Deep learning for onboard SAR intelligent applications

L. Dell'Amore[1*], N. Gollin[1], M. Martone[1], P. Rizzoli[1]

[1]Deutsches Zentrum für Luft- und Raumfahrt, Institut für Hochfrequenztechnik und Radarsysteme, Münchenerstraße 20, 82234, Weßling, Deutschland

[*]luca.dell'amore@dlr.de

Spaceborne Earth observation (EO) systems play a paramount role in addressing both civil and defense needs, making them increasingly vital in today's complex European environmental and geopolitical landscape. As climate change accelerates and natural disasters become more frequent, EO systems provide essential data for environmental monitoring, disaster response, and sustainable resource management, thereby strengthening societal resilience. In this scenario, onboard intelligence is essential to enable autonomous and rapid decision-making by EO spaceborne sensors, allowing them to provide valuable insights in near real time. This capability is especially critical in time-sensitive scenarios such as early disaster detection, extreme natural hazards (e.g., floods, storms, volcanic eruptions, and gas leaks), maritime situational awareness, and automatic target recognition.
In this context, the concept of cognitive radar, first introduced by S. Haykin in 2006[1], describes a radar system capable of dynamically adapting its operations through intelligent decisions derived from interactions with the environment. Onboard intelligence is essential to enable autonomous and rapid decision-making by the sensor, allowing it to adjust radar acquisition modes in real time to meet specific downstream tasks. Up to now, this concept remains a significant challenge. This is primarily due to the complex nature of radar signals and the intensive processing required to generate interpretable images, including SAR image formation through range and azimuth focusing.
We propose to tackle this challenge by designing a physics-informed deep learning (DL) model, named **FocusNet**, for fast generation of low-resolution amplitude-focused SAR images, which approximate of fully-focused SAR data, derived by coherent multi-looking of the original single-look complex (SLC) image by a factor M. In this approach we leverage a convolutional neural network (CNN) that emulates conventional SAR focusing algorithms, by designing an architecture which explicitly reflects the physical principles and inherent limitations of theoretical SAR image formation. Indeed, when considering a standard stripmap acquisition mode, where the radar keeps a fixed orientation of the radar during the SAR survey, the information coming from a target on ground is distributed along the synthetic aperture in the azimuth dimension (i.e., along the so-called odograph), corresponding to the azimuth Doppler bandwidth in the frequency domain, and along the chirp length in the slant range direction, corresponding to a certain range bandwidth. High-resolution SAR imagery is achieved through range and azimuth compression (i.e., focusing), which maximizes signal-to-noise ratio (SNR) via matched filtering in both dimensions. When employing a CNN, however, the achievable resolution is limited by the network's receptive field, i.e. the spatial context that the network sees in the input feature maps to make a prediction. This allows for illuminating only a portion of the azimuth synthetic aperture and of the range chirp length that can be utilized to reconstruct the target's backscattered energy at the zero-Doppler position (i.e., the real target position in the final image. This constraint guided the design of an encoder-style CNN architecture, trained in a fully supervised manner, where the model ingests a complex-valued SAR raw data matrix and outputs a lower-resolution amplitude image that approximates the fully-focused SAR output.
A preliminary example of SAR image focused using the proposed approach is presented in Figure 1.

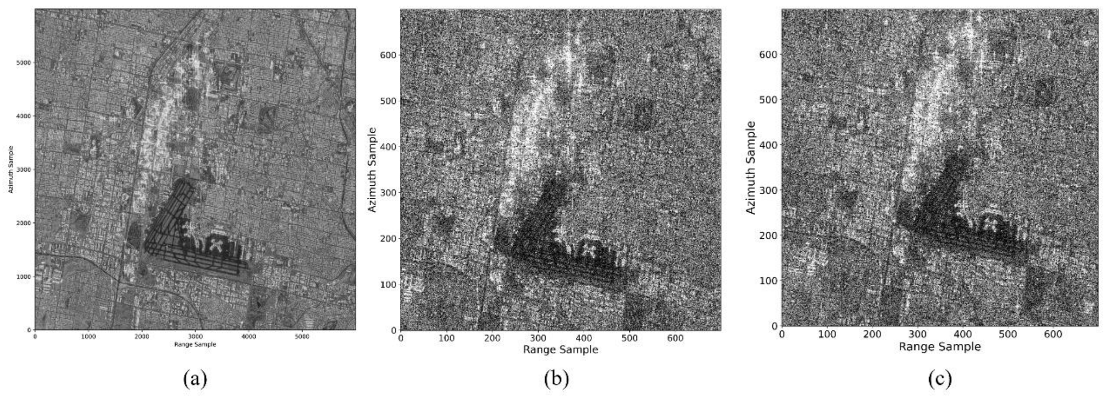

Figure 1: Example of FocusNet. (a) Fully-focused single-look complex SAR image, (b) Reference low-resolution image, (c) Predicted image using FocusNet.

---

[1] S Haykin, Cognitive radar: a way of the future, IEEE Signal Processing Magazine, vol. 23, no. 1, pp. 30–40, 2006.

This approach represents an extremely promising backbone architecture for the development of an end-to-end AI-based framework for onboard high-level SAR applications, aiming not only at maximizing the use of limited onboard resources but also at advancing smarter, more responsive spaceborne SAR systems, specifically tailored to meet a wide range of environmental and security needs.