Interactive Dynamic Range Reduction for SAR Images

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Abstract

The visualization of SAR data involves the mapping of high dynamic range amplitude values to gray values of a lower dynamic range display device. This dynamic range reduction process controls the amount of information in the displayed result and is therefore an important part of each SAR visualization system. Interactive systems provide the user with immediate feedback on changes of the reduction method and its parameters.

In this paper, we examine different dynamic range reduction techniques known from tone mapping of optical images. The techniques are analyzed regarding their applicability to SAR data and incorporated into our interactive visualization framework based on programmable graphics hardware.

Keywords: Synthetic Aperture Radar, Dynamic Range, Tone Mapping, Graphics Processing Units

1. Introduction

Data sets from Synthetic Aperture Radar (SAR) systems are typically visualized by mapping their amplitude values, coming from single look complex (SLC) data files, to gray levels (in this paper, only single channel amplitude data sets are considered). A SLC SAR data set contains information of the combined reflectivity (including both amplitude and phase) of the individual resolution cells. The reflectivity strongly depends on the radar cross section (RCS) of the backscattering target. The RCS can vary very much depending on the point of view and the nature of the backscatterer. Corner reflectors, used for calibration and geocoding purposes, generate especially large values. This results in a large dynamic range of the amplitude values. It is usually much higher than the dynamic range of typical display devices. Therefore, the mapping to gray levels implies dynamic range reduction.

This mapping is often done using ad-hoc methods that give visually pleasing results for most data sets. For example, the RAT radar tools [1] first apply gamma mapping to the amplitude values, then clip values that are larger than a threshold, and then map the results linearly to the gray level range $[0,1]$. There are many similar possibilities, e.g. mapping an interval $[a,b]$ to $[0,1]$ using a linear or logarithmic function after estimating the bounds a and b from the amplitude data. Such methods are largely undocumented in the literature.

Dynamic range reduction methods should maximize the contrast in the interesting amplitude ranges and minimize information loss caused by clipping high amplitude values to white. These goals contradict each other.

The dynamic range reduction problem for SAR data is related to the tone mapping problem for optical images. Tone mapping is used to prepare high dynamic range optical images for display on low dynamic range display devices. For this purpose, tone mapping operators reduce the dynamic range of the luminance of optical images.

In interactive visualization systems, the user can choose the dynamic range reduction method and its parameters interactively and get immediate feedback on adjustments. This enables the user to get the most out of the visualized data. Graphics Processing Units (GPUs) are well suited for the task of interactive SAR data visualization because they provide the necessary computational power [2].

In this paper, we examine a selection of tone mapping operators regarding their applicability to SAR data and their usability for GPU-based interactive visualization. Sec. 2 gives an overview of the tone mapping problem. In Sec. 3, we analyze the applicability of tone mapping methods to SAR data. Sec. 4 discusses the implementation of global and local dynamic range reduction methods in our GPU-based visualization framework. Results are presented in Sec. 5.

2. Tone Mapping

Tone mapping operators (TMOs) prepare high dynamic range (HDR) optical images of both natural and generated scenes for display on low dynamic range (LDR) display devices.

Global TMOs use an identical mapping function for all image pixels. In contrast, *local* TMOs map pixels depending on their neighborhood. Bright pixels in dark areas are treated differently than bright pixels in bright areas. This gives local TMOs more flexibility both for reduction of the dynamic ranges and for preservation of local image details [3].

A number of global and local TMOs have been proposed in recent years; see [3] for an overview.

Some TMOs are based on sophisticated models of color perception, e.g. the Fairchild iCAM model and the Pattanaik Multiscale Observer Model [3]. Additionally, a few TMOs aim to reproduce certain perceptual effects of the human visual system, e.g. night vision and glare effects [4]. These methods are not considered in this paper.

An additional selection criterion for TMOs in this paper is the implementability in our GPU-based visualization framework. The GPU is a parallel stream processor. Operations are defined via microprograms and then applied to data streams. Thus, input and output data sets are strictly separated. A discussion of the stream programming model and the restrictions of GPU programming can be found in [5]. To achieve interactive performance even with very large data sets, we use a tile-based data management approach [2]. TMOs that require access to the whole data set to process each pixel, e.g. the Fourier-transform based Oppenheim operator [3], are therefore not considered in this paper.

The majority of TMOs work on single channel data. They first extract the luminance information from the optical image, then reduce its dynamic range, and re-add the color information afterwards. By omitting the color handling, such TMOs are applicable to other types of data in a straightforward way.

Single-channel TMOs map world luminances L_w to display luminances L_d using a mapping function f. The world luminances L_w can either be absolute luminance values in physical units, or relative values (usually from $[0,1]$) that are linearly related to absolute luminances. For TMOs that require absolute luminances as input, a prescaling parameter p can be applied in order to transform relative values to a suitable range [3].

The mapping function f of global TMOs depends only on the world luminance of the current pixel:

$$L_d(x,y) = f(L_w(x,y)) \tag{1}$$

For local TMOs, f depends on a neighborhood $\mathcal{N}(x,y)$ of the current pixel instead:

$$L_d(x,y) = f(\{L_w(x',y')|(x',y') \in \mathcal{N}(x,y)\}) \tag{2}$$

Global techniques are the natural choice when processing speed is critical [3], but using the GPU, it is also possible to realize interactive visualization systems based on local methods [4].

3. Dynamic Range Reduction for SAR Data

In this section, we first summarize important differences between tone mapping for optical images and dynamic range reduction for SAR data. After that, we list some commonly used dynamic range reduction methods for SAR data. We then examine a selection of both global and local TMOs with regard to their applicability to dynamic range reduction of SAR data. A description of all TMOs mentioned in this section can be found in chapters 7 and 8 of [3].

In the following, the input values are amplitude values A (from SLC data) instead of world luminances L_w. The amplitude values are normalized to $[0,1]$. If necessary, a prescale factor p is used as a parameter to map normalized amplitude values to a range that can substitute absolute L_w values.

3.1. Challenges

Although the purpose is similar, there are several important differences between tone mapping for optical images and dynamic range reduction for SAR data.

Tone mapping approximates the appearance of HDR optical images on LDR displays. Therefore, quality measurement techniques for TMOs can be based on comparisons of the reproduced result with the original scene (or with the original scene as reproduced by a special HDR display) [6, 7]. For SAR data, no original appearance exists, and objective quality measurements for dynamic range reduction methods are currently not possible.

Furthermore, the distribution of amplitude values in SAR data sets differs from the distribution of luminance in optical images [8]. For example, corner reflectors and other strong scatterers cause small peaks of high amplitude in areas of significantly lower amplitude in the SAR data. This may cause problems for TMOs. Additionally, local average values in optical images are often estimated using a Gaussian distribution. This does not work well with the multiplicative speckle in SAR data.

Finally, the goal of TMOs is often to produce results that look "natural". The reproduction of details is not of high importance for this goal [9], but it is central for dynamic range reduction for SAR data. Local methods can enhance local contrast and thereby improve the visibility of details, but they have the disadvantage that the SAR data calibration is not maintained. Resulting gray levels in different areas are not directly comparable anymore.

3.2. Commonly Used Methods

3.2.1. Linear Mapping

Linear mapping from amplitude values to gray levels is only usable if a relatively small range of the amplitude values is selected and all values outside of this range are clipped to black or white respectively. Otherwise, most details are lost in very dark regions of the resulting image. A possible mapping function is the following, where μ is the mean of the amplitude values and σ is the standard deviation:

$$L_d(x,y) = \frac{\min(t, A(x,y))}{t}, \quad t = \mu + 3\sigma$$

All information in amplitude values greater than t is lost when using this method.

3.2.2. Logarithmic Mapping

Logarithmic mapping is often used with SAR data. It is usually adjustable with one parameter c that controls the overall brightness of the result. The following mapping function can be used:

$$L_d(x,y) = \frac{\log(1 + cA(x,y))}{\log(1 + c)}$$

To make better use of the available gray level range, often only a part of the amplitude range is mapped to gray levels in this way. Values outside of this range are clipped to black or white respectively. Various methods exist to estimate suitable threshold values from the amplitude data. Interactive systems allow the user to change thresholds on the fly.

3.2.3. Gamma Mapping

This is an ad-hoc dynamic range reduction method based on gamma mapping:

$$L_d(x,y) = A(x,y)^\gamma, \quad \gamma \in (0,1)$$

The RAT radar tools [1] use the following variant: First, gamma mapping with $\gamma = 0.7$ is applied to the amplitude values. Then the mean value m of the results is computed. After that, the interval $[0, 2.5m]$ is linearly mapped to $[0,1]$. Values larger than $2.5m$ are clipped to white.

3.3. Global Methods Based on TMOs

3.3.1. Drago Logarithmic Mapping

The Drago method [10] is a logarithmic mapping method that adapts the base of the logarithm depending on the amplitude of the current pixel.

$$L_d(x,y) = \frac{m}{\log(1+c)} \cdot \frac{log(1 + cA(x,y))}{log(2 + 8A(x,y)^b)}$$

The parameter c is analogous to the simple logarithmic mapping. The parameter m determines the brightness of the result, and the parameter b steers the amount of contrast.

3.3.2. Tumblin-Rushmeier Brightness Preserving Operator

The Tumblin-Rushmeier operator [11] is based on psychophysical experiments that measure the interrelation of luminance and perceived brightness. It aims to preserve the perceived brightness in the resulting image. The method uses two adaptation parameters, L_{da} and A_a, for display luminances and amplitude values respectively. Additionally, a prescaling parameter is used.

$$L_d(x,y) = L_{da}\left(\frac{pA(x,y)}{A_a}\right)^{\gamma(A_a)/\gamma(L_{da})}$$

The function γ is a logarithmic function that models the human contrast sensitivity.

3.3.3. Schlick Uniform Rational Quantization

The Schlick method [12] is applicable to single channel data such as normalized SAR amplitude values in a straightforward way. The resulting mapping function is not based on assumptions about the human visual system:

$$L_d(x,y) = \frac{bA(x,y)}{(b-1)A(x,y)+1}, \quad b \in [1,\infty)$$

It uses a single parameter b which controls the overall brightness of the result.

3.3.4. Reinhard-Devlin Photoreceptor Model

The Reinhard-Devlin method [13] is motivated by photoreceptor behaviour and is designed to work on the RGB channels of optical images. Using sophisticated models for the computation of a photoreceptor adaptation level, effects such as light adaptation and chromatic adaptation can be simulated. If the method is applied to single channel data, only the light adaptation term L_a remains.

$$\begin{aligned} L_a(x,y) &= lA(x,y) + (1-l)A_{\text{avg}}, \quad l \in [0,1] \\ L_d(x,y) &= \frac{A(x,y)}{A(x,y) + (bL_a(x,y))^m}, \quad b > 0 \end{aligned}$$

The constant m is computed from the minimum and average amplitude values: $m = 0.3 + 0.7((1-A_{\text{avg}})/(1-A_{\text{min}}))^{1.4}$. The parameter l steers the light adaptation term and influences the contrast in the resulting image. The parameter b determines the brightness.

3.4. Local Methods Based on TMOs

3.4.1. Chiu Spatially Variant Operator

The Chiu method [14] was one of the first local methods to be used for tone mapping. The mapping function is as follows:

$$L_d(x,y) = \frac{A(x,y)}{cA_a(x,y)}$$

Here, A_a is a Gauss-filtered version of A. Therefore, $L_d(x,y)$ depends on the neighborhood $\mathcal{N}$ as described by Eq. 2. The parameter c is a constant of proportionality between the two values.

3.4.2. Rahman Retinex

Like the Chiu method, the Rahman method [15] uses Gauss filtering to reduce the dynamic range. Multiple filtered versions of the input data set are produced using different Gauss filter sizes. A set of weights determines the influence of each filtered data set on the result. The weights can be computed from a single user parameter w. Additionally, the method uses a prescaling parameter.

3.4.3. Ashikhmin Spatially Variant Operator

The Ashikhmin TMO [16] was designed to be contrast-preserving. It uses multiple Gauss filtered versions of the input data set to determine a local adaptation value A_a for each pixel. The largest Gauss filter that does not cross high gradients is used. This avoids blurring of data features. The mapping function is then defined as

$$L_d(x,y) = F(A'_a(x,y))\frac{A'(x,y)}{A'_a(x,y)}$$

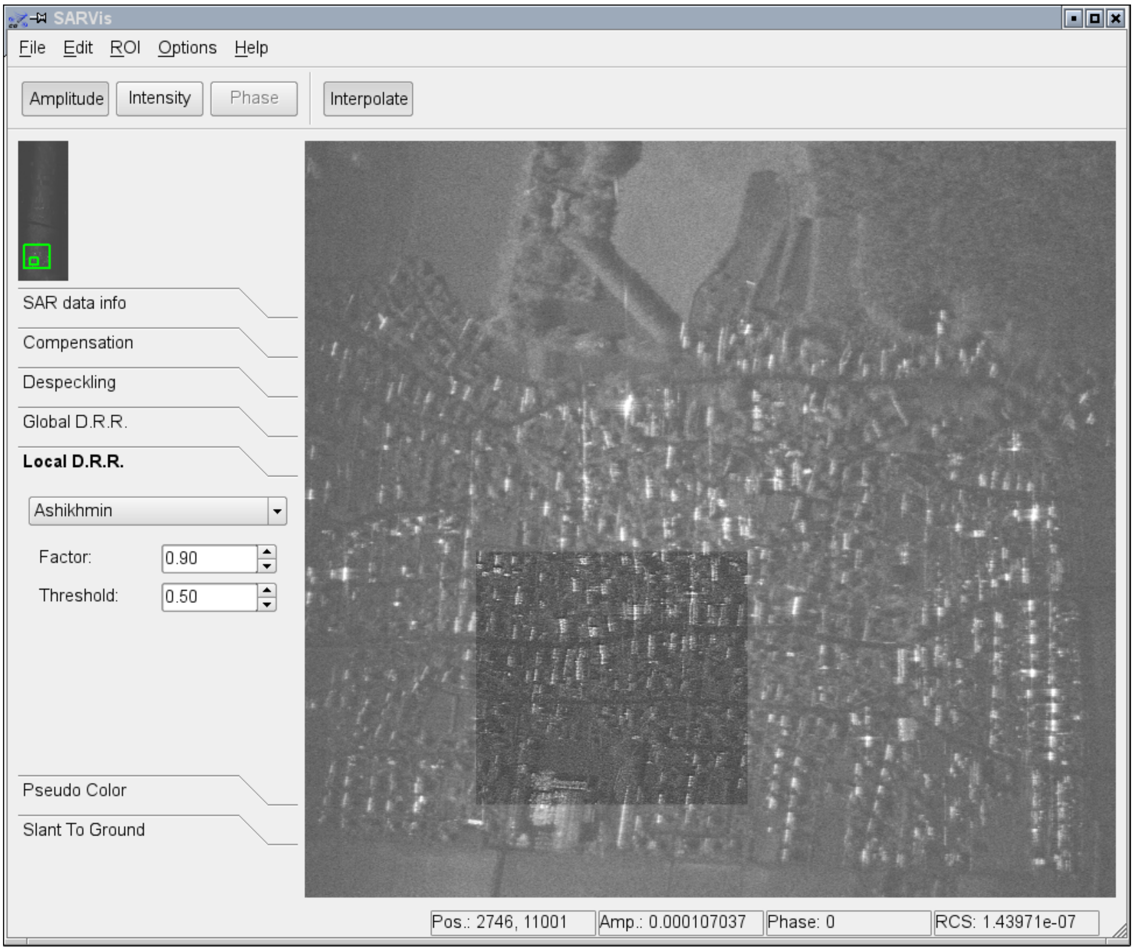
Here, A' and A'_a are computed after prescaling the amplitude values with a prescaling factor p. An additional parameter t determines the minimum strength of gradients that the Gauss filters are not allowed to cross. The function F is designed using perceptual motivations.

3.4.4. Reinhard et al. Photographic Tone Reproduction

The Reinhard TMO [17] uses ideas from photography, namely scene keys and dodging-and-burning. The basic mapping function is

$$L_d(x,y) = \frac{A'(x,y)}{1 + A'_a(x,y)}$$

Here, A'_a is a Gauss filtered version of the prescaled amplitude values A', using the biggest filter size that does not cross strong gradients. Reinhard et al. propose some refinements to this equation to better use the available gray level range. Parameters of the resulting mapping function are the prescaling factor p and a parameter w that influences the smallest amplitude that is mapped to white. Additionally, the computation of A_b requires a sharpness-influencing parameter s and a gradient threshold t.



Ashikhmin

Factor: 0.90

Threshold: 0.50

Pos.: 2746, 11001 | Amp.: 0.000107037 | Phase: 0 | RCS: 1.43971e-07

Figure 1: *Simultaneous use of global and local dynamic range reduction methods in our interactive GPU-based visualization framework. Data courtesy of FGAN/FHR, processed at ZESS/IPP.*

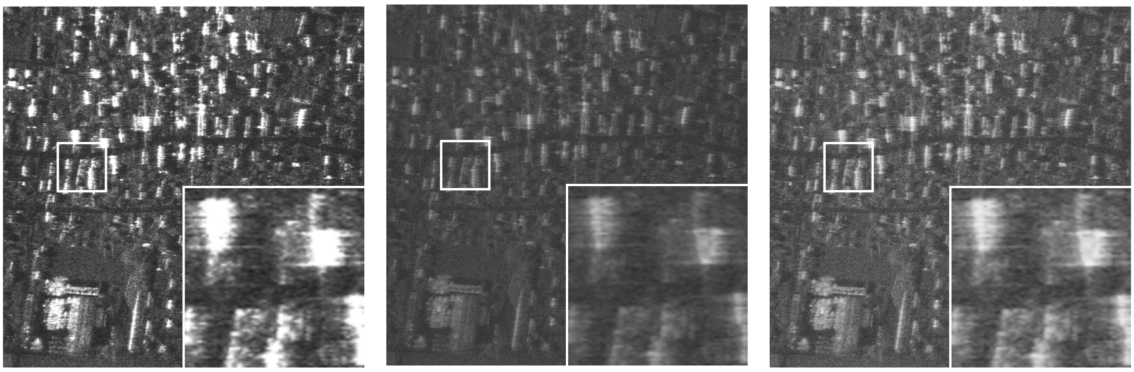
3.4.5. Durand Bilateral Filtering

The Durand TMO [18] splits the data set into a base layer and a detail layer. Dynamic range compression is applied only to the base layer. The details are later re-added. The base layer is produced by applying a bilateral filter to the original data set. The bilateral filter is a smoothing filter that avoids to smooth across boundaries, i.e. high amplitude differences. The detail layer is the difference between the original and the filtered data set.

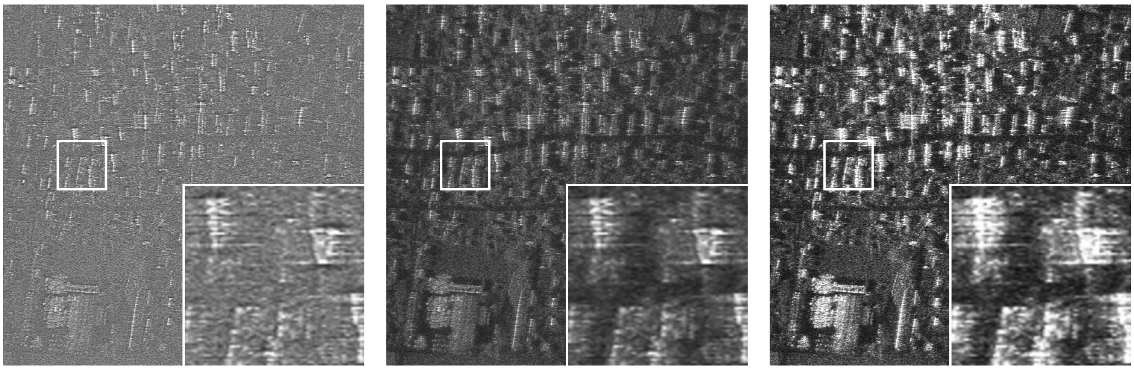
4. GPU-based Interactive Dynamic Range Reduction

We implemented the techniques listed in Sec. 3 in our interactive GPU-based visualization framework [2]. This allows to explore the properties of each method in a wide range of situations.

Having a variety of dynamic range reduction methods is only useful if the user can interactively adjust method and parameters to both the current SAR data set and his analysis goals.



Linear Logarithmic Reinhard-Devlin



Rahman Ashikhmin Reinhard

Figure 2: *Results from a selection of global (Linear, Logarithmic, Reinhard-Devlin) and local (Rahman, Ashikhmin, Reinhard) dynamic range reduction methods. The bottom right part of each image shows a closeup of the area framed by the white rectangle. Data courtesy of FGAN/FHR, processed at ZESS/IPP.*

In particular, the user must be able to interactively switch between global methods that allow a direct comparison of different image regions, and local methods that show more details in specific regions. In our GPU-based framework, global and local methods can also be used simultaneously. The local method is then applied to a subregion of the displayed region of interest as shown in Fig. 1. This allows users to benefit from the more detailed results of local methods while still allowing the direct comparison of different image regions permitted by global methods.

5. Results

Fig. 2 shows results for one exemplary data set produced with the AER-II sender and PAMIR receiver [19]. The methods were also applied to different single-channel SAR SLC data sets from the ERS-1/2 and Envisat sensors.

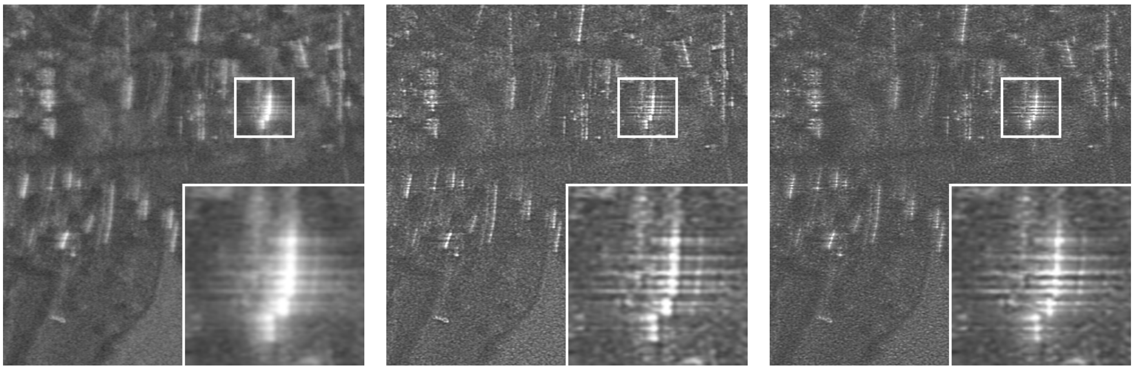


Figure 3: *Results of logarithmic mapping (left), the Ashikhmin method using Gauss filtering (middle), and the Ashikhmin method using Median filtering (right). Data courtesy of FGAN/FHR, processed at ZESS/IPP.*

Global methods

The result of linear mapping clearly shows that high amplitude ranges are clipped to white, and therefore details are lost. Both the logarithmic and gamma mappings avoid this problem to some extent. The result of gamma mapping lacks contrast when compared to other results. The Drago logarithmic mapping method can produce better results than the simple logarithmic mapping due to its adaptability and additional parameters, but this requires some fine-tuning.

The Tumblin-Rushmeier method is adjustable to a wide range of input data via its parameters, but it tends to clip higher amplitude ranges to white. The psychophysical model that motivates the method is likely not suitable for SAR data.

The Schlick and Reinhard-Devlin methods both produce high contrast results without clipping high amplitude values. The brightness parameter of the Schlick method and the brightness/contrast parameter pair of the Reinhard-Devlin method are easily adjustable. Both methods are valuable alternatives to the commonly used simple logarithmic mapping method.

Local methods

The Chiu method emphasizes very high frequencies corresponding to very fine local structures even when used with relatively strong Gauss filtering. Therefore, it is very difficult to obtain usable results for SAR data sets because of their speckled nature. The Rahman method has similar problems, but the influence of speckle can be reduced using its parameter f.

The Ashikhmin method works well for SAR data even though it is based on perceptual motivations. The parameter t influences the amount of detail that is emphasized. By setting t appropriately, the results are much less affected by speckle than the results of the Chiu and Rahman methods.

The Reinhard method, like the Tumblin-Rushmeier method, tends to clip higher amplitude ranges to white when applied to SAR data. Additionally, for our test data sets, it is hard to adjust the four parameters to produce reasonable results. The Durand method is a little bit easier to adjust, but like the Tumblin-Rushmeier and Reinhard methods it tends to clip higher amplitude ranges to white. For all three methods, this effect may be caused by the photo-centric nature of the underlying assumptions.

Fig. 2 shows that local methods can produce results with increased local contrast, and significantly increase the preservation of local details. This helps to analyze image details. Nevertheless, the results should still be improved. All presented local methods use variants of Gauss filtering to determine a local adaptation value. This works well for optical images, but is not ideal for SAR data. Fig. 3 shows that the results of the Ashikhmin method improve when a Median filter is used instead of a Gauss filter. Local peaks are more clearly separated, and their original distribution is preserved better. More complex filters that are better adapted to the properties of SAR data may further improve the results. To avoid skewed results, such filters must match the TMO's assumptions about local adaptation values.

6. Conclusion

Dynamic range reduction is an important step in SAR data visualization. Interactive adjustment of dynamic range reduction and other visualization steps, e.g. despeckling, helps to interactively explore and analyze SAR data.

We have adapted tone mapping techniques for optical images to the problem of dynamic range reduction of SAR data. The resulting methods have been implemented in our GPU-based interactive visualization framework.

The results show that some of the presented global methods can provide reasonable alternatives to the commonly used methods. Local methods have high potential to increase local contrast and thereby make details better visible. However, to make full use of this approach, it is necessary to develop methods that are tailored to the properties of SAR data. In particular, the methods must cope with multiplicative speckle and the presence of high peaks with small spatial extension in the data. This is subject of future work.

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