# Sidelobe Suppression Using the SVA Method for SAR Images and Sounding Radars.

Jens Fischer, German Aerospace Center, Oberpfaffenhofen, Germany, jens.fischer@dlr.de
Ioachim Pupeza, Technische Universität Braunschweig, Germany, e.pupeza@tu-bs.de
Rolf Scheiber, German Aerospace Center, Oberpfaffenhofen, Germany, rolf.scheiber@dlr.de

## Abstract

The method of Spatially Variant Apodization (SVA) has been developed for eliminating and suppressing sidelobes in SAR images as far as possible while maintaining the original image resolution. In this paper, we investigate the applicability of SVA to E-SAR data acquired in standard side-looking geometry and for the first time to the nadir looking sounder mode. In contrast to usual SAR imagery, sounding radar data feature a very strong backscatter from nadir due to directly down-looking rather than slant-looking. The strong nadir echo corresponds to the air-ice interface directly below the aircraft. It causes accordingly severe sidelobes interfering neighboring pixels in the data such that snow or ice layers close to the surface usually cannot be detected. The paper describes the SVA implementation into SAR processing and concludes that SVA is capable to achieve a better image resolution in both kind of data, usual SAR imagery and sounding radar data, reducing the sidelobe level at the same time.

## 1 Introduction

The focusing of SAR images is usually realized according to the Matched Filter theory because of its noise stability. Thereby, the approximate rectangle-shaped SAR data spectrum remains rectangle-shaped also after SAR image focusing and, thus, SAR images are convolved with a more or less ideal $sinc(t) := sin(t)/t$ function. Let $\sigma$ be the radar reflectivity to measure, $t \in \mathbb{R}^2$ slow-time/fast-time, $N = (N_1, N_2)$ the number of pixels in azimuth and range, $n = (n_1, n_2)$ the pixel position in the image and $T = (T_1, T_2)$ the sampling in azimuth and range direction then

$$image(t) = \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} \sigma(nT)\, \delta(t - nT) \tag{1}$$

is the ideally focused image of measured radar reflectivity and

$$sinc * image(t) = \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} \sigma(nT)\, sinc(t - nT) \tag{2}$$

describes the corresponding SAR image. Sampling in azimuth is given by $T_1 = 1/PRF$ the Pulse Repetition Frequency (PRF). The presence of sinc functions in SAR images is a result of limited bandwidth in SAR systems and leads to using more pixels for image depiction than actually having image information. The dynamic of a sinc mainlobe at a certain pixel position, here given by the radar reflectivity, represents the actual image information, the widening of the mainlobe corresponds to image redundancy and sinc sidelobes express the introduced position uncertainty due to the lack of sufficient bandwidth. As sinc sidelobes interfere with other mainlobes, they must be eliminated or, at least, suppressed in order not to hide useful image information.

This paper is structured as follows. In **Section 2** we reason why *ideal* sinc elimination from SAR images is impossible and summarize usual techniques to cope with sinc functions. **Section 3** describes the way SVA filtering is integrated in our SAR processing chain and discusses the pre-conditions which must be fulfilled prior SVA application. In **Section 4** we present our experimental results of applying the SVA filter to usual E-SAR imagery and for the first time to the nadir-looking sounder data.

## 2 Sidelobe Control Techniques

An ideal elimination of the sinc function in SAR images would produce (1) from (2) but the convolution performed is not invertible. It corresponds to divisions by zero in the rectangle-shaped data spectrum. In the one-dimensional discrete case, this can be verified by writing sinc-convolution as matrix operation with

$$C_s = \begin{bmatrix} s_0 & s_{N-1} & \dots & s_1 \\ s_1 & s_0 & \dots & s_2 \\ \vdots & \vdots & \dots & \vdots \\ s_{N-1} & s_{N-2} & \dots & s_0 \end{bmatrix} \tag{3}$$

which is singular, i.e. $|C_s| = 0$. Matrix (3) convolves some sampled signal $x \in \mathbb{C}^N$ with the discrete $sinc$ function $s = \begin{bmatrix} s_0, & s_1, & \dots & s_{N-1} \end{bmatrix}$. The original signal $x$ cannot be obtained from the sinc-convolved signal $x_s := C_s\, x$ because $C_s^{-1}$ does not exist.

There are, at least, three approaches to face $sinc$ functions:

First, the so-called super-resolution techniques try to process the SAR image such that all $sinc$ functions in the image converge to $\delta$ 'functions' for enhancing the image resolution. This is done by extrapolating the rectangle shaped spectra such that they become constant-shaped. Due to noise and computational accuracy limits, those techniques necessarily produce spurious peaks somewhere in the processed image and, hence, their application for sidelobe suppression is not advisable in general. Also, the image calibration is not maintained which restricts the number of applications furthermore.

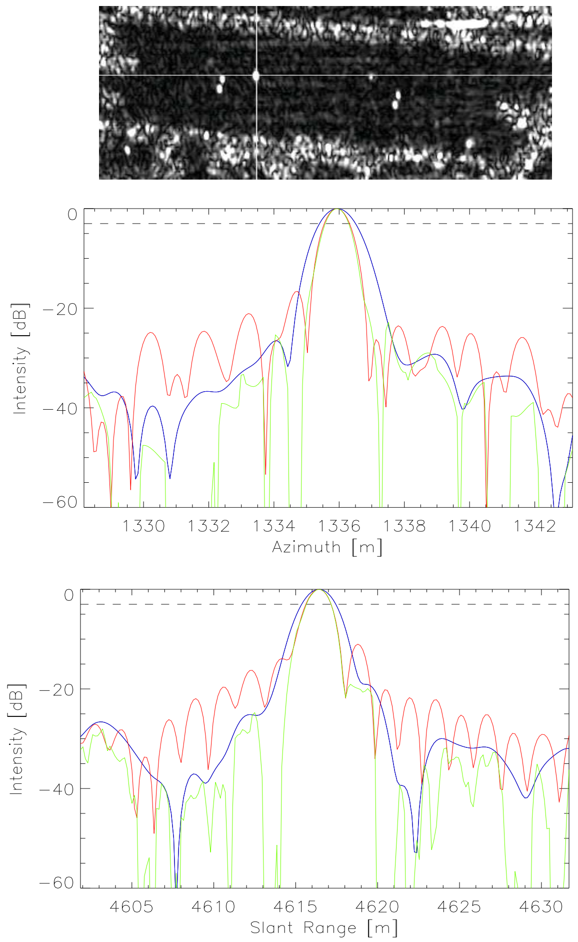


**Figure 1:** Corner reflector analysis in a L-band, HH polarized SLC image of a sports field in Dresden, 10x oversampled. Red=Corner reflector response without sidelobe suppression, Blue=suppression with Hamming, Green=with SVA. SVA preserves the original mainlobe (red) but suppresses sidelobes better than Hamming (below blue). The image resolution is determined via the -3dB level (dashed line).

Secondly, and this is the most common approach, it is possible to keep $sinc$'s in each pixel position but only the sinc sidelobes are tackled. This can be achieved based on the property that the multiplication of a broad window function in frequency domain corresponds to the convolution with a narrow window in time domain. By that, each sinc in time domain is multiplied with a narrow window pressing down its sibelobes while maintaining the mainlobe dynamic. Usual weighting functions are Hamming, Hanning and Taylor for instance [1]. This approach is most popular because the sidelobe suppression is applied to each pixel position equally and, therefore, the image calibration can be maintained. A major drawback is that the sinc mainlobe widens, i.e. it degrades the image resolution.

A third approach, which application is described in this paper, relaxes the constraint of equally applying the same amount of suppression to each pixel: Spatially Variant Apodization (SVA) [2]. It spatially varies the kind of suppression such that it is locally optimal and is, therefore, capable even to *delete* sidelobes as far as they are recognized unambiguously. Compared to the method described before, the original image resolution is maintained and, thus, SVA filtered images appear higher resolved than usually expected (see **Figure 1**).

# 3 SVA Filter Implementation

Spatial Variant Apodization is well-described in the literature [2], [3], [4]. Here, we only describe its implementation for E-SAR data and the results obtained when applied to usual E-SAR imagery and, finally, to E-SAR data acquired in sounding radar mode.

## 3.1 Securing SVA's Preconditions

SVA requires the attention to three pre-conditions which must be fulfilled before it can be applied successfully to the data:

1. The data spectrum should be ideally rectangle-shaped,
2. The data should be integer-oversampled or exactly Nyquist-sampled
3. Any shifts in the data spectrum (e.g. due to squint) must be removed.

SVA performs perfectly if the three conditions are perfectly fulfilled but moreover, it behaves continuously better the better the conditions are fulfilled. The latter property is especially nice if any pre-conditioning step was not perfectly successful, e.g. the over-sampling factor is no integer but $k = 1.98$. The first condition is easily fulfilled by applying the following 'normalization' step applied to the non-zero data spectrum

$$spec_{rect}(\omega) = \frac{spec(\omega)}{|spec(\omega)|} \cdot m \tag{4}$$

where $m$ is a mean value such that the spectrum energy is maintained. Of course, the non-zero pixels must be successional to form a rectangle together with the zero pixels and their number $n$ must fulfill the following equation

$$N = n + z = n + (k-1)n \tag{5}$$

where $N$ is the number of all complex-valued pixels in frequency domain and $z$ is the number of zero pixels. If the oversampling factor $k \geq 1$ is no integer then as many zeros as necessary must be padded such that $k$ is integer and (5) is fulfilled. The authors in [3] propose that the Fourier transform necessary for (5) can be avoided when using an Interpolated Spatially Variant Apodization method. The additional time necessary for time-domain interpolation due to non-integer oversampled data is less than performing a forward and backward Fourier transform and, hence, the method is somewhat faster.

According to our experiences, oversampling factors of $k = 2$ are optimal in both, azimuth and range direction. The image size is doubled and adapts well to the increased image resolution. Oversampling rates larger than two only enlarge the image and, correspondingly, the computational effort for the SVA-filter step.

### 3.2 SVA Filter Insertion into Processing

SVA may be applied to real- and complex-valued data. In the complex case, SVA is applied to both, real and imaginary part, separately. We apply SVA line-by-line first in azimuth, then in range direction on two-dimensional complex data. In each line, we secure the pre-conditions and then perform SVA. However, as checking the pre-conditions is time-consuming it may be ensured as far as possible during the preceding SAR raw data processing step. For example, the desired resolution might be chosen such that the processed bandwidth yields integer-oversampled data.

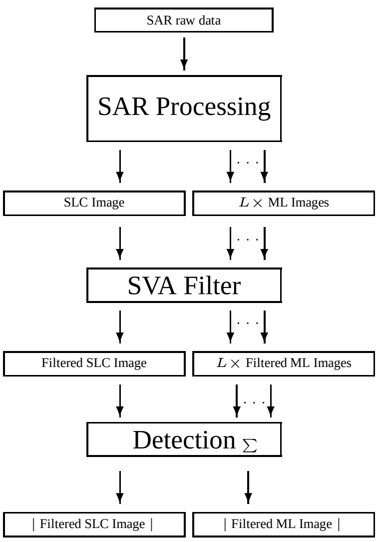


**Figure 2:** SVA integration into SAR data processing

Due to the filter length of only three pixels [2], a maximum of two pixels becomes invalid at the image margins after SVA application. Thus, in order to run SVA on large arrays a two-pixel-overlapped blocking technique must be implemented for avoiding any visibility of blocking effects in the data. Unfortunately, the impact of SVA on complex-valued SAR data after SVA-filtering has generally not been investigated so far for phase-sensitive applications such as polarimetry and/or interferometry. Up to now, we have only evaluated the application of SVA as far as the SVA filtered data stand at the *end* of the processing chain only followed by detecting the complex-valued data and doing data evaluations based on detected data (**Figure 2**). However, an impact on classification quality based on SVA filtered data is investigated in [4].

We apply SVA on both, complex-valued multi-look (ML) and also single-look complex (SLC) data. The improvement in image resolution is obvious in either case. For multi-channel data (e.g. polarizations HH-HV-VV-VH) it is applied to each channel separately. On multi-look data, SVA is applied to each complex look independently and after that the looks are added incoherently

$$image_{ML}(t) = \frac{|image_0(t)| + \cdots + |image_{L-1}(t)|}{L}$$

where $L$ is the number of looks.

## 4 Experimental Results

We implemented and tested SVA first on usual E-SAR imagery. In a second step, SVA is applied for the first time to sounding radar data. These data were acquired with E-SAR during the 2005 SVALEX campaign on Spitzbergen.

### 4.1 Effects on Usual SAR Images

As can be seen in **Figure 1**, both SVA but also the usual windowing technique (e.g. Hamming) are capable to suppress sidelobes. Apparently, the advantage of SVA is not the sidelobe suppression but the increased image resolution compared to the windowing method. This can also be observed visually in multi-look and in single-look complex imagery (**Figures 3** and **4**).

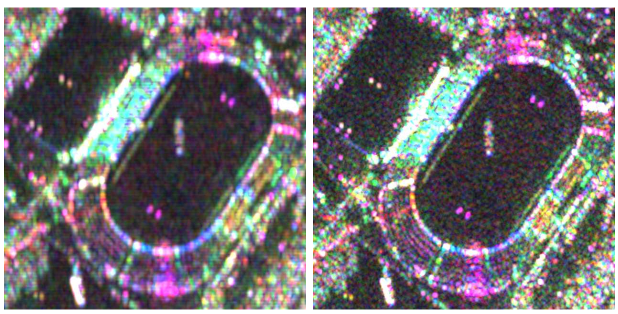

**Figure 3:** Rudolf-Harbig-Stadium in Dresden, imaged in L-band, four azimuth looks, polarization color-composite (RGB=HH-HV-VV). Sidelobe suppression (a) with Hamming, (b) with SVA

The image is processed with four azimuth looks and has a nominal multi-look resolution of $3 \times 2$ meters in azimuth/range. Its nominal single-look resolution is given by $1.2 \times 2$ according to azimuth resolution $1.2 = 3/((L+1)/2)$ meters with $L = 4$ looks. The actually achieved SLC resolution of is measured in **Figure 1**. It amounts to $1.11 \times 2.12$m for Hamming and and $0.77 \times 1.54$m for SVA.

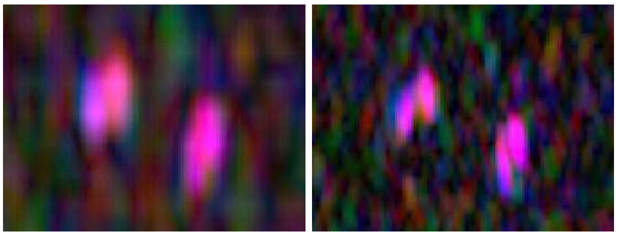

**Figure 4:** Corresponding SLC image detail with respect to the ML image in Figure 3: South-west goal of Rudolf-Harbig-Stadium, Dresden, (a) wide mainlobe with Hamming (b) better resolved with SVA.

### 4.2 Effects on Sounding Radar Data

In April 2005, the Alfred-Wegener-Institute (AWI) and the Microwaves and Radar Institute (HR) of German Aerospace Center (DLR) conducted a joint airborne campaign acquiring optical and SAR data near and on the islands of Spitzbergen, roughly 1550 miles from North Pole.

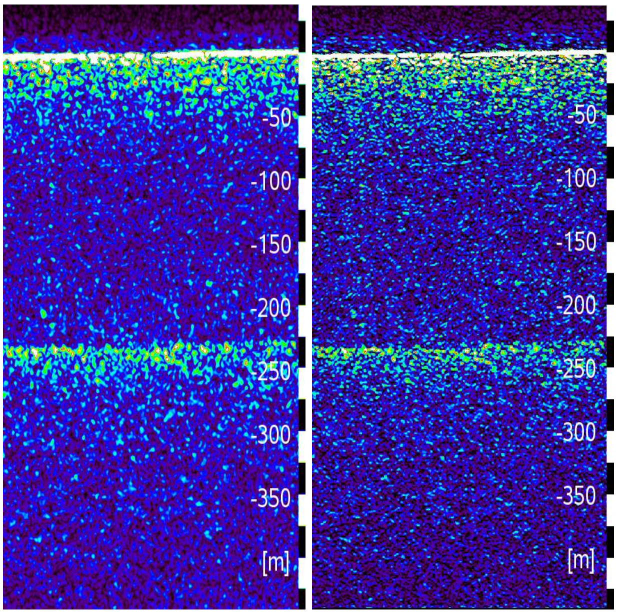


**Figure 5:** Ice sounder data acquired with E-SAR in P-band. Sidelobe suppression (a) with Hamming, (b) with SVA. The latter is better resolved in depth direction. The ice thickness of approximately 230 meters is determined via the difference between ice surface reflection (at 0m) and reflection from ground (at -230m).

Among other experiments, E-SAR's P-band antenna was operated in nadir looking mode for the first time in order to acquire sounding radar data on a glacier. Sounding radars serve the estimation of ice and snow layer thickness for the purposes of monitoring ice mass balance. The ambition to filter those data such that the nadir echo dominance is reduced initiated us to implement SVA and to test whether its application helps to retrieve valuable information hidden in nadir sidelobes. In two-dimensional sounder data, we apply SVA only in depth direction. The ambition to eliminate nadir sidelobes better than usual is not quite satisfied due to the dominance of off-nadir clutter but it turns out that, similarly as in usual SAR imagery, SVA achieves better resolution in depth direction (see **Figure 5**) compared to Hamming. This in turn might enable a better interpretation of ice layers close to the surface in data of space-borne bandwidth limited sensors.

## 5 Conclusions

We showed that SVA filtering allows excellent sidelobe suppression *without* degrading the original image resolution. Thus, it enhances the image resolution compared to usual outcomes which applies to both, usual SAR images but also to sounding radar data. SVA is robust with respect to minor deviations from ideal pre-conditions which must be fulfilled for SVA but also to the presence of noise [2]. A major drawback of SVA is its non-linearity not maintaining the radiometric image calibration. So far, we only investigated the use of detected SVA filtered data. The impact of SVA for phase sensitive applications such as polarimetry or interferometry is subject to further work.

## References

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