Automatic Compensation of Antenna Beam Roll-off in SAR Images

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ABSTRACT

The effects of a non-uniform antenna beam are sometimes visible in Synthetic Aperture Radar (SAR) images. This might be due to near-range operation, wide scenes, or inadequate antenna pointing accuracy. The effects can be mitigated in the SAR image by fitting very a simple model to the illumination profile and compensating the pixel brightness accordingly, in an automated fashion. This is accomplished without a detailed antenna pattern calibration, and allows for drift in the antenna beam alignments.

ACKNOWLEDGEMENTS

CONTENTS

FOREWORD

During the course of development of several Synthetic Aperture Radar (SAR) systems by Sandia, early engineering evaluation flights were at fairly short ranges, with inadequate antenna pointing calibration. This resulted in otherwise perfectly good SAR images, but with noticeable brightness attenuation at one or both edges of the image. These images were salvaged and/or enhanced with the technique described in this report.

1 Introduction & Background

Synthetic Aperture Radar (SAR) processing effectively forms a synthetic beam pattern that offers azimuth resolution much finer than the real beamwidth of the real antenna. Both the real aperture (antenna) beam, and the synthetic aperture beam constitute spatial filters. Proper target scene selection requires that these spatial filters be properly pointed and aligned in the desired direction. That is, the SAR scene of interest must be adequately illuminated by the real antenna beam.

Furthermore, the real antenna beam pattern rarely offers uniform illumination over its nominal width, typically taken as the angular region between its -3 dB illumination directions. Consequently, SAR images may show a reduction in brightness towards the edges of the scene being imaged. This is exacerbated whenever imaged scenes are large compared with the illumination footprint, such as at near ranges or coarse resolutions. While careful antenna calibration and alignment allows compensating for antenna beam roll-off with an inverse of the relative two-way gain function, any unexpected illumination gradients from other system sources will be left unmitigated. For example, any misalignment of synthetic beam from real beam will cause unexpected brightness gradients across the image. Such misalignment might be due to the mounting or environment of the real antenna. Such misalignment might also be due to motion measurement errors affecting the synthetic beam orientation.

An example SAR image exhibiting illumination roll-off is given in Figure 1.

Figure 1. SAR image of static aircraft display exhibiting antenna illumination roll-off on left side (Ku-band, 0.1 m resolution, 3.2 km range, 31 degree grazing angle)

Illumination anomalies are also known to be caused by atmospheric phenomena.[1]

A number of algorithms attempt to characterize from the data the synthetic beam direction in relation to the real beam direction. These go generally by the name of Doppler Centroid Estimation. Papers by Madsen[2], and Yu and Zhu[3], discuss various techniques for Doppler Centroid Estimation. Generally they are not concerned with beam shape beyond using it to calculate the Doppler frequency at the beam center. This is required to correctly process the data, especially for orbital systems. De Stefano and Guarnieri[4] use a polynomial fit in their technique.

Correcting for antenna illumination patterns often go by the name Radiometric Calibration of SAR images. Zink and Bamler[5], and Frulla et al.[6] discuss radiometric calibration for a satellite SAR. As is typical for orbital SAR systems, the greater concern is often for the elevation pattern, due to their favored processing methods and typically larger range swaths. Nevertheless, the methodology is typically one of ensuring that any measured pattern matches the theoretical one, with the theoretical one being used for the purposes of correcting the larger data set with a single calibration correction. Correcting a single image based on the image itself is not addressed by these papers.

Burns & Cordaro[7] describe compensating the antenna azimuth beam pattern during image formation processing, but do not mention doing so in any data-driven fashion.

LaHaie and Rice [8] present a modified algorithm that compensates for the antenna beam pattern during image formation processing, but also require that the beam pattern be known before processing.

What remains required is a reasonably effective mechanism for removing the two-way antenna beam illumination pattern from a SAR image, based on the image itself rather than on an elaborate calibration scheme.

2 Overview & Summary

The antenna illumination roll-off effects in the SAR image can be mitigated by measuring the actual illumination profile in the image, fitting a model of the antenna beam pattern to it, and compensating the image with a model-based inverse relative gain function.

In particular, in measuring the actual illumination profile, it is advantageous to use a non-linear filter in the range direction to select a representative pixel brightness value across range (from each column of Figure 1) for each azimuth position in the image.

3 Detailed Description

Consider the image of Figure 1. The ultimate aim is to render an image that is corrected, that is, compensated for the obvious illumination roll-off. We note that in this image, the illumination gradient is horizontal, or in the azimuth direction. For the subsequent discussion, we shall presume that any image to which this technique is applied can be oriented in a like manner.

The first step is to extract an illumination profile from the image. To avoid undue influence from bright target points or shadow regions, we select a representative pixel magnitude value from each vertical column, or across range. In this case we use the median value from each column. These values are plotted in Figure 2.

This data is next smoothed by fitting it to a representation of the antenna beam pattern. If the antenna beam pattern is known, then it may be used directly. However, if the antenna beam pattern is not known, then a suitable polynomial can be employed. Most antenna patterns exhibit a strong quadratic behavior in the neighborhood of their peak response. Subtle variations from the quadratic behavior may be captured with a relatively few higher-order terms. In practice, a 4th order polynomial works well for most antenna patterns for this purpose. Figure 3 illustrates a 4th order polynomial fit to the data. The fit is accomplished by standard minimum-mean-squared-error techniques. The resulting curve is a data vector or array.

This polynomial model curve can then be normalized to unit amplitude by dividing each element of the vector by the vector's maximum value. The result of this is shown in Figure 4.

The inverse of this function is calculated by dividing each vector value into one. The resulting illumination correction vector is shown in Figure 5.

The pixels of each row of the original image are now corrected by multiplication with this vector. The resulting image is shown in Figure 6.
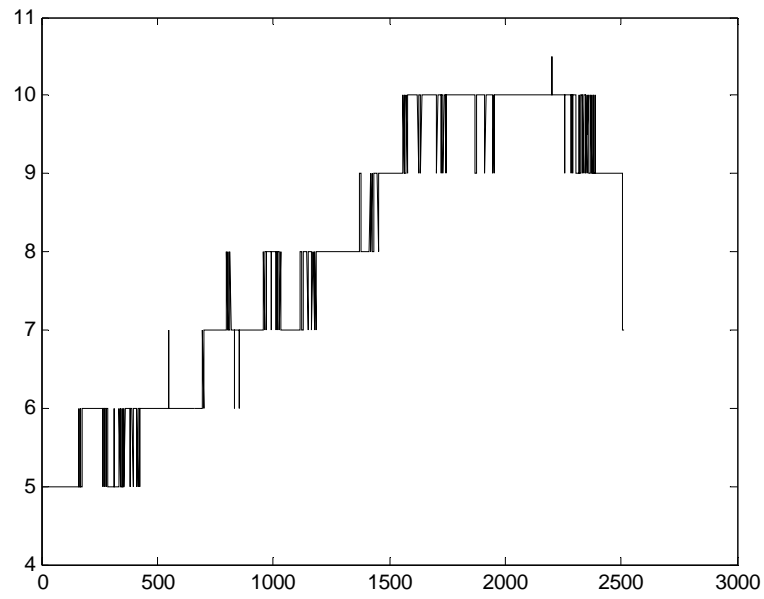
Figure 2. Plot of median pixel magnitude value versus horizontal azimuth index.
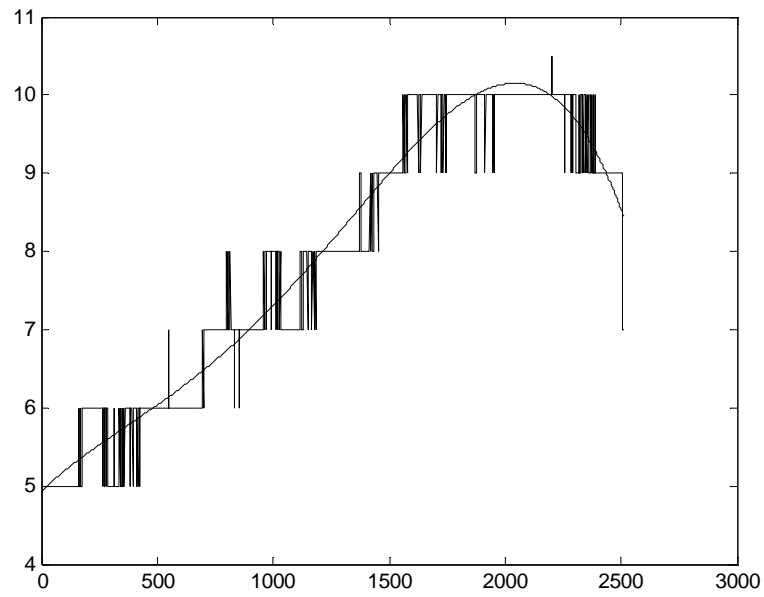
Figure 3. A 4th order polynomial fit to the median pixel magnitude data.

- 10 -
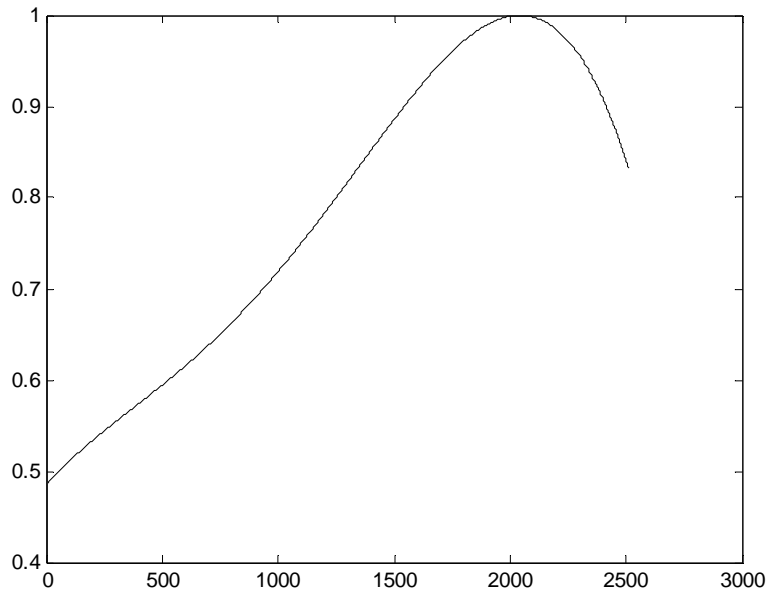
Figure 4. Normalized polynomial fit data to unit amplitude.
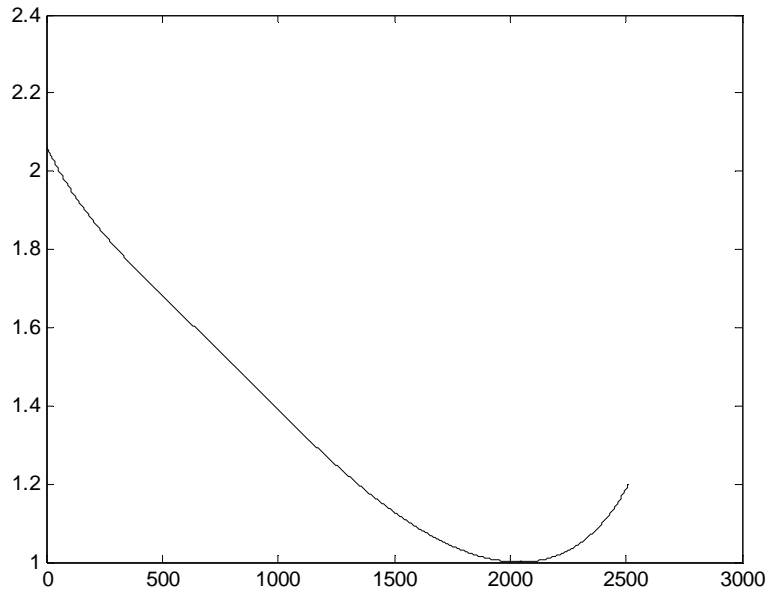
Figure 5. Illumination correction vector.

Figure 6. SAR image with illumination corrected.

Note the improved appearance of Figure 6 over the original Figure 1, with the original obvious illumination roll-off mitigated.

We note that this general technique may be applied to images even after other brightness corrections (e.g. lookup tables applied, gamma corrections, etc.).

Extensions to this basic technique might include averaging the illumination correction vector over several images to mitigate peculiarities resulting from anomalies of a single image.

While we have demonstrated this technique on azimuthal illumination gradients, one can easily envisage a similar technique for range gradients.

The next figures show that this technique is remarkably effective over a variety of scene contents.
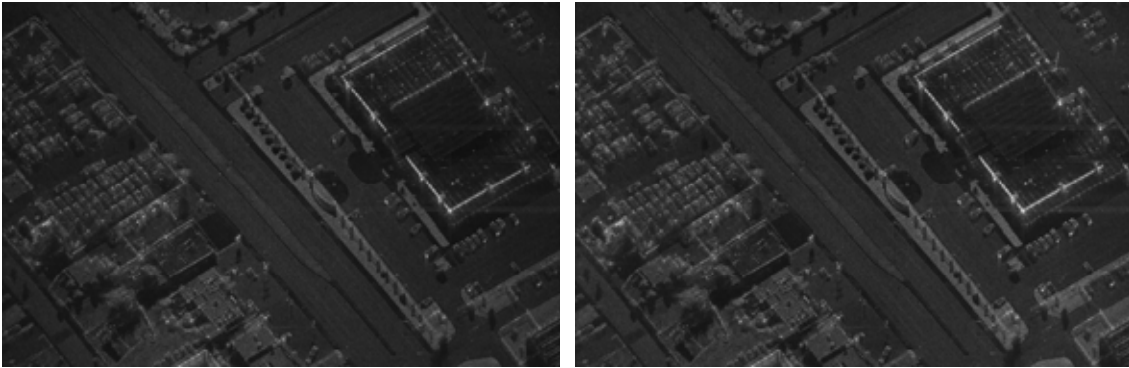
Figure 7. Buildings in an urban environment.
(Ku-band, 0.1 m resolution, 3.3 km range, 29 degree grazing angle)
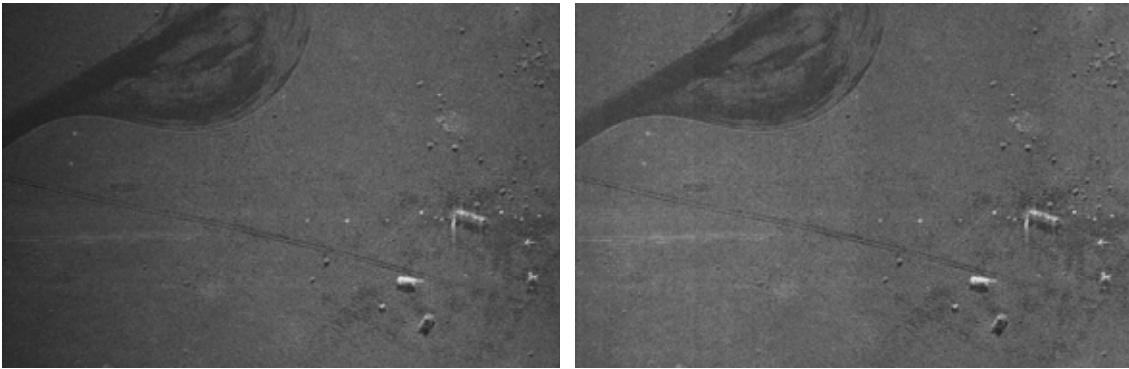
Figure 8. Desert field with vehicles.
(Ku-band, 0.1 m resolution, 3.3 km range, 30 degree grazing angle)
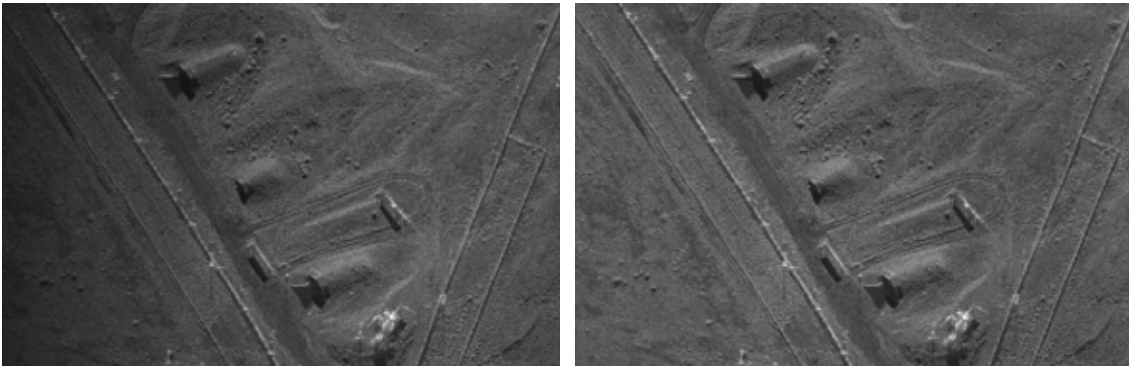
Figure 9. Storage bunker complex.
(Ku-band, 0.1 m resolution, 3.3 km range, 31 degree grazing angle)

This process is summarized in the diagram of Figure 10.

```
┌─────────────────────┐
│ Orient for          │
│ horizontal azimuth, │
│ and vertical range  │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│ For each column,    │
│ select median       │
│ magnitude           │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│ Fit median values   │
│ to azimuth antenna  │
│ pattern model       │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│ Normalize           │
│ curve to unit       │
│ amplitude           │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│ Invert values       │
│ such that           │
│ yn = 1 / xn         │
└─────────────────────┘
           │
           ▼
┌─────────────────────┐
│ Apply magnitude     │
│ corrections to      │
│ image rows          │
└─────────────────────┘
```

The "Invert values such that" box contains the equation $y_n = 1 / x_n$.
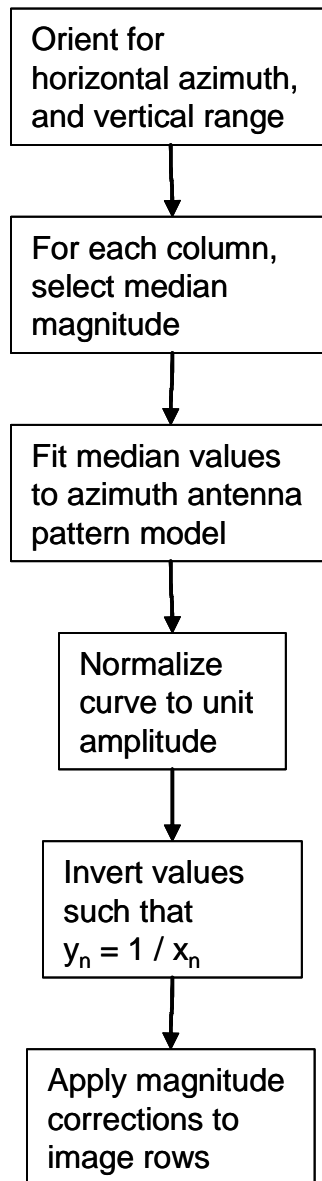
Figure 10. Processing steps for automatic compensation of antenna beam roll-off in SAR images.

The following Matlab™ source code suggests an implementation of this algorithm. Matlab is a product of The MathWorks.[9]

In this case, the variable `im_qp` contains the image, or more precisely the square-root of the magnitude of the original image.

```
[V,U] = size(im_qp);

brightness_raw = median(im_qp);

coeff = polyfit([1:U],brightness_raw,4);

curve = polyval(coeff,[1:U]);

curve = curve / max(curve);

curve = 1./curve;

im_qp = im_qp .* (ones(V,1)*curve);
```

4 Conclusions

The significant points discussed include

- The illumination profile can be extracted from the image itself.

- Nonlinear techniques such as a median filter facilitate illumination profile extraction.

- The extracted illumination profile can be fit to a model of the antenna two-way illumination pattern.

- In the absence of an antenna pattern model, a polynomial of order 2 to 4 can be effectively substituted.

- An inverse intensity correction can be calculated from the best-fit model.

- The image intensity can be effectively compensated with the correction.

The technique proves to be robust, and can accommodate a wide variety of scene types.

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[9] http://www.mathworks.com/

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