

# Non-Linear Synthetic Aperture Radar Techniques.

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## Abstract

*The Non-Linear Synthetic Aperture Radar (SAR) technique uses a combination of platform manoeuvre and novel processing to separate the effects of a target's radial velocity and cross-range displacement, giving accurate estimates of both. The technique provides high resolution images free from the image distortion caused in conventional SAR imagery by moving targets, and allows the accurate target location of both stationary and moving objects. The technique also allows the platform to fly a wide range of planned and unplanned manoeuvres, improving platform survivability in potentially hostile environments.*

Keywords: Synthetic Aperture Radar (SAR), Platform Motion, Moving Target Detection and Location

## Introduction

Synthetic Aperture Radar (SAR) is a well-known technique for generating high-resolution images, usually from airborne or space-based platforms. Extensive research over the past few decades has led to significant improvements in SAR imagery, and further refinement is anticipated from current research programmes.

However, conventional SAR suffers from a number of fundamental problems, particularly in military applications. This paper describes some of these inherent deficiencies, shows how the non-linear SAR approach could overcome them, and indicates some of the significant military benefits given by this approach.

## Principles of Conventional SAR

Conventional SAR requires the platform to fly an approximately linear trajectory, ie a straight and level flight path at a constant speed. An Inertial Measurement Unit (IMU) detects any deviations of the antenna phase centre from the notional linear

trajectory, and corrections to the phase of the received signals are computed and applied to compensate for these deviations.

As the antenna follows its linear trajectory, the changing path length to any single point on the ground gives rise to a Doppler that is a linearly decreasing function of time, as illustrated in Figure 1.

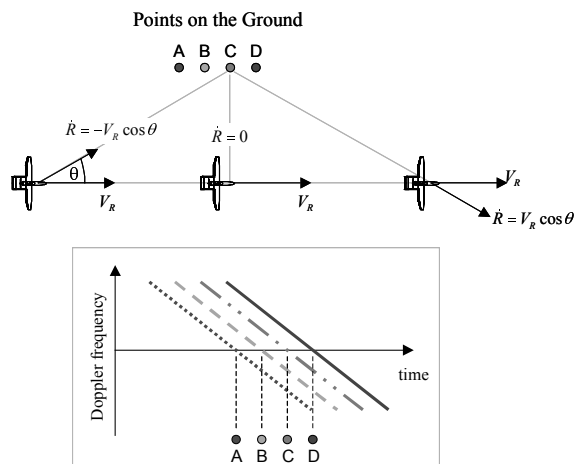


Figure 1 - Doppler History of Conventional SAR Trajectories

Phase corrections are normally applied to the returns received from each pulse to remove the slope of the Doppler histories in

a process known as focussing. Each stationary point on the ground then gives a constant Doppler corresponding to its cross-range position within the image, with the difference in azimuth between two points being proportional to the frequency difference.

Fast Fourier Transforms (FFT) may then be used to form a bank of Doppler filters in order to determine the intensity of each cross-range cell in every down-range bin.

Although the linear trajectory used for conventional SAR gives some advantages, principally the ability to use FFTs which greatly reduces the amount of computation, it also gives rise to some significant drawbacks.

There is complete ambiguity between the Doppler history given by a cross-range displacement and that given by a target with a non-zero velocity towards or away from the synthetic aperture, as illustrated in Figure 2.

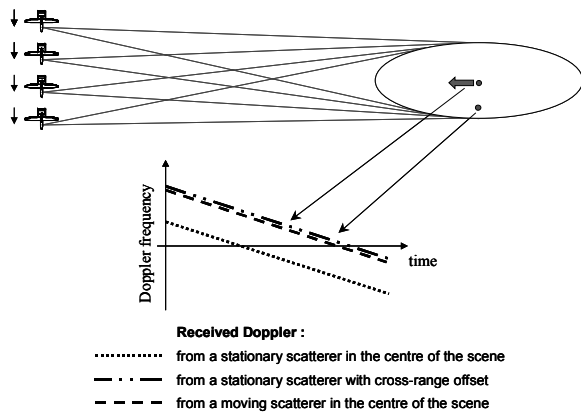


Figure 2 - Azimuth Ambiguity Problem

The Doppler shift is normally interpreted by conventional SAR processing as a displacement in the cross-range direction. The target will then be displayed in the wrong position within the image.

This “azimuth ambiguity problem” is often overcome by using a separate, interleaved, Ground Moving Target Indication (GMTI) mode to detect and locate moving targets.

Various methods may be used, such as classical Displaced Phase Centre Antenna and clutter nulling/notching. GMTI gives relatively poor sensitivity, accuracy and resolution compared with that of a SAR image of stationary targets because GMTI is based on the real rather than the synthetic antenna aperture. GMTI increases the complexity of the radar system, often requiring three antennas, and can also impose additional constraints on the platform trajectory.

Furthermore, the straight and level trajectory flown by conventional SAR platforms reduces the routing options available to image a particular scene, especially in mountainous terrain, and hence increases the platform’s vulnerability to hostile action.

### Principles of Non-Linear SAR

The fundamental idea behind the non-linear SAR technique is illustrated in Figure 3.

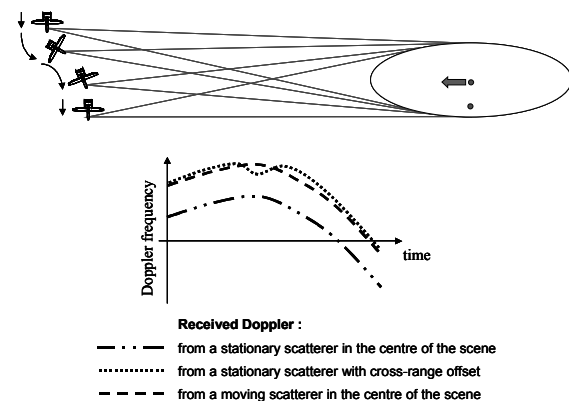


Figure 3 - Principle of Non-Linear SAR

By deliberately manoeuvring the platform, the effects of a target’s radial velocity on the Doppler of the received signal will be different from the effects of a cross-range displacement. This allows the effects of radial velocity and cross-range offset to be separated, giving accurate estimates of both the actual position and radial velocity of every scatterer within the scene regardless of its motion.

In the non-linear SAR technique, an IMU measures the actual platform trajectory. For each pixel in the image, the measured trajectory is used to calculate the expected phase histories of a scatterer in that pixel but with a range of different radial velocities. These alternative phase histories are then correlated with the received signal to find the best match.

The radial velocity giving the best correlation to the received signal will correspond to the radial velocity of the brightest scatterer within that pixel. The amplitude of the correlation will give a measure of the scatterer's Radar Cross Section. The non-linear SAR processing is illustrated conceptually in Figure 4.

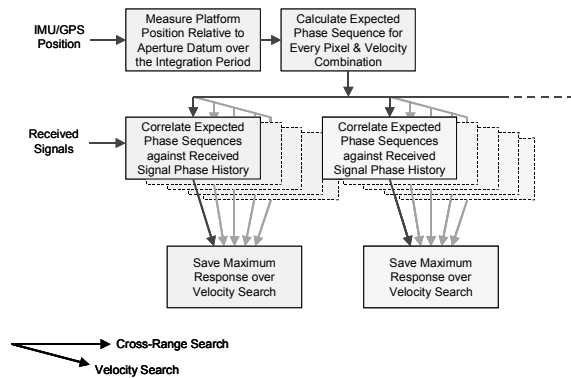


Figure 4 - Non-Linear SAR Processing

In practice, it is not necessary to correlate the received signal against the phase histories corresponding to every possible radial velocity. Techniques have been developed to narrow down the velocity search rapidly, reducing the number of correlations needed for each pixel by an order of magnitude.

### Analysis of the Technique

For each pixel in the image, the expected phase history of a scatterer at that position but with a range of different radial velocities can be calculated. The difference between the actual and the expected phase of the received signal may be expressed as:

$$\frac{4\pi}{\lambda}(\Delta - \Delta_0)$$

where  $\Delta$  and  $\Delta_0$  are functions of time within the integration period ( $t_0, t_1$ ).

The best estimate of the target's cross-range position and radial velocity would then be given by the peak of the correlation integral

$$I = \frac{1}{(t_1 - t_0)} \int_{t_0}^{t_1} \exp\left(\frac{4\pi}{\lambda} j(\Delta - \Delta_0)\right) dt$$

where the integral is evaluated for all possible target cross-range positions and radial velocities.

The behaviour of the Non-Linear SAR technique can be assessed by considering the correlation surface for an isolated point scatterer with a cross-range position  $x_0$  and radial velocity  $v_0$ . The response for adjacent cross-range cells or for different trial velocities is indicated by the brightness of the surface at the corresponding location.

The correlation surface for a straight and level trajectory, typical of conventional SAR, is shown in Figure 5.

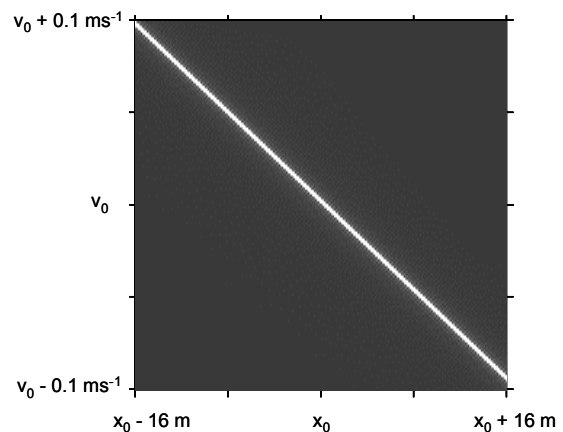
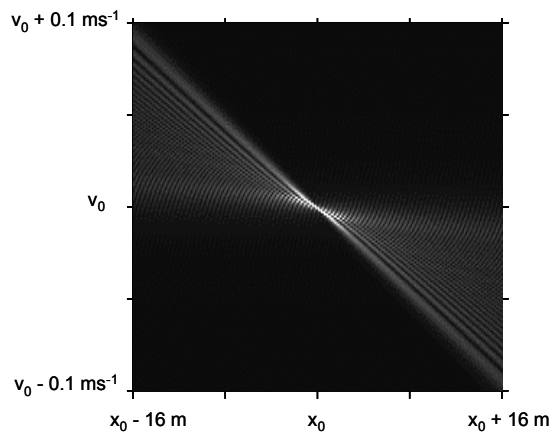


Figure 5 - Correlation Surface for a Linear Trajectory

This correlation surface comprises a single ridge of constant amplitude. Every radial velocity assumption gives a response at one cross-range position within the image. This illustrates the azimuth ambiguity problem for conventional SAR: by assuming every

scatterer is stationary, moving scatterers will appear in the wrong place in an image.

A typical correlation surface for an accelerating SAR platform trajectory is shown in Figure 6. In this case there is a single peak; the Non-Linear SAR processing would therefore be able to determine both the correct radial velocity and cross-range position of the target in the image.



**Figure 6 - Correlation Surface for an Accelerating (Non-Linear) Trajectory**

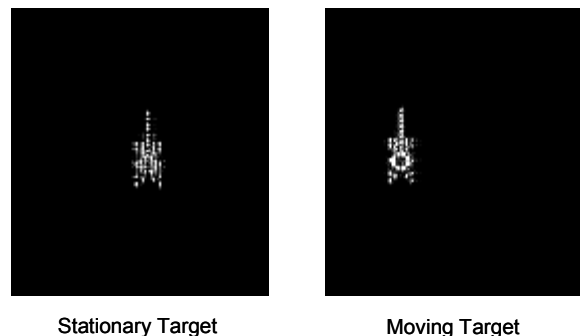
The sidelobes of the correlation surface will give some residual ambiguity: a bright scatterer will also produce smaller responses in adjacent pixels but with a slightly different radial velocity. These effects can be removed using simple post-processing, for example by assuming that a group of adjacent pixels with very similar radial velocities all belong to a single rigid body and therefore all have an identical radial velocity.

Following such post-processing, the Non-Linear SAR technique would give the same image resolution as conventional SAR for the same synthetic aperture width, but small errors in the target's cross-range position may still remain. For the example trajectories described below, these residual positional errors are less than 2m; other feasible trajectories could reduce this to sub-metre levels.

## Modelling Results

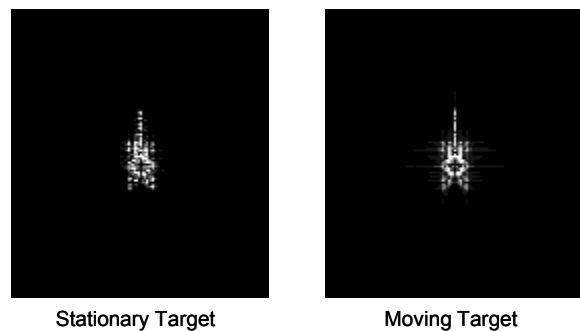
The analytical results were corroborated by modelling. A target comprising a number of point scatterers in the shape of a T72 tank was placed in the centre of the scene. The signals expected from stationary and moving targets were then calculated explicitly and used to generate images using conventional SAR processing and the Non-Linear SAR technique.

Figure 7 shows conventional SAR images of a stationary and a slow-moving target taken from a straight and level (linear) platform trajectory. The cross-range displacement caused by the target's radial velocity is clearly visible.



**Figure 7 - Conventional SAR Images**

The same targets were then imaged from a variety of non-linear platform trajectories, including gentle turns and weaves with a lateral acceleration of around 0.5g. Typical results following post-processing are shown in Figure 8. In each case the Non-Linear SAR technique gives the correct position and radial velocity of the target with no loss of image quality.



**Figure 8 - Non-Linear SAR Images**

## Trajectory Requirements

The non-linear SAR platform is able to fly any trajectory, including planned and unplanned manoeuvres, as long as the radar antenna can still be steered to observe the scene being imaged. The greater the manoeuvre, the more effective the non-linear SAR technique becomes; if the platform chooses to fly a straight and level trajectory, the non-linear SAR technique becomes equivalent to conventional SAR processing.

This gives the platform a great deal of flexibility in planning the trajectory to achieve the mission aims, and also allows complete freedom to diverge from the planned trajectory in response to the developing situation. Some example missions and corresponding trajectories are described below. In each case, it is assumed that the SAR has a 3cm wavelength.

One potential fast jet mission is high resolution (0.3m) imaging to support the Detection, Recognition and Identification of targets before an engagement with a stand-off weapon having a range of around 8km. Allowing 30s for processing, image assessment and targeting before missile launch, and assuming a platform speed of around  $200\text{ms}^{-1}$  (400 knots), the image of the target scene needs to be available at a range of 15km at the latest.

Assuming a maximum integration time of 10s, the “jink” trajectory illustrated in Figure 9 (not to scale) would achieve the mission requirements using a maximum lateral acceleration of 3g.

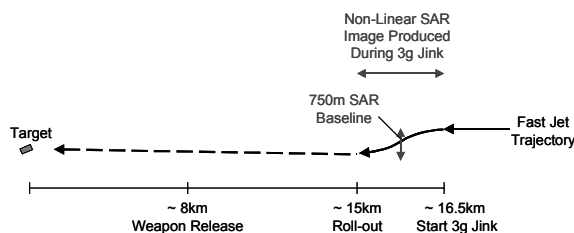


Figure 9 - Example Fast Jet Trajectory

Higher accelerations would achieve the required SAR baseline with a shorter integration time; lower accelerations would need longer integration times to achieve the required baseline and hence the 0.3m resolution using this “jink” trajectory.

A typical UAV mission would be high resolution (0.3m) imaging of an area containing stationary and moving targets. The UAV is assumed to have a relatively low rate of turn, with a maximum lateral acceleration of 1g, and a speed of around  $60\text{ms}^{-1}$  when on task. If it flew a straight and level trajectory, these characteristics would make the UAV a relatively simple target for surface-to-air weapons, so it is assumed that the UAV would want to manoeuvre almost continually in order to enhance survivability.

The horizontal weave shown in Figure 10, in which the UAV flies a  $90^\circ$  weave over an integration period of 12s, would achieve the required resolution and give the position of moving targets to within 2m. Longer integration times or higher accelerations would give correspondingly better resolution and positional accuracy.

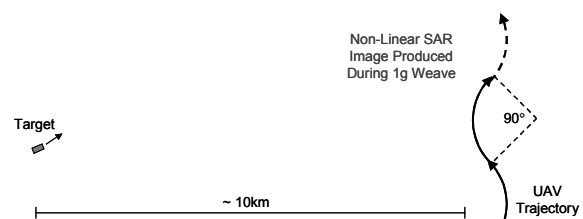


Figure 10 - Example UAV Trajectory

## Benefits of Non-Linear SAR

The ability of the SAR platform to manoeuvre during the integration period allows much greater flexibility in the choice of routes, and also allows the platform to turn frequently, giving a significant improvement in platform survivability.

Manoeuvring the platform allows the non-linear SAR technique to determine the correct location of both stationary and

moving targets in a single process, rather than the interleaved SAR and GMTI modes of conventional systems. The greater the acceleration, the more accurate the resulting image, although even gentle turns with a lateral acceleration of 0.5g would satisfy the requirements of many missions.

The non-linear SAR technique uses the full synthetic aperture to determine the location of moving targets. The positional accuracy of moving targets given by this technique is therefore expected to be significantly better than that of conventional GMTI techniques whose cross-range accuracy is determined by the much smaller physical aperture size. Furthermore, the longer integration times used by non-linear SAR compared to conventional GMTI modes is expected to give a significant improvement in detection sensitivity.

The non-linear SAR technique can be applied to a wide range of systems, including forward-looking as well as sideways-looking radars. The resolution achievable is dictated by the width of the synthetic aperture, so platforms fitted with forward-looking radars would need to jink or weave in order to produce SAR images along their mean line of advance. This could be used by fast jet radars or seekers in air-to-surface missiles, for example, to support target recognition and aim point selection in an engagement.

Non-linear SAR is a combination of platform manoeuvre and a novel processing technique. It needs no special transmitter,

receiver or antenna hardware, and so could be applied to most or all existing SAR systems. The ability to detect target radial velocity and correctly locate moving targets means that the additional antennas needed by some conventional GMTI modes would be unnecessary for non-linear SAR.

## **Conclusions**

Mathematical analysis and modelling has shown that the non-linear SAR technique can give high resolution images and the correct position of both stationary and moving targets within an image.

A number of significant operational benefits have been identified. The non-linear SAR technique allows the platform almost complete freedom to manoeuvre during the integration period, enhancing survivability and operational flexibility in potentially hostile airspace.

The non-linear SAR technique could be applied to a wide range of existing systems, and offers the potential to reduce the complexity of future SAR/GMTI systems.

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