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PREFACE

The chapters in this volume were presented at the July–August 2006 NATO Advanced Study Institute on *Imaging for Detection and Identification*. The conference was held at the beautiful Il Ciocco resort near Lucca, in the glorious Tuscany region of northern Italy. For the eighth time we gathered at this idyllic spot to explore and extend the reciprocity between mathematics and engineering. The dynamic interaction between world-renowned scientists from the usually disparate communities of pure mathematicians and applied scientists which occurred at our seven previous ASI's continued at this meeting.

The fusion of basic ideas in mathematics, radar, sonar, biology, and chemistry with ongoing improvements in hardware and computation offers the promise of much more sophisticated and accurate detection and identification capabilities than currently exist. Coupled with the dramatic rise in the need for surveillance in innumerable aspects of our daily lives, brought about by hostile acts deemed unimaginable only a few short years ago, the time is ripe for image processing scientists in these usually diverse fields to join together in a concerted effort to combat the new brands of terrorism. This ASI was one important initial step.

To encompass the diverse nature of the subject and the varied backgrounds of the participants, the ASI was divided into three broadly defined but interrelated areas: the mathematics and computer science of automatic detection and identification; image processing techniques for radar and sonar; detection of anomalies in biomedical and chemical images. A deep understanding of these three topics, and of their interdependencies, is clearly crucial to meet the increasing sophistication of those who wish to do us harm. The principal speakers and authors of the following chapters include many of the world's leading experts in the development of new imaging methodologies to detect, identify, and prevent or respond to these threats.

The ASI brought together world leaders from academia, government, and industry, with extensive multidisciplinary backgrounds evidenced by their research and participation in numerous workshops and conferences. This forum provided opportunities for young scientists and engineers to learn more about these problem areas, and the crucial role played by new insights, from recognized experts in this vital and growing area of harnessing mathematics and engineering in the service of a world-wide public security interest. An ancillary benefit will be the advancement of detection and identification capabilities for natural threats such as disease, natural disasters, and environmental change.

The talks and the following chapters were designed to address an audience consisting of a broad spectrum of scientists, engineers, and mathematicians involved in these fields. Participants had the opportunity to interact with those individuals who have been on the forefront of the ongoing explosion of work in imaging and detection, to learn firsthand the details and subtleties of this exciting area, and to hear these experts discuss in accessible terms their contributions and ideas for future research. This volume offers these insights to those who were unable to attend.

The cooperation of many individuals and organizations was required in order to make the conference the success that it was. First and foremost I wish to thank NATO, and especially Dr. F. Pedrazzini and his most able assistant, Ms. Alison Trapp, for the initial grant and subsequent help. Financial support was also received from the Defense Advanced Research Projects Agency (Drs. Joe Guerci and Ed Baranoski), AFOSR (Drs. Arje Nachman and Jon Sjogren), ARO (Drs. Russ Harmon and Jim Harvey), EOARD (Dr. Paul Losiewicz), ONR (Mr. Tim Schnoor, Mr. Dave Marquis and Dr. Tom Swean) and Prometheus Inc. This additional support is gratefully acknowledged.

I wish to express my sincere appreciation to my assistants Parvaneh Badie, Marcia Byrnes and Ben Shenefelt and to the co-director, Temo Matcharashvili, for their invaluable aid. Finally, my heartfelt thanks to the Il Ciocco staff, especially Bruno Giannasi, for offering an ideal setting, not to mention the magnificent meals, that promoted the productive interaction between the participants of the conference. All of the above, the speakers, and the remaining conferees, made it possible for our Advanced Study Institute, and this volume, to fulfill the stated NATO objectives of disseminating advanced knowledge and fostering international scientific contacts.

August 6, 2006

Jim Byrnes
Il Ciocco, Italy

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CONTENTS

MULTI-PERSPECTIVE IMAGING AND IMAGE INTERPRETATION

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Abstract. High resolution range profiling and imaging have been the principal methods by which more and more detailed target information can be collected by radar systems. The level of detail that can be established may then be used to attempt classification. However, this has typically been achieved using monostatic radar viewing targets from a single perspective. In this chapter methods for achieving very high resolutions will be reviewed. The techniques will include wide instantaneous bandwidths, stepped frequency and aperture synthesis. Examples showing the angular dependency of high range resolution profiles and two-dimensional imagery of real, full scale targets are presented. This data is examined as a basis for target classification and highlights how features observed relate to the structures that compose the target. A number of classification techniques will be introduced including statistical, feature vector and neural based approaches. These will be combined into a new method of classification that exploits multiple perspectives. Results will be presented, again based upon analysis of real target signatures and are used to examine the selection of perspectives to improve the overall classification performance.

Key words: ATR, radar imaging, multi-perspective classification

1. Introduction

Target classification by radar offers the possibility of remotely identifying objects at ranges well in excess of those of any other sensor. Indeed radar has been employed in operational systems for many years. However, the systems use human interpretation of radar data and performance is generally unreliable and slow. Nevertheless, the benefits of fast and reliable classification are enormous and have the potential for opening huge areas of new application. Research in recent years has been intense but still, automated or semi-automated classification able to work acceptably well in all conditions

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seems a long way off. The prime approach to developing classification algorithms has been to use higher and higher spatial resolutions, either one dimensional range profiles (Hu and Zhu, 1997) or two-dimensional imagery (Novak et al., 1997). High resolution increases the level of detail in the data to be classified and this has generally been seen as providing more and better information. However, the performance of classifiers, whilst very good against a limited set of free space measurements is much less satisfactory when applied to operationally realistic conditions. In this chapter we will review methods for obtaining high resolution, use these to generate high resolution target signatures and subsequently illustrate some of their important aspects that require careful understanding if classification is to be successful. We then examine some typical classifiers before considering in more detail an approach to classification that uses a multiplicity of perspectives as the data input. This also enables much information about the nature of target signatures and their basis for classification to be evaluated.

Firstly though, the concepts of resolution and classification are discussed as these terms are often used with imprecise or varying meanings. Most often resolution is defined as the ability of radar (or any sensor) to distinguish between two closely spaced scatterers. A measure of this ability is captured in the radar system point spread function or impulse response function with resolving power being determined by the 3-dB points. This is a reasonable definition but care needs to be taken as there is an implicit assumption that the target to be considered has point like properties. This is well known not to be the case, but nevertheless it has proved a useful descriptor of radar performance. As will be seen later, if resolution is improved more scatterers on a target can be distinguished from one another and there is undoubtedly an improved amount of detail in the resulting signature. Care also has to be taken with synthetic aperture imaging in two dimensions such as SAR and ISAR. These imaging techniques again have an implicit assumption that targets have point like properties and are continuously illuminated during formation of the image. Once again most targets are not points and quite often there is occlusion of one target by another. For example high placed scatterers near the front of a target often place the scatterers further back in shadow and hence they are not imaged. Thus the resolution in a typical SAR image is not necessarily constant, a fact often overlooked by developers of classification algorithms. However, once again, these assumptions have still resulted in robust SAR and ISAR image generation and as larger apertures are synthesised there is an undeniable increase in detail in the resulting imagery. We will return to these themes as we explore high resolution techniques and approaches to classification of the resulting target signatures.

2. High Down Range Resolution Techniques

Despite the reservations discussed above we nevertheless begin by modelling the reflectivity from a target as the coherent sum of a series of spatially separated scatterers (Keller, 1962). Its simplicity offers valuable insight into some of the scattering processes observed. Thus the frequency domain reflectivity function $\zeta_{\theta}(f)$ of a complex target illuminated at a given aspect angle θ by an incident field of frequency $\lambda \ll D$, where D is the physical dimension of the target, is given by:

$$\zeta_{\theta}(f) = \sum_{i=1}^{N} \zeta_{\theta}^{i}(f) \tag{1}$$

where

$$\zeta_{\theta}^{i}(f) = A_{\theta}^{i}(f) \exp\left[-j\vartheta_{\theta}^{i}(f)\right]. \tag{2}$$

Thus we see that the amplitude and phase of the ith scatterer depend on both frequency and aspect angle. An inverse FFT will yield the complex reflectivity function or range profile, where the magnitude in each of the IFFT bins represents the magnitude of the reflections from the scatterers in a range resolution cell.

The resolution in the range dimension is related directly to the pulse width (T_{p}) of the waveform. Two targets of equal RCS are said to be recognized as being resolved in range when they are separated from each other by a distance:

$$d = \frac{cT_{\mathrm{p}}}{2}. \tag{3}$$

This equation tells us the range resolution of a pulsed radar system when the pulse is not modulated. Thus a very short pulse is needed if high range resolution is required. Indeed to resolve all the scatterers unambiguously the pulse length has to be short enough such that only one scatterer appears in each range cell. Normally as high a range resolution as possible is used and it is accepted that not all scatterers will be resolved. The resulting ambiguity is one source of ensuing difficulty in the next stage of classification.

In long range radar, a long pulse is needed to ensure sufficient energy to detect small targets. However, this long length waveform has poor range resolution. The use of a short duration pulse in a long range radar system implies that a very high peak power is required. There is a limitation on just how high the peak power of the short pulse can be. Ultimately the voltage required will 'arc' or breakdown, risking damage to the circuitry and poor efficiency of transmission.

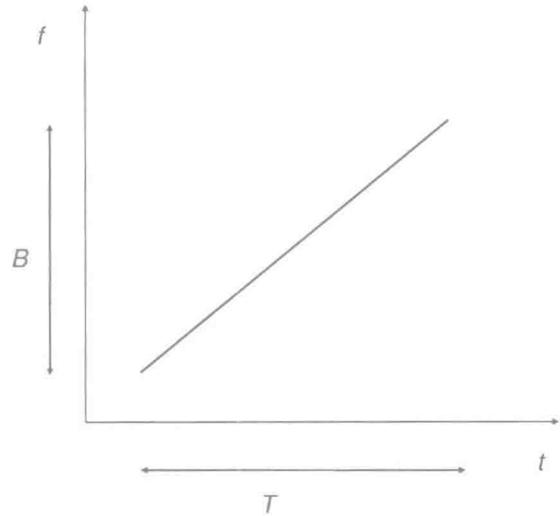

Figure 1. Changing the frequency as a function of time across the duration of a pulse. B is the modulation bandwidth and T the pulse duration.

One method which is commonplace today that overcomes this limitation is pulse compression (Knott et al., 1985).

Pulse compression is a technique that consists of applying a modulation to a long pulse or waveform such that the bandwidth B of the modulation is greater than that of the un-modulated pulse (i.e. $1/T_p$). On reception the long pulse is processed by a matched filter to obtain the equivalent resolution of a short pulse (of width $1/B$). In the time domain the received signal is correlated with a time reversed replica of the transmitted signal (delayed to the chosen range). This compresses the waveform into a single shorter duration that is equivalent to a pulse of length given by $1/B$. In other words it is determined by the modulation bandwidth and not the pulse duration. Thus the limitation of poor range resolution using long pulses is overcome and long range as well as high resolution can both be achieved together. Here pulse compression can be achieved by frequency, phase and amplitude modulation. The most common form of modulation used is to change the frequency from the start to the end of the pulse such that the required bandwidth B is swept out as shown in Figure 1. This leads to a resolution given by:

$$d = \frac{c}{2B}. \tag{4}$$

To achieve even higher range resolutions a frequency modulated stepped-frequency compressed waveform may be employed. This reduces the instantaneous modulation bandwidth requirement while increasing the overall bandwidth. In other words the necessary wider bandwidth waveform is

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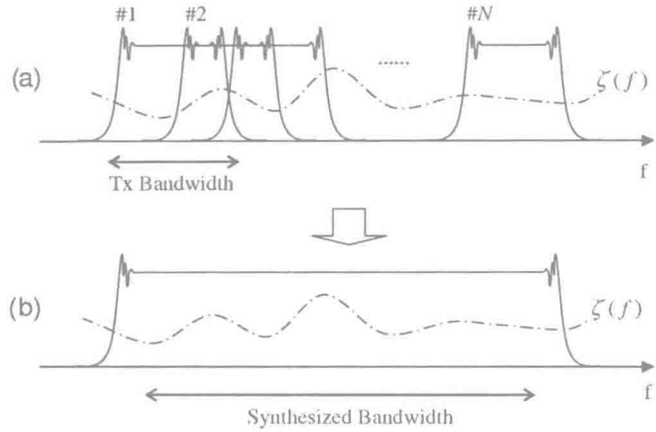

Figure 2. Spectrum reconstruction of the target reflectivity function using a series of chirp pulses (a) and the corresponding synthesised bandwidth (b).

synthesised using a number of pulses. However, note that this has the disadvantage of collecting the individual waveforms over a finite period of time making the required coherency vulnerable to target motion. High range resolution (HRR) profiles are subsequently produced by processing a wideband reconstruction of a targets reflectivity spectrum in the frequency domain (Wilkinson et al., 1998). By placing side by side N narrower chirp waveforms or pulses of bandwidth B and using an inter-pulse frequency step increment also equal to B, it is possible to synthesise a total bandwidth of $B_t = (N + 1)B/2$. This is illustrated in Figure 2.

A range profile may then be defined as a time sequence of the vector sum of signals reflected back by different scatterers within a range cell. By matched filtering this stepped frequency waveform a range resolution $d = c/(2NB)$ is achieved. The received signal is the transmitted pulse modulated by the corresponding sub-spectrum representing the target reflectivity function. By adding the compressed individual portions of reflectivity function, which result from time convolution between each received pulse with the complex conjugate of the corresponding transmitted pulse, the entire spectrum is eventually obtained commensurate with the extended bandwidth. The HRR profile may then be synthesised from an inverse FFT applied to each row of the time history of the target's frequency domain signature matrix.

3. High Cross Range Resolution

In real aperture radar the cross range resolution is determined by the antenna beamwidth. This is often thought of as being so large that it effectively produces no resolution of any value and is why HRR profiles are often referred to as one-dimensional target signatures. In reality they are two dimensional images where one of the dimensions of resolution is very poor.

The real beamwidth (or cross range resolving power) is defined as the width at the half power or 3-dB points from the peak of the main lobe. The beamwidths may be the same in both the elevation (vertical) and the azimuth (horizontal) dimensions, although this is by no means mandatory. The beamwidth in radians is a function of antenna size and transmission wavelength. For a circular aperture (i.e. a circular profile of a parabolic dish) the beamwidth in radians at the half power or 3-dB points is given approximately by:

$$B_{\mathrm{az}} = \frac{\lambda}{D}. \tag{5}$$

This means that the cross-range extent of the beam at a range R is given by:

$$R_{\mathrm{az}} = R\frac{\lambda}{D}. \tag{6}$$

Thus for a range of only 10 km and a wavelength of 3 cm, a 0.5 m diameter antenna will have a cross range resolution of 600 m. This contrasts with a fre quency modulated pulse bandwidth of 500 MHz leading to a range resolution of 30 cm. It is typical to have equal down and cross range resolutions.

Two techniques by which much higher cross range resolution may be obtained are SAR and ISAR. These are essentially completely equivalent and rely on viewing a target over a finite angular ambit to create a synthetic aperture with a length in excess of that of the real radar aperture and hence able to provide a higher resolution. The greater the angular ambit traversed, the greater the length of the synthesised aperture and the higher the cross range resolution. Here we will confine our discussions to ISAR imaging only and the interested reader is referred to excellent textbooks that cover SAR imaging (Curlander and McDonough, 1991; Carrara et al., 1995).

To form an ISAR image the HRR profiles assembled using the step frequency technique reviewed in the previous section are used. To obtain the magnitude of the ISAR image's pixel in lth range cell and jth Doppler cell ($D_{l,j}$) an FFT is applied to each column of the matrix representing the time history of target's range profile. This is demonstrated in Figure 3.

For ISAR, the resolution achieved in cross-range depends upon the minimum resolvable frequency Δf_D between two adjacent scatterers (Wehner, 1995). Doppler resolution is also related to the available coherent time of integration T which is equal to the time required to collect the N chirp returns.

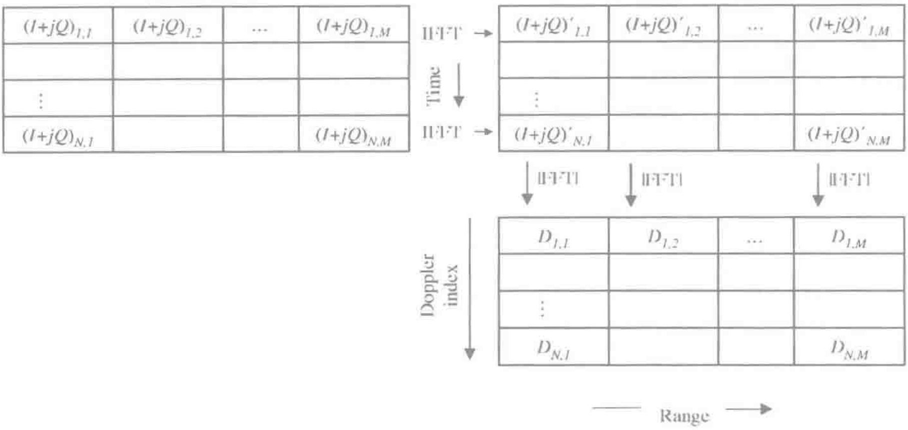

Figure 3. Matrix decomposition for HRR profiles and ISAR imagery.

Therefore, consecutive reflectivity samples from the same range cells are taken every $N\Delta T$ seconds:

$$\Delta f_D = \frac{1}{N\Delta T} \approx \frac{1}{T}. \tag{7}$$

As a consequence, the cross-range resolution Δr_c can be written as:

$$\Delta r_c = \frac{c\Delta f_D}{2\omega_0 f_c} = \frac{\lambda}{2\omega_0 T} \tag{8}$$

where $\lambda = c/f_c$ is the illuminating wavelength and ω_0 is the angular velocity of the target rotational motion.

In ISAR image processing the motion of the target is usually unknown. The target motion can be seen as the superposition of rotational and translational motions with respect to the radar system. If the former contributes to the ability to resolve in cross-range, in order to obtain a focused image of the target it is necessary to compensate for phase errors due to the translational motion occurring during data collection. This is usually referred to as motion compensation. After this correction an ISAR image may be obtained by processing data collected over an arc of circular aperture whose dimensions depend on the rotational speed of the target ω_0 and the integration time T. There may still be further residual motions that require correction using autofocus techniques. We now introduce experiments by which HRR profiles and ISAR images are generated.

4. High Resolution Target Signatures

In this section we exploit the high resolution techniques introduced above to examine the form of the resulting signatures. To do this we use measurements made of calibration and vehicle targets that have been mounted on a slowly rotating platform. Figure 4 shows the experimental set up. Here the radar system views a turntable at a shallow grazing angle of a few degrees. The figure shows corner reflector calibration targets in place. Two are located on the turntable and two are located in front of and behind the turntable. Additional experiments have also been performed with the corners removed and a vehicle target situated on the turntable instead. The profiles are generated from an X-band radar having an instantaneous bandwidth of 500 MHz. Eight frequency steps spaced by 250 MHz are used to synthesise a total bandwidth of 2.25 GHz. The turntable data is first enhanced by removing any stationary clutter (Showman et al., 1998). Estimation and subtraction have been performed in the frequency domain.

Figure 5 shows the resulting range profiles and their variation as the turntable rotates through 360°. The two stationary trihedrals show a constant response at near and far range as expected. For the two rotating trihedral targets, when the line-of-sight is on the trihedral bisector, a peak of reflection occurs. This is consistent with the expected theoretical response. As the trihedral targets rotate, the backscattered field decreases progressively until a point is reached where there is a peak of specular reflection. This is a reflection from one of the sides making up the trihedral which is orthogonal to the illuminating radar system (i.e. it faces the radar beam and looks like a flat plate reflector). At increasing rotation angles the RCS of the target drops since the orientation of the trihedral is such that it tends to reflect incident radiation away from the radar.

This angular dependency of the RCS of a well known reflector such as a trihedral begins to illustrate how the backscattering properties of real targets may vary with the orientation of observation. For example if a target has part of its structure that mimics a trihedral it may show this feature over a similarly

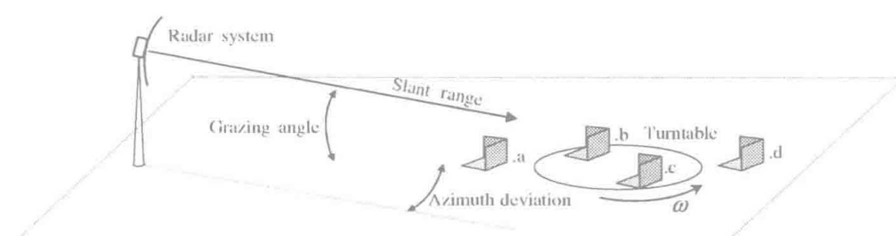

Figure 4. ISAR geometry: two stationary corner reflectors are in front of and behind the turntable, while two rotating ones are placed on the turntable.

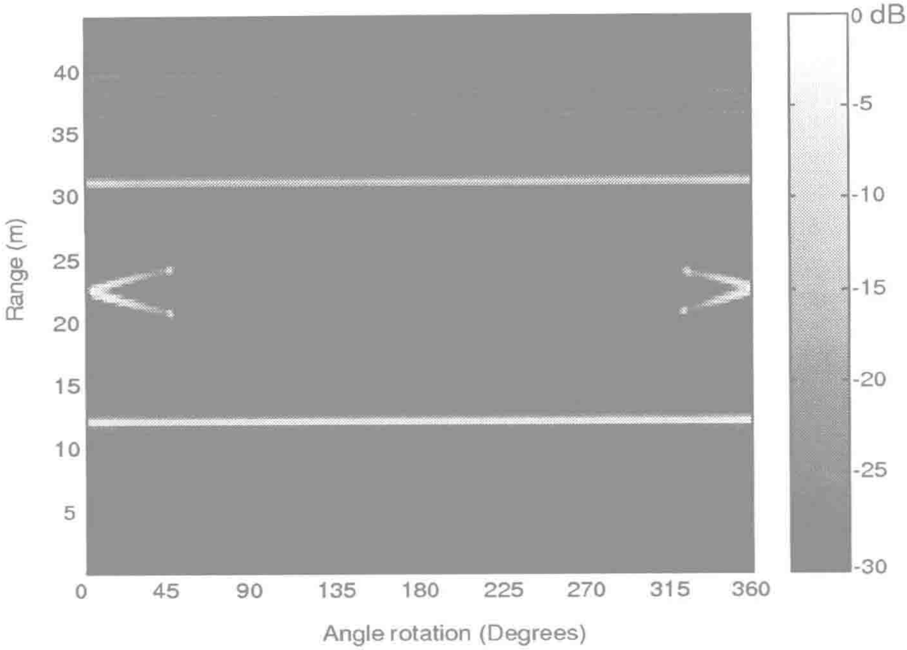

Figure 5. History of HRR range profiles (30 cm of range resolution) from four corner reflectors, two rotating and two stationary. The 0° angle is in correspondence of the two corners having the same range relative to the system and facing directly the radar beam.

limited angular range. Thus in a multi-perspective (M-P) environment, different angular samples of a target's signature should improve the likelihood of observing a corner or corner like reflector and recognising it as such. Particular shapes such as flat plates and corners can be common on many manmade structures and are often quite dominant features that may prove useful for classification.

In Figure 6, the complete angular ambit of range profiles spanning 360° from a Land Rover vehicle rotating on the turntable is shown.

This highlights a number of different scattering behaviours: the strong peaks from specular reflections (0°, 90°, 180°) appear over a very limited angle range and obscure nearby point-like backscattering. Corner-like returns can be observed at far range (~6 m) for two range angular spans (~[10° − 60°] and [130° − 180°]). These returns correspond to the trihedral like structures formed at the rear of the Land Rover. This is a vehicle without the rear soft top and has a metallic bench seat that makes a corner where it joins the rear bulkhead of the drivers cabin. At ~8 m range there is a double bounce return corresponding to one of the corners. This type of effect increases the information that can be processed which would be otherwise impossible to reconstruct by a traditional single perspective approach. It also illustrates the

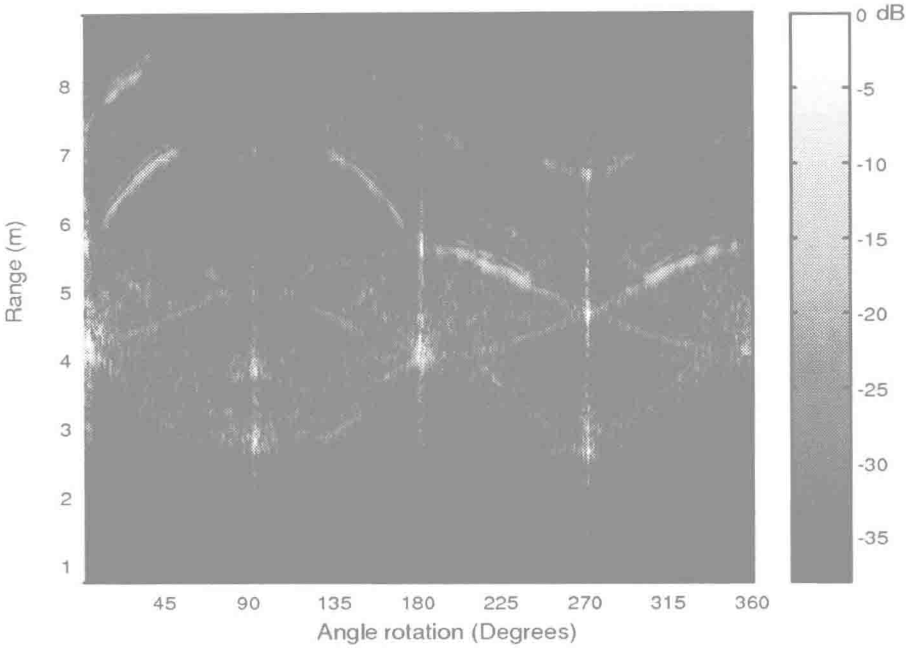

Figure 6. History of HRR range profiles (range resolution less than 15 cm) from a series of X-Band stepped frequency chirps illuminating a ground vehicle as it rotates over 360°. At 0°, the target is broadside oriented, while at 90° has its end-view towards the radar.

complexity and subtlety of radar target scattering. Note also that here we are dealing with targets on turntables where there is no clutter or multipath and the signal to noise ratio is high. In more realistic scenarios the scattering from targets will in fact be even more complicated.

The turntable data can be processed using the ISAR technique to yield two-dimensional imagery.

Figure 7 shows a series of ISAR images of a Ford Cougar car in which the number of perspectives used to form the imagery is slowly increased. It is clear that when only a single perspective is used there is considerable self-shadowing by the target and the shape cannot be determined with good confidence. When all eight perspectives are employed then the effects of self-shadowing are largely eliminated and much more complete information is generated. Note, however, that the concept of resolving scatterers as seemed to be observed in the range profiles of the Land Rover is much less obvious. As with most modern vehicles the Cougar is designed to have low wind resistance and has little in the way of distinct scattering centres. This begins to place in question both the image formation process and classification techniques if they are using a point target scatterer model assumption.

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