The Effect of Topography on SCORE: an Investigation Based on Simulated Spaceborne Multichannel SAR Data

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Abstract

Scan-on-Receive (SCORE) is an established Digital Beamforming technique for multichannel spaceborne Synthetic Aperture Radar (SAR) systems. Nevertheless, the effect of topographic variations on SCORE deserves further investigation, especially when SCORE involves the use of sharp elevation and/or wide azimuth beams, as in case of advanced operational modes. This paper investigates the effect of topography on the SAR image obtained by SCORE, in dependence of main SAR system parameters, by means of a simple end-to-end simulator based on real data acquired by the German satellite TerraSAR-X.

1 Introduction

Digital Beamforming (DBF) techniques for spaceborne multichannel Synthetic Aperture Radar (SAR) systems have received great attention from the research community in the last decades [1-6]. Among these techniques, a prominent position is occupied by the so called Scan-on-Receive (SCORE) or SweepSAR [1], which is planned to be included in forthcoming missions, such as the United States-Indian NISAR, the European HRWS and the German Tandem-L [4-6].

According to SCORE, the antenna receive channels are combined by DBF to form a sharp, high gain elevation beam, steered in real-time toward the instantaneous direction of arrival (DOA) of the radar pulse echo backscattered from the imaged swath [1]. This maximizes the energy received from the signal of interest and effectively reduces the ambiguous returns. As a result, in comparison with conventional (single channel) systems, SCORE based systems allow for improved radiometric quality and range ambiguity suppression. These capabilities support the imaging of wide areas, which is a key requirement for the forthcoming SAR missions. Moreover, they make SCORE appealing for the development of advanced operational modes for high-resolution and wide-swath imaging [2], [3].

Despite the received interest, SCORE technique requires further investigation. In fact, SCORE is generally described as a one-dimensional DBF, operating in the elevation plane, neglecting any morphological variation of the imaged surface along the azimuth direction [1]. More in detail, the SCORE beam steering direction is computed based on an assumed reference topographic profile, modelling the height of the imaged surface in the vertical, zero Doppler plane. Accordingly, due to discrepancies between the reference and the real topographic profile in the elevation plane, and/or topographic variations within the azimuth pattern footprint, an angular mismatch between SCORE steering direction and the actual DOA of the echo occurs during the acquisition (Figure 1). This phenomenon should not be critical, if the width of the elevation receive beam obtained by SCORE is large enough in comparison with the mentioned angular mismatch, and the topographic variations in the azimuth direction are moderate. Nevertheless, in case of sharp elevation beams and/or wide azimuth beams, as well as fast topographic variations, a degradation of the SAR image radiometric quality is expected [2], [7]. Moreover, it should be clarified how the topography affects features of the received signal, such as azimuth spectrum shape and intensity, which are relevant when advanced operational modes, based on SCORE, are considered [3].

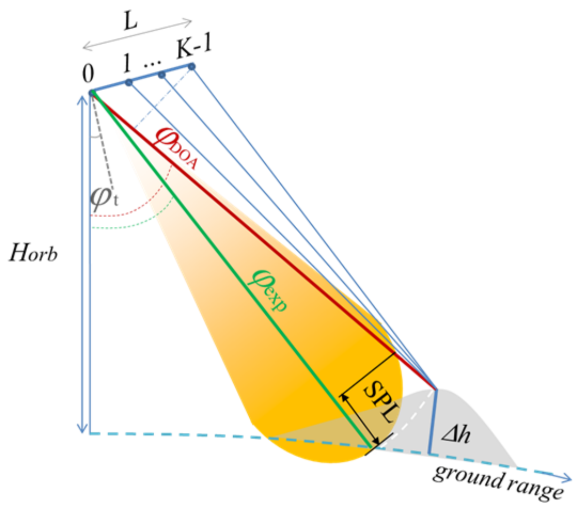

Figure 1 Vertical, zero Doppler plane: angular mismatch between actual and expected DOA in presence of an unmodelled terrain height, Δh, and related SCORE pattern loss (SPL).

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This paper investigates for the first time the effect on SCORE of morphological variations of the imaged surface, extended both in the range and azimuth directions. In order to support this analysis, a simple end-to-end simulator, based on real SAR data acquired by the German satellite TerraSAR-X (TSX) [8], was developed and used to reproduce the multichannel acquisition and the related SCORE processing. The properties of the simulated SCORE SAR image were analysed in dependence of key SAR system parameters by considering different topographic scenarios. The following sections present a description of the end-to-end simulator and the main results of the analysis.

2 SCORE Simulation Procedure

A reference SAR system, based on a planar rectangular antenna array with K digital elevation receive channels uniformly distributed along the height of the antenna, L, is assumed (Figure 1). The corresponding multichannel acquisition is simulated starting from a real, single-look, slant range, complex (SSC) SAR image and the related digital elevation model (DEM), i.e. the topography representing the real morphology of the imaged surface. More in detail, based on the acquisition geometry, the actual DOA, φ_{DOA}, is computed. Then, K complex SAR images (one for each elevation channel) are generated by multiplying each pixel of coordinates (τ, t) of the real SAR image by

$$\exp\left\{ j\,\frac{k-0.5(K-1)}{K-1}\,\varphi_{\mathrm{int}}(\tau,t) \right\}, \tag{1}$$

where $k = 0, ..., K-1$ denotes the channel number;

$$\varphi_{\mathrm{int}}(\tau,t) = -\frac{2\pi}{\lambda} L \sin(\varphi_{DOA}(\tau,t) - \varphi_{\mathrm{t}}), \tag{2}$$

the interferometric phase associated with the baseline L; τ the fast (range) and t the slow (azimuth) discrete time; λ the radar wavelength; φ_{t} the antenna tilt angle (Figure 1). Note that, without loss of generality, the layover is assumed not to be present, so that each pixel is associated with a single DOA.

The K multichannel SAR images are regarded as the complex reflectivity of the surface imaged by the channels. From these images, the K multichannel SAR raw data matrices, i.e. the raw data recorded by the channels, are generated by performing a convolution with a reference range and azimuth chirp (each chirp with a bandwidth no larger than that of the real SAR image).

Successively, SCORE is applied. More in detail, in a first step, each sample of coordinates (τ, t) of the $k-th$ raw data matrix is multiplied by the SCORE coefficient

$$\exp\left\{ j\,\frac{k-0.5(K-1)}{K-1}\,\varphi_{s}(\tau) \right\}, \tag{3}$$

where

$$\varphi_s(\tau) = \frac{2\pi}{\lambda} L \sin(\varphi_{\mathrm{exp}}(\tau) - \varphi_{\mathrm{t}}), \tag{4}$$

with φ_{exp} denoting the SCORE steering direction, i.e. the expected DOA of the echo (Figure 1). Note that φ_{exp} depends only on the fast time, τ, since it is computed based on a reference topographic profile, invariant during the illumination time [1]. In a second step, the K raw data matrices are combined (added up, sample by sample) in a single raw data matrix. These two steps are equivalent to generate a sharp receive elevation pattern, i.e. SCORE pattern, given by the array factor of the antenna (computed with reference to the geometrical centre of the antenna) pointed toward φ_{exp} at each recorded instant.

It is worth to remark that the considered implementation of SCORE neglects any compensation for the pulse extension [1]. Accordingly, the so called pulse extension loss (PEL) occurs, if the chirp extension is not negligible with respect to SCORE pattern beamwidth [9].

Finally, from the raw data matrix, the simulated SCORE SAR image is obtained by applying a matched filter in range and azimuth, each with the assumed processed bandwidth.

It must be pointed out that the presented simulator neglects the range cell migration (RCM), reducing the SAR imaging processing to a range/azimuth separable problem. Moreover, a consideration is due about the simulated antenna pattern. Since a rectangular antenna is assumed, the patter can be decoupled in the azimuth and elevation components. The assumed azimuth pattern is constant over the azimuth angle corresponding to the processed Doppler bandwidth and zero elsewhere. The elevation pattern, on transmit, is constant over the elevation angle corresponding to the imaged swath and zero elsewhere; on receive, it is approximated by the antenna array factor steered according to SCORE algorithm, whereas the element factor is assumed to be constant over the imaged swath and zero elsewhere.

3 Numerical Analysis

For the numerical analysis, a reference SAR system operating in X-band (λ = 3.1 cm) and orbiting at a height of 514 km is considered. It is based on a planar rectangular antenna array, with $K = 24$ digital elevation channels uniformly distributed along the antenna height, L = 1 m (Figure 1). The antenna tilt angle, φ_{t}, is about 38.9 deg.

The reference topographic profile, used to compute SCORE steering direction, φ_{exp}, is based on a flat spherical Earth model, i.e. the reference topographic height is always zero [1].

The considered real SAR SSC SAR image is shown in Figure 2. It was acquired by the German satellite TSX in stripmap mode. For the related DEM, determining the actual DOA, φ_{DOA}, two different scenarios are assumed. The first scenario (Figure 3, top) is characterized by topographic variations extended exclusively in the range direction. Specifically, proceeding from near to far range, the topographic height is initially equal to zero, increases linearly without layover until a maximum value, $\Delta h_{\max}$, and remains then constant. The second scenario (Figure 3, bottom) presents also periodical fluctuations of the topographic height in the azimuth direction, with period smaller than extension of the azimuth beam footprint (which is about 4 km).

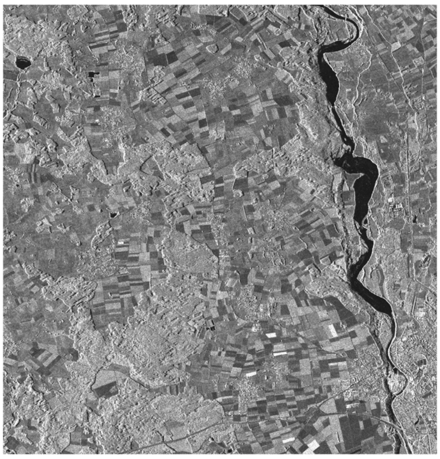

Figure 2 TSX SLC SAR image. The azimuth (range) direction corresponds to the vertical (horizontal) axis.

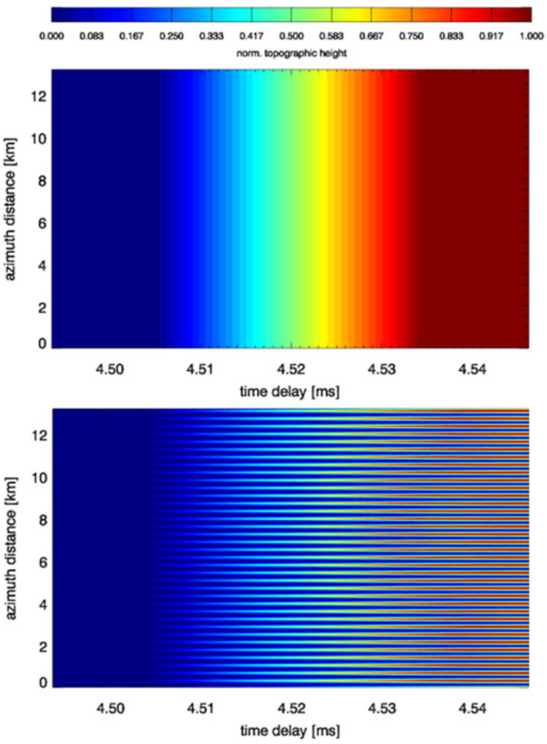

Figure 3 DEMs (contour representation). Topographic height value normalized to $\Delta h_{\max}$.

The value of $\Delta h_{\max}$ is chosen such that the related SCORE mispointing, $\Delta\varphi = \varphi_{DOA} - \varphi_{\exp}$, is about 0.68 the half power beamwidth (HPBW) of the antenna array factor. Accordingly, the SCORE pattern gain at φ_{DOA} is about 6 dB lower than in $\varphi_{\exp}$ (Figure 1), i.e. a SCORE pattern loss (SPL) of -6 dB occurs at φ_{DOA} [7].

In order to have an idea of the value of $\Delta h_{\max}$ for different systems and geometries, it is useful to recall that [2]:

$$\Delta h_{\max} \approx \Delta\varphi \, R \sin(\vartheta_i) \approx 0.68\left(0.89\frac{\lambda}{L}\right) R \sin(\vartheta_i), \qquad (5)$$

where R and ϑ_i denote the slant range and incidence angle, respectively. Accordingly, for the reference SAR system, $\Delta h_{\max}$ assumes the quite huge value of about 7900 m; whereas, it is below 2000 m for an X-band SAR system orbiting at 514 km, having an antenna higher than 3 m and operating in near range (Figure 4).

As regards the SCORE image simulation, a range and azimuth processing bandwidth of 100 MHz and 2765 Hz are assumed, respectively. The chirp pulse duration is about 56 μs, which corresponds to a pulse extension equal to 0.5 the SCORE pattern HPBW. Thus, a light PEL occurs [9].

Figure 5 (top) shows the intensity of the simulated SCORE SAR image for the first scenario: a radiometric loss, evidenced by a darker coloration, affects the imaged surface with non-zero elevation.

It must be pointed out that an apparently identical SCORE SAR image could be obtained by applying SCORE algorithm not to the K multichannel raw data (as described in Section 2) but directly to the K multichannel SAR images. This could be advantageous, since it considerably reduces the computational cost of the simulation.

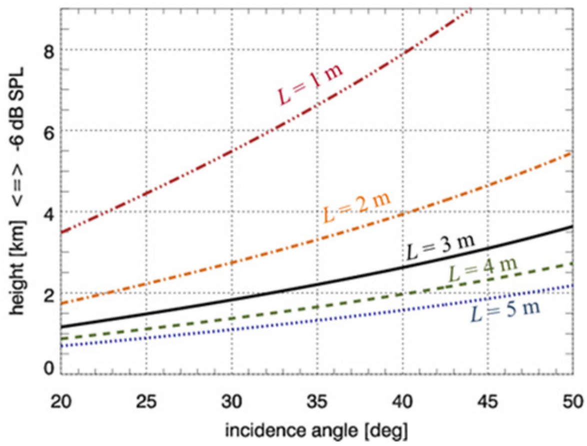

Figure 4 Topographic height associated with a SPL of -6 dB, for an X-band system orbiting at 514 km, with an antenna length, L, of 1, 2, … , 5 m.

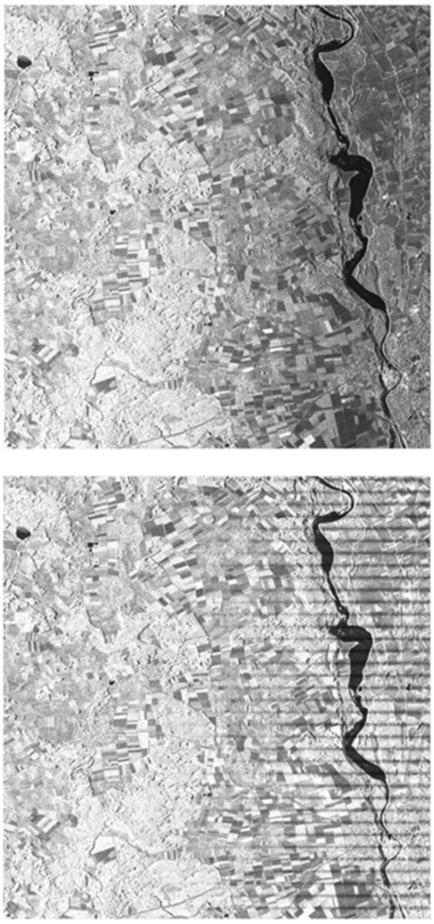

Figure 5 Simulated SCORE SAR images.

In order to quantify the radiometric loss induced by the topographic height, the mean value (averaged along the azimuth direction) of the pixel intensity, normalized to the intensity of the corresponding pixel of the SCORE image obtained in absence of topographic error (i.e. assuming a flat DEM), was computed. The results are shown in Figure 6 (top), both for the case that SCORE algorithm is applied to the K multichannel raw data and to the K multichannel SAR images: in both cases the radiometric loss increases from near to far range, according to the SPL associated with the topography, until about -6 dB; in the first case, larger fluctuations are present, due to the pulse extension and the related SCORE pattern modulation.

Figure 5 (bottom) shows the intensity of the simulated SCORE SAR image for the second scenario. Here the topography variates also in the azimuth direction. Again, the correspondence between radiometric loss and topographic height is evident.

The radiometric loss was quantified by the mean normalized value of the pixel intensity, computed as done for the first scenario but averaging only the range lines whose topographic height reaches the same maximum value, $\Delta\bar{h}_{\max}$. The results obtained for the case $\Delta\bar{h}_{\max} = \Delta h_{\max}$ are shown in Figure 6 (bottom): again the radiometric loss increases from near to far range until about -6 dB, both for the case that SCORE algorithm is applied to the K multichannel raw data and to the K multichannel SAR images. The fluctuations associated with the pulse extension are also evident. They become wider for increasing topographic height, due to the larger variation (slope) of the SCORE pattern, weighting the (extended) pulse echo. More in general, the obtained results show that, in presence of topographic height, the radiometric loss affecting each range line of the SCORE SAR image depends only on the corresponding acquisition geometry in the vertical, zero Doppler plane and can be explained in terms of SPL and PEL. Indeed, there is no dependence on the azimuth aperture length. In fact, in presence of topographic height, the azimuth impulse response function is scaled by SCORE, but not distorted. The previous observations rely on SCORE invariance vs. the azimuth time [1], which applies also in presence of topographic height variations. In fact, all the samples within an iso-range line of the raw data matrix, associated with an elevation channel, experience the same SCORE coefficient, given by eq. (3). In other words, a target is weighted by the same elevation receive pattern (SCORE pattern) value during the whole

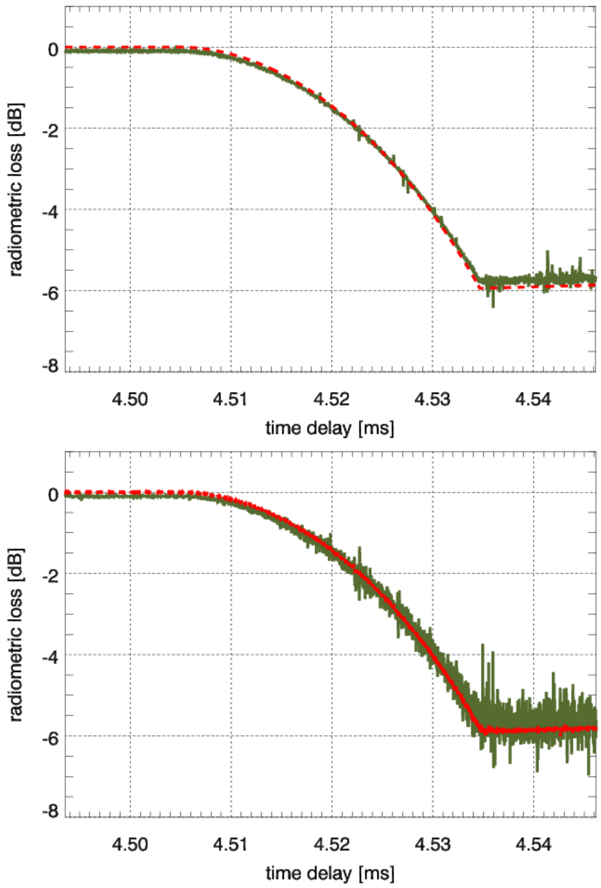

Figure 6 Mean radiometric loss affecting the SCORE SAR image range lines. SCORE algorithm applied to the multichannel raw data (green line), to the multichannel SAR images (red, dashed line). Top: first scenario, all range lines are considered. Bottom: second scenario, only range lines associated with $\Delta h_{\max}$ are considered.

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azimuth illumination time. Nevertheless, this value depends on the topographic height of the target. Accordingly, iso-range targets with a different topographic height are weighted by a different SCORE pattern value (Figure 7). Specifically, they experience a radiometric loss, whose value depends on the target actual DOA and is given by the corresponding SPL, with a deviation due to the pulse extension and the related SCORE pattern modulation.

From the previous considerations, recalling that SCORE patter beam is characterized by a constant phase equal to zero, it follows also that the topography does not affect the phase of the SCORE image.

As regards the relationship between the SCORE SAR images obtained, respectively, by applying SCORE algorithm to the multichannel raw data and directly to the multichannel SAR images, it could be demonstrated that they are equivalent (i.e. in both cases the resulting SAR image is the same), if the pulse extension is negligible compared with the SCORE pattern HPBW. Otherwise, if the pulse is longer, to apply SCORE to the K multichannel SAR images is equivalent to neglect the modulation induced by the SCORE pattern on the pulse, i.e. the PEL.

Finally, it must be pointed out that the previous observations rely on the assumption that in the simulation the RCM is neglected and the SAR imaging could be decoupled in range and azimuth processing. Nevertheless, despite these simplifications, the previous results are expected to provide a useful representation the effect of SCORE for many scenarios of interest.

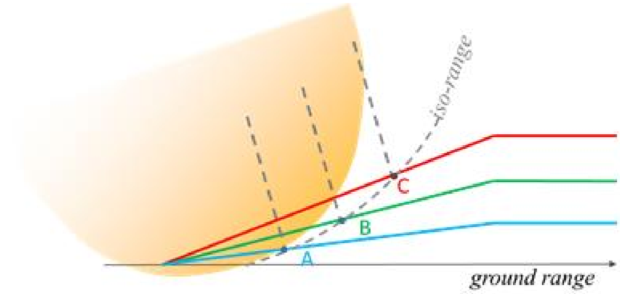

Figure 7 Projection onto the vertical, zero Doppler plane of three topographic profiles (cyan, green and red lines), displaced in the azimuth direction: SCORE pattern weight for the iso-range targets A, B and C.

4 Summary

The effect on the SCORE SAR imaging of morphological variations of the imaged surface, extended both in the range an azimuth direction, was investigated by means of a simple end-to-end simulator and assuming reference SAR system based on a planar rectangular antenna array.

In presence of topographic variations a radiometric degradation of the SCORE SAR image occurs. This degradation depends essentially on the topographic profile in the elevation plane, the SCORE beamwidth and the pulse duration, but is not influenced by any azimuth parameter of the system, such as the extension of the azimuth aperture. In fact, the azimuth impulse response function is not distorted, but just scaled by a factor given by the SCORE pattern loss and the pulse extension loss.

The analysis shows also that an approximation of the SCORE SAR image can be easily obtained by applying SCORE algorithm directly to the multichannel SAR images, avoiding any simulation of the raw data processing.

The entity of the radiometric loss associated with the topographic height was quantified as a function of the system and acquisition geometry. As expected, it becomes critical if sharp SCORE beams are involved in the SAR imaging. Possible solutions are under investigation.

References

[1] M. Suess, B. Grafmueller, R. Zahn, “A Novel High Resolution, Wide Swath SAR System”, in Pro. IGARSS, vol. 3, pp. 1013-1015, July 2001.

[2] G. Krieger, N. Gebert, A. Moreira, “Multidimensional Waveform Encoding: A New Digital Beamforming Technique for Synthetic Aperture Radar Remote Sensing”, IEEE Trans. on Geosci. and Remote Sens., vol. 46, no. 1, pp.31-46, Jan. 2008.

[3] G. Krieger, S. Huber, M. Villano, M. Younis, T. Rommel, P. Lopez Dekker, F. Queiroz de Al-meida, A. Moreira, “Cebras: Cross Elevation Beam Range Ambiguity Suppression for High-Resolution Wide-Swath and MIMO-SAR Imaging”, Pro. IGARSS, pp. 196-199, July 2015.

[4] S. Huber, M. Villano, M. Younis, G. Krieger, A. Moreira, B. Grafmueller, R. Wolters, “Tandem-L: Design Concepts for a Next-Generation Spaceborne SAR System”, Pro. EUSAR, June 2016.

[5] P. Rosen, S. Hensley, S. Shaffer, W. Edelstein; Y. Kim; R. Kumar; T. Misra; R. Bhan; R. Satish; R. Sagi, “An update on the NASA-ISRO dual-frequency DBF SAR (NISAR) mission”, Pro. IGARSS, July 2016.

[6] Adamiuk, C. Schaefer, C. Fischer, and C. Heer, “SAR Architectures Based on DBF for C- and X-Band Applications”, Pro. EUSAR, June 2014.

[7] M. Younis, S. Huber, A. Patyuchenko, F. Bordoni, G. Krieger, “ Performance Comparison of Reflector- and Planar-Antenna based Digital Beam-Forming SAR”, Int. Journal of Ant. and Propaga., pp 1-13, June 2009.

[8] R. Werninghaus, S. Buckreuss, “The TerraSAR-X Mission and System Design”, IEEE Tran. on Geosci. and Remote Sens., vol. 48, no. 2, pp. 606-614, Feb. 2010.

[9] M. Younis, T. Rommel, F. Bordoni, G. Krieger, A. Alberto, “On the Pulse Extension Loss in Digital Beamforming SAR”. IEEE Geosci. and Remote Sensing Let., vol. 12, no. 7, pp 1436-1440, July 2015.

