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In collaboration with SAPIENZA UNIVERSITÀ DI ROMA

Inverse SAR processing for maritime awareness

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Living Planet Symposium 2022

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Inverse SAR (ISAR) processing project

- We present the results of a project, funded by ESA, aimed to identify techniques for refocusing SAR images of moving ship targets and to estimate their motion parameters.
- The study has focused on the maritime awareness domain, interesting because of:
  - high interest for applications
  - complex motion of the vessels (subject also to sea waves)
  - typically good contrast of maritime target over the sea clutter
- The study explores ISAR technology, which makes possible to deal with unknown target motions…
- … differently from standard SAR imaging, which assume a complete knowledge of the mutual geometry and motion between radar and target.

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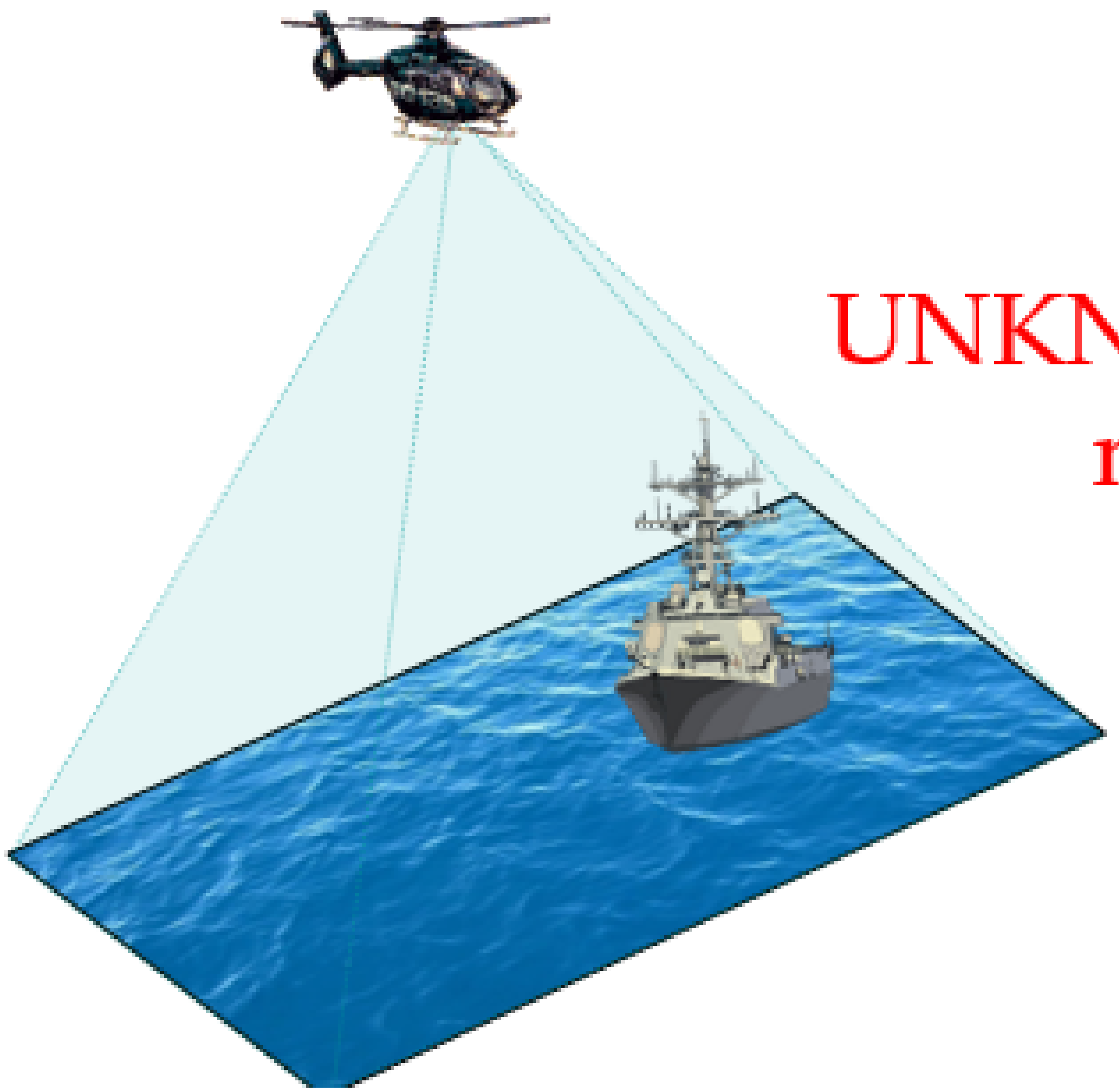
SAR and ISAR

As in SAR imaging, ISAR exploits the relative motion between the radar and the target to image the target ...

…. but the source of this relative motion depends on the target itself (usually assumed stationary in conventional SAR processing)

DIFFERENCE

SAR:
KNOWN
motion



ISAR:
UNKNOWN
motion

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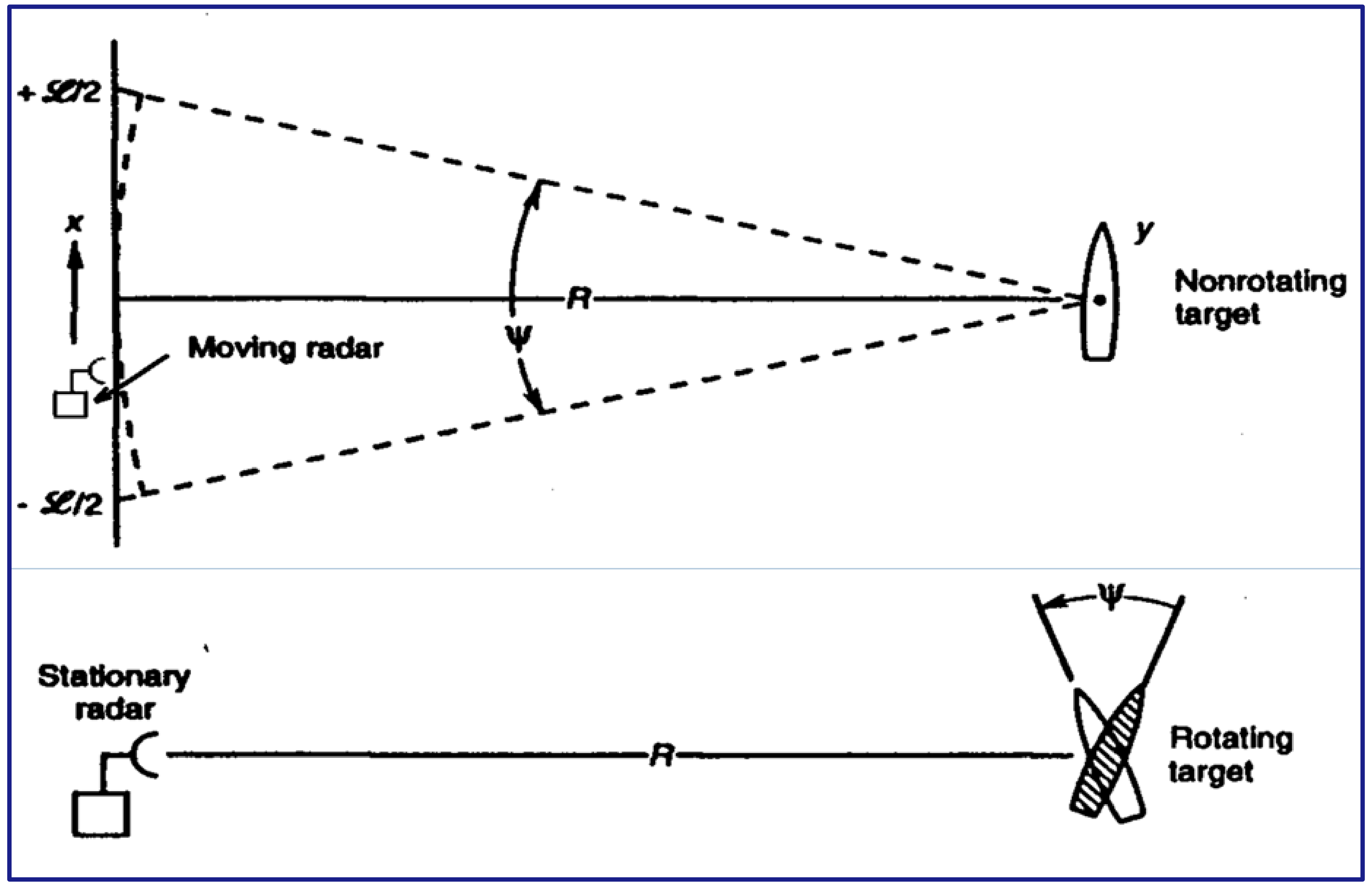
ISAR imaging

- SAR systems are active sensors on moving platform for imaging of stationary targets.
- On the other hand, ISAR systems consider that the target is moving.
- This perspective change has a strong impact in the radar image formation. Indeed, the motion of the target in unknown and must be estimated from the radar data itself.
- In both cases the across-range imaging is re-solved by the relative radar-target motion that can be characterized by the composition of:

  i. Linear relative translation between sensor and target → across-range component of the relative movement contributes to image formation for all target scatterers

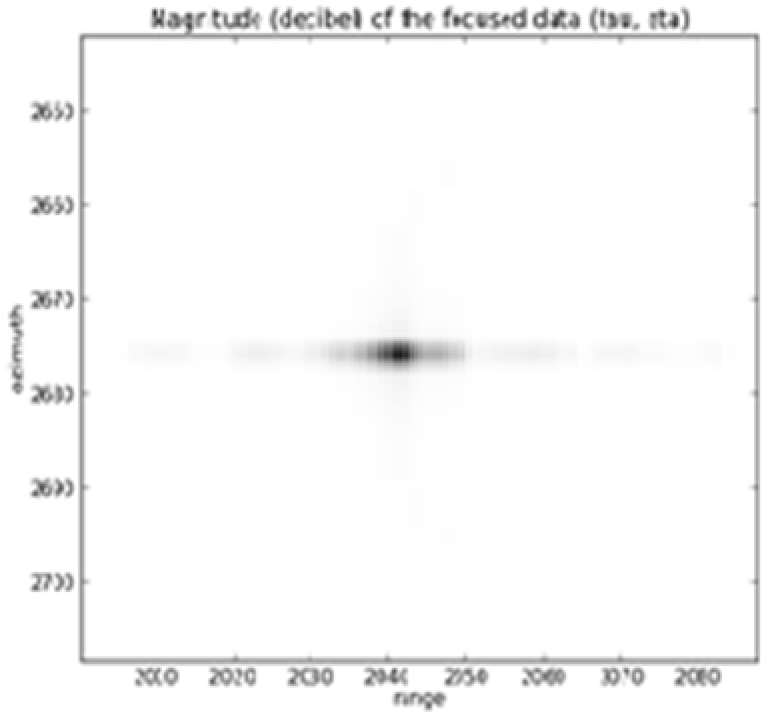
  ii. Rotation motion → scatterers undergo different dopplers depending on the distance from the rotation center.



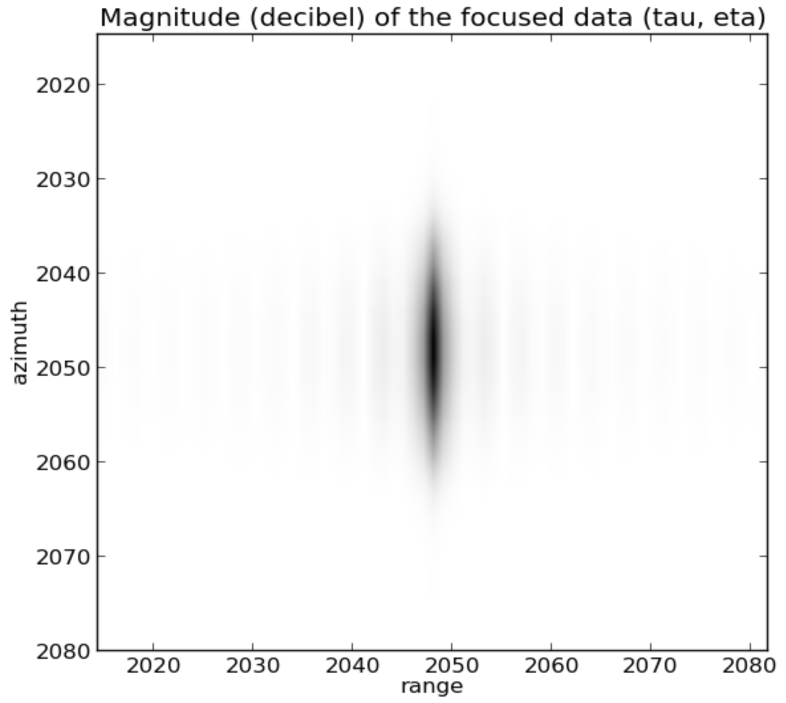
Typical SAR defocusing effects

For moving targets the application of standard focusing produces defocusing effects that degrade range and azimuth resolutions and produce azimuthal displacements. In particular:

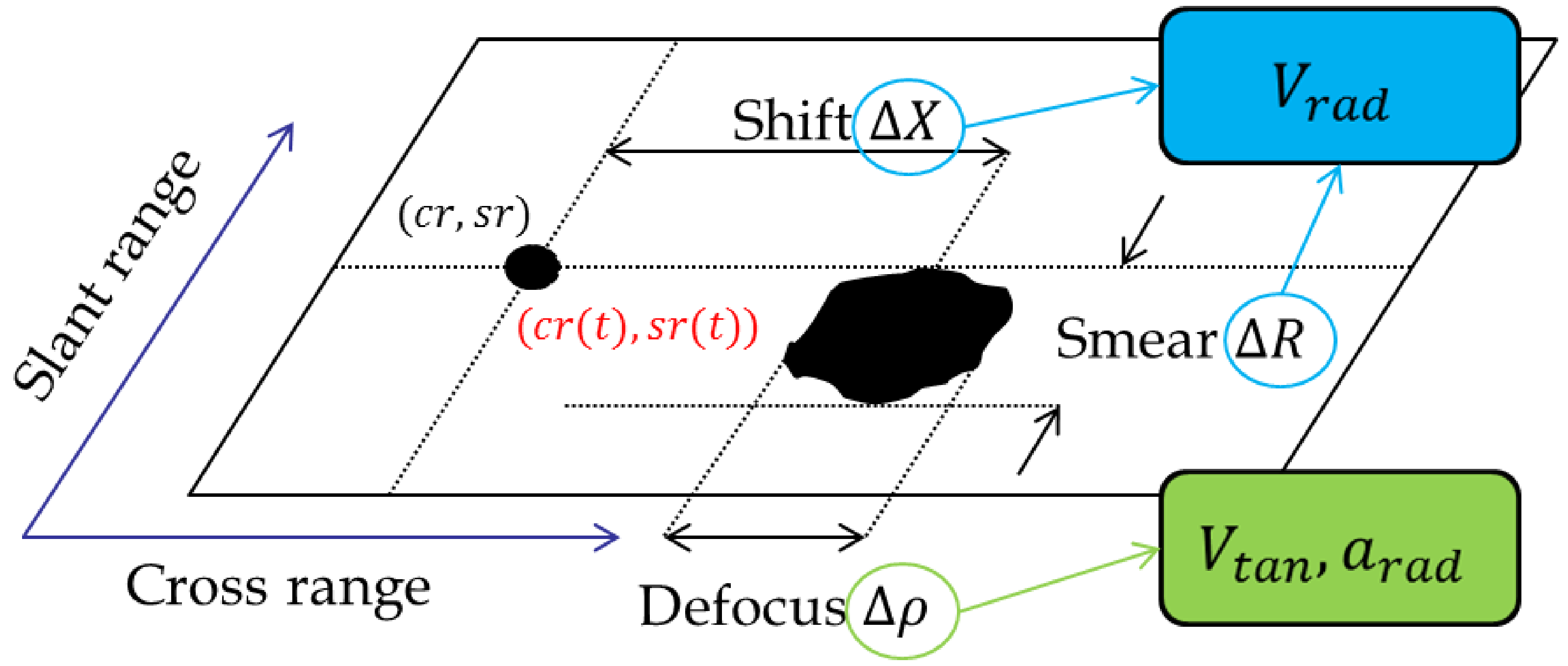
- Range velocity component (V_{rad}) produces:
  - shift of the target imaging along the azimuth direction
  - smearing along the range (walking through different ranges)



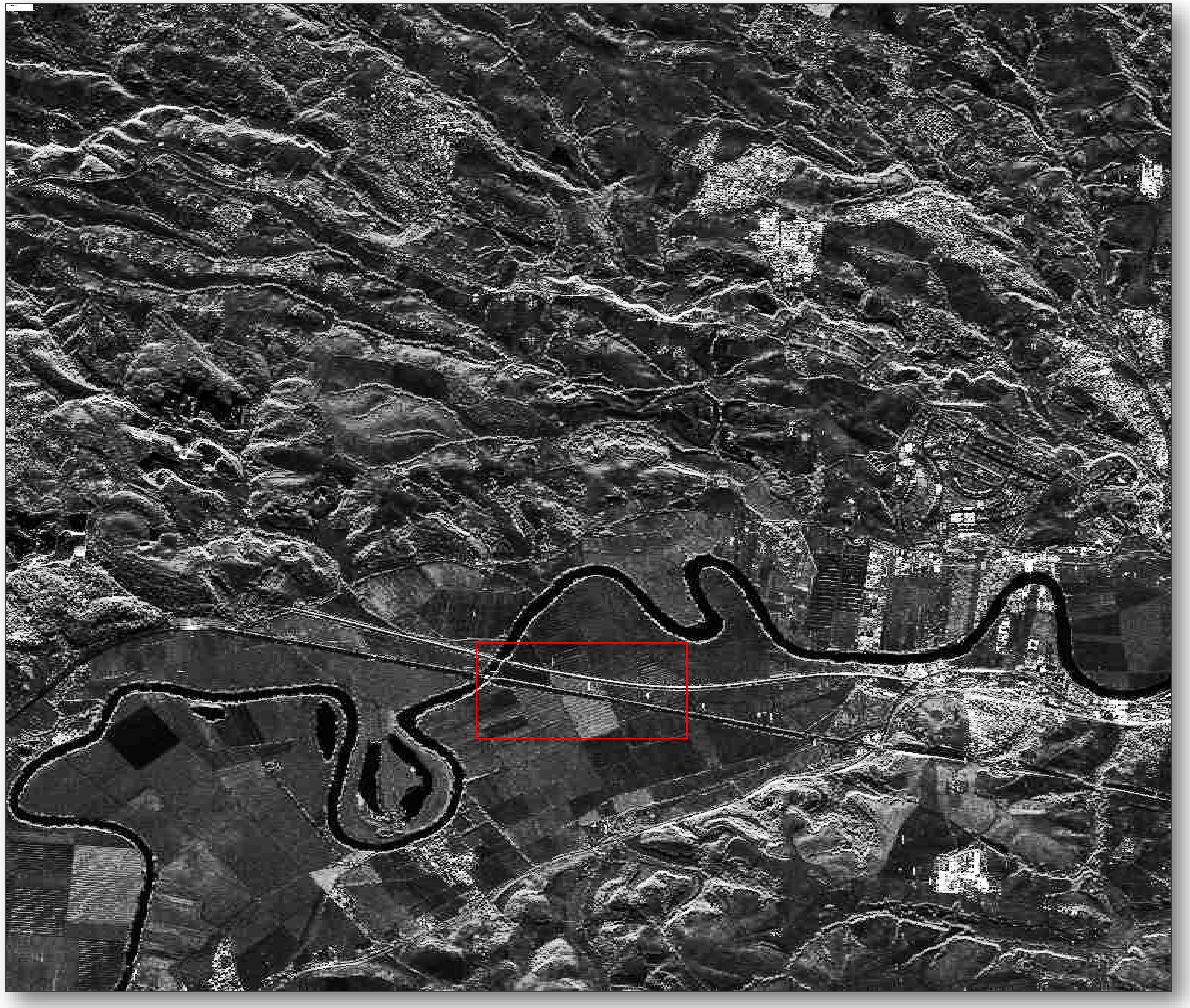
- Range acceleration (A_{radial}) and azimuth velocity (V_{tan}) components produce:
  - smearing (walking through different azimuths) and defocusing (change of the Doppler rate) along the azimuth direction.
  - SNR losses



- **ISAR refocusing process attempts to remove smearing effects and to estimate motion parameters**

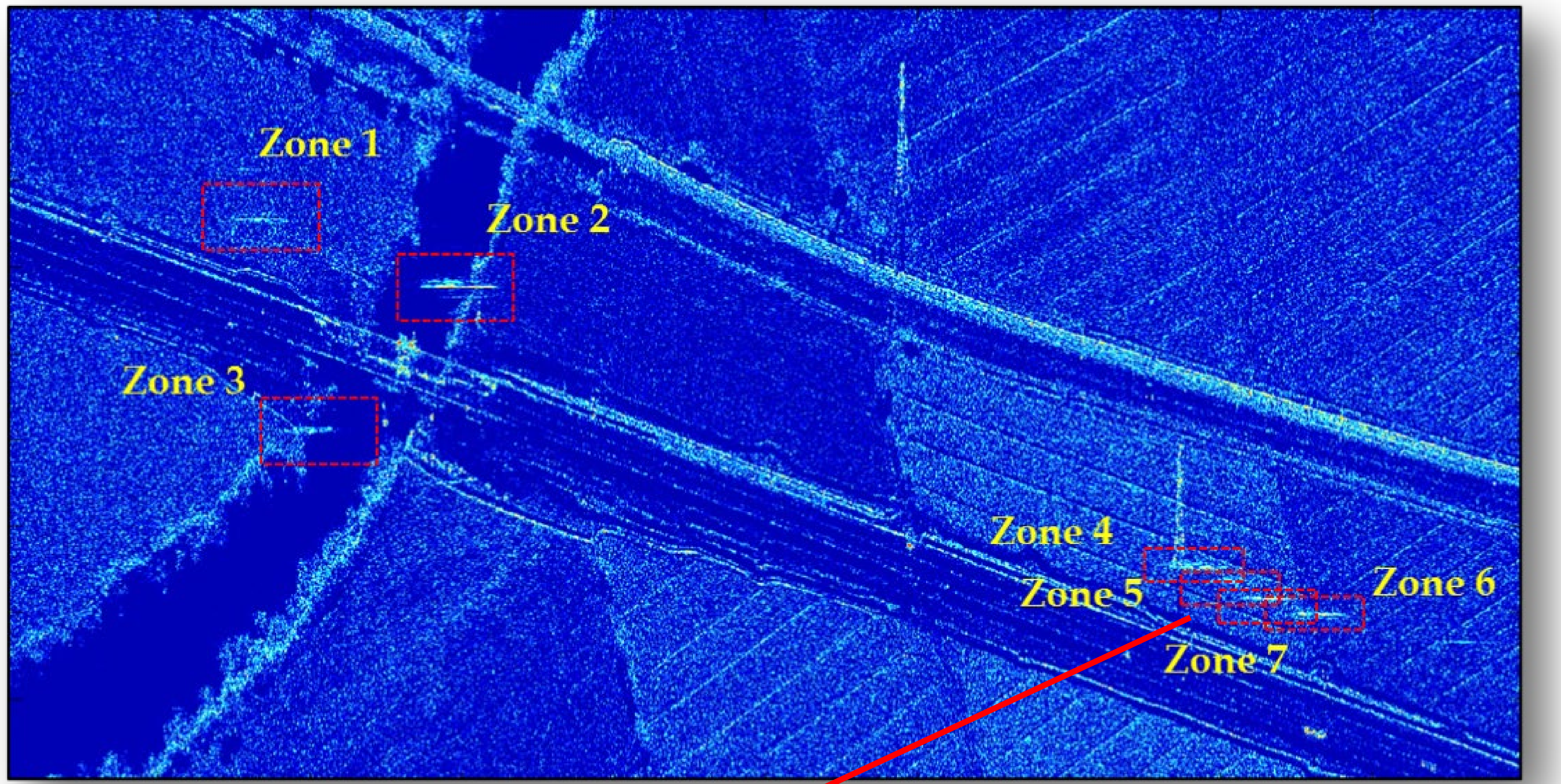


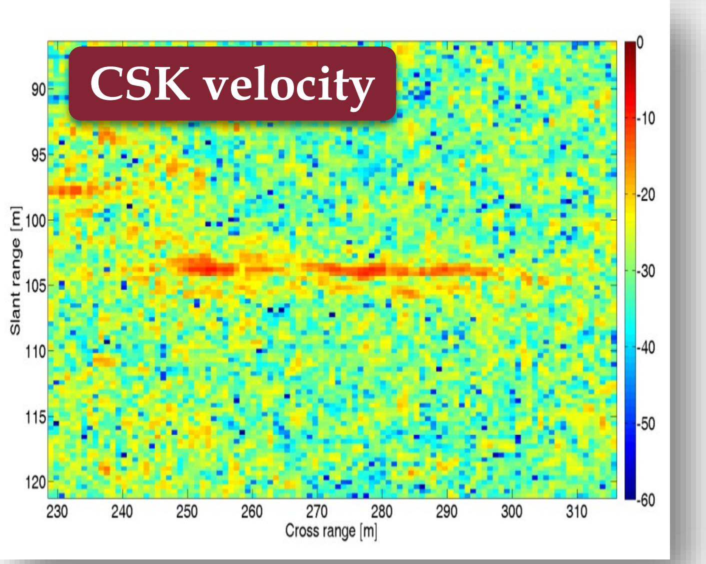
Moving target imaging: an example ….. Cars in CSK images

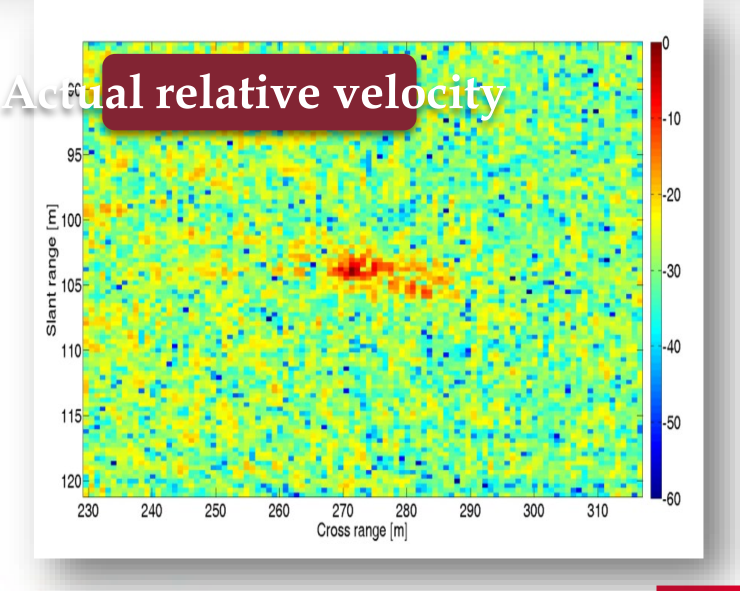


Pastina, Turin, «**Exploitation of the COSMO-SkyMed SAR system for GMTI applications**», IEEE JSTARS, 2015

- **Scene features** :
  - Area location : North of Rome
  - Acquisition date : May 5 2010
  - Acquisition time : 18:01:21
  - Image content : A1 motorway (Milan-Naples), Tiber river
- **Dataset properties** :
  - Product Level : 1A SSC
  - Acquisition Mode : E-Spotlight
  - Covered Area : $D_{cr} \times D_{sr}$ (10.01×6.22) $[km]$
  - Spatial resolutions : $r_{cr} = 1.13\ [m]; r_{sr} = 0.48[m]$
  - Acquisition duration : 1,39 [s]

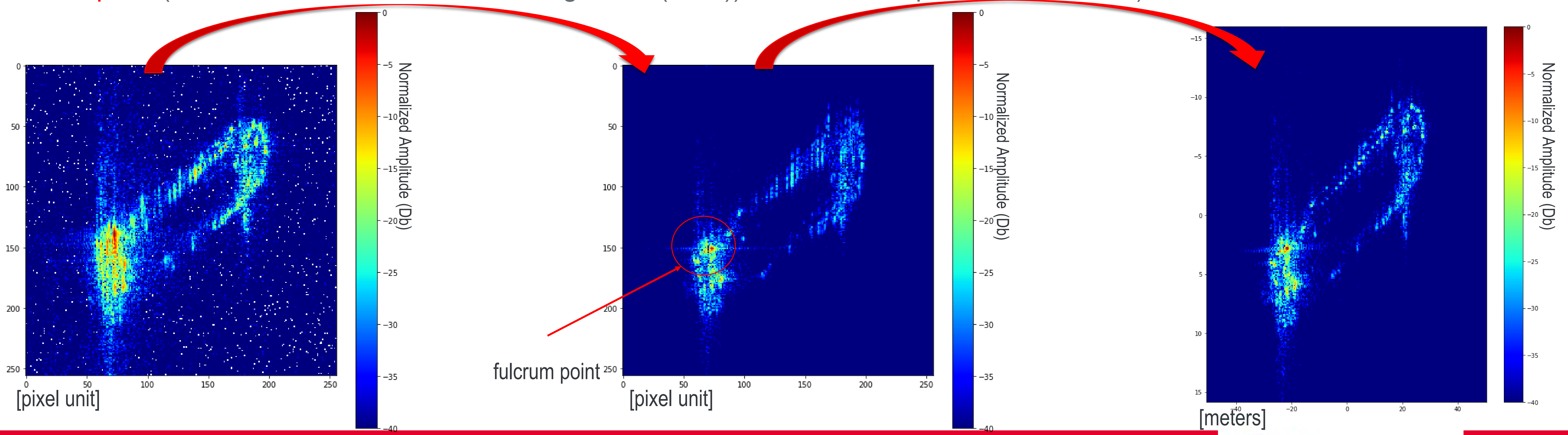






ISAR processing outline

- In ISAR systems, the composition of the radar platform and target movements is modelled as the superposition of:
  - Relative translation motion between the radar platform and the considered target;
  - Relative 3D rotation between the radar platform and the considered target (roll, pitch, yaw)
- In order to retrieve these motion parameters and correct defocusing effects, ISAR processing maximizes the image contrast by:
  - Compensation with respect to translation motion and stabilization of a fulcrum point (Autofocus and Phase Gradient Algorithm (PGA))
  - Compensation with respect to rotations (cross-range scaling with sub-apertures, and PGA)



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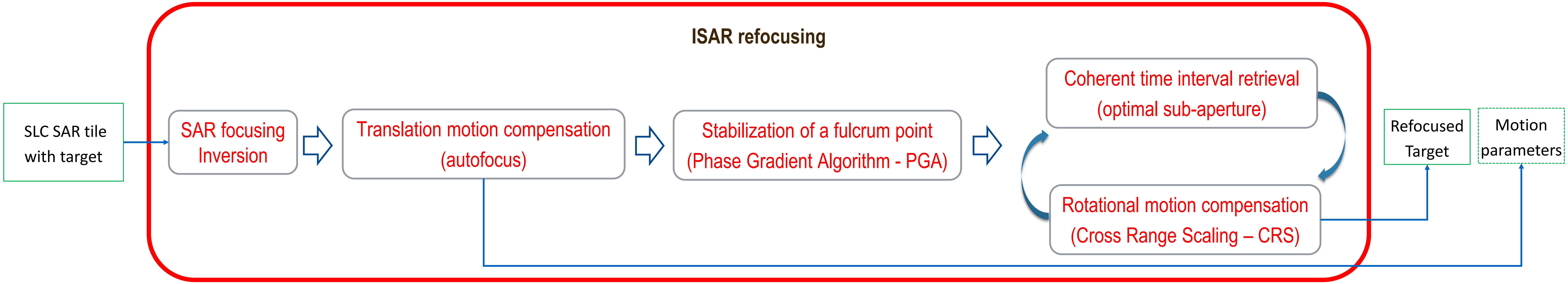
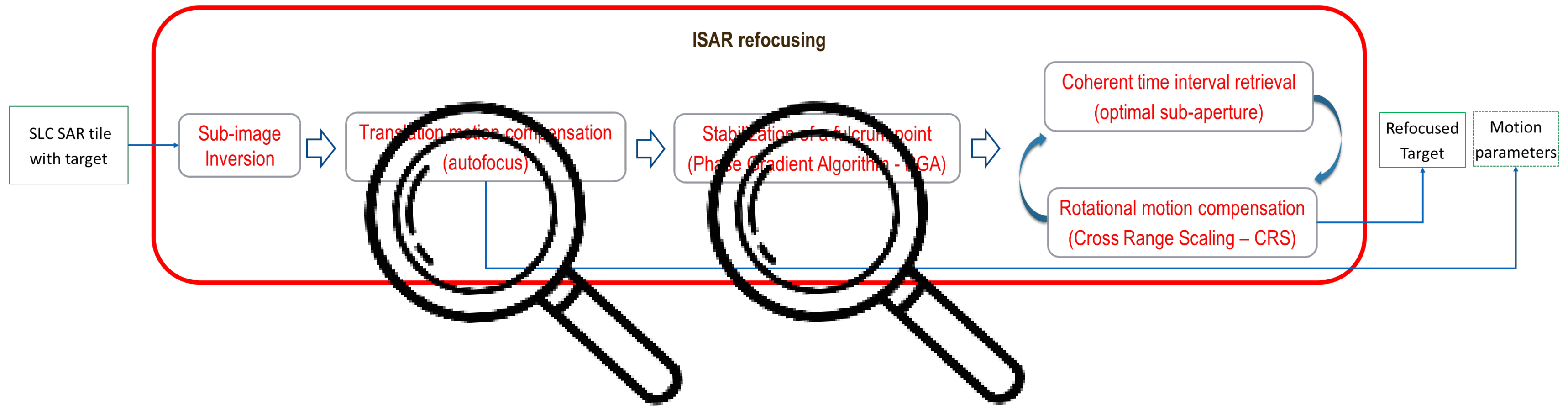
Processing workflow

End to end SAR data processing

ISAR refocusing processing of the target sub-image



Compensation of translation motion (autofocus)

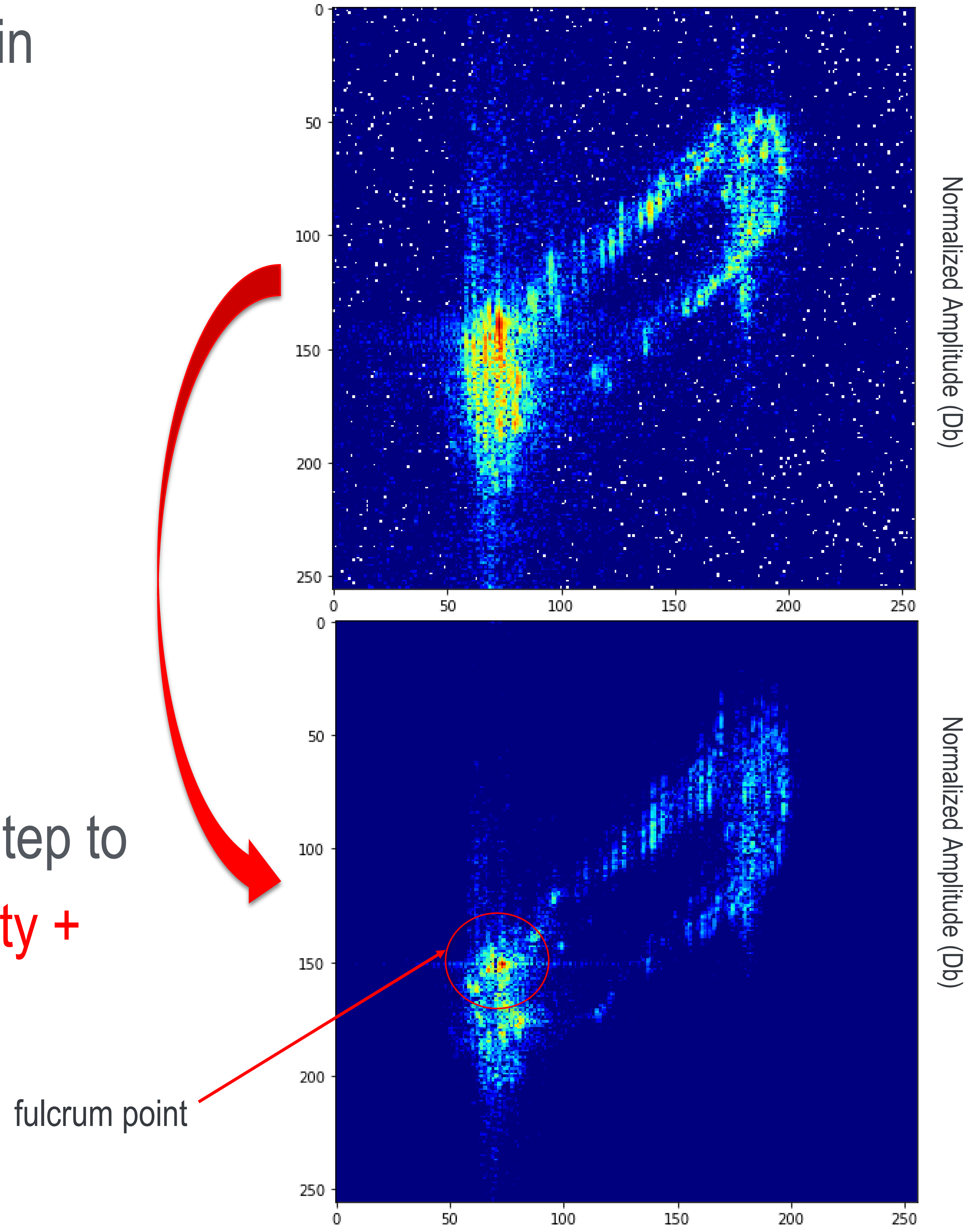


- The raw SAR data (which can be obtained from SLC by inverse focusing) is iteratively focused, by using Chirp Scaling focusing Algorithm (CSA), in a optimization process to maximize the contrast of the focused image.
- The optimization parameters are the azimuth component of the vessel velocity and, only for stripmap mode, the range component.
- The outputs are: (a) better focused target image and (b) target velocity.

Stabilization of a fulcrum point (PGA)

- The Phase Gradient Algorithm is applied to the output of the autofocus step to remove the complete Doppler phase (parabolic component due to velocity + higher order terms) of a selected “fulcrum” point

D.E Wahl, P.H. Eichel, D.C. Ghiglia, C.V. Jr Jakowatz, "Phase gradient autofocus-a robust tool for high resolution SAR phase correction, " IEEE TAES, Vol. 30, Issue: 3, 1994, pp. 827-835.



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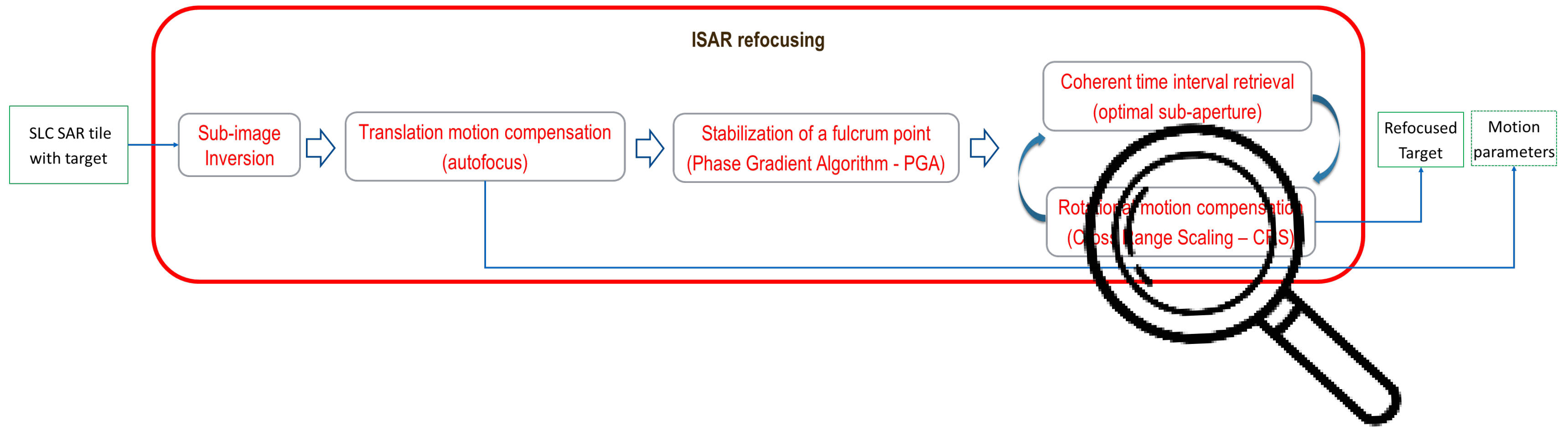
Rotational motion compensation: CRS



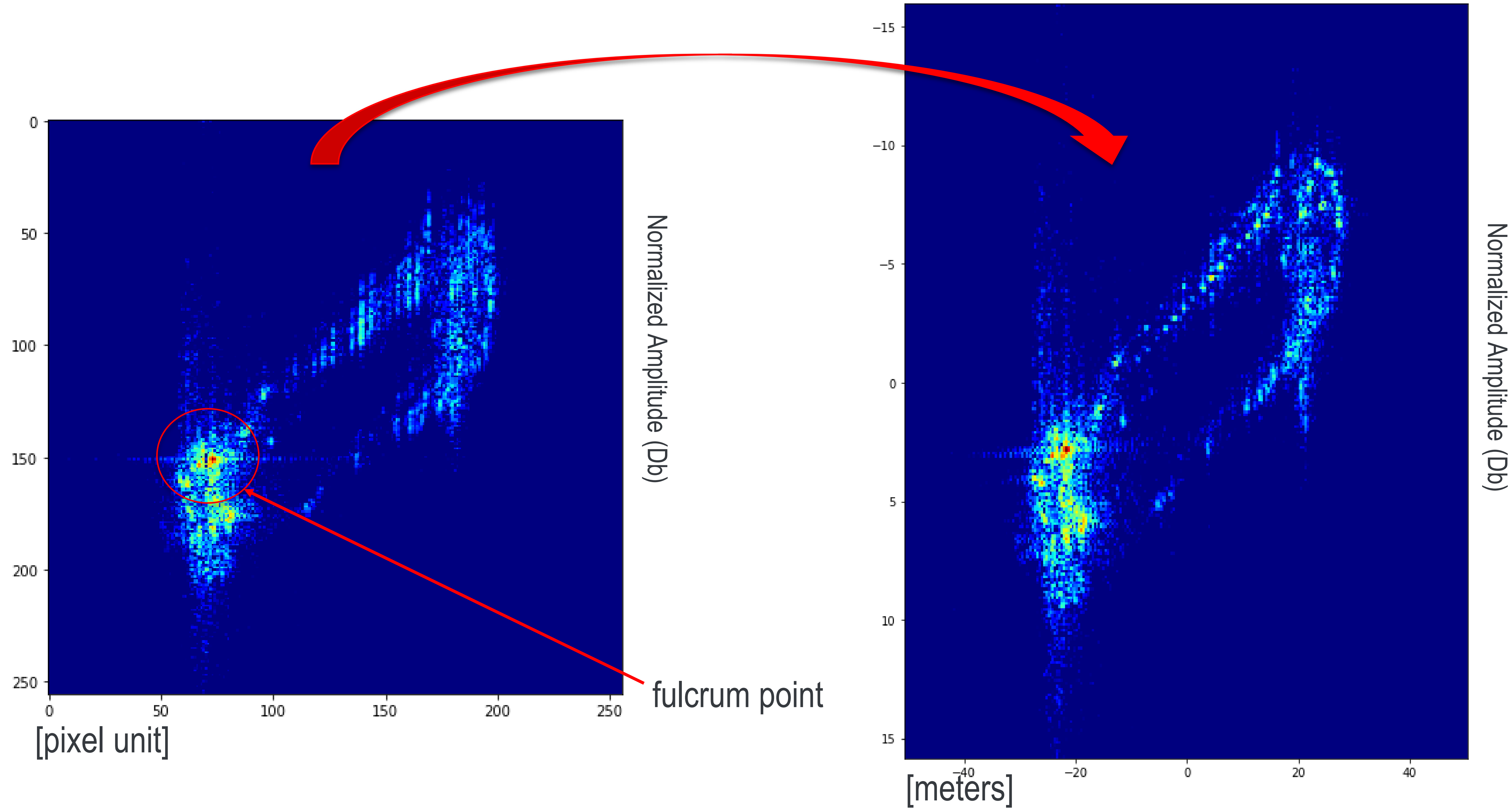
▪ Cross Range Scaling (CRS)

- Cross-Range Scaling is done by maximizing the image contrast through an iterative range and Doppler dependent refocusing

- Cross-Range Scaling is used for two purposes:
  - Estimation of the effective target rotation velocity (normal to the Line of Sight (LOS)) ω_E, enabling correction of the cross-range resolution:

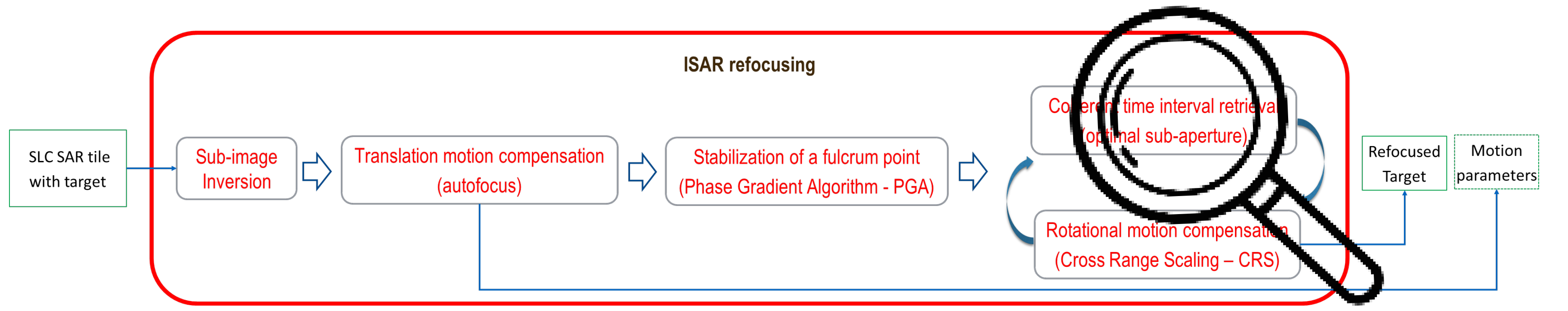
$$\Delta y = \frac{\lambda}{2\omega_T T}, \ \omega_T = \sqrt{\omega_S^2 + \omega_E^2};$$

  - Range and Doppler dependent refocusing (autofocus) of the SAR image to compensate rotational motion defocusing effects

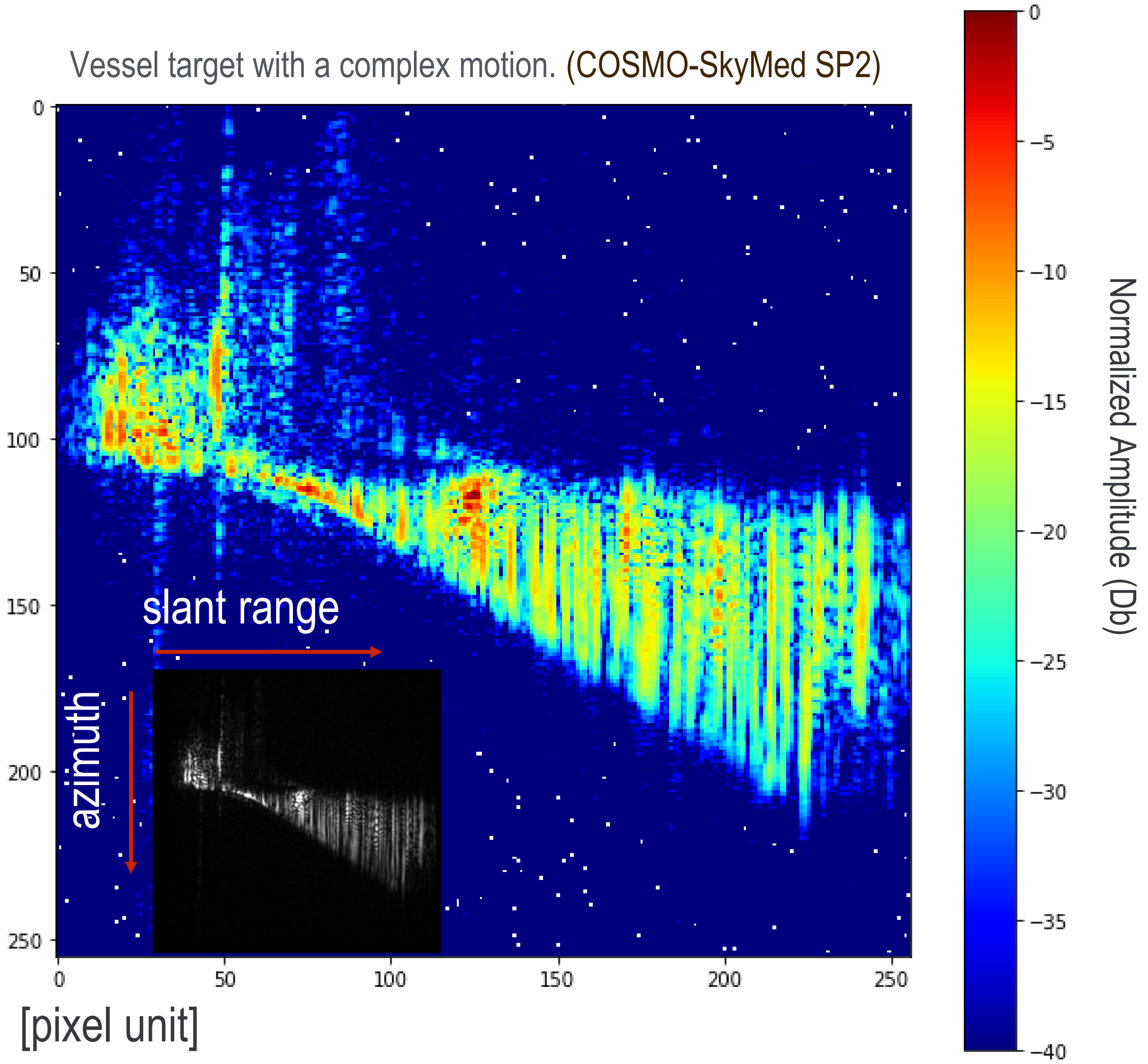


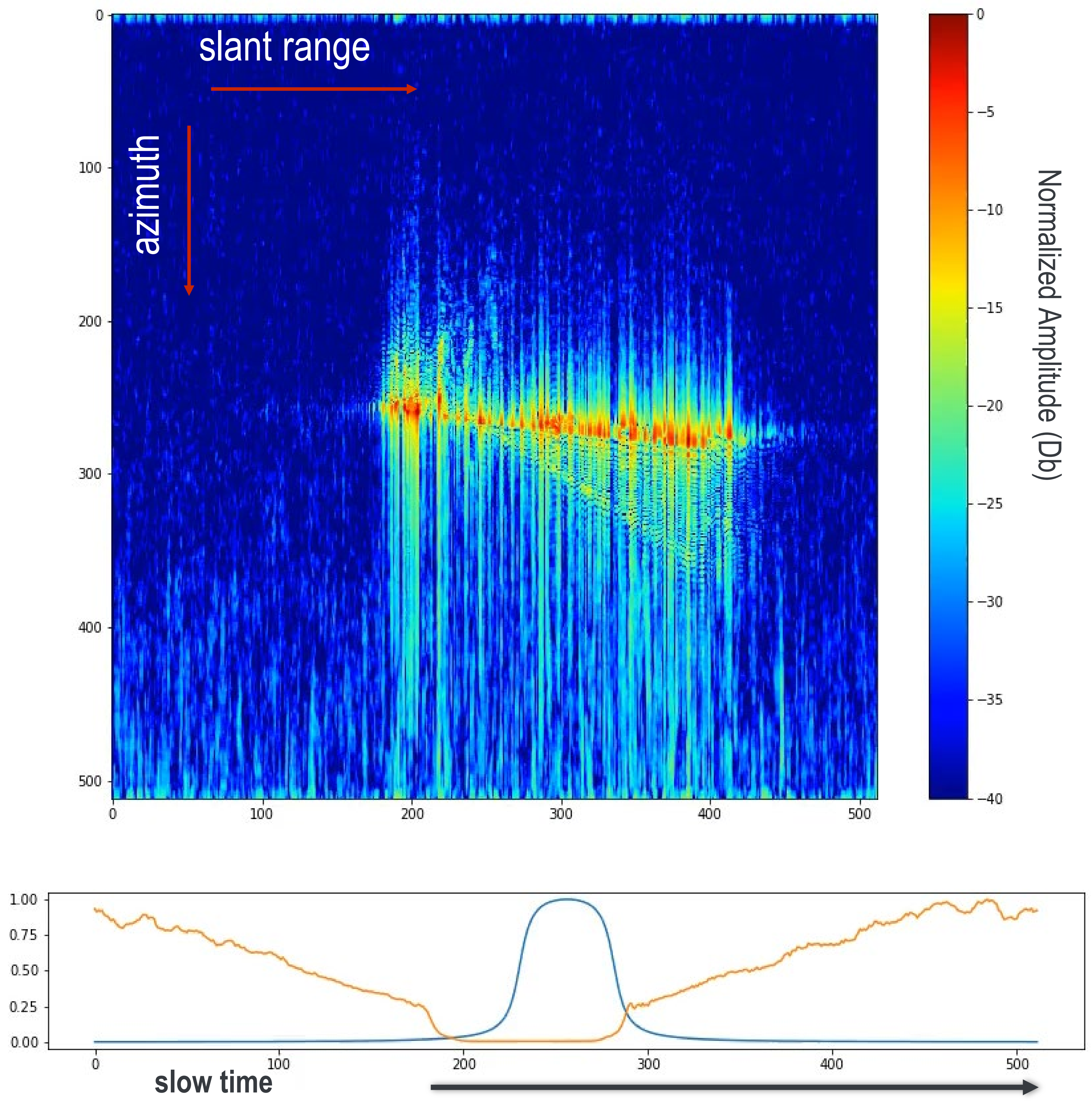
D. Pastina, "Rotation motion estimation for high resolution ISAR and hybrid SAR/ISAR target imaging", 2008 IEEE Radar Conference, Rome (Italy), May 2008.

Coherent time interval retrieval (sub-aperture)



- A data sub-aperture (time windowing) approach is used to make sure that the radar-target motions can be considered smooth and almost constant during the sub-aperture (in particular, the rotation axis should be fixed to avoid the superposition of different image projection plans IPPs).
- Sub-aperture is applied as a passband filter in the Doppler space (after azimuth IFFT)
- The optimal sub-aperture (center and width of the band window) is searched by maximizing the image contrast
- The optimization process to maximize the contrast is performed jointly with the cross-range scaling step (compensation of the rotation effects of defocusing)



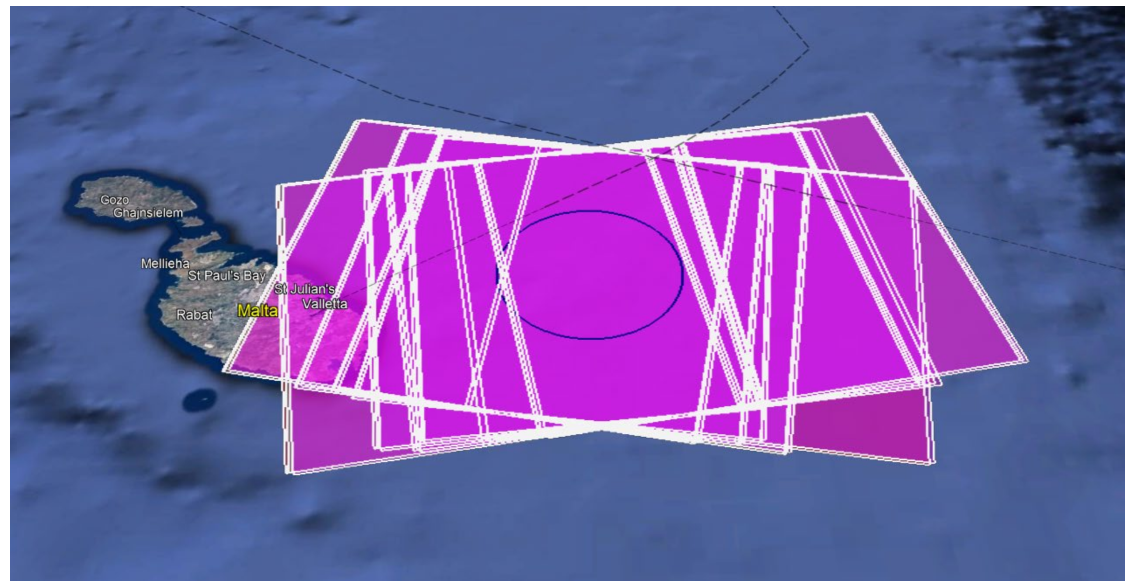


Orange plot: SAR azimuthal spectrum; Blue plot: SAR sub-aperture

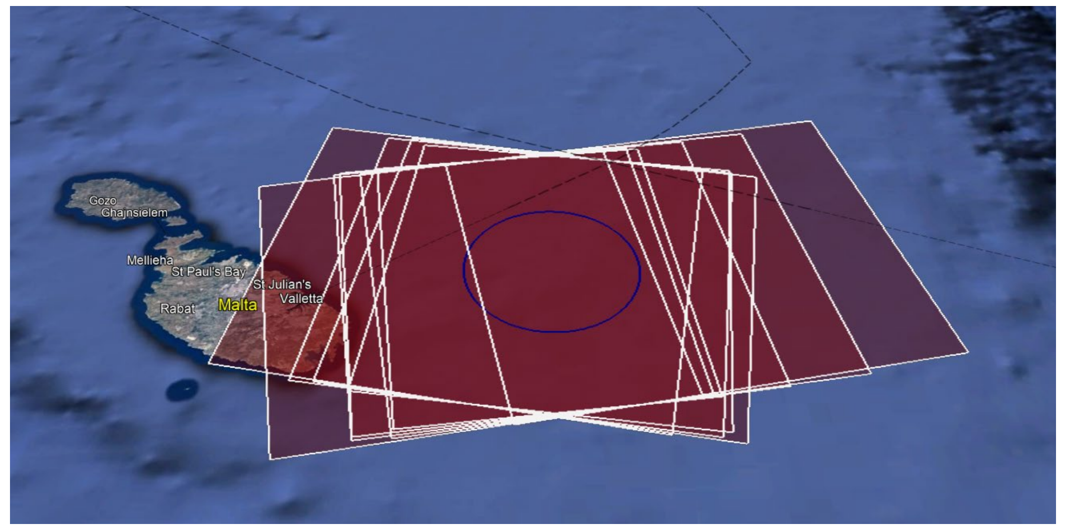
Validation activity

- Estimation of algorithms performances is ongoing on stripmap and spotlight COSMO SkyMed and CSG images
- Exploitating AIS information assumed as the “ground truth”

Malta

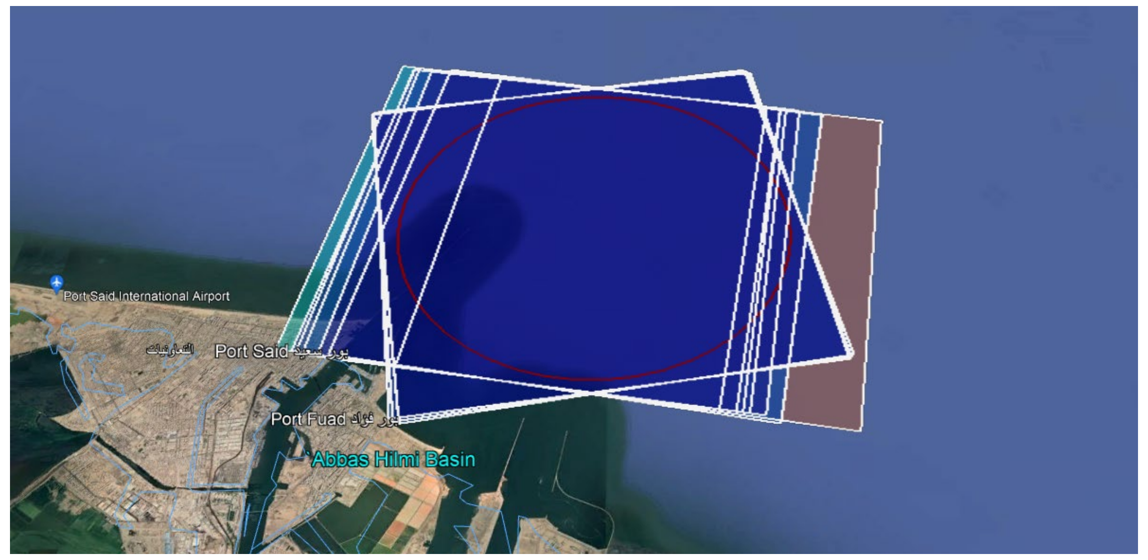


Stripmap COSMO-SkyMed DTOs
(acquired 13 images)

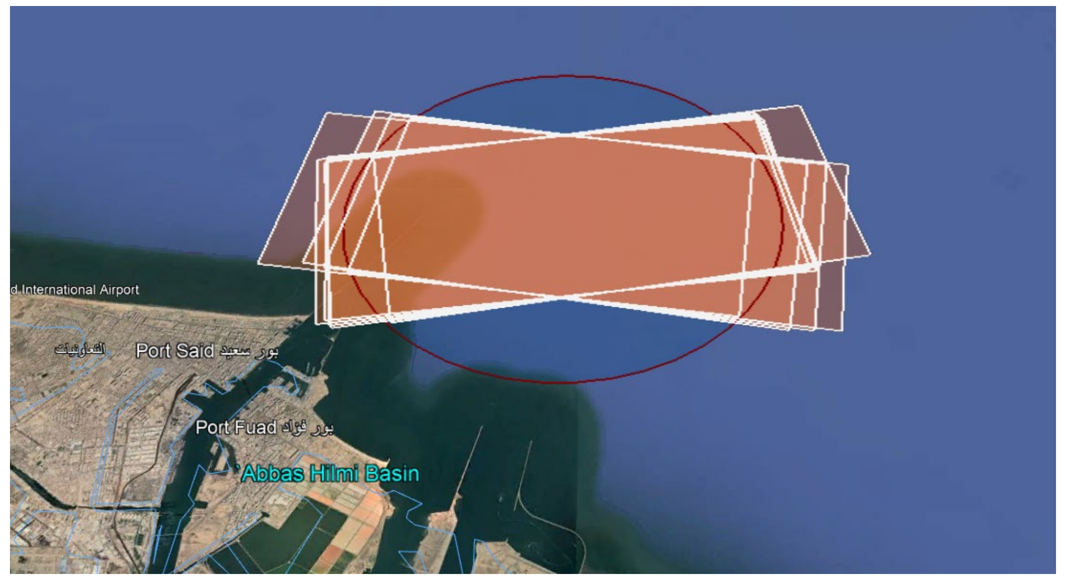


Stripmap CSG DTOs
(7 images)

Suez Canal

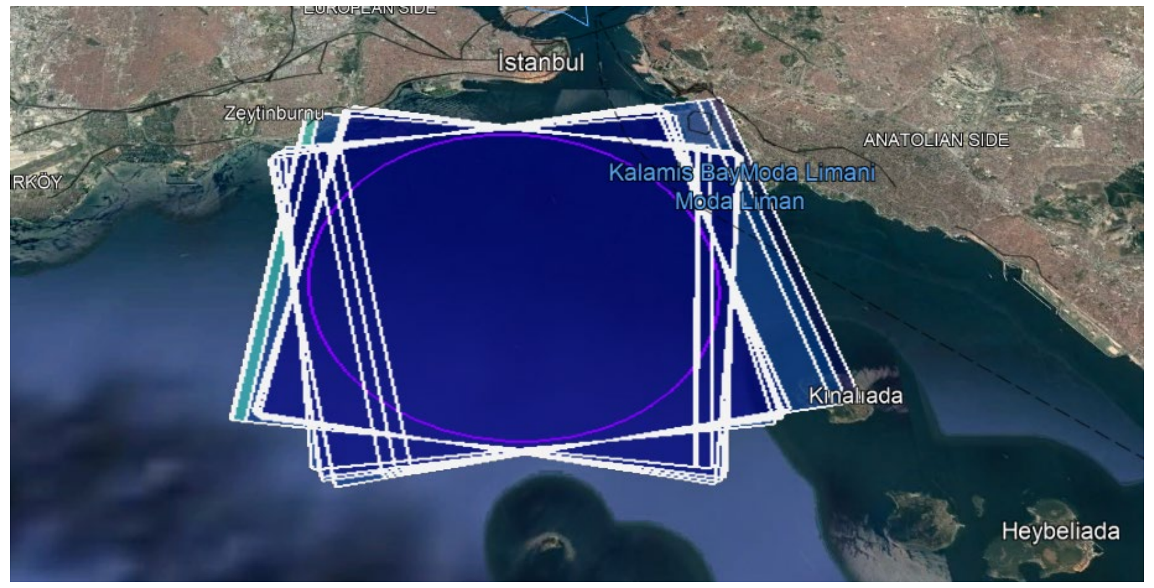


Spotlight COSMO-SkyMed DTOs
(acquired 2 images)

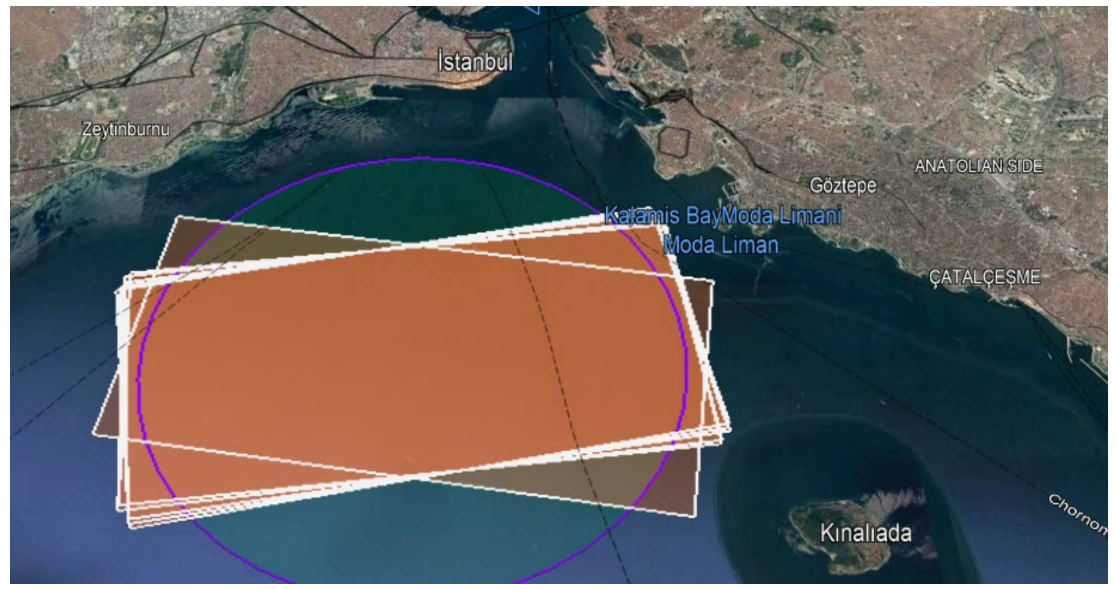


Spotlight CSG DTOs
(7 images)

Bosphorus Canal



Spotlight COSMO-SkyMed DTOs
(acquired 6 images)



Spotlight CSG DTOs
(5 images)

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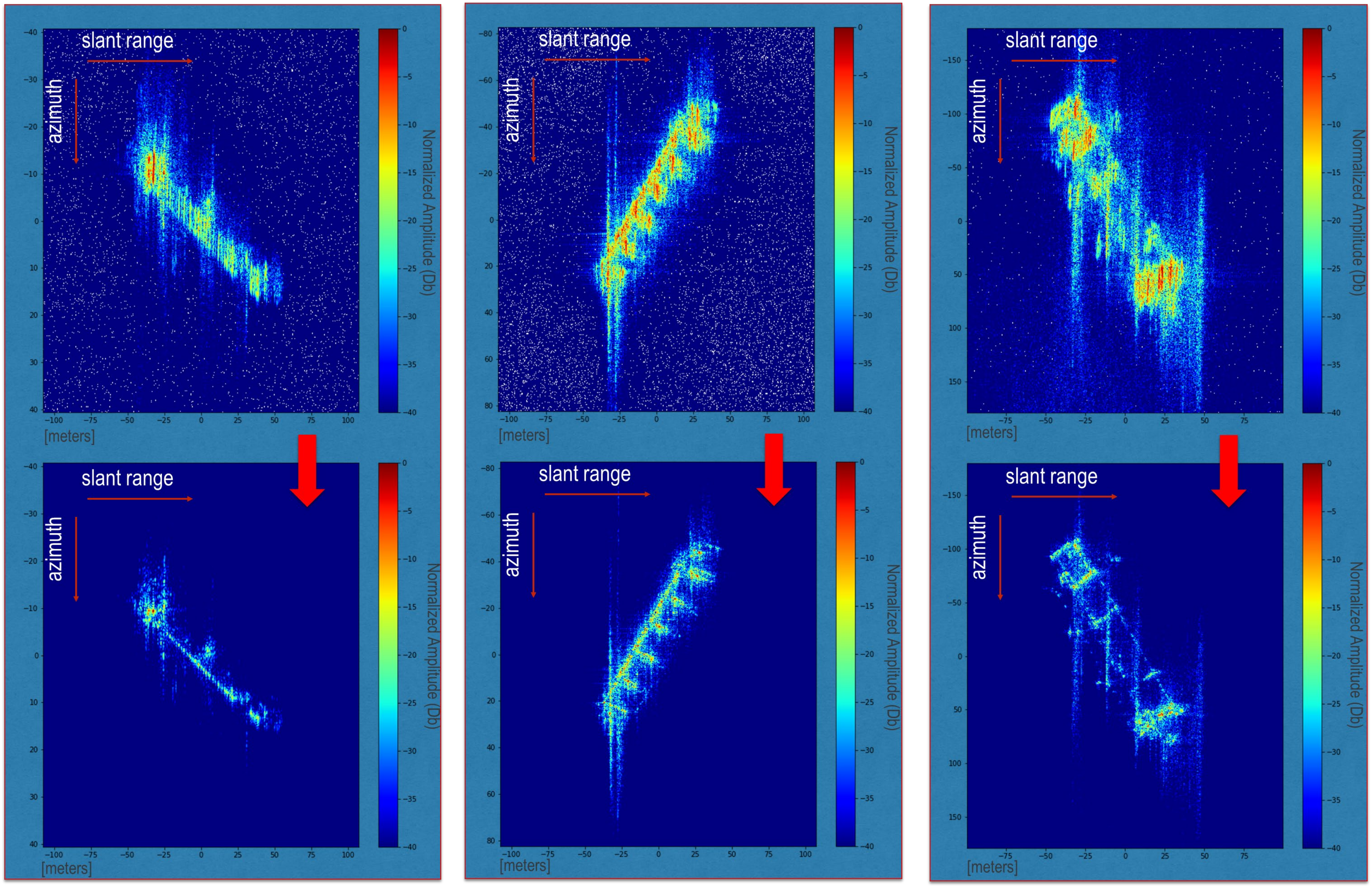
Examples of results (1)



- Refocusing and motion estimation for ships (experiencing mainly translation motion)
- Recover of full azimuth resolution
- Reconstruction of details for strong scatterers
- Backscattering energy is compressed in the few true scattering cells

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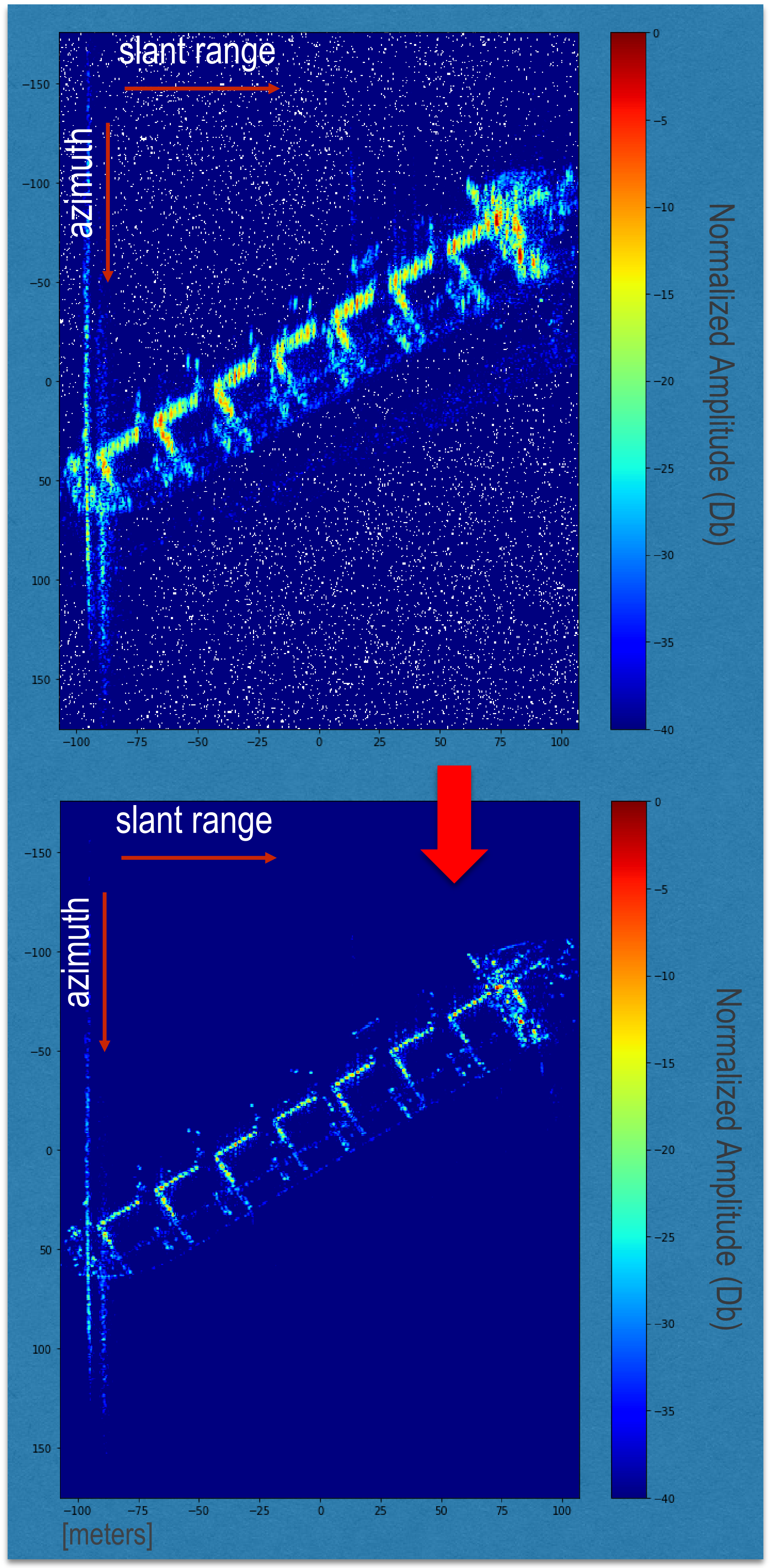
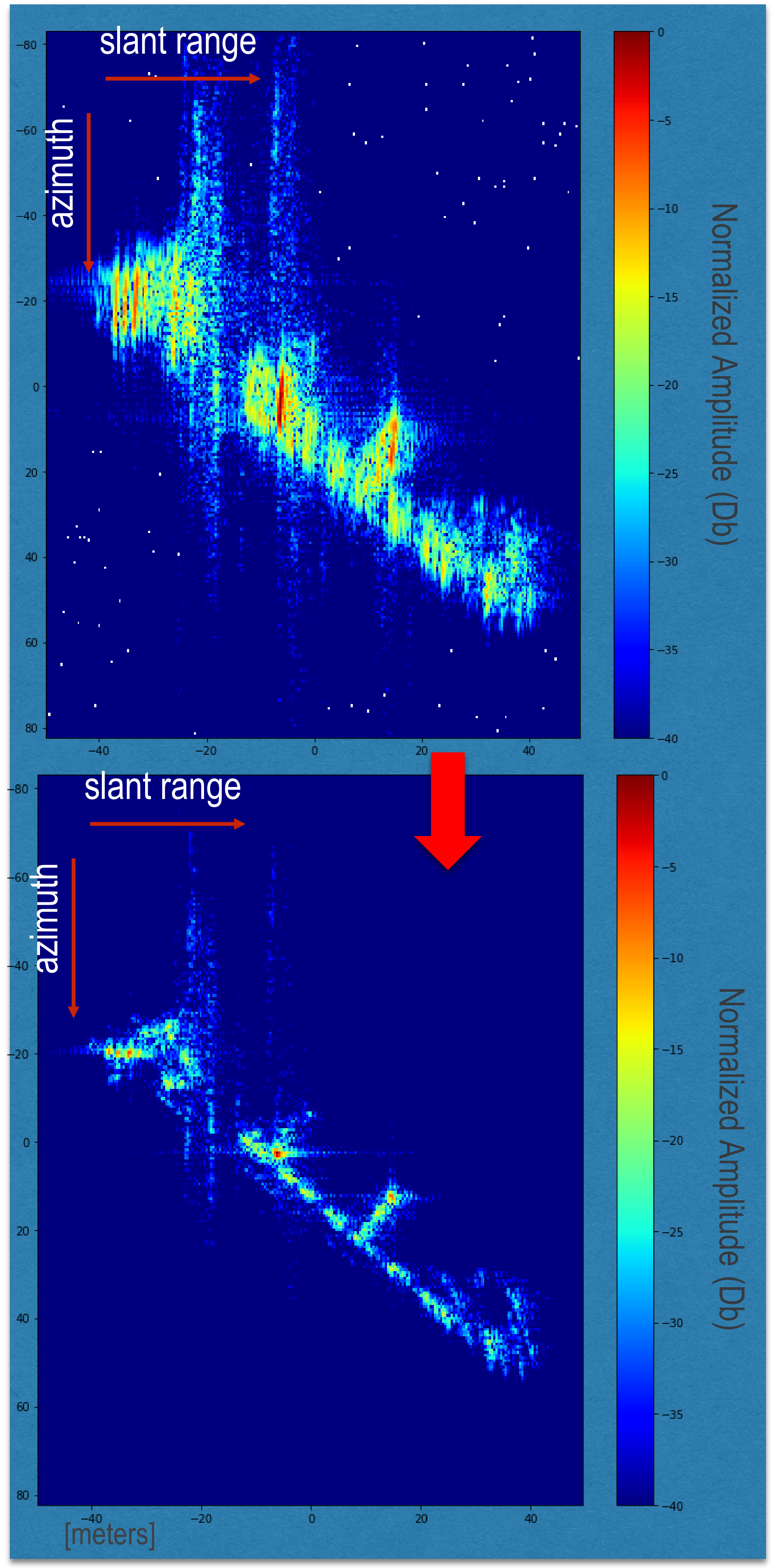
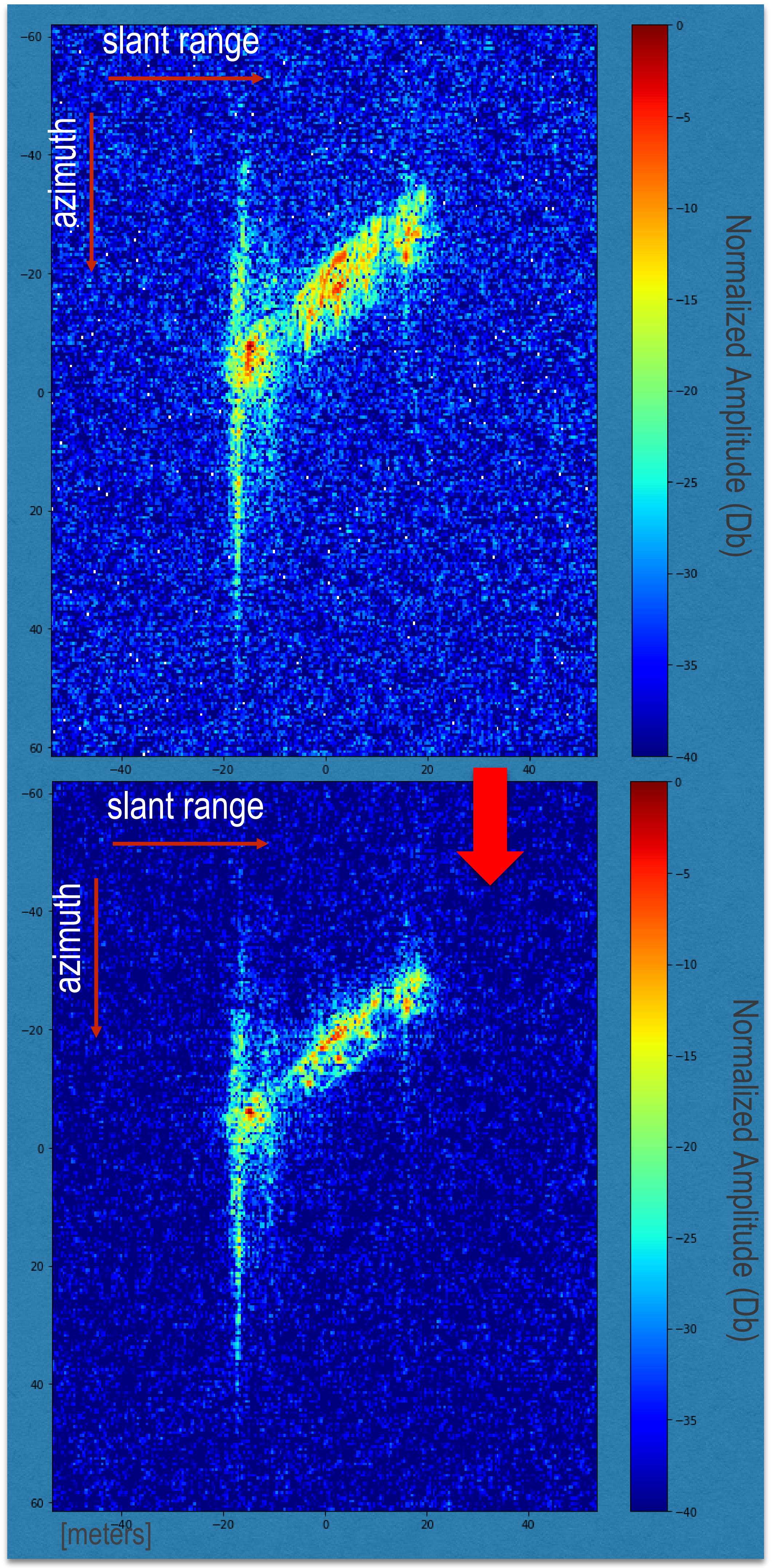
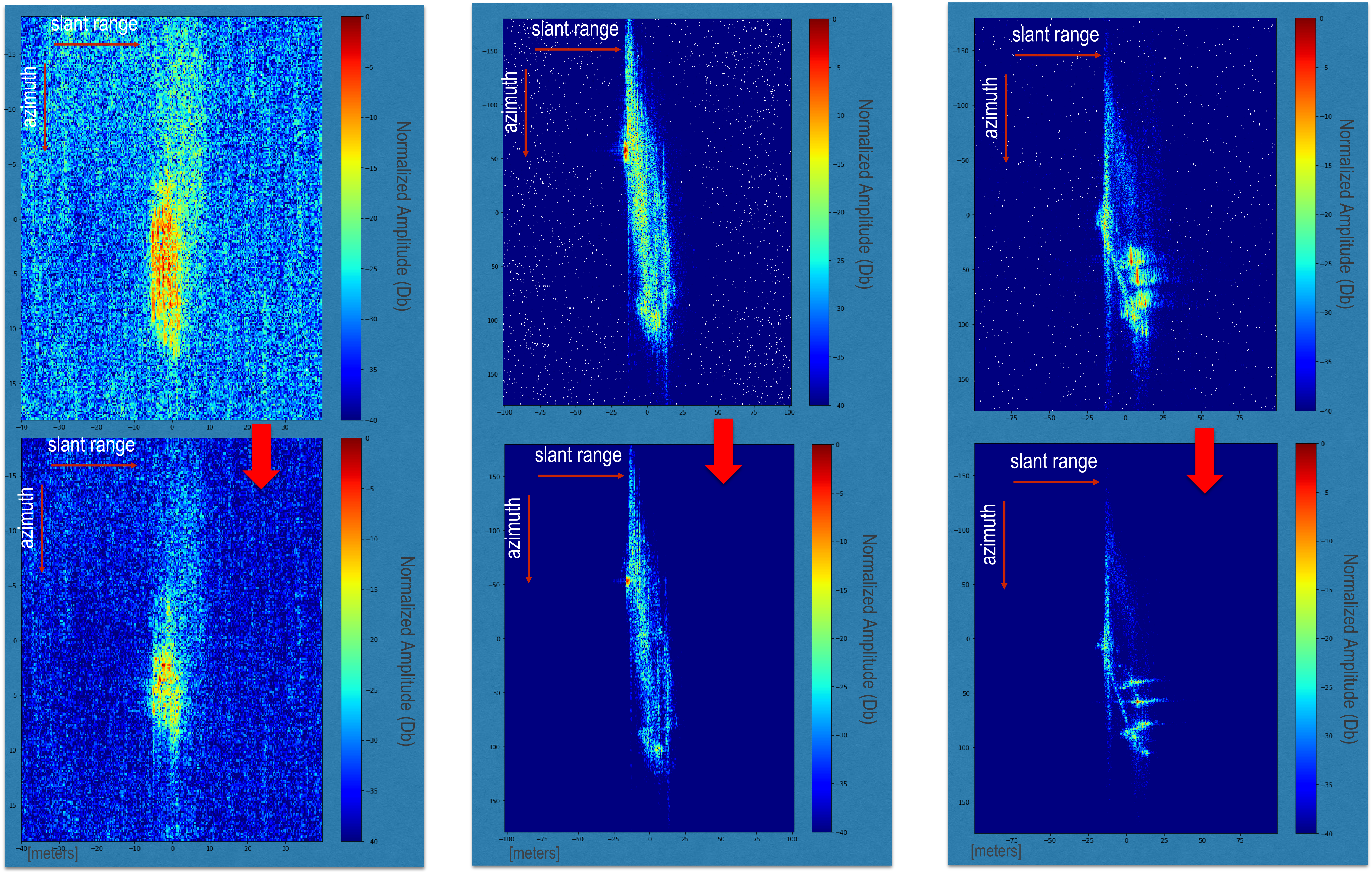
Examples of results (2)







Examples of results (3)



- Not all vessel are well focused. The refocusing is strongly dependent on the vessel motion
- A contrast improvement is generally achieved
- Refocusing of the target leads to defocus the sea clutter

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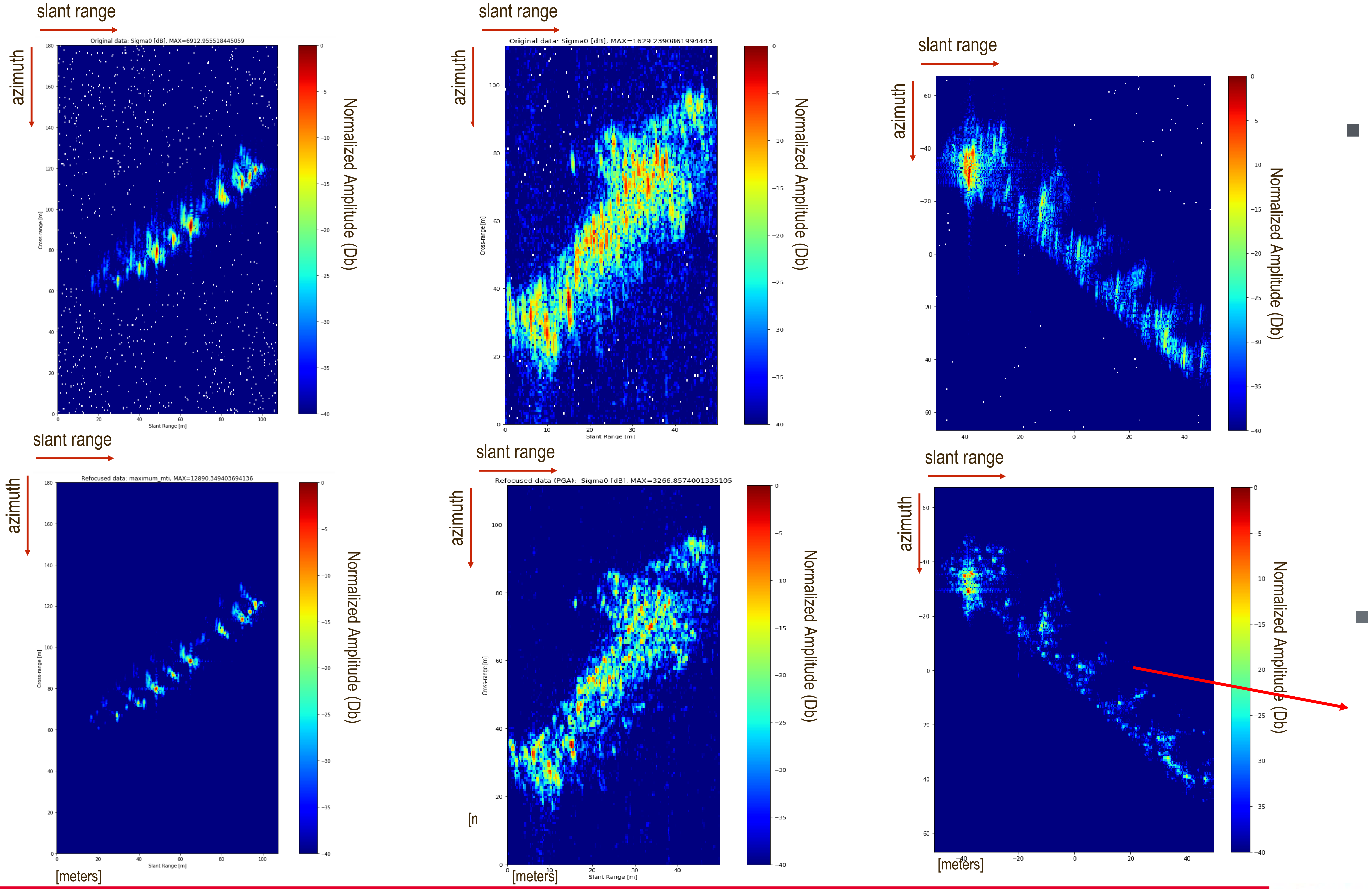
Examples of results (4)



- Refocusing process, defocuses sea clutter and compresses target energy in fewer scattering cells.Then the contrast is enhanced

- Reconstructed scatterers enable recognition for automatic AI systems

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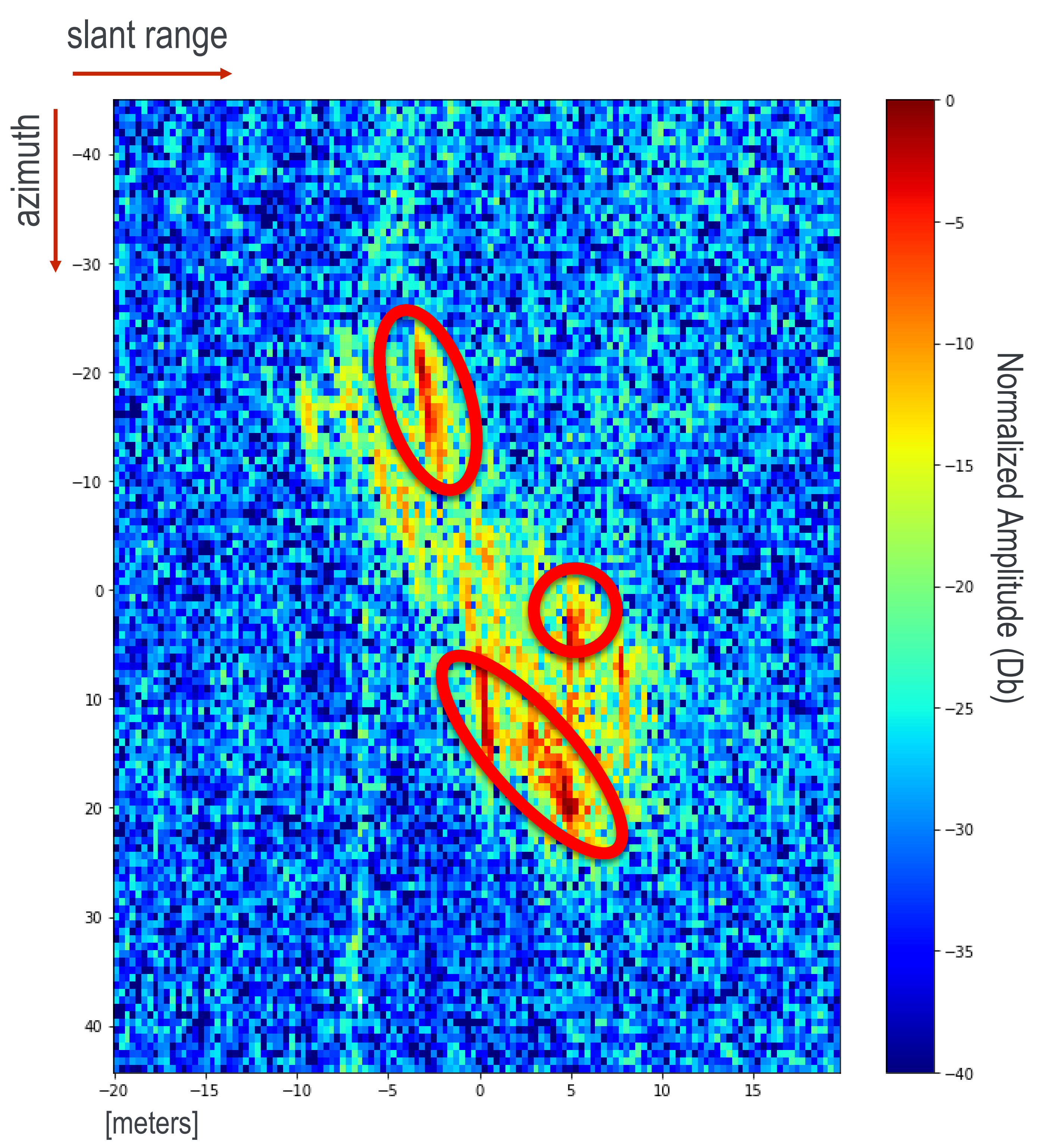
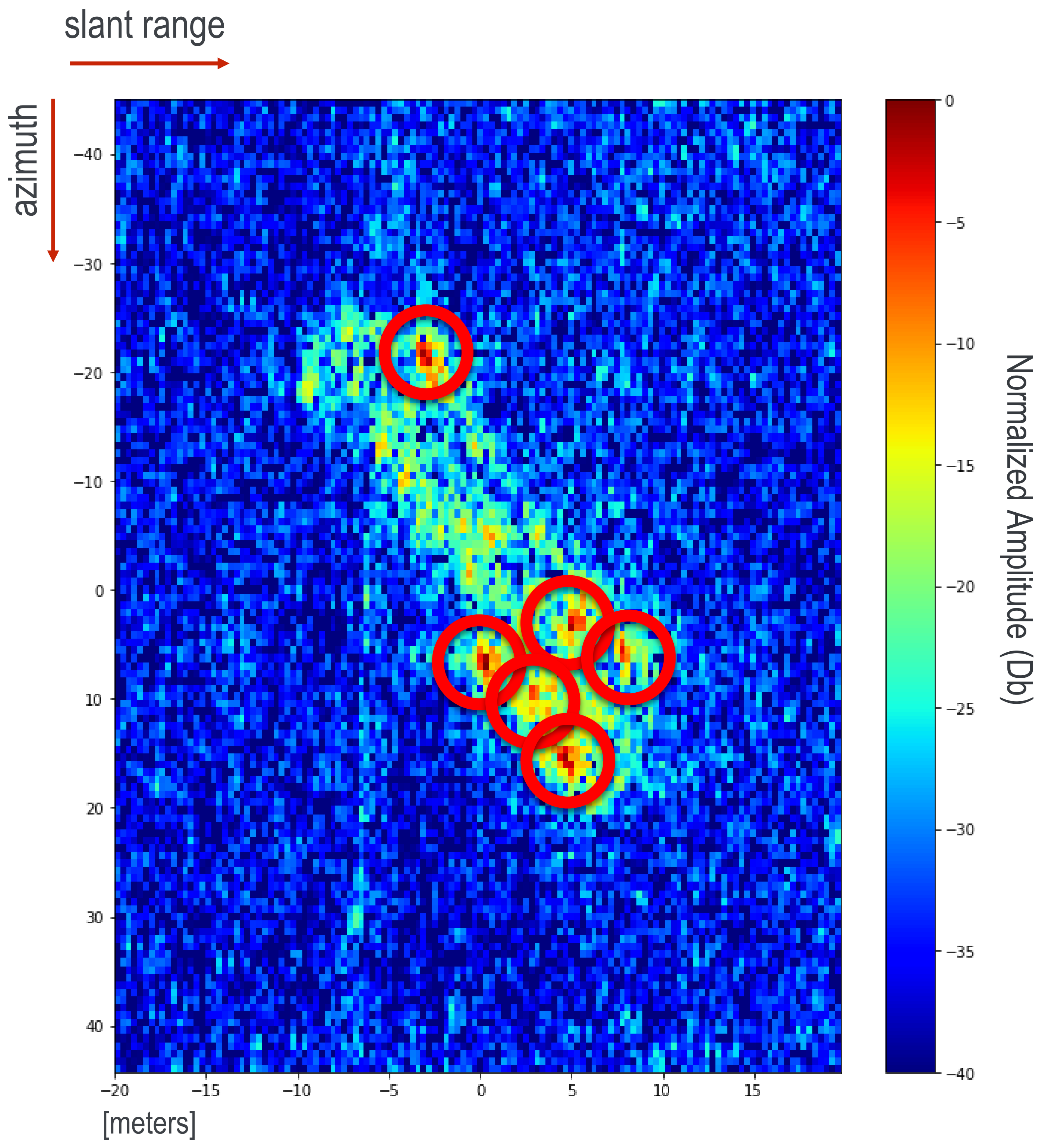
Examples of results (5)

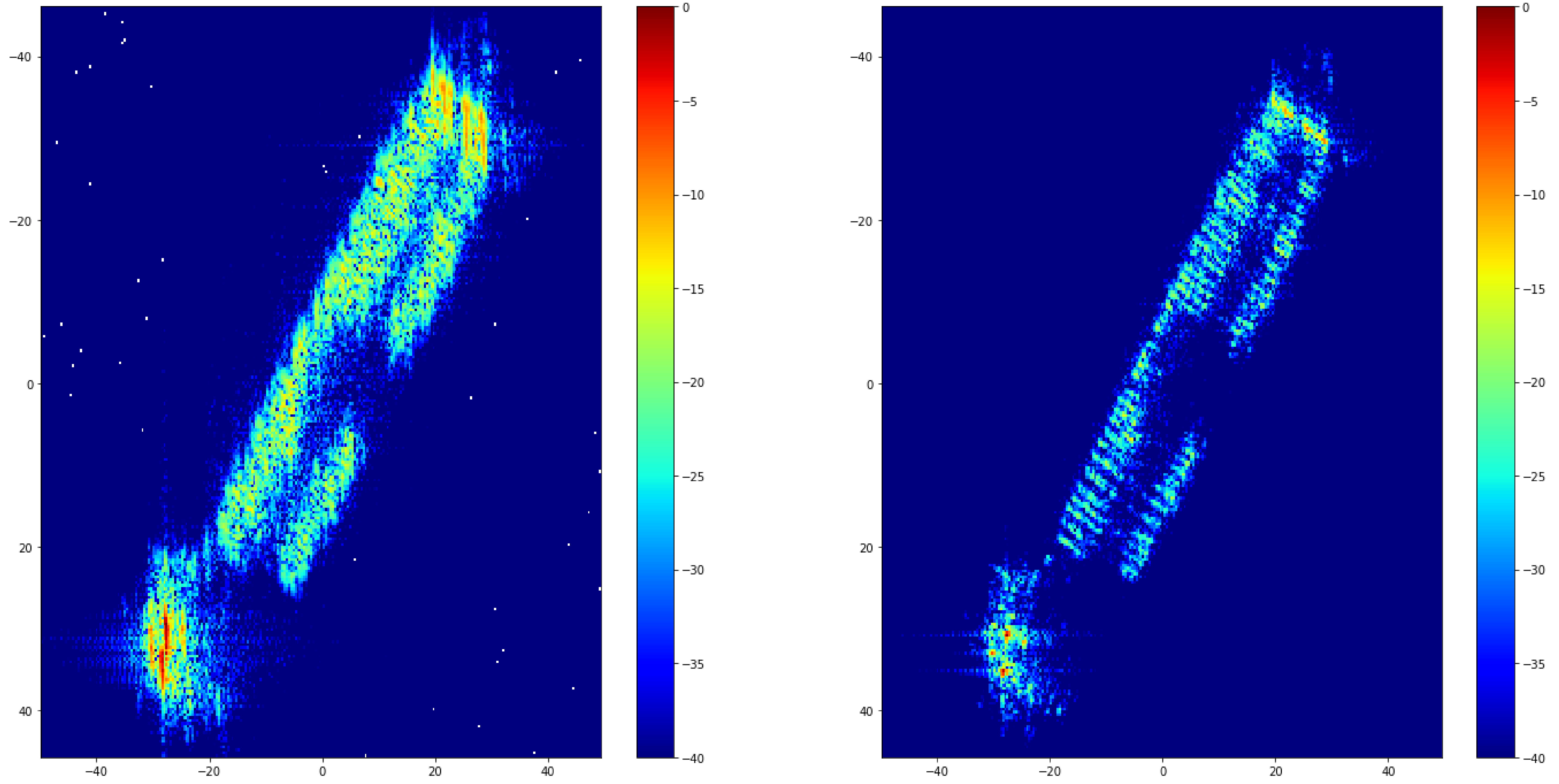




Reconstruction of details even in small vessels

Single scatterers are recovered from confused blobs

Examples of results (6)



Reconstruction of details enables analysis of the vessel charge and, in this case, determining the number of containers

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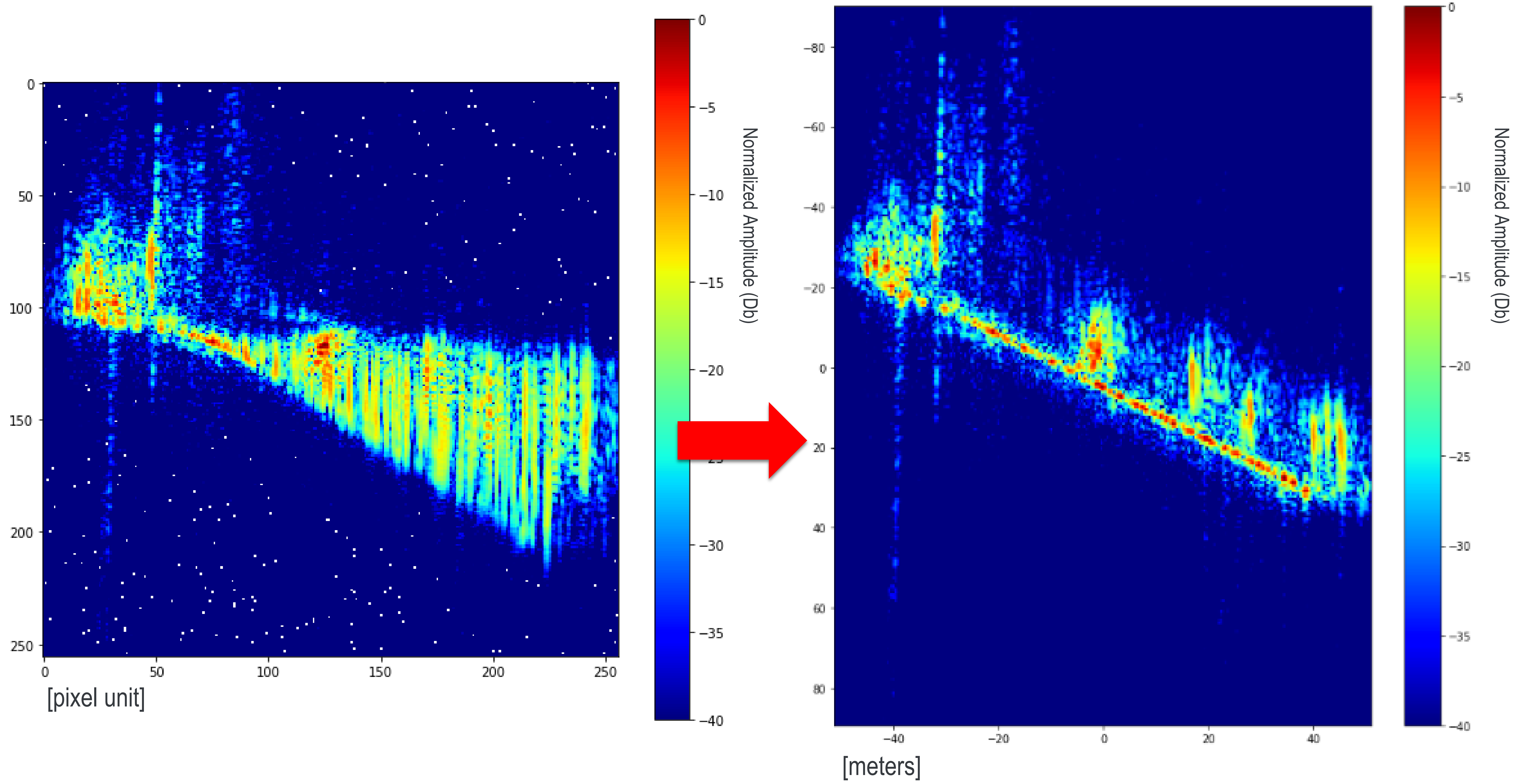
Examples of results (7)



In this case the rotational movement of the scatterers on one side of the vessel is completely reconstructed, by the processing (Autofocus, PGA, Sub Aperture, CRS).

In this case, most of the refocusing is due to the Cross-Range scaling step

Conclusions

- An automatic processing prototype has been developed to produce refocused and rescaled hybrid ISAR images of moving ship targets. imaged by very high resolution satellite SAR systems.
- Examples obtained by processing Cosmo-SkyMed spotlight SAR images have been shown.
- The analysis has highlighted that the proposed processing technique is able to reconstruct well focused ISAR images of the detected targets
- These images can be usefully exploited for non-cooperative classification and identification purposes, thus supporting maritime surveillance and awareness.
- Validation activity is in progress;
- Exploitation of AIS information assumed as the “ground truth” for the assessment and validation

Future work

- Development of a joint detection&refocusing processing chain suitable for the joint detection and imaging of small/low RCS ship targets (i.e. of interest when the assumed initial super-clutter visibility condition does not apply)
- Exploitation of the output ISAR products for the control of false alarms at the detection stage (i.e. confirmation or rejection of detected targets on the basis of ISAR results)
- Exploitation of polarimetric information (when SAR is working in polarimetric modes) for performance improvement

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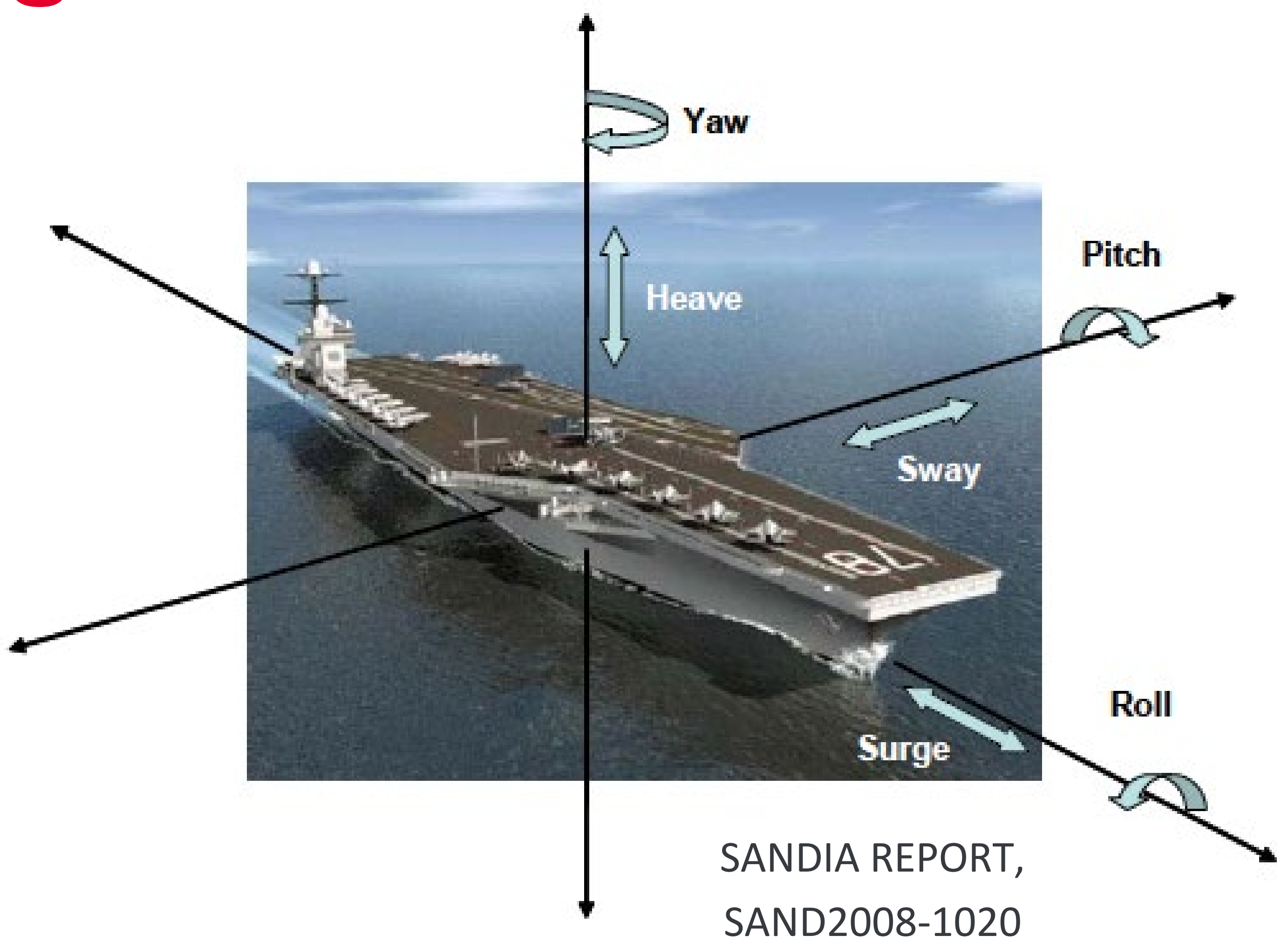
ISAR and target refocusing …

- Let's consider for example a ship
  - extending over many image resolution cells
  - interested by complex motions comprising 3D rotations (and subject to sea wave)

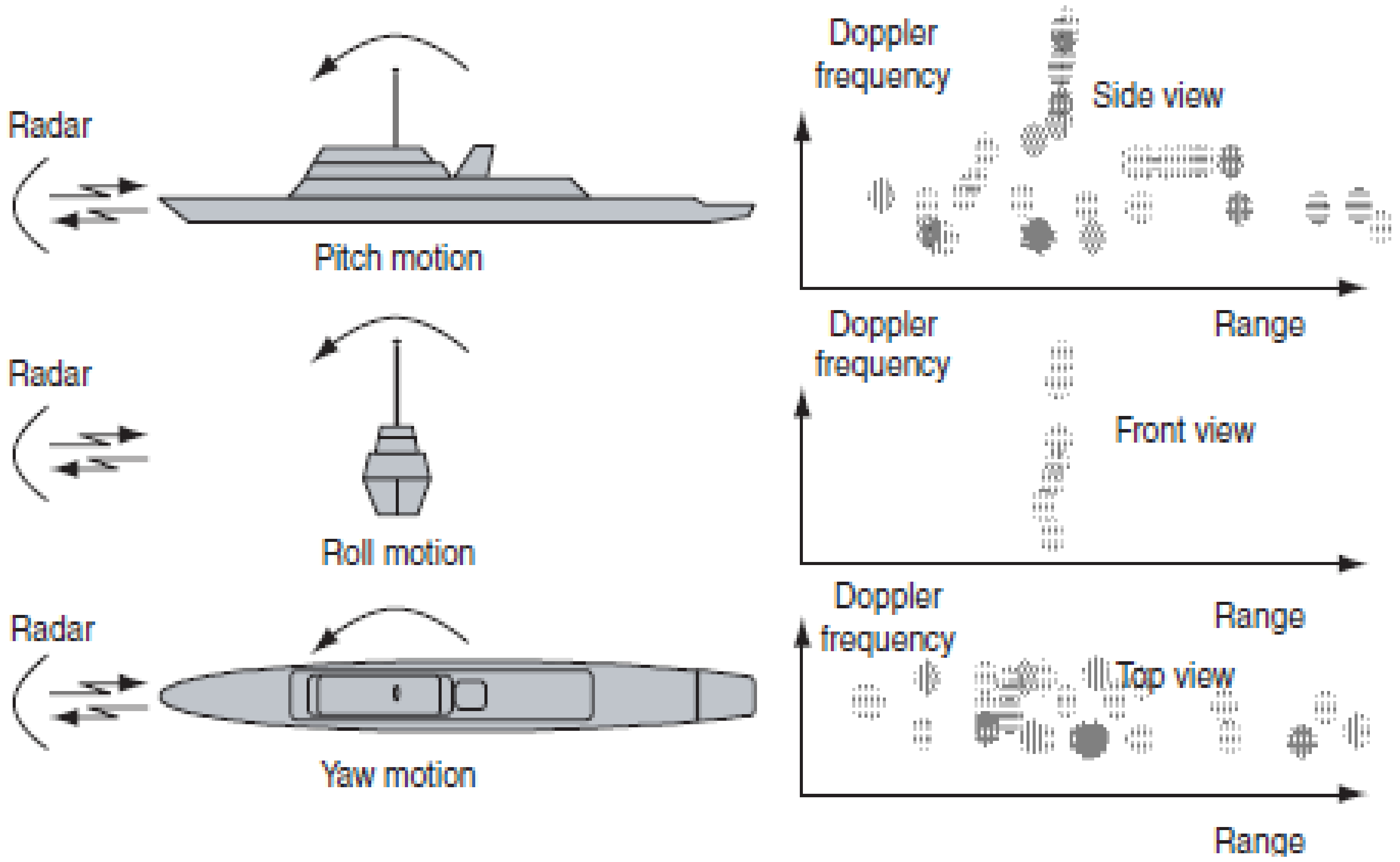


SANDIA REPORT, SAND2008-1020

- ISAR cross-range resolution:
  - $\Delta x = \frac{\lambda}{2\omega_E T} = \frac{\lambda}{2\Delta\theta}$;
  - Image scaling (Hz → m) requires the knowledge of the target rotation rate ω_E
  - ω_E can be estimated from the data

- ISAR systems exploit ship rotation motion for image formation
  - The effective rotation vector ω_E is the component of the rotation vector ω normal to the Line of Sight (LOS) and belonging to the plane containing the radar LOS and ω
  - ω includes also apparent target rotation due to SAR platform movement
  - The image plane is the slant range/Doppler frequency plane, containing the LOS and orthogonal to ω_E → Image Projection Plane (IPP)
  - Projection plane orientation depends on the specific target motion

Projection Plane in relation to ω and the LOS



Lacomme, P., Hardange, J.P., Marchais, J.C., and Normant, E.: "Air and Spaceborne Radar Systems", William Andrew publishing, 2001, Scitech publishing inc., Norwich, NY, USA, pp. 329-335.