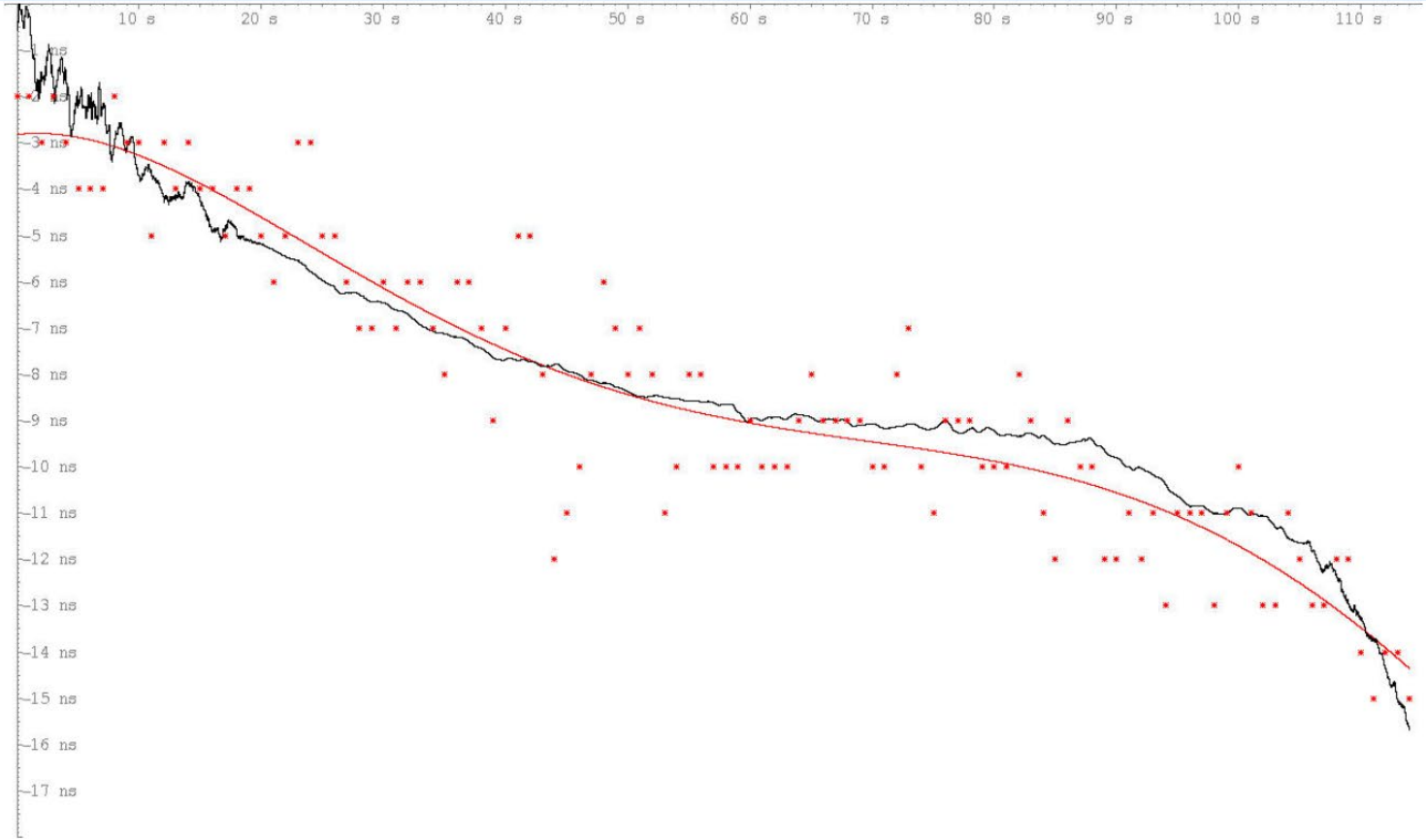
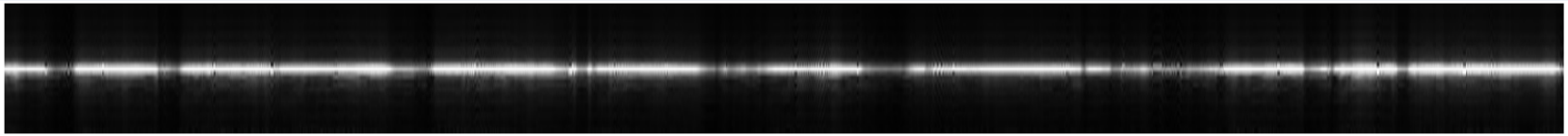
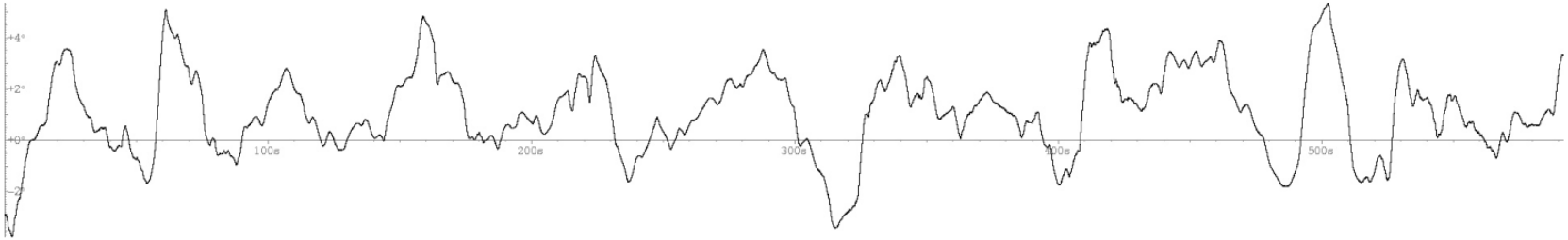


Synchronisation: direct signal tracking

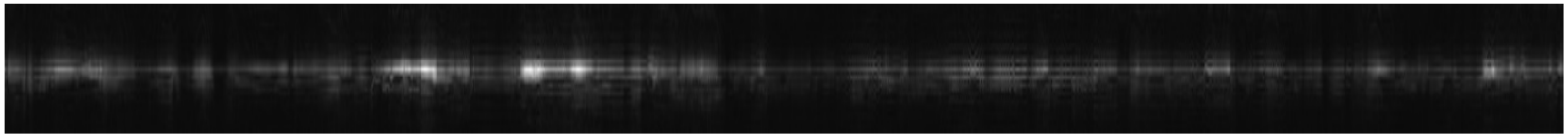


range-compressed direct signal (circle w. 5° bistatism)



Stemme (Rx) bank angle during circle

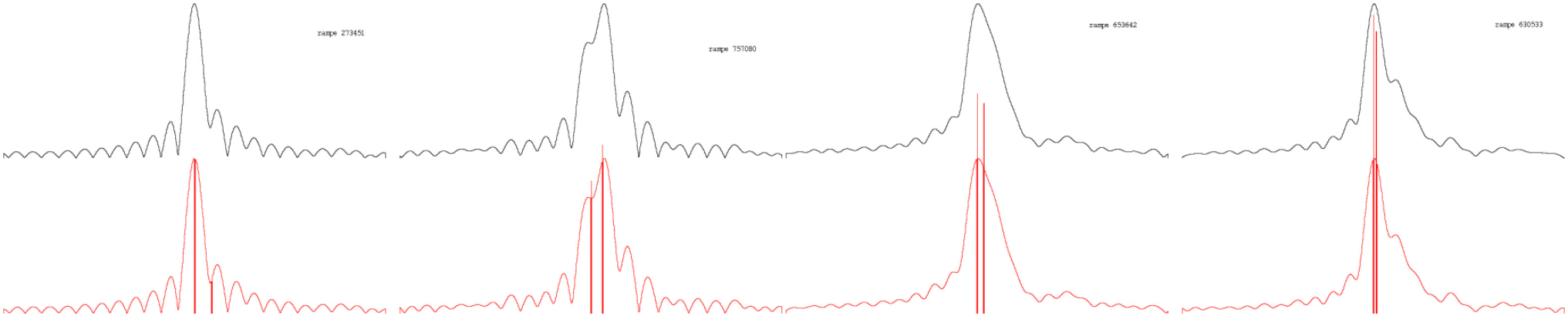
range-compressed direct signal (“slow” line w. 0 to 20° bistatism)



range-compressed direct signal (circle w. 80° bistatism)

Synchronisation: direct signal tracking

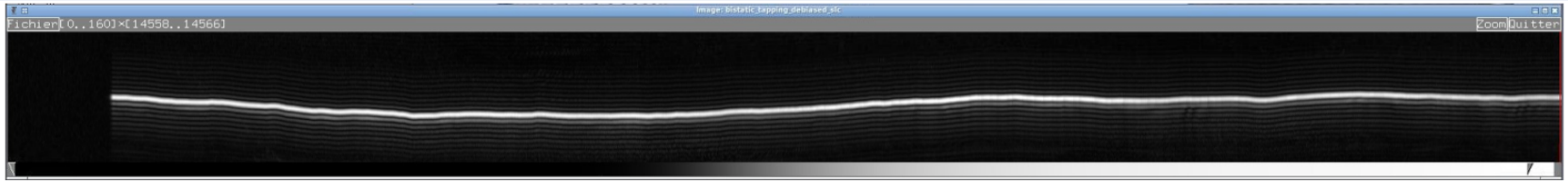
The plague of multiple paths with omnidirectional Rx antenna.



zoom on the direct signal peak, and its resolution as first (direct path) and secondary (multiple echo) replicas.

Feasible for moderate bistatism, but typically 1.5 M ramps (circle at η=45°) to 3 M ramps (circle at η=15°) to be resolved...

Synchronisation: transponder echo tracking



range-compressed transponder signal (circle w. 5° bistatism)

Phase tracking the transponder echo is the easiest way of recovering an accurate clock synchronisation, provided:

- Transponder Tx and Rx antenna positions known w. cm accuracy (positionner joint-point t.b.p.)
- Transponder internal Rx to Tx delay is known and compensated in the waveform (delay – "joint-point to antenna phase centre" propagation t.b.p)
- Transmitter trajectory is shifted by the transponder Tx to transpondeur Rx distance (this makes the transponder appear as a pointwise "reflector")
- Last but not least, transponder must be close to the ROI within the antennae foorprints and switched on! Not possible when multiple distant ROI where acquired during a single flight and not practical for truely operational use (e.g. on remote/battle fields).

Synchronisation: top-hat echo tracking

When $\eta_T = \eta_R$ a top-hat w. cylinder radius R can be seen as a bistatic point reflector (at the horizontal disc centre) with a negative delay of:

$$\frac{-2\,R\,\sin(\eta)\,\cos(\Delta\Omega)}{c}$$

As the transponder, this can be used for clock synchronisation but...

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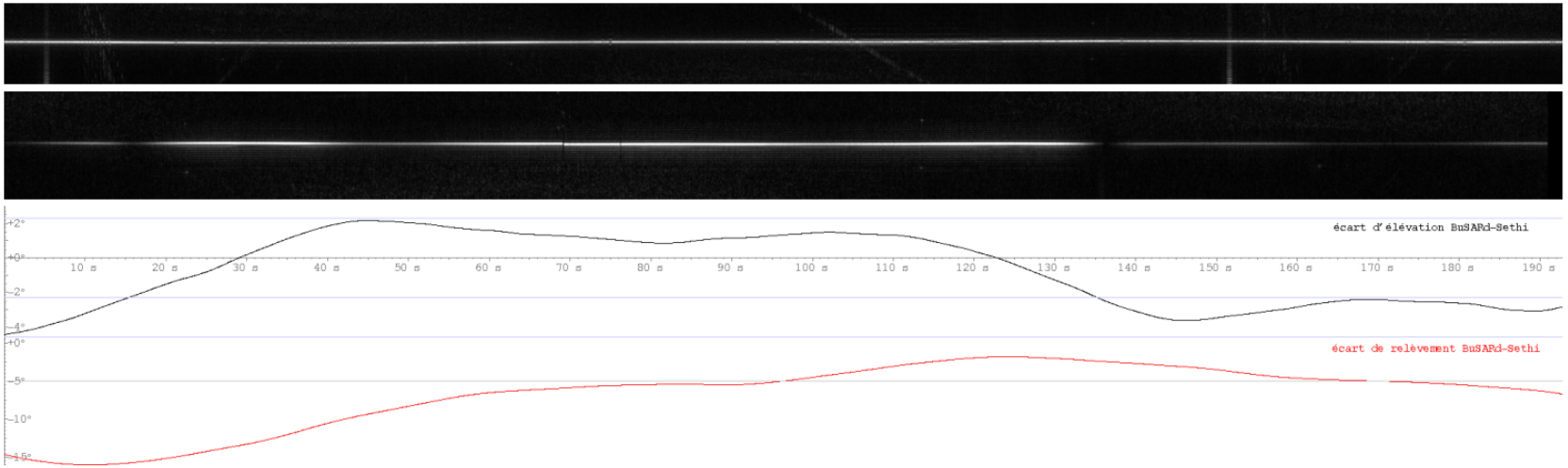

← monostatic @ 45°

← bistatic w. 5° bistatism

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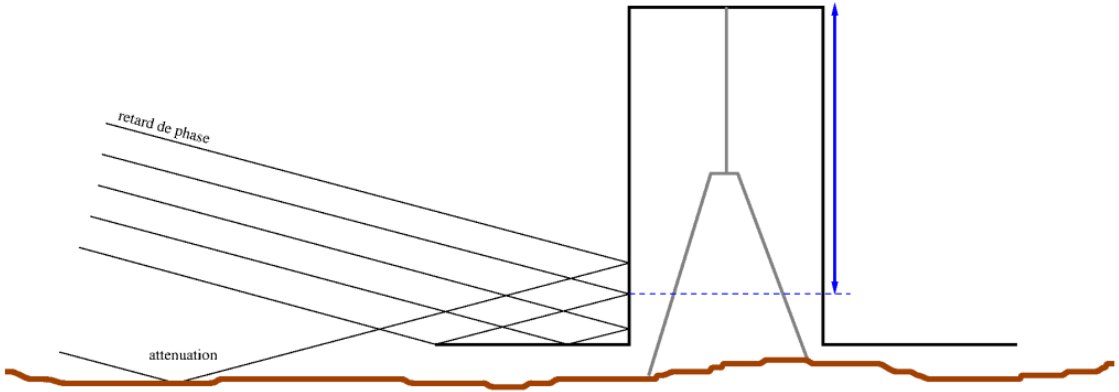


Synchronisation: Autofocus / autoregistration with reference image

Autofocus: derive the clock error signal from geometrical mis-matching between successive bistatic sub-aperture images (from contrast maximisation or correlation).

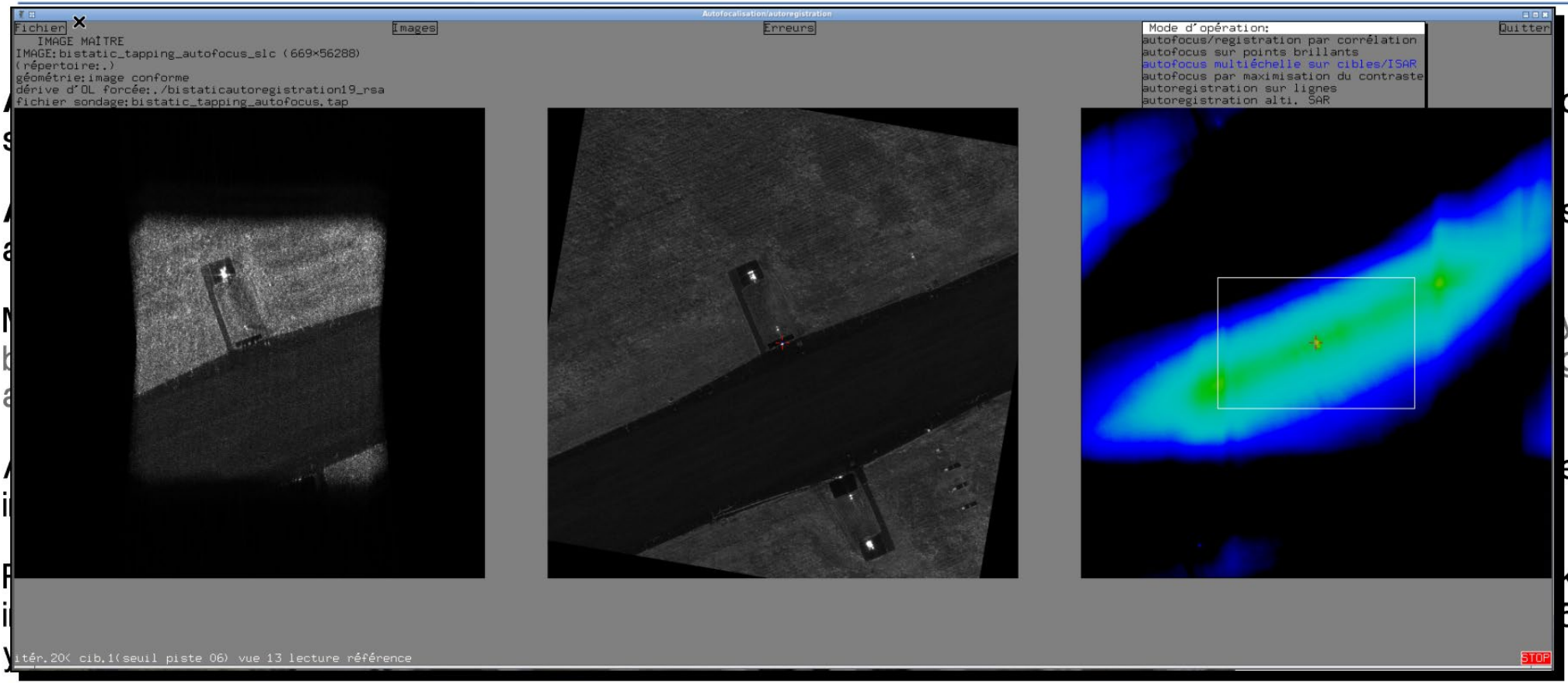
Autoregistration: derive the clock error from geometrical mis–matching between bistatic sub-aperture images and a fixed reference image.

Multi-scale "coarse to fine" approach, from short integration (low resolution sub-aperture images, but short delay between images, hence higher measurable error frequency) to long integration (high resolution images, yielding accurate measure of lower error frequencies).

Autoregistration preserves the geometric (position) accuracy of the bistatic image (provided the reference images is well registered).

Reference image can be the simultaneous monostatic image, but for all but one ROI, the monostatic multi-look image from the first acquisition could be used regardless of the incident angle (and one ROI was imaged 25 years ago by RAMSES).

Synchronisation: Autofocus / autoregistration with reference image



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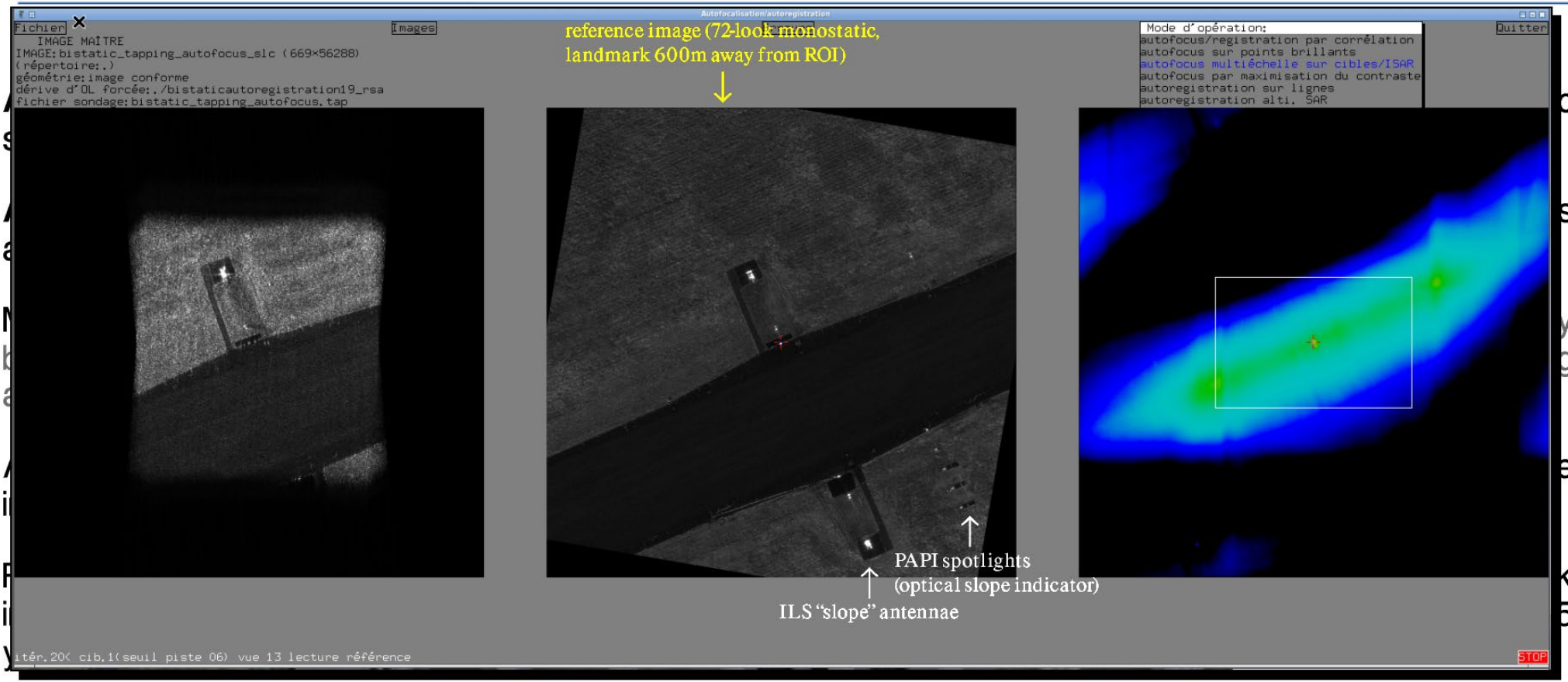

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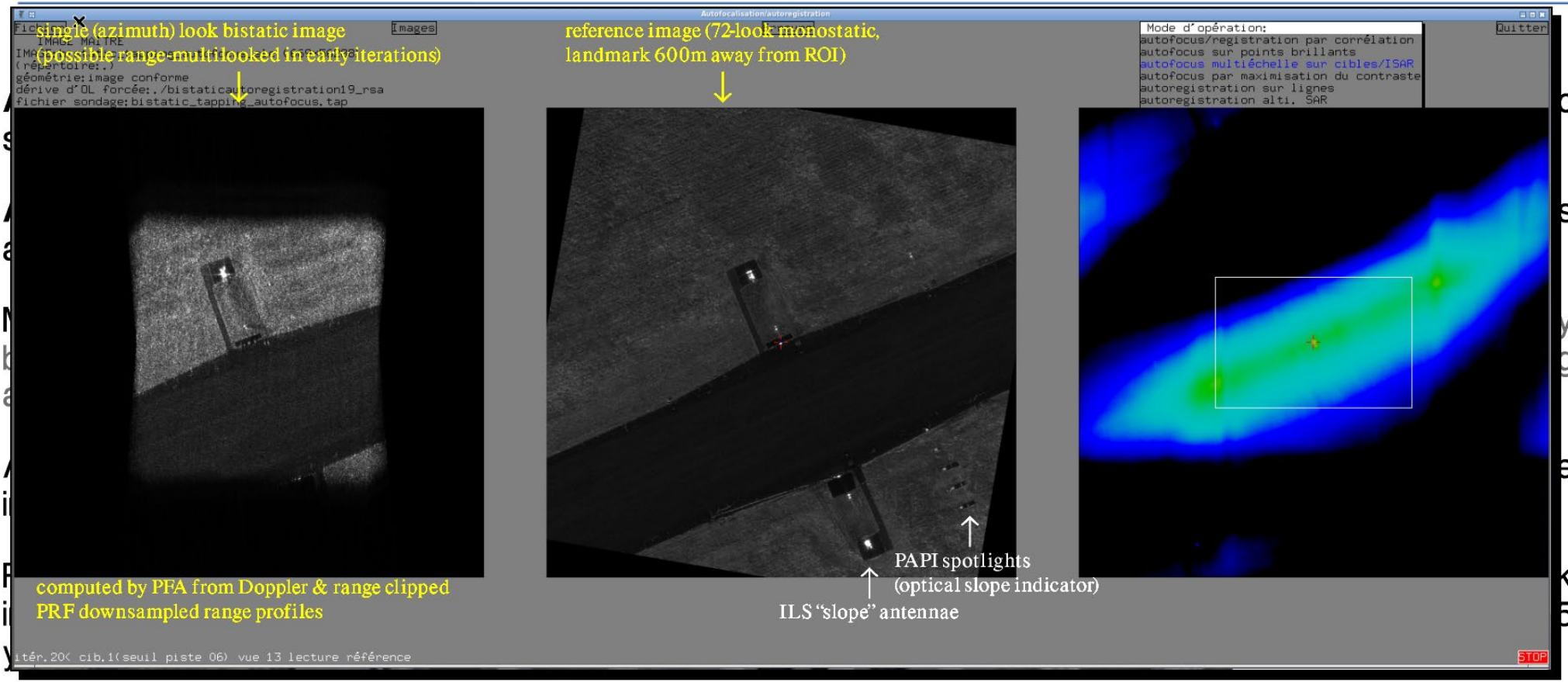

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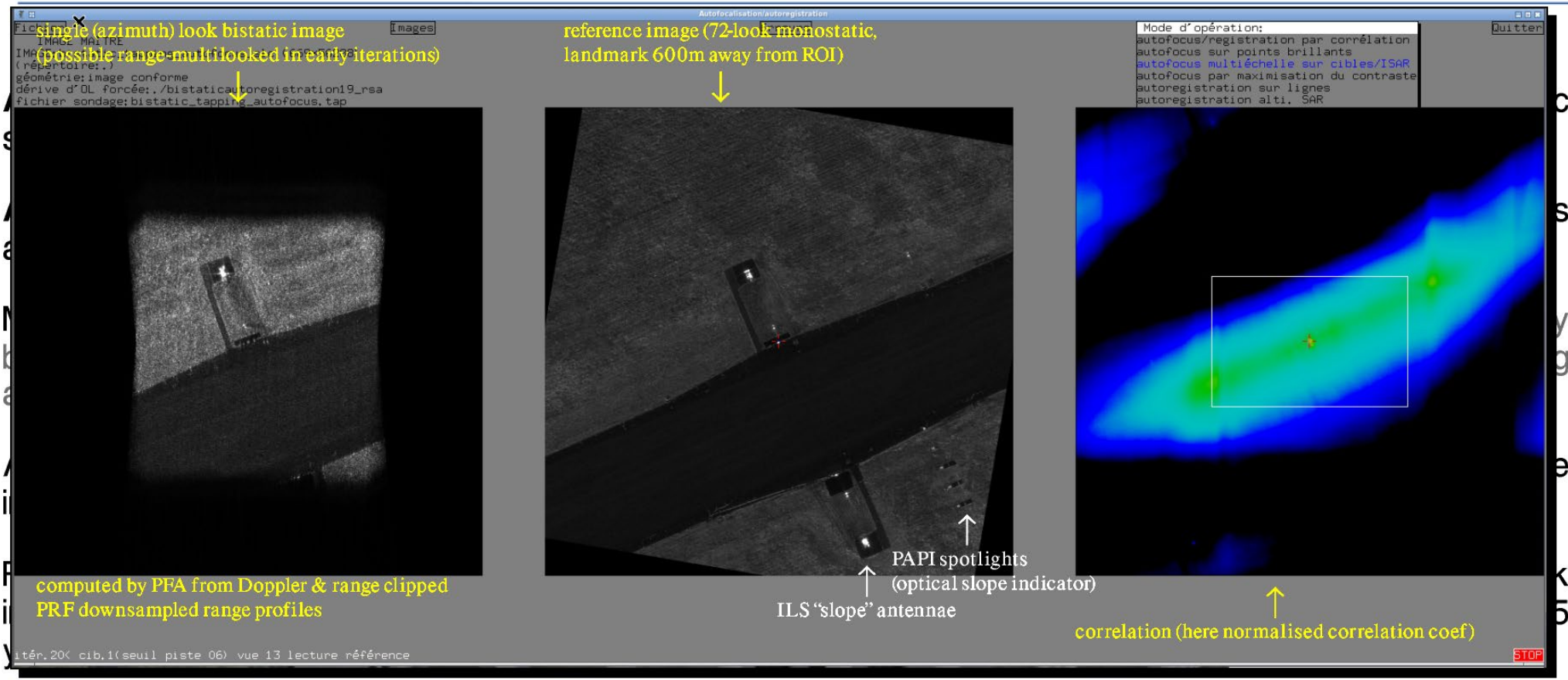

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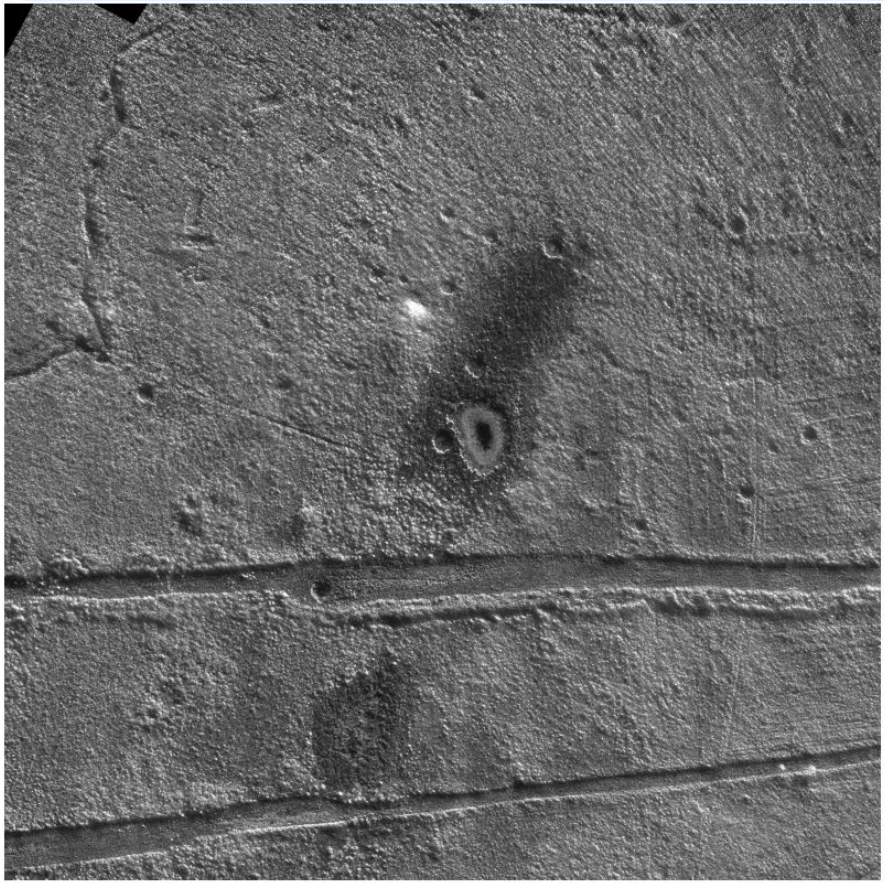
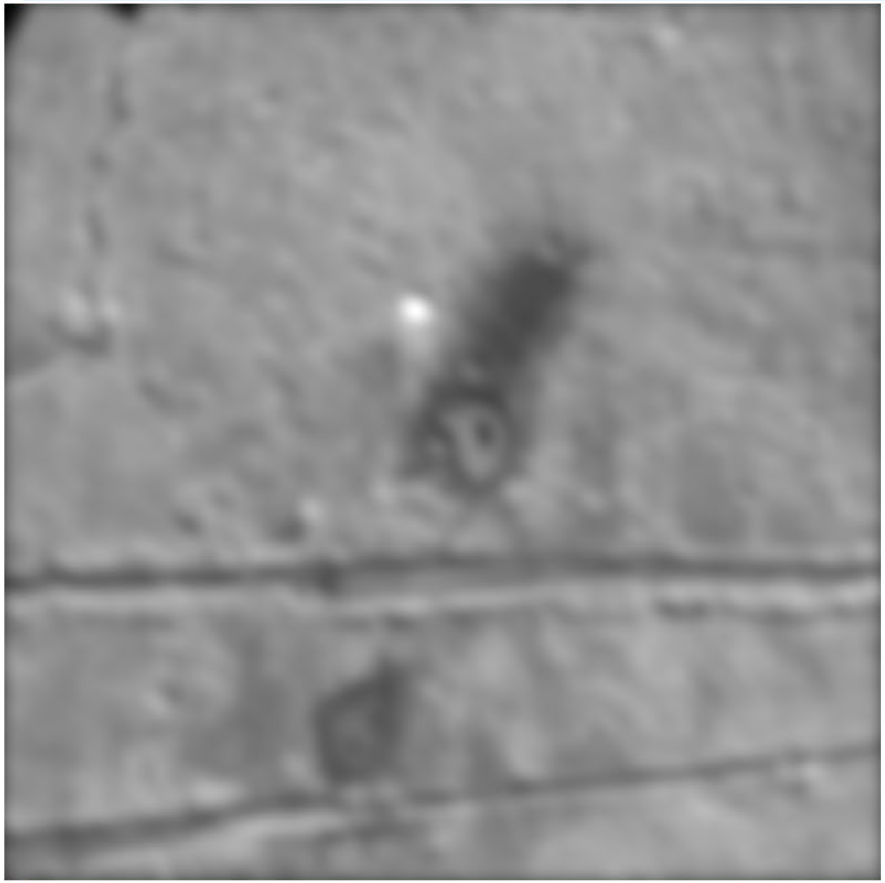


← 72-look reference monostatic image @ 15°

72-look monostatic image @ 45° →

Synchronisation: Autofocus / autoregistration with reference image



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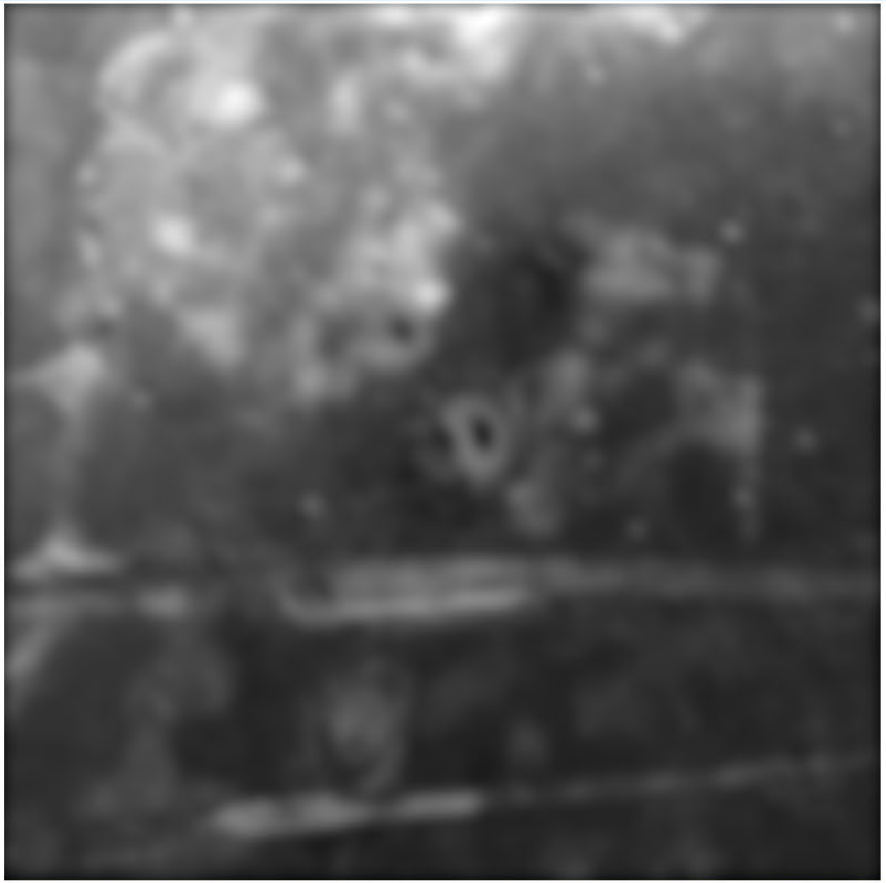

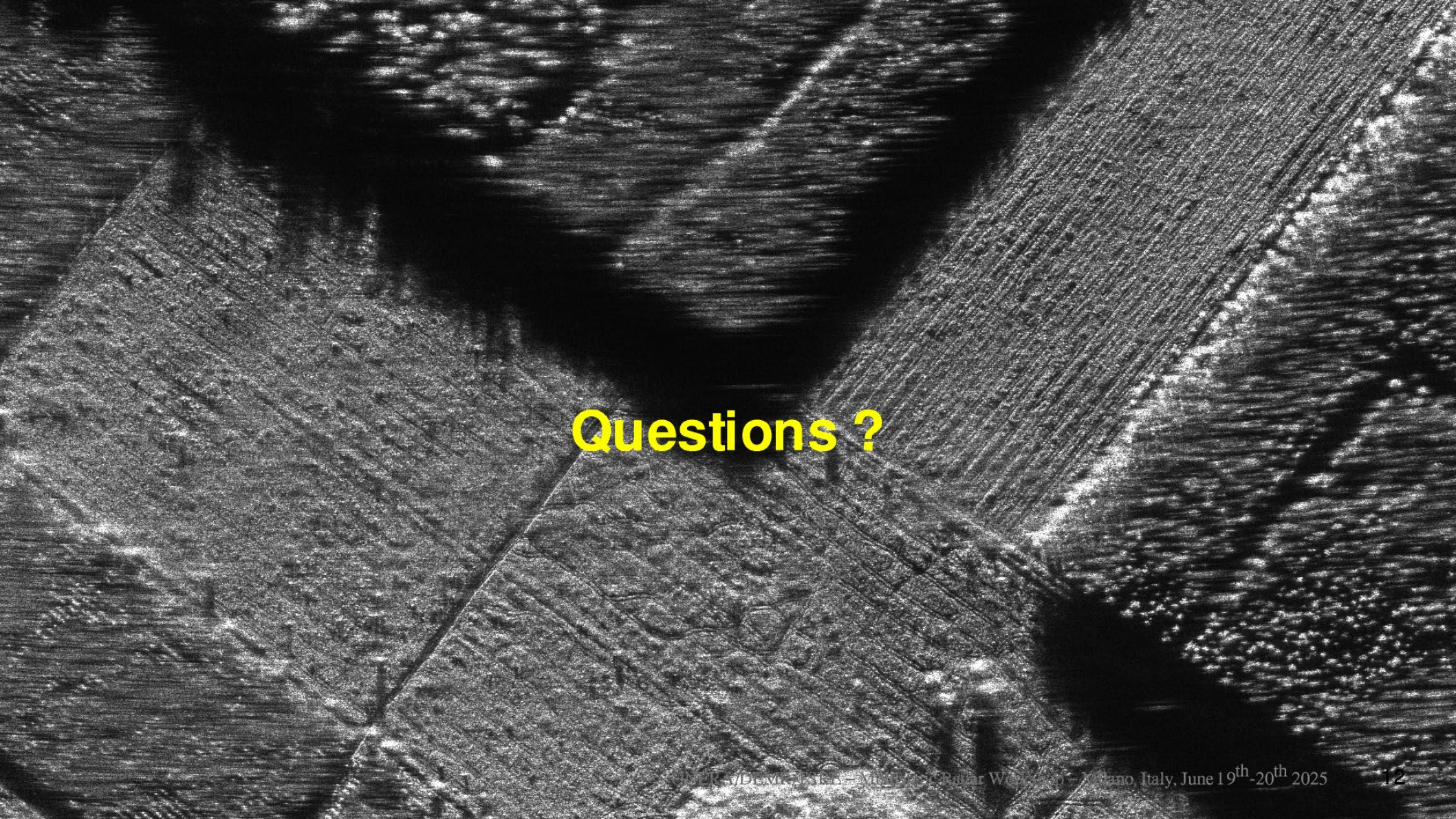
Questions ?