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# SIGNAL PROCESSING FOR TARGET MOTION ESTIMATION AND IMAGE FORMATION IN RADAR IMAGING OF MOVING TARGETS

*Trygve Sparr*

Norwegian Defence Research Establishment (FFI), Land and Air Systems Divsision
PO Box 25, NO-2027 Kjeller, Norway
phone: + (47) 63 80 72 44, fax: + (47) 63 80 72 12, email: Trygve.Sparr@ffi.no
web: www.ffi.no

## ABSTRACT

*Radar imaging of moving targets is often called ISAR (Inverse Synthetic Aperture Radar.) Imaging of moving targets generally consists of two separate tasks: Estimation and correction of target motion, and the explicit image formation. Both tasks must be implemented with great care, as it is the coherent processing of the received radar signal phase that makes imaging possible. Of the two tasks, the motion compensation is often most difficult, as many radar targets move in a complicated and fairly unpredictable manner.*

*When the motion is complicated, the imaging step can be a challenge as well. The reason is that the target 3D-structure begins to matter, and projection plane effects may cause blurred images for even well designed ISAR processors.*

## 1. INTRODUCTION

The task of extracting information from various types of sensor data is becoming more and more important as modern sensors are generally producing ever increasing data amounts. Operational radar sensors today are easily capable of overwhelming available analysis capacity. On the other hand, the information is needed faster than ever before to enable decision making in many areas, from civilian disaster relief to precision targeting in military applications. Accordingly, there is a continued and increasing interest in fast and accurate methods to go from sensor data to information. Such methods are essential to provide sifting and refining capability for sensor data. A general view of a system is given in Figure 1.

One way to produce radar signatures of moving targets is often called ISAR (Inverse Synthetic Aperture Radar) [1]. Imaging of moving targets generally consists of two separate tasks: Estimation and correction of target motion, and the explicit image formation. Both tasks must be implemented with great care, as it is the coherent processing of the received radar signal phase that makes imaging possible. Of the two tasks, the motion compensation is often most difficult, as many radar targets move in a complicated and fairly unpredictable manner.

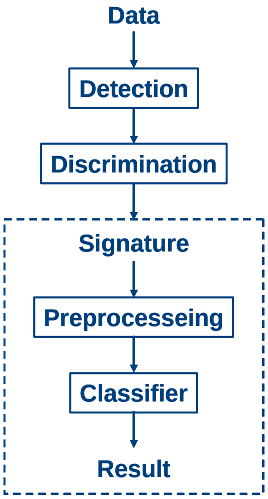

Figure 1 Basic steps of a recognition system.

Many different ways have been tried to implement the motion compensation. The methods include prominent point processing (PPP), contrast optimization, time-frequency methods and phase gradient autofocus (PGA). However, it is difficult to discuss the relative merits of the various methods without considering the application. The underlying motivation is usually an automatic target recognition (ATR) system as shown in Figure 1.

## 2. ISAR IMAGE FORMATION

The general steps of an ISAR image formation processor is shown in Figure 2. The starting point is high range resolution (HRR) profiles of the target. The target must move in such a manner that an effective rotation as seen from the radar is obtained. The motion compensation mentioned in the introduction is included in the “accurate tracking” step. When the tracking is successful, the final imaging step can be as simple as a fast Fourier transform (FFT), although more complicated methods are occasionally needed, particularly when the effective rotation is large. In such cases, it is necessary to take the range migration effect into account.

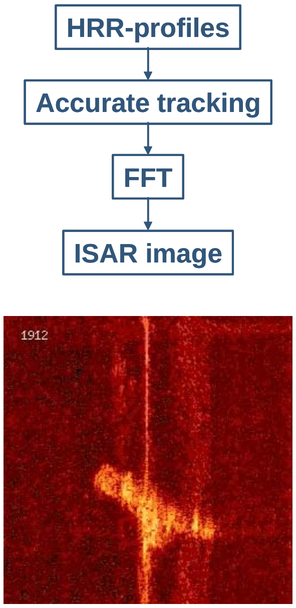

Figure 2 Basic ISAR imaging

In its simplest form, however, the position of a scattering point on the target is found by measuring its range and Doppler frequency simultaneously. This is expressed as

$$r = r_a + x_0$$

$$f_d = 2y_0\Omega / \lambda$$

The target range and cross range position is given by $(x_0, y_0)$, the range to the centre of rotation is given by $r_a$, the radar carrier wavelength is $\lambda$ and the target (instantaneous) rotation is given by the angular velocity $\Omega$.

Alternatively, the tomographic formulation of imaging radar is useful [3]. Mathematically, the formulation is similar to what is obtained for computerized axial tomography as used in medical applications. Any 1D range profile of the target may be seen as a 3D-to-1D projection of the target complex reflectivity distribution. This is illustrated in Figure 3. Conceptually, it does not matter whether the profile is a mono- or bistatic profile. As the target moves relative to the radars, several different projections of the target are seen, and many such 3D-to-1D projections are collected. Together they can be used to fill 3D wavenumber space with target data, and an image of the target may be obtained by transforming the 3D data (coherently) to the spatial domain, see Figure 4.

The concept, while simple in principle, is complicated to apply in practice. There are two main reasons: (1) It is difficult to find the correct position in wavenumber domain of the collected data, and (2) Interpolation and transformation to spatial domain is computationally demanding.

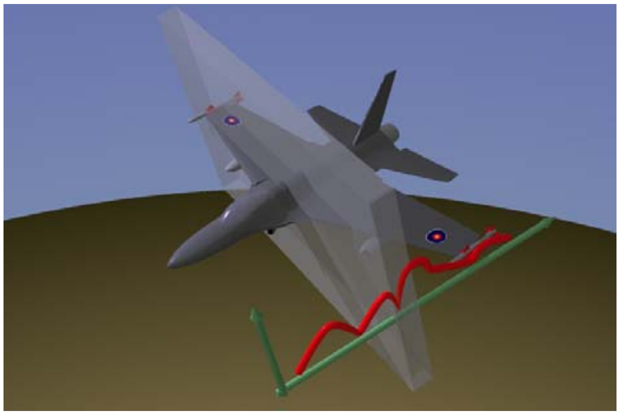

Figure 3 3D-to-1D projection of target.

The main signal processing problem for ISAR imaging of a target with general motion is the motion estimation. The motion is generally unknown and may be complicated. Examples are manoeuvring aircraft or ground targets as well as ships that roll in the ocean waves. This is important since the projection geometry must be estimated to decide where to put data in the wavenumber domain. The accuracy of the motion estimation must be sufficient to make coherent processing possible, which corresponds to relative accuracy of fractions of a radar carrier wavelength. Various autofocus methods are usually useful, many methods relying on optimisation algorithms.

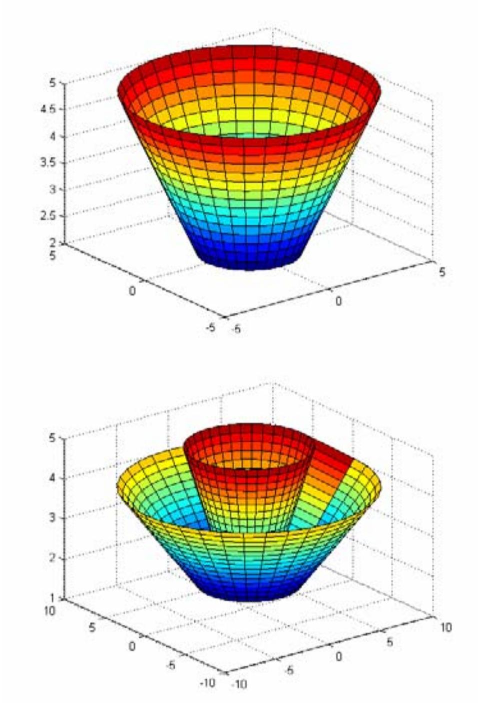

Figure 4 Wavenumber domain sampling for a target with fairly simple motion. Upper is for a single aspect (or radar), lower is for two aspects (or radars).

## 3. COMPARISON OF SIGNAL PROCESSING METHODS

It is difficult to say something general about the quality of an image when the target is not known. This is a problem for autofocus methods, as many of them rely on measures or cost functions. As an example, there are a number of methods that optimize on contrast, a quantity that may be defined in different ways. It is, however, impossible to know a priori what contrast a good image is supposed to have. Furthermore, an image may have a high contrast, yet be blurred due to complicated projection effects.

Accordingly, a possible strategy to evaluate different methods is to make a complete processing chain from data to classification. The performance of a certain method is then compared to others using the classification rate as measurable quantity.

## 4. RANGE ALIGNMENT

The range alignment part of ISAR processing is often challenging. The aim of the range alignment part is to take away all range motion to within a range cell for the rotation centre of target. This motion compensation makes the rotation centre stationary with respect to the radar. It is difficult to make general statements about how the range alignment is to be accomplished, as most radar systems have their own particulars that influence what the high range resolution data needed for ISAR looks like. Most systems rely on a narrowband tracker (at same or different carrier frequency) to place the wide-band data collection window on the target. Accordingly, the idiosyncrasies of the particular tracker implementation influences the target location within the wide-band window. Furthermore, interference between the scatterers on the target effectively changes the global phase centre of the target, an effect that may cause unpredictable shifts in the target location within the collection window. Figure 5 and Figure 6 shows data before and after compensation for the range tracker window placement

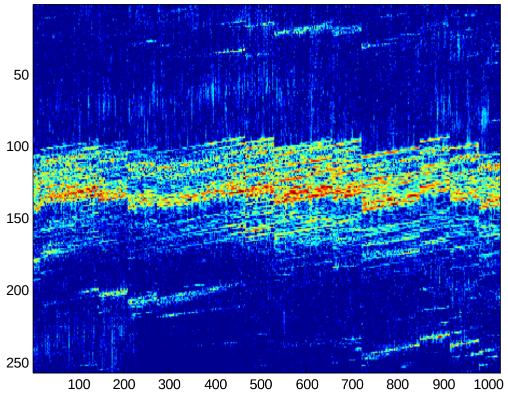

Figure 5 Range profiles before compensation for range tracking.

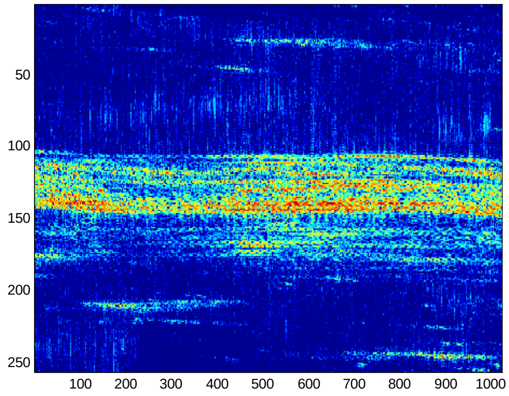

Figure 6 Range profiles after compensation for range tracking.

The actual range alignment is performed in frequency domain. If a certain profile is to be moved by an amount $\Delta r$, the profile is transformed to frequency domain, and the profile is multiplied by the linear phasor

$$\exp\left[ j\varphi(f) \right], \text{ with } \varphi(f) = 4\pi f \Delta r / c.$$

The frequency $f$ is the actual carrier frequency corresponding to that point in the frequency domain representation of the profile. In the discrete case, it is the carrier frequency corresponding to a certain frequency bin.

Often, the range alignment based on the tracking information alone is not sufficient. If this is the case, it is necessary to do further alignment based on the radar data itself. Signal processing options include

- Centre-of-mass tracking.
- Front edge tracking.
- Prominent point tracking.

Several effects influence how well the methods work. The primary effects are the signal-to-noise ratio and the target complexity. The signal-to-noise ratio places a physical limit on the accuracy of the range estimate of the centre-of-mass, front edge or prominent points. If the target moves reasonably smoothly (at a time scale sufficiently longer than the radar pulse repetition interval) the results may be low pass filtered in time to improve the results. Target complexity is important, especially when there are many scatterers in a given range cell. The scatterers interfere with each other and the interference effects make the tracking difficult. Furthermore, strong scatterers with narrow angular response (such as flat plates) may cause bias in the estimates.

The range tracking is essential to get right in order to lay the foundation for a sharp ISAR image. Uncompensated range motion will result in problems that cannot easily be rectified later in the processing.

## 5. PHASE ALIGNMENT

ISAR processing is coherent processing that uses both signal amplitude and phase. The phase measurement must be highly accurate in order to successfully focus the ISAR image. Depending on the characteristics of the phase errors present, the impact on the ISAR image varies from a general increase in the image noise floor to complicated smearing and blurring. Generally, the phase errors should be much smaller than $2\pi$ if a sharp image is to be obtained. Well behaved (low-frequency) errors that are greater may be tolerated in some cases, but generally the requirement is rather strict. Phase errors are of two kinds. The easiest to compensate for is the phase errors that are constant with range, i.e. there is one phase value valid for an entire range profile. Such errors are caused among other by uncompensated range motion, phase drifts and jumps in the radar hardware, and variations in microwave propagation conditions. More difficult is the kind of phase errors that are not constant with range. When the errors have been taken away, the phase history is ideally a linear ramp. But this is the case only for a planar rotation of the target with *constant* angular velocity. When target 3D structure and complicated rotation is taken into account, each reflector will have its own curve shape, and the focusing cannot necessarily be accomplished by a straightforward Fourier transform.

As an example, consider the SAR signature shown in Figure 7. Here, we see azimuth smearing caused by target motion. The target was a corner reflector on top of a car [4].

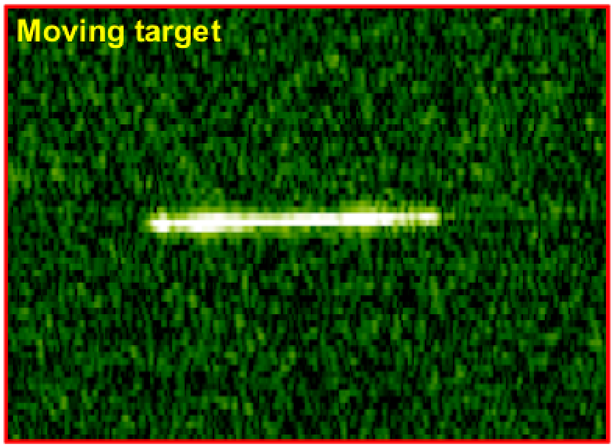

Figure 7 Blurred SAR signature of moving target (corner reflector).

Here, the ideal image would be a point reflector, while the actual image shows an azimuth smear. The smear is caused by the phase history of the uncompensated motion. Since the range bin contains one point reflector much stronger than anything else, it is fairly simple to measure the phase history and focus the reflector. A good way to illustrate the information contained is using a time-frequency technique [5]. Time-frequency techniques of the Cohen's class have been shown to be very useful in analysing complicated phase histories [6], and we use here the adaptive optimal kernel (AOK) method [7]. The result is shown in Figure 8.

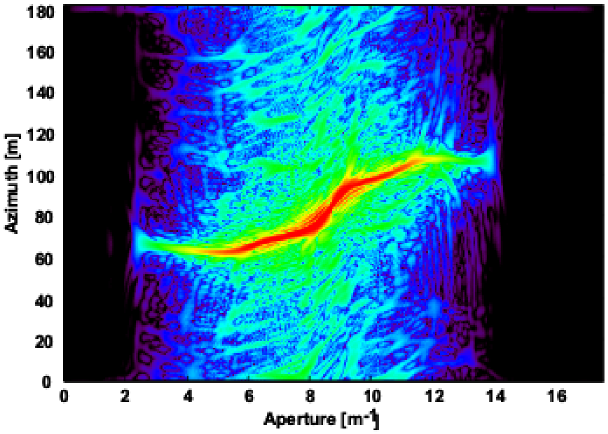

Figure 8 Time-frequency signature of moving reflector.

Here, the phase history time-frequency distribution is seen to correspond to just one reflector, but with time-dependent frequency. A fixed reflector would show up as just a constant frequency, corresponding to a linear phase ramp. Accordingly, the time-frequency method accomplishes the phase tracking, and a series of focused images of the reflector (corresponding to horizontal slices of the time-frequency response) are obtained.

## 6. CONCLUSIONS

ISAR processing relies on accurate tracking in range as well as in phase. Signal processing techniques such as tracking, interpolation, Fourier imaging and time-frequency methods must be used in order to obtain sharp images. With careful design, a processor can compensate for errors and motion effects, and images useful for ATR may be obtained.

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