SAR AUTOFOCUS AND PHASE CORRECTION TECHNIQUES

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Introduction

Both satellite and airborne SAR data is subject to a number of perturbations which stem from various causes and lead to unknown phase changes in the raw data and subsequent imagery which may be defocussed or non-linear. As part of their SAR processing capability, NASoftware offer a combined autofocus with phase correction capability that allows unknown sensor motions to be derived from the received SAR signal. The derived motions can then be applied in a motion compensation process to correct the sensor track to a straight line. This report illustrates the use of these techniques; as it shows, they enable sharply-focused images to be obtained with objects accurately located in the along-track direction. This is an essential component where accurate SAR imagery is required, such as in change detection.

1. Simulated focused SAR image from segmented image.

We start by simulating realistic SAR data. A segmented SAR image, derived previously (using InfoPACK), is adopted as the RCS at each pixel and illustrated as Figure 1. The simulated flight geometry assumes that the sensor is situated to the left of the image and progresses from bottom to top of the scene. Broadside SAR operation is assumed. The SAR parameters used in the simulation are as follows:

- Range = 50000 Km
- Range spacing = 3 m
- Antenna length = 6 m
- Antenna sample spacing = 0.75 m
- Along-track velocity = 200 ms⁻¹

Thus the image covers a distance of about 16 Km along track by 2.2 Km across-track. In order to make detailed visual comparison of the different reconstructions we shall select the extracted portion of this image, shown in Figure 2.

Let us now consider simulating SAR imagery, from the background illustrated in Figure 1. The advantage of using simulated data is that it ensures we know “ground truth”.

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It can be shown that a reasonable approximation to fully developed speckle can be obtained using this simulation approach:

1. Assume that the scattered amplitude at each pixel is determined by the RCS that has previously been derived from a real image by either segmentation or despeckling.
2. The effect of speckle can be derived by generating a complex Gaussian random phase at each pixel.
3. The SAR processing is over-sampled by many (say 4) pixels per azimuthal resolution cell.
4. The received background signal is then simulated by convolving the scattered return, as simulated above, with the linear FM chirp instrument function. For a correctly focused image this reference function corresponds to zero error in the slope parameter.
5. Target returns are simulated with no speckle and then inserted into a separate part of the image. This allows us to investigate the effect of the different processes on the point spread function (PSF). These targets will not be used in autofocus processing, of course.

At this point we have simulated the total received signal in a SAR system. The underlying RCS, speckle properties and reference function can all be varied as required in this process. A typical detail of the focused SAR image derived from Figure 2 is illustrated in Figure 3.

The final SAR image length is the sum of the length of the data with that of the SAR reference. Thus the simulated output image has a blank region of half the reference length at each end. In Figure 3 we show the detail corresponding to that in Figure 2.
Figure 1: Original RCS image used in simulation
Figure 2: Extracted detail from Figure 1 used for comparisons.
The PSF returns for the specimen point targets can be extracted to illustrate the quality of the focused reconstruction. The amplitude response for these is illustrated in Figure 4. It can be seen that the full width at 71% maximum is about 3.5 pixels, each of 0.75 m. The position of the peak response is important as it reveals how the image becomes distorted and defocused when the sensor undergoes unknown motion.
2. Defocus SAR data and form image

Figure 3 showed a focused SAR image where the sensor motions were completely known. However, real SAR images will be degraded by random, unknown, fluctuations in the focus conditions. These may be a consequence of unknown radial velocity of the sensor, atmospheric refractive index fluctuations affecting the path length or along-track velocity fluctuations. Each of these would give rise to a variation in the quadratic focus parameter leading to defocused and distorted imagery when processed with the ideal SAR processing parameters.

A complete history of unexpected phase variations can be compiled in terms of the velocity and acceleration contributions in each direction. In this simulation we apply a narrowband noise signal to represent radial acceleration, as illustrated in Figure 5. The along-track acceleration and initial velocities in each direction are set at zero.
The phase of the received return in a broadside SAR can be expressed as

\[ \phi(t) = -\frac{4\pi}{\lambda} \left[ V_r t + t^2 \left( \frac{V^2}{2R_0} + \frac{a_r}{2} + \frac{V^2}{R_0} \frac{\Delta V}{V} \right) + ... \right] \]

(1)

The linear term in \( t \) is controlled by the radial (across-track) velocity, \( V_r \). This has the effect of moving the apparent broadside SAR position along track, since the image is formed at the zero Doppler position. The first component of the term in \( t^2 \) is the normal quadratic SAR dependence with the coefficient described as the focus parameter,
\[ \beta = \frac{2\pi V^2}{R_0\lambda} \]  

where \( V \) is the along-track velocity, \( \lambda \) the wavelength and \( R_0 \) the range. The second and third terms in \( t^2 \) then represent perturbation in this focus parameter caused by radial acceleration, \( a_r \), and along-track velocity mismatch, \( \Delta V \).

The consequent error in the focus parameter, shown in Figure 6, can be derived directly from the imposed acceleration using eqn. (1).

As a final step in this section, the consequential phase error in the received signal as a function of time can be derived. Assuming the values of the different motions specified for this example, the consequent imposed phase error takes the form illustrated in Figure 7.

![Figure 7: Imposed phase error derived from focus error shown in Figure 5.](image)

This phase error is directly associated with a one-way range error between the sensor and a given point on the ground. This associated imposed range error is shown in Figure 8. Note that the range error becomes larger than the range spacing of 3 m at position 4500. This means that the response for a single object will undergo range walk around this position. This means that initial SAR processing will not encounter the complete scatterer phase history around this position. The resulting resolution will be degraded because of an incomplete integration time as well as the actual error in the focus parameter. A detail of the defocused image is shown in Figure 9 where the effect of defocus is very clearly visible.
Figure 8: Imposed range error corresponding to the phase error in Figure 6.

Figure 9: Detail of the defocused image for comparison with Figure 3.
It can be seen in more detail in Figure 10 when the same set of point targets are viewed as those shown in Figure 4. These target responses show that the reconstruction is both defocused (blurred) and geometrically distorted. Of course you would not be aware of this distortion in an arbitrary SAR image because you normally have no ground truth with which to compare positions; but it's there anyway.

Figure 10: PSFs for the point targets in the defocused image
3. First iteration of autofocus

The NASoftware autofocus technique is iterative. We look first at the effects of the first iteration. A plot of the dependence of the estimated correction to the focus parameter as a function of position along track is shown in Figure 11.

Figure 11: Comparison of estimated correction to focus parameter, $\beta$, derived from the first autofocus pass (green), with the imposed error in beta (red).

Figure 11 shows that the general structure of the imposed error is well represented by the autofocus process. It is also apparent that individual estimates fluctuate about the imposed value.
The phase correction can now be applied to the original signal that had the imposed phase error shown in Figure 7. The result should correspond to resampling the received data to a straight track such that a properly compressed image can be obtained using the nominal reference. The residual phase error is shown in Figure 12.

For the final stage in this cycle the image phase and range are corrected and a corrected image formed, as shown in Figure 13. It is obvious that the quality of this image is greatly improved compared with the defocused example in Figure 9. Indeed, it is difficult to identify differences between this and the original focused image in Figure 3. Such differences are best illustrated by the point spread functions, shown in Figure 14, which can be compared with the corresponding defocused and focused results, illustrated in Figures 10 and 4 respectively.
We can draw the obvious conclusion that the quality of the reconstructions after this first autofocus and phase-correction stage is considerable improved compared with the defocused result. If we consider the full width at 71% of the peak maximum we observe that it is generally around 3.5 pixels, i.e. essentially the same as the focused performance. However, if we consider the peak positions we find that these are shifted by a few pixels when compared with the focused results in Figure 4. This establishes an important consequence that acceptable image sharpness can be obtained after a single pass of autofocus and phase correction. However, there is still residual geometric distortion. Thus if one wishes to make detailed pixel by pixel comparisons between SAR images, such as in change detection or target change detection, it is necessary to strive for further correction.
4. Second iteration of autofocus

We now carry out a second iteration of the autofocus algorithm. The derived correction to the focus parameter is shown in Figure 15. The general appearance of the estimated error is broadly similar to that obtained after the first pass, indicating that little has been gained. The associated residual phase is illustrated in Figure 16.

In fact the residual phase error appears shows little change after the second pass compared to the first. However, the smoothness of the curve is greater, showing that higher-frequency fluctuations have been compensated better than in the first pass.

The results for the range shift and the PSFs show only small changes from this iteration, as one would expect from Figure 18.
Figure 15: Comparison of imposed error in beta (red), estimated value from first iteration (green) and second iteration (blue).

Figure 16: Comparison of residual phase error after first (red) and second (green) pass.

5. Third iteration of autofocus
We next carry out a third iteration; the details of this differ from those of iteration 2. The result is illustrated in Figure 17.

![Figure 17: Comparison of imposed error in beta (red), estimated value from first (green), second (blue) and third (magenta) iterations.](image)

The overall phase discrepancy is much improved, as illustrated in Figure 18. This result shows that the phase error has now been corrected very accurately over the whole image. The associated range error, illustrated in Figure 19, reveals a similar improvement compared with Figure 12. Indeed the range distortion is now shown to be a very small fraction of a range cell.

![Figure 18: Comparison of residual phase error after first (red), second (green) and third (blue) passes.](image)
This improvement is also evident in the reconstructed single target responses, shown in Figure 20. The width of the PSF was already close to ideal after the first pass. Now it is apparent that the along-track geometric distortion is approximately 1 pixel over the entire scene, which is about 30% of the actual resolution. This means that techniques such as change detection and target change detection are feasible once SAR images have been phase-corrected and linearised in the manner described here.