Applications of Time-Frequency Processing to Radar Imaging

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Abstract

High resolution radar image is always demanded. To achieve high resolution, wideband signal and longer imaging time are required. However, due to time-varying behavior of returned radar signals and due to multiple backscatering behavior of targets, radar image resolution can be significantly degraded and images become blurred.

Conventional radar processor uses the Fourier transform to retrieve Doppler information. In order to use the Fourier transform adequately, some restrictions must be applied: the scatterers must remain in their range cells and their Doppler frequency contents should be stationary during the entire imaging time duration. However, due to target's complex motion, the Doppler frequency contents are actually time-varying. Therefore, the Doppler spectrum obtained from the Fourier transform becomes smeared, and, thus, the resolution of the radar image is degraded. However, the restrictions of the Fourier processing can be lifted if the Doppler information can be retrieved with a method which does not require stationary Doppler spectrum. Therefore, the image blurring caused by the time-varying Doppler spectrum can be resolved without applying sophisticated motion compensation. By replacing the conventional Fourier transform with a time-frequency transform, a 2-D range-Doppler Fourier frame becomes a 3-D time-range-Doppler cube. By sampling in time, a time sequence of 2-D range-Doppler images can be viewed. Each individual time-sampled image from the cube provides superior image resolution and also enhanced signal-to-noise ratio.

When target contains cavities or duct-type structures, these scattering mechanisms appear in radar images as blurred clouds extended in range dimension. It is very useful to combine adaptive time-frequency wavelet transform with the radar imaging technique so that the "clouds" can be removed and their resonance frequencies can be identified. By applying time-frequency processing for each cross-range lines of radar image, a 3-D range-Doppler-frequency cube is generated. The frequency slices of the cube provide information for identifying scattering centers as well as resonance frequencies.

Keywords: Radar imaging, adaptive wavelet transform, time-frequency processing

1 Background on Radar Imaging of Moving Targets

Since radar images convey information which may not be obtainable by other imaging means, they are widely used in many areas, such as remote sensing and wide area surveillance [1, 2, 3].

Radar transmits electromagnetic waves to a target which consists of a number of point scatterers and receives the scattered waves from the target. In the radar receiver, the returned signal from the target is the sum of the returned signals from the scatterers of the target. The scattering properties of the target describe the features of the target. Since the integrated effect of the scattered fields can be measured directly by the radar, the spatial distribution of the reflectivity corresponding to the target can be constructed by a radar processor. The distribution of the reflectivity is refered to as the radar image of the target. The target's reflectivity is usually mapped onto a range (or down-range) and cross-range plane and is viewed as a radar image of the target. The range is the dimension along the radar line-of-sight to the target. The cross-range is the dimension transverse to the line-of-sight.

A useful radar image must represent the spatial distribution of the radar reflectivity faithfully. Therefore, high resolution radar images are always demanded. The range resolution is directly related to the bandwidth of the transmitted radar signal. Stepped-frequency waveforms and frequency-modulated chirp waveforms are examples of the wide-band radar signal, which are commonly used in radar imaging system to achieve high range resolution. The cross-range resolution is determined by the antenna beamwidth, which is inversely proportional to the length of the antenna aperture.

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Thus, a larger antenna aperture can provide higher cross-range resolution. To achieve high cross-range resolution without using a large antenna aperture, synthetic array processing is widely employed. Synthetic array radar processing coherently combines signals obtained from sequences of small apertures to emulate the result from a large aperture.

Synthetic array radar includes both synthetic aperture radar (SAR) and inverse synthetic aperture radar (ISAR). Traditionally, SAR refers to the situation where the radar is moving and the target is stationary; ISAR refers to the geometrical inverse in which the target is moving and the radar is stationary. For ISAR, the synthetic aperture is formed by coherently combining signals obtained from a single aperture as it observes a rotating target. The rotation of the target emulates the result from a larger circular aperture focusing at the rotation center of the target.

ISAR uses Doppler information to obtain the cross-range resolution. Due to the target's rotation, which can be characterized as a superposition of pitch, roll, and yaw motions, different parts of the target have slightly different velocities relative to the radar and, hence, produce slightly different Doppler frequencies in the radar receiver. The differential Doppler shift of adjacent point scatterers can be observed in the receiver; therefore, the distribution of the target's reflectivity can be measured by the Doppler spectrum. The conventional method to retrieve Doppler information is the Fourier transform.

Based on the returned signal from a single point scatterer, the returned signal from the target can be represented as the integration of the returned signals from all scatterers in the target:

$$S(f,t) = exp(-j4\pi f R(t)/c) \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x,y) exp\{-j2\pi(x f_x(t) - y f_y(t))\} dxdy \tag{1}$$

and the components of the spatial frequency are

$$f_x = \frac{2f}{c}\cos\theta(t) \tag{2}$$

and

$$f_y = \frac{2f}{c}\sin\theta(t) \tag{3}$$

where the range $R(t)$ and the rotation angle $\theta(t)$ of the aircraft are functions of time.

The objective of radar processing is to estimate the target's reflective density function $\rho(x,y)$ from received baseband signal samples, the so-called frequency signature $S(f,t)$. From Eq.(1) we know that if the target's range is known exactly and the velocity and acceleration of the target's motion are constant and known exactly over the imaging time duration, then the extraneous phase term of the motion $exp\{-j4\pi f R(t)/c\}$ can be exactly removed by multiplying $exp\{+j4\pi f R(t)/c\}$ on both sides of Eq.(1). Therefore, the reflective density function $\rho(x,y)$ of the target can be obtained simply by taking the inverse Fourier transform of the phase compensated frequency signature $S(f,t)\exp\{+j4\pi f R(t)/c\}$. The process of estimating the target's range $R(t)$ and removing the extraneous phase term $exp\{-j4\pi f R(t)/c\}$ is called focusing or gross translational motion compensation. Then, the inverse Fourier transform can be used to construct the reflective density function of the target. For SAR, the motion compensation is facilitated by measuring the actual motion of the radar platform. In ISAR, the actual motion can be measured by a range-tracker, or estimated by a motion compensation algorithm which estimates motion parameters and compensates motion with respect to the target's range, velocity, acceleration and other higher order terms.

Fig.1 illustrates the process of the synthetic aperture radar imaging using the stepped-frequency waveform. The stepped-frequency radar transmits a sequence of N bursts. Each burst consists of M narrow-band pulses. Within each burst, the center frequency of each succesive pulse f_m is increased by a constant frequency step Δf. The total bandwidth of the burst, i.e., M times the frequency step Δf, determines the radar range resolution. The total number of bursts, N, determines the Doppler or cross-range resolution. The returned pulse is heterodyned and quadraturely detected in the radar receiver.

To form a radar image, after collecting the returned signals, the M-by-N complex data are organized into a two-diemensional array which represents the unprocessed spatial frequency signature of the target, $S(f_{mn}, t_{mn})$.

The received frequency signatures of the bursts can be treated as the time history series of the target's reflectivities at each discrete frequency. The radar processor uses the frequency signatures as the raw data to perform range processing and Doppler processing. Range processing functions as a matched filter for use with pulse compression, which removes frequency or phase modulation and resolves range. For the stepped-frequency signals, the range processing performs M-point inverse discrete Fourier transform (IDFT) for each of the N received frequency signatures. Therefore, N range profiles (i.e., the distribution of the target reflectivities in range) each containing M range cells can be obtained. For

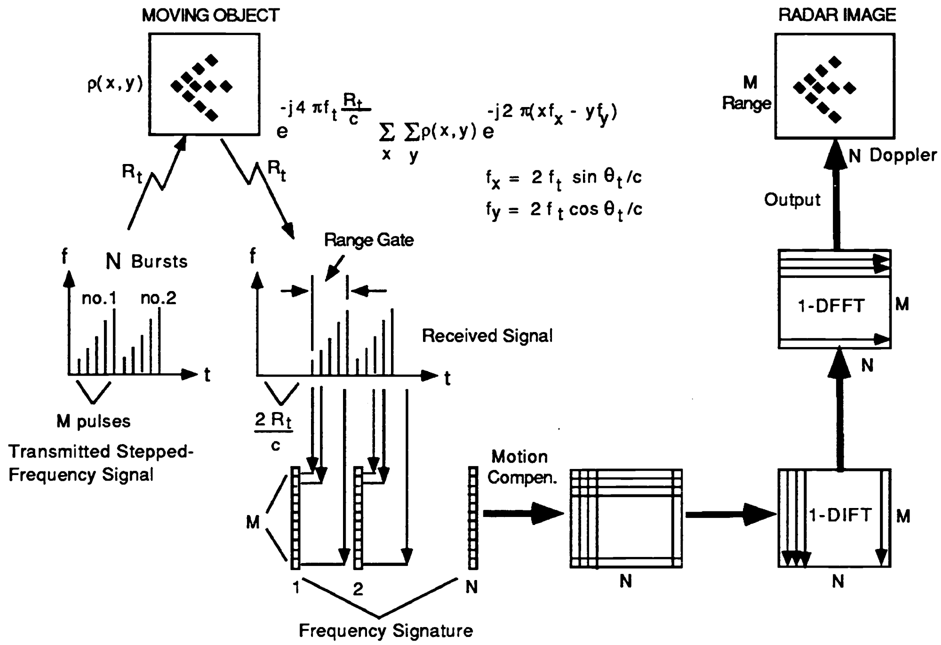

Figure 1: Illustration of a stepped-frequency inverse synthetic radar imaging of a moving target.

each range cell, the N range profiles constitute a new time history series, which is sampled at baseband with N in-phase (I-channel) and N quadrature-phase (Q-channel) data. Then, the Doppler processing takes the discrete Fourier transform (DFT) for the time history series and generates an N-point Doppler spectrum, or profile. By combining the M Doppler spectra at M range cells, finally, the M-by-N image is formed. Therefore, the radar image is the target's reflectivities mapping onto the range-Doppler plane.

2 Time-Frequency Transform for Doppler Processing

Conventional Doppler processing of radar imaging systems uses the Fourier transform. In order to use the Fourier transform properly, some restrictions must be applied. Doppler processing using Fourier transforms is adequate only in the case that the scatterers remain in their range cells and that their Doppler frequency shifts are constant during the entire observation time. If the scatterers drift out of their range cells or their Doppler frequency shifts are time-varying, then the constructed image becomes blurred. A process of establishing aligned range and constant phase change-rate for each individual scatterer is called a complete motion compensation procedure.

Motion compensation is a very important step to achieve the reqirements of using Fourier processing and to have a clear radar image. Conventional motion compensation is a gross compensation for the whole target. It performs mainly the range and the Doppler tracking. While a target is moving smoothly, the conventional motion compensation is good enough to produce a clear image of the target. The conventional approach for range tracking uses simple hot-spot tracking [4].

However, when a target exhibits complex motion, such as pitching, yawing, rolling, or maneuvering, the conventional motion compensation for the whole target is not sufficient to produce an acceptable image for viewing and analysis. In this case, a more sophisticated motion compensation procedure for each individual scatterer such as polar reformatting [2] and sub-aperture approach [5] is needed. It keeps each scatterer within its range cell and to maintain constant Doppler frequency shift for each of them. Thus, the Fourier transform may be applied properly to construct a clear image of the target.

In case a target exhibits significant maneuvering, even sophisticated motion compensation is still not sufficient, and the residual of the motion is still large. With large motion residuals or phase errors, individual scatterers may still drift

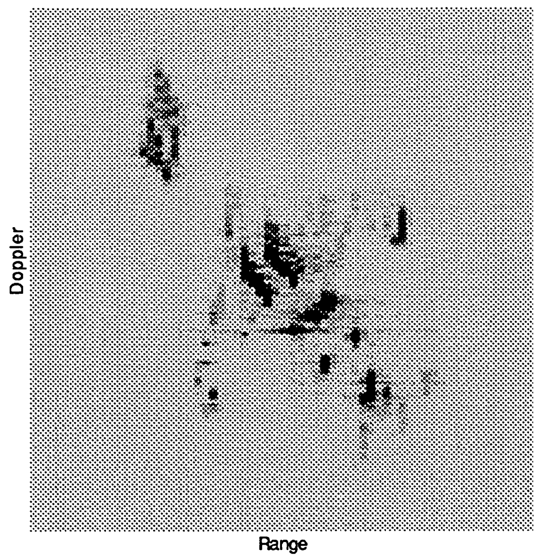

Figure 2: Radar image of the aircraft from simulated data with uncompensated phase errors by using Fourier transform.

through their range cells; thus, the Doppler spectrum may still be time-varying. Therefore, the resulting image could be blurred if the Fourier transform were used. If a high resolution time-frequency processing can be used to replace the Fourier transform, then the restrictions of the Fourier transform can be lifted. Thus, there is no need to eliminate the drift through range cells and no need to keep Doppler frequency shift constant for each scatterer. By using high resolution time-frequency processing, the motion of each individual scatterer is actually examined at each time instant. Since each scatterer has its own range and its own Doppler shift at each time instant, there is no scatterer overlapping; therefore, no image blurring occurs [6,7,8,9].

By replacing the conventional Fourier transform with a joint time-frequency transform, a 2-D range-Doppler Fourier frame becomes a 3-D time-range-Doppler cube. By sampling in time, a time sequence of 2-D range-Doppler images can be viewed. Each individual time-sampled image from the cube provides not only higher resolution but also the temporal information within each observation time.

From time-varying spectrum point of view, the uncompensated phase error causes the Doppler spectrum to be time-varying. If we deal with the time-varying Doppler spectrum using the conventional Fourier transform processing, the image becomes blurred as shown in Fig.2. By replacing the Fourier transform with a time-frequency transform, the single image frame is resolved into a stack of its temporal frame elements. For each temporal frame element, its range-Doppler resolution is higher than the single Fourier frame. Fig.3 shows a sequence of frames from the image sequence constructed by the joint time-frequency transform. We can easily see that by using the joint time-frequency transform, the time-varying spectrum can be represented very well and, therefore, the smeared Fourier image is resolved into a sequence of time-varying images, which not only has higher resolution, but also shows the Doppler changing and range walking from time to time.

3 Noise Reduction by Time-Frequency Processing

By representing in the time-frequency domain, signals usually concentrate their energy within a limited time interval and a limited frequency bandwidth while the background noise may spread its energy onto the entire time-frequency plane.

At each time instant, the window function of the time-frequency processing will eliminate noise outside the window, therefore, noise can be significantly reduced in each time-sliced time-frequency radar image.

A noisy ISAR image processed by the time-frequency transform compared with that by the Fourier transform is shown in Fig.4. Measuring the peak signal and the background noise, the peak signal-to-noise improvement with the

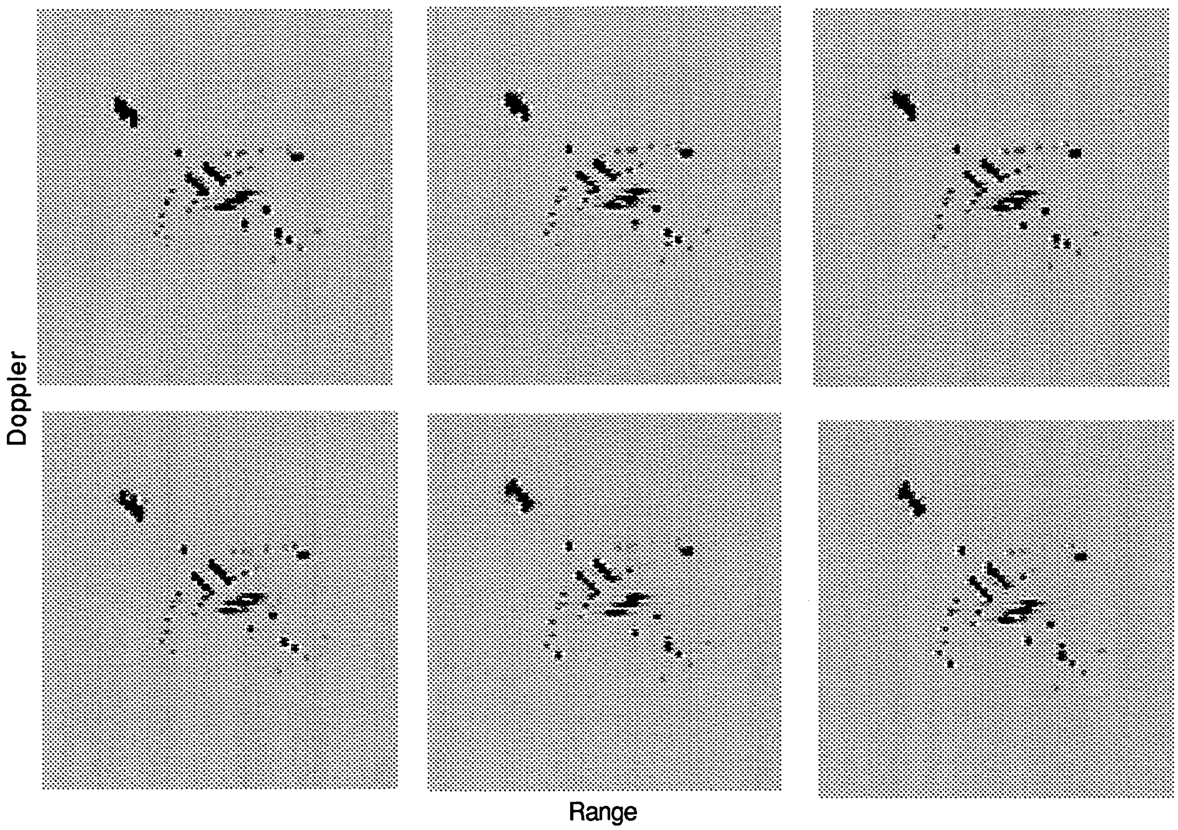

Figure 3: Radar image of the aircraft from simulated data with uncompensated phase errors by using the time-frequency transform.

time-frequency processing can be found and is approximately $18dB$ over the Fourier processing.

4 Time-Frequency Transform for Extraction of Backscattering Features

Radar target usually consists of a number of scatterers. They can be discontinuities, corners, or cavities in the target. Different type of scatterers has different backscattering behavior. When there are cavities or duct-type structures in the target, these scattering mechnisms appear in the radar image as blurred "clouds" which extend in the range dimension. Trintinalia and Ling [10,11,12] applied an adaptive time-frequency wavelet transform to decompose the range data of the complex radar image. The portion of the signal represented by wideband basis functions is used to reconstruct the radar image, and the portion represented by narrowband basis functions is used for identification of resonant features. The time-frequency decomposition scheme not only can improve radar image by removing the blurring "clouds", but also can be used for target recognition.

An example of a simple target structure is a strip containing an open cavity. Fig.5 shows the obtained radar image for this target, with the outline of the target superimposed on it. It can be seen that besides these scattering centers, there is a large cloud, spreading through the down-range, which corresponds to the energy coupled inside the cavity, and re-radiated at its corresponding resonance. This "cloud" not only makes the image more crowded, but also obscure some other important scattering centers. However, this portion of the scattered signal does contain information on the resonance frequency of the cavity.

It will be very useful to combine the time-frequency processing with the radar imaging technique so that the clouds can be removed and their resonances frequencies can be identified. To do this, each cross-range line of the image is

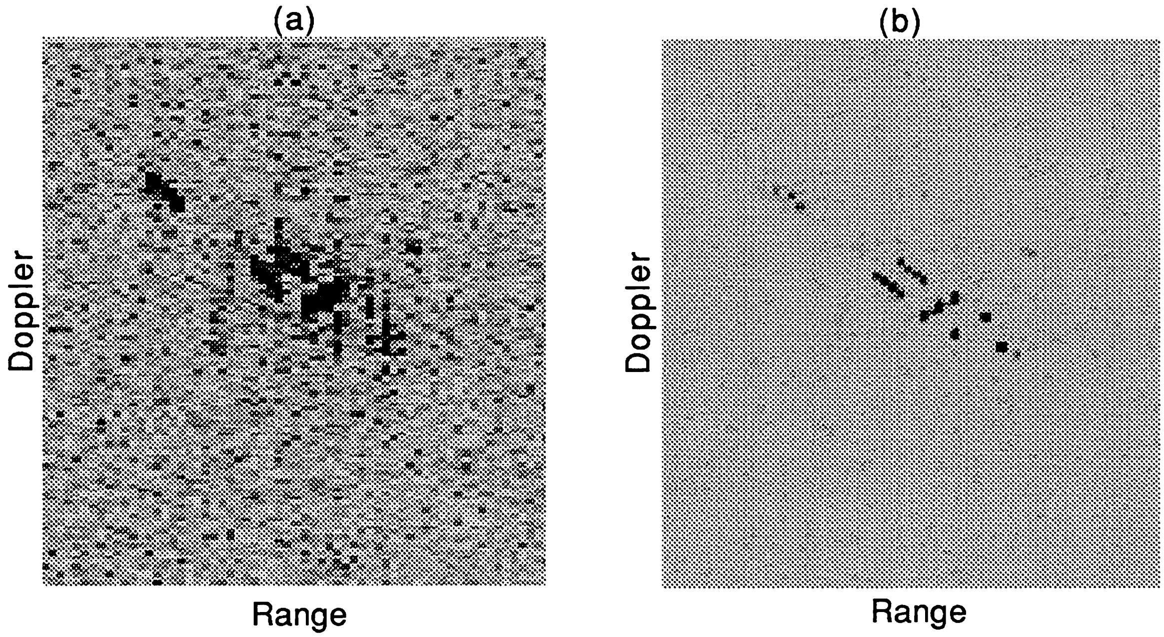

Figure 4: Noisy ISAR image construction using (a) Fourier transform, (b) time-frequency transform.

processed with the time-frequency transform, thus generating a 3-dimensional display : range, cross-range and frequency. Each frequency slice of this "cube" will be a narrow-bandwidth radar image, and so it will allow us to identify scattering centers, which will be present in all slices, and resonances, which will appear only in the slices close to the resonance frequencies. The adaptive Gaussian representation [13] or matching pursuit algorithm [14] can be used for this purpose. By applying the adaptive time-frequency procedure to each cross range line of the standard radar image, the original image can be separated into two new images based on the width of the Gaussian basis function: an enhanced radar image containing only scattering centers and a frequency-aspect image containing only resonance information. Using only the Gaussian basis functions corresponding to the scattering centers, radar image can be reconstructed, and, thus, a clean, enhanced image that contains only scattering center information can be generated as shown in Fig.6.

Fig. 7 shows an ISAR image of an airplane. The airplane has two long engine inlet ducts, which are rectangular at the open ends but merge together into one circular section before reaching a single-compressor face. the large cloud outside of the airframe structure is the inlet return. Fig. 8 shows the enhanced ISAR image of Fig.7, obtained by applying the above adaptive time-frequency wavelet algorithm and keeping only the small variance Gaussians. Only the scattering center part of the original signal remains in the image. The strong return due to engine inlet has been removed, but the scattering from the tail fin remains.

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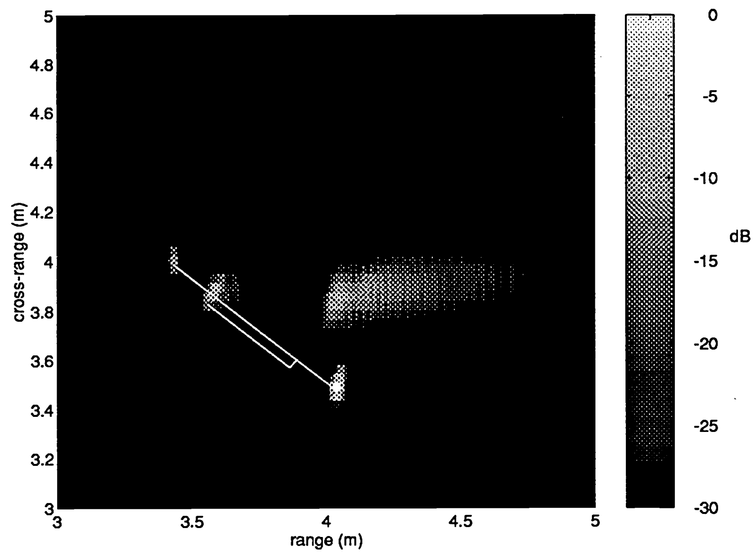

Figure 5: Radar image of an open-cavity's strip (courtesy of Trintinalia and Ling [12]).

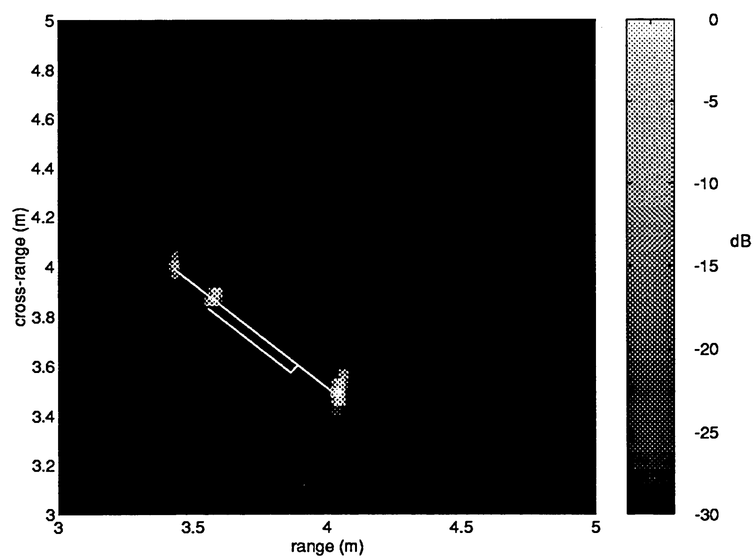

Figure 6: Enhanced radar image of an open-cavity's strip containing only scattering centers (courtesy of Trintinalia and Ling [12]).

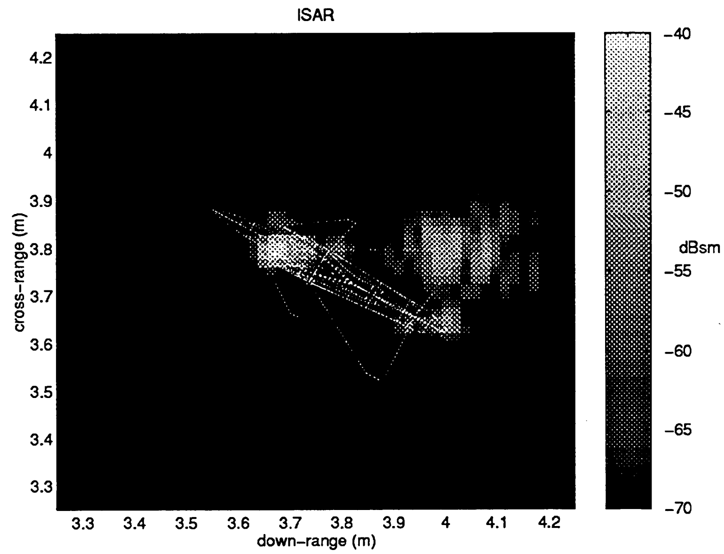

Figure 7: ISAR image of an airplane (courtesy of Trintinalia and Ling [12]).

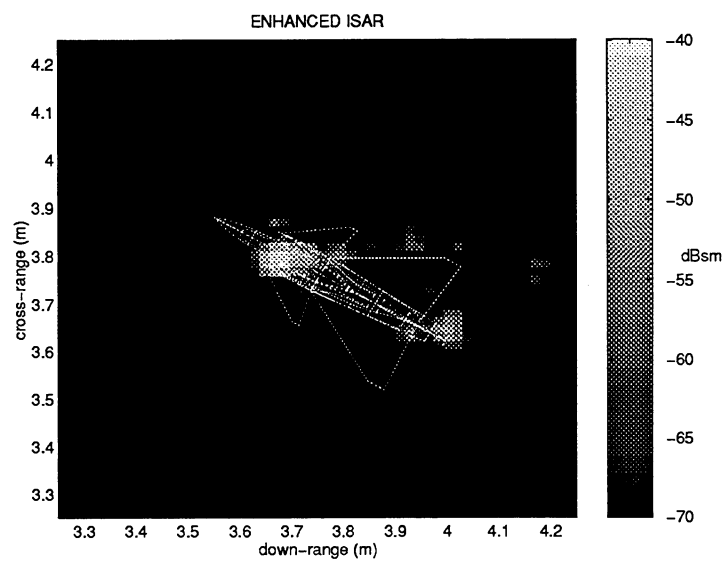

Figure 8: Enhanced ISAR image of an airplane containing only scattering centers (courtesy of Trintinalia and Ling [12]).