Mitigation of the SAR Image Radiometric Loss Associated with the SCORE DBF in Presence of Terrain Height Variations

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Abstract

Scan-on-receive (SCORE) is a key digital beamforming (DBF) technique for future high-resolution wide-swath synthetic aperture radar (SAR) systems. Compared to a conventional approach, it allows to improve the SAR imaging performance. Nevertheless, it also exposes the system to new errors. In particular, the mutual effect of terrain height variations and pulse duration should be carefully considered, in view of the demanding requirements on the radiometric quality of future SAR images. This paper investigates possible strategies to mitigate the SAR image radiometric loss associated with the SCORE DBF in presence of topographic variations, with minimum impact on the SAR system complexity.

1 Introduction

Scan-on-receive (SCORE) is one of the most important digital beamforming (DBF) techniques for future high-resolution wide-swath (HRWS) spaceborne synthetic aperture radar (SAR) systems [1]. It plays a key role in the implementation of advanced missions and projects, such as the U.S.-Indian NISAR and Japanese ALOS-4 missions, the European Copernicus missions ROSE-L and Sentinel-1 Next Generation, and the highly innovative German mission proposal Tandem-L [2]-[5].

According to SCORE, a wide swath is illuminated by using a broad transmit (Tx) beam; whereas on receive (Rx), multiple digital channels are combined onboard in order to realize a sharp and high gain elevation beam, that scans the illuminated swath from near to far range, following the pulse echo as it travels along the ground range direction. Compared to a conventional technique, higher antennas can be exploited on receive to improve the signal-to-noise ratio and the range ambiguity suppression.

Particularly advantageous for its relatively simple and cost-effective implementation is the basic SCORE formulation, conceived for "short pulses" and considered for the realization of systems using pulses with an extension lower than the SCORE beam width [1], [6]. Here the Rx beam is steered in real time towards the expected direction of arrival (DoA) of the Rx signal by a simple DBF, obtained by summing up the multichannel digital signals, previously multiplied by a time-variant phase. Specifically, the expected DoA is assumed to correspond one-to-one with the range time, and to be independent of the azimuth time; it is computed based on the zero-Doppler geometry, a pure spherical Earth model (with no terrain height), and the centre of the travelling pulse [1].

Despite its advantages, the basic SCORE solution may work under model mismatch in a real acquisition scenario, since it neglects the pulse duration, the elevation of the backscattering surface, and terrain height variations in the azimuth direction. In particular, a SCORE pattern mispointing may occur (see Fig. 1), with a consequent degradation of the Rx power and the SAR image radiometric quality [6]-[10]. Indeed, even more sophisticated implementations of the SCORE technique do not sufficiently addressed so far this limitation [9].

The mutual effect of unmodelled terrain height and pulse duration on the SAR imaging performance of SCORE-based systems has been recently analysed in detail by the authors in [9]. The study evidences the relevance of this effect, especially in view the demanding requirements on the radiometric quality of future SAR images (the radiometric accuracy is expected to be below about 0.9 dB). Moreover, it presents a novel, quantitative, description of the radiometric degradation occurring at SAR image level, the so-called SCORE loss (SL), in dependence of the acquisition geometry, the SAR system parameters, and the SCORE steering law.

This paper investigates the possibility to mitigate the SAR image radiometric loss associated with the SCORE DBF in presence of topographic variations. The focus is on solutions with a minimum impact on the system architecture, and an implementation complexity comparable with that of the basic SCORE formulation. With this aim, the choice of

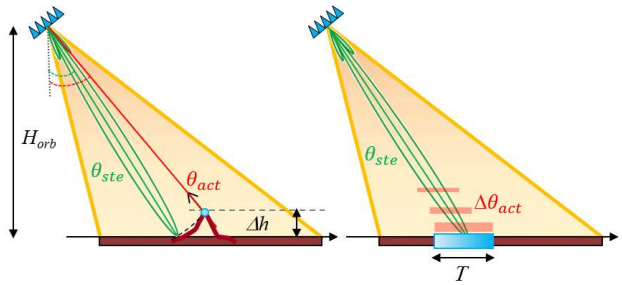

Figure 1 Zero-Doppler geometry: mismatch between expected (θ_{ste}) and actual (θ_{act}) DoA, due to unmodelled terrain height (Left) and pulse duration (Right).

the SCORE steering law and possible optimization strategies, relying on the novel SL expression, are examined. The necessary theoretical background is recalled in the next section, followed by the analysis of the SL mitigation.

2 SCORE Loss (SL)

Let us consider a spaceborne DBF SAR system with SCORE capability, operating in stripmap mode (coupled with SCORE). The architecture is based on a planar array antenna with K digital Rx elevation channels, uniformly distributed along the antenna height, h_{ant}. Without loss of generality, the array element spacing, $d = h_{ant}/K$, is assumed small enough to allow approximating the antenna elevation Rx pattern by the array factor (AF):

$$AF(\theta) = \sum_{k=1}^{K} \exp\left\{ j \frac{2\pi d\left(k - 0.5 - 0.5K\right)\sin\left(\theta - \theta_{tilt}\right)}{\lambda} \right\} \approx$$
$$\approx K \operatorname{sinc}\left\{ \frac{h_{ant}\sin\left(\theta - \theta_{tilt}\right)}{\lambda} \right\}, \qquad (1)$$

where θ denotes the elevation angle measured w.r.t. nadir in the zero-Doppler plane, i.e., the look angle; θ_{tilt} the antenna tilt angle; λ the radar wavelength associated with the carrier frequency (the dependence on the pulse bandwidth is neglected, for simplicity [10]).

The elevation Rx pattern is steered in real time towards the expected DoA of the Rx signal by the SCORE DBF. This is obtained by summing up the multichannel digital Rx signals, previously multiplied by a time-variant phase [1]. In particular, the SCORE steering direction, θ_{ste}, is independent of the azimuth time, and corresponds one-to-one with the range time, t, according to the zero-Doppler geometry, a simple reference topographic profile, and the expected ground position of the center of the travelling pulse [1]. It is worth to remark that, since the SCORE steering law, $\theta_{ste}(t)$, does not depend on the azimuth time, terrain height variations in the azimuth direction remain unmodelled and may result in a steering error [7], [9].

Let us neglect, for simplicity, the effect of the range cell migration on SCORE. This is justified, at least in first approximation, for typical HRWS spaceborne systems parameters [9], [10].

Based on the previous assumptions, SCORE behavior can be investigated by considering only the zero-Doppler geometry, and the one-dimensional SAR processing in range. In fact, the relevant SCORE image formation process can be modelled as a linear time-varying filter, whose transfer function (TF) for a point target at (t_0, τ_0), is given by [9]:

$$\begin{aligned} H_s(f, t_0, \tau_0) &= \mathrm{FT}\left\{h_s(t, t_0, \tau_0)\right\} = \\ &= C(f)\; W_{AF}(f, t_0, \tau_0)\, W_{Rx}(f)\, C^*(f) \end{aligned}, \qquad (2)$$

where $h_s(t, t_0, \tau_0)$ denotes the SCORE impulse response function (IRF); t and τ the discretized range and azimuth time, respectively; $C(f)$ the discrete-time Fourier transform (FT) of the transmitted chirp pulse; $(\cdot)^*$ the complex conjugate operator; $W_{Rx}(f)$ a possible SAR processing Rx window, used at range compression stage to reduce the sidelobe level of the IRF; and

$$W_{AF}(f, t_0, \tau_0) = w_{AF}(t, t_0, \tau_0)\big|_{t = f/K_r}, \qquad (3)$$

with

$$w_{AF}(t, t_0, \tau_0) = AF\left(\theta_{ste}(t), \theta_{act}(t_0, \tau_0)\right), \left|t - t_0\right| \le \frac{T}{2}, \qquad (4)$$

being K_r the chirp rate, T the chirp pulse duration, $AF\left(\theta_{ste}(t), \theta_{act}(t_0, \tau_0)\right)$ the antenna AF, i.e., the SCORE Rx pattern, steered towards $\theta_{ste}(t)$ and computed in the actual DoA of the Rx signal, $\theta_{act}(t_0, \tau_0)$.

Eqs. (2)-(4) show that the SCORE DBF behaves like a SAR processing Rx window, $w_{AF}(t, t_0, \tau_0)$. In fact, each sample received from the point target with DoA, $\theta_{act}(t_0, \tau_0)$, during the pulse duration, is weighted by a different SCORE pattern value, according to the SCORE steering law, $\theta_{ste}(t)$ [9].

Note that in the *ideal case* of a very short pulse and a steering direction matching the actual DoA of the target in t_0:

$$H_s(f) = K\, C(f)\, W_{Rx}(f)\, C^*(f), \qquad (5)$$

i.e., the SCORE system just amplifies by a factor K the TF of the conventional (single channel) SAR system. In a more realistic case, where the pulse duration is not negligible and unmodelled terrain height characterizes the imaged scene, the SCORE pattern window in (4) modulates the IRF. Then, since $|AF| \le K$, a radiometric degradation may occur compared to the ideal case. In particular, the ratio between the actual and ideal values of the IRF energy and peak power are given respectively by the following factors, denoted as SCORE loss (SL) [9]:

$$SL_e(t_0, \tau_0) = \frac{\sum_{t=t_0-T/2}^{t_0+T/2} \left| w_{Rx}(t - t_0)\, AF\left(\theta_{ste}(t), \theta_{act}(t_0, \tau_0)\right)\right|^2}{K^2 \sum_{t=-T/2}^{T/2} \left| w_{Rx}(t)\right|^2} \qquad (6)$$

$$SL_p(t_0, \tau_0) = \frac{\left| \sum_{t=t_0-T/2}^{t_0+T/2} w_{Rx}(t - t_0)\, AF\left(\theta_{ste}(t), \theta_{act}(t_0, \tau_0)\right)\right|^2}{K^2 \left| \sum_{t=-T/2}^{T/2} w_{Rx}(t)\right|^2} \qquad (7)$$

where $w_{Rx}(t) = FT^{-1}\left\{W_{Rx}(f)\right\}$ is the SAR processing Rx window in the time domain.

It is worth to remark that, for a SAR image representing a homogeneous scene, eq. (6) quantifies, for a resolution cell at (t_0, τ_0), the pixel mean intensity reduction w.r.t. the ideal case, i.e., the so-called distributed SL, $SL_d(t_0, \tau_0)$ [9]. Eqs. (6) and (7) provide an analytical description of the radiometric loss at SAR image level, due to the mutual effect of unmodelled terrain high and pulse duration. This allows quantifying the radiometric loss on the SAR image in dependence of the SCORE Rx pattern shape, the SCORE

steering law, the acquisition geometry, and the SAR processing parameters [9].
The influence of the choice of the SCORE steering law on the SL is investigated in the following section.

3 SL Mitigation

Let us consider, without loss of generality, the SAR reference system described in Tab. 1: an X-band system, with an antenna height of 2 m, flying at an altitude of 514 km. The half power beam width of the SCORE pattern, $0.89\lambda / h_{ant}$, is about 0.8 deg. The sharp beam and the relatively low orbit make the system possibly sensitive to the topography, especially in the near range [10].
Figs. 1-2 are obtained for an imaged scene based on a single point target, with an elevation, h, of 500 m and actual DoA, $\theta_{act}(t_0,\tau_0)$, of 28.95 deg; the SCORE steering angle is computed according to a pure spherical Earth model (SEM), with no terrain elevation.
Fig. 2 shows the normalized SCORE pattern sector, weighting the samples received from the target, versus look angle (nominal value, corresponding to the range time). Note that the figure refers to the equivalent representation of the SCORE pattern window in (4):

$$w_{AF}(t,t_0,\tau_0) = AF\left(\theta_{act}(t_0,\tau_0),\theta_{ste}(t)\right), \quad |t-t_0| \le \frac{T}{2}, \quad (8)$$

where the AF is pointed towards $\theta_{act}(t_0,\tau_0)$ and computed over the steering interval, $\theta_{ste}(t)_{|t-t_0|\le T/2}$. The SL arises since not all the samples, received from the point target, are weighted by the maximum value of the pattern. Note that the SAR processing Rx window, $w_{Rx}(t)$, plays a role too: in general, it mitigates the SL, since it attenuates the higher frequency components of the IRF, typically associated with the lower pattern values [9].
Fig. 2 evidences also the dependence of the SL on the SCORE steering law. In particular, two effects can be distinguished:
(i) the so-called *topographic steering error* [7], [10], given by the offset between the steering direction at the pulse centre and the actual DoA ($\theta_{ste}(t_0)=$ 28.86 deg, $\theta_{act}(t_0,\tau_0)=$ 28.95 deg, in the figure), and determined by the mismatch between reference and actual topography;
(ii) the SCORE steering velocity, i.e., the steering variation during the pulse duration, which determines the width of the pattern sector weighting the Rx samples.
Fig. 3 shows the intensity of the corresponding IRF, obtained according to (2), together with the ideal IRF, obtained in case of SL= 0 dB according to (5). The SL on the peak power and energy of the IRF are of -0.592 dB and -0.497 dB, respectively.
Let us now consider a distributed target, with homogenously backscattering surface. The actual topographic profile in the vertical zero-Doppler plane, for a given azimuth position τ_0, is represented in Fig. 4 versus the look angle. It resembles an isolated mountain: moving from the near to the far range, the terrain height, $h(\tau_0)$, is 0 m, increases linearly until 2000 m, decreases linearly until 0 m, and remains constant (layover and shadow are not present). To investigate the influence of the SCORE steering law, let us consider the following options to steer SCORE Rx pattern:
(i) based on a SEM with no terrain elevation;
(ii) based a SEM with constant terrain elevation of 1000 m;
(iii) based on the actual topographic profile (in Fig. 4).

Quantity	Value
Orbit Height, H_{orb}	514 km
Ant. Tilt Angle, θ_{tilt}	29 deg
RF Center Frequency	9.65 GHz
Rx Antenna Height, h_{ant}	2 m
Nr. of Digital Rx Elev. Channels, K	25
Chirp Pulse Duration, T	25 µs
SAR processing Rx window, W_{Rx}	Hamming ($\alpha = 0.8$)

Table 1 Reference system parameters.

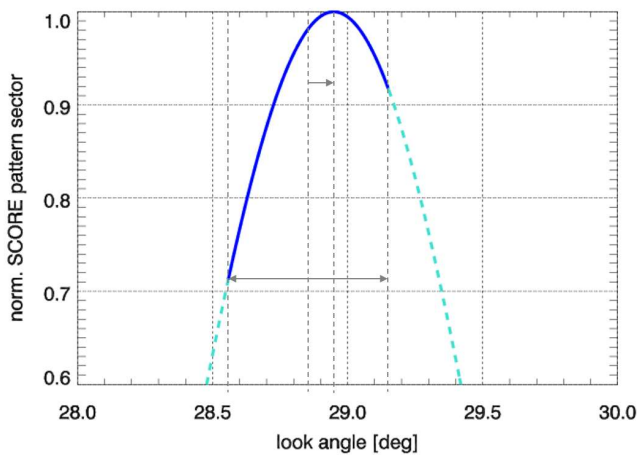

Figure 2 Point target: normalized SCORE pattern sector (solid blue line) weighting the Rx samples versus nominal look angle. [h: 500 m; $\theta_{act}(t_0,\tau_0)$: 28.95 deg, $\theta_{ste}(t_0)$: 28.856 deg.]

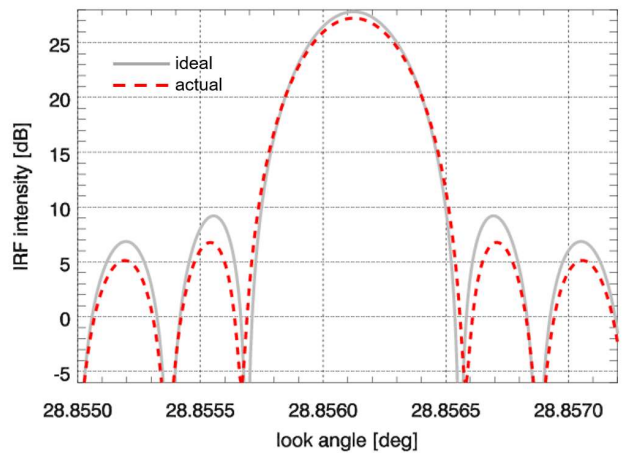

Figure 3 Point target: intensity of the IRF in the ideal case of SL=1 and the actual case versus nominal look angle. [h: 500 m; θ_{act}: 28.95 deg, $\theta_{ste}(t_0)$: 28.856 deg.]

The SCORE steering direction, θ_{ste}, for the three steering options is illustrated in Fig. 5, versus nominal look angle. Fig. 6 shows the corresponding radiometric loss, associated with SCORE DBF, affecting the range line at τ_0 of the SAR image. Specifically, it illustrates the distributed SL versus look angle, obtained according to (6), for the three steering options. In case of a steering based on no elevation, in the near and far range edges of the swath, where the actual terrain height is 0 m, the SL is determined only by the pulse duration. Note that for an actual terrain height of 0 m, constant over the whole swath, the SL value would improve almost linearly of about 0.1 dB from the near to the far range, due to the corresponding reduction of the steering velocity [10]. With respect to this trend, in presence of unmodelled terrain height, an additional degradation occurs, which is proportional (not in a linear way) to the absolute value of the unmodelled terrain height. A similar behaviour is observed when the steering is based on a SEM with constant terrain elevation of 1000 m. In case of a steering based on the actual topography, the SL is strongly affected by the variation of SCORE beam steering velocity: the higher the steering velocity, the wider the pattern sector weighting the pulses received from a resolution cell during the pulse duration, the higher the SL.

The relevance of the choice of the steering law is evident: in case (i) the SL varies from about -0.3 dB to about -2.6 dB; in case (ii) between -0.35 and -1 dB; in case (iii) between about -0.05 dB to -1.4 dB. It is worth to remark that the image quality suffers not only due to the radiometric level reduction, but also due to the spurious radiometric variation. It is then desirable that both the span and the maximum value of the SL remain limited. Accordingly, for the scenario considered in Fig. 6, the SCORE pattern steering based on a constant topographic height of 1000 m is the best option.

The difference between the SL curves in Fig. 6 highlights the crucial role of the SCORE steering law on the achievable radiometric performance. Moreover, it suggests that the expression of the SL in (6) can be usefully exploit to optimize the steering, under the reasonable assumption that a raw knowledge of the imaged topography is available. The selected steering would then allow mitigating possible radiometric degradations, associated with the SCORE DBF in presence of topographic variations, without significantly affecting the complexity of the architecture.

It is worth to point out that the SL strongly depends on the acquisition geometry (orbit height, actual topography, SCORE beam width, swath location in the near or far range) and the pulse duration [9]. The SAR processing Rx window may also play a role, especially for long pulses [9]. As an example, Fig. 7 shows the SL obtained for the same parameter values considered in Fig. 6, except for the pulse duration, that here is 7 µs. In this scenario, the best option is a SCORE pattern steering based on the actual topographic profile. These observations suggest that the effect of the choice of the steering law on the SL should be verified based on the actual acquisition parameters. As general indication, if the pulse duration is very short, it is reasonable to expect that the SL is optimized when the topographic steering error is minimized. In particular, when the imaged surface topography is approximately constant in the

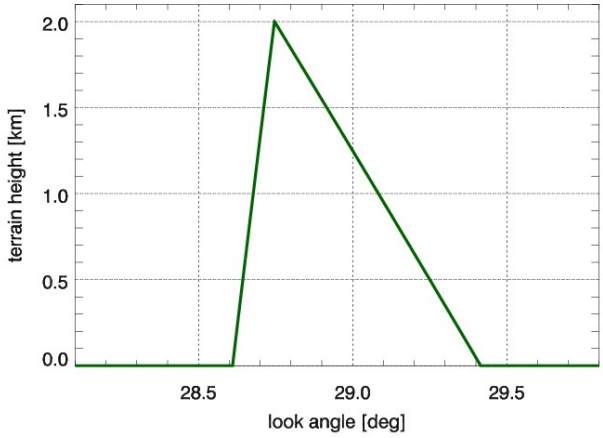

Figure 4 Distributed target: actual topographic profile, h, versus nominal look angle, at a given azimuth instant, τ_0.

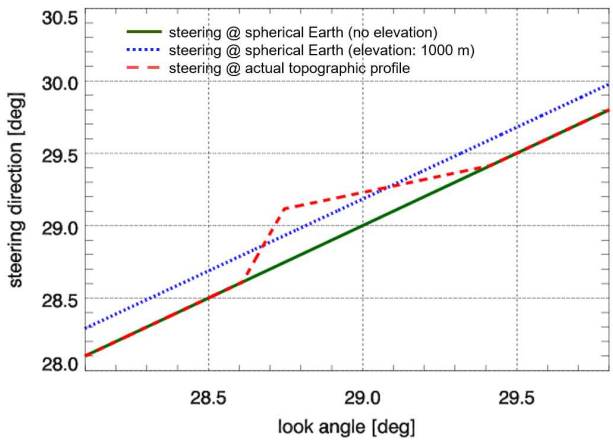

Figure 5 SCORE pattern steering direction, θ_{ste}, versus nominal look angle.

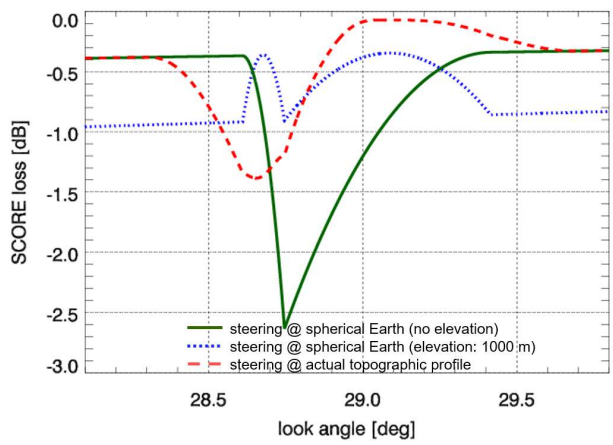

Figure 6 Distributed target (T = 25 µs): SL_d at a given azimuth instant, τ_0, versus nominal look angle for different steering laws.

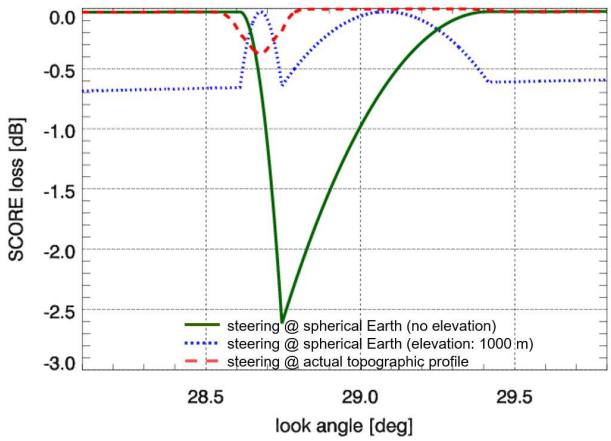

Figure 7 Distributed target (T = 7 µs): SL_d at a given azimuth instant, τ_0, versus nominal look angle for different steering laws.

azimuth direction, a SCORE pattern steering reflecting the actual range topographic profile appears as the best choice. Indeed, this scenario resembles the *ideal case* in (5), characterized by a SL of 0 dB. It is anyway worth to remark that the pulse duration cannot be arbitrarily short, due to the antenna thermal and power constraints. As the pulse duration increases, the choice of the optimum steering becomes less obvious, as shown in Fig. 6. Here the analysis based on the SL mathematical expression, (6), could be very useful to select the SCORE steering law and reduce a possible radiometric degradation. It should anyway be remarked that the optimization of the SCORE steering law does not allow, in general, to arbitrary reduce the SL and may not be enough to satisfy the demanding requirements on the radiometric quality of future SAR images.

4 Conclusion

SAR images acquired by SCORE DBF may be affected by a specific radiometric loss, the so-called SCORE Loss (SL), due to the mutual effect of the imaged surface topography and the pulse duration. The SL can be quantified by means of a simple mathematical equation, for a given acquisition geometry, pulse duration, SAR processing Rx window, and SCORE beam steering law.

This paper investigates the possibility to mitigate the SL through a proper choice of the SCORE beam steering law, based on the SL equation and the knowledge of the imaged topography and of the acquisition parameters.

The obtained results show that the analysis based on the SL mathematical expression could be usefully exploited to select the SCORE steering law and reduce a possible SAR image radiometric degradation induced by the terrain height and pulse duration. The optimal choice and the achievable SL mitigation depend on the acquisition scenario.

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