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Detection and Classification of Multiple Targets Using Millimeter Wave Imaging

Ch. Sunanda[1], A. Venkat Reddy[2], Dr D. Gowrishankar Reddy[3]
PG Student [signal processing], Dept. of ECE, Sri Venkateshwara University, Tirupati, AP, India[1]
Scientist 'F', Research Centre Imarat, DRDO, Hyderabad, Telangana, India[2]
Assistant professor, Dept. of ECE, Sri Venkateshwara University, Tirupati, AP, India[3]
Corresponding Author:Ch. Sunanda

Abstract:*Millimeter wave imaging is the emerging technique for detection of targets and distinguishes different targets from one another. Millimeter frequency band is the combination of both visible region and infrared region. As a result it has a combined feature of both visible region and infrared region. MM wave imaging is quite useful for imaging because of certain frequencies which have low attenuation and can be able to detect target in low visibility area. In this paper, we focus an area to detect presence of short range targets. Target is focused with some grazing angle of narrow beam width. The returned echoes are detected by 2D array of imaging sensors. This raw data of image is further processed to detect presence of multiple targets and distinguish them.*

Index terms*: Active and passive imaging, focal plane array, interpolation, linearly frequency modulation, Millimeter frequencies, RCS.*

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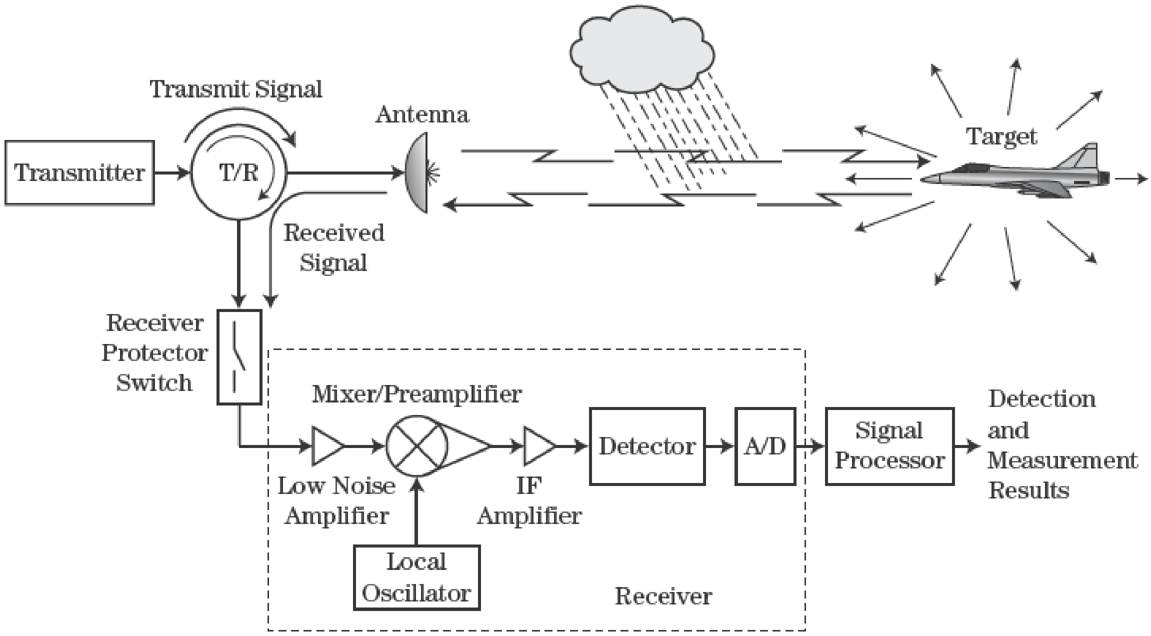
I. Introduction

Now-a-days imaging techniques play a prominent role in many fields. It has its major role in defence, medical and surveillance. Imaging is mostly done at higher frequencies to detect targets of small radar cross section. Imaging at higher temperatures gives us thermal images which is easy to detect different objects and distinguish them. At such frequencies, imaging is done with high number of pixel count to get better detection. Infrared imaging is mostly used for detecting long range objects. This imaging feature from infrared region is added as an advantage to millimeter wave region. Few frequencies of mm wave region have a feature of low attenuation and at these frequencies they can be able to penetrate into object at certain depth. At these frequencies, they can be able to detect any objects even at low visibility area. To encourage this feature of imaging, we hereby add another feature called active imaging which is capable of imaging in any weather condition.

Basics of radar

RADAR means radio detection and ranging. It is mainly used in determining the range, direction, velocity and other characteristics of an object. The transmitted pulses when hit the object, return back to the receiver in the form of echo from which all the characteristics of an object can be determined. The basic block diagram of working of radar is shown in Fig 1.

Fig 1: Basic block diagram of RADAR



Electromagnetic waves are transmitted into free space by transmitter antenna. This antenna is used for both transmitting and receiving purpose with the help of duplexer. Duplexer is maintained in such a way that it isolates receiver getting damaged because of high power transmitter. The transmitted signal reflects back as an echo after hitting the target. This return signal is received by the receiver and processed to detect presence of target using different parameters which are helpful in detecting presence of target.

Target's presence can be identified with the help of parameters namely range, azimuth angle, elevation angle, SNR and Doppler affect.

Range is measured using time delay that caused by the transmitted signal to return back to the receiver.

$$R = \frac{c*\text{time delay}}{2} \quad (1)$$

SNR is the sensitivity performance of the radio receiver. Greater the SNR value, better the radio receiver sensitivity performance.

$$SNR_{dB} = 10\log_{10}\frac{P_{signal}}{P_{noise}} \quad (2)$$

Doppler Effect is the relative motion between target and radar, changes the frequency of echo signal.

Radar range equation

Range equation of radar helps not only in finding out the range of the target from the radar but also in designing the radar system. Maximum range (R_{max}) occurs at minimum detectable received signal (S_{min}), Therefore, Maximum range is

$$R_{max}^4 = \frac{P_t G_t A_e \sigma}{(4\pi)^2 S_{min}} \quad (3)$$

Minimum received power (S_{min}) is limited by the noise. Hence, we rewrite S_{min} as

$$S_{min} = kT_oBF_n \quad (4)$$

Where, k = Boltzmann's constant ($1.38*10^{-23}\frac{W}{K\ Hz}$)

T_o = Standard temperature (290K)

B = Receiver bandwidth

F_n= Noise Figure

Now we can rewrite range equation as

$$R_{max}^4 = \frac{P_t G_t A_e \sigma}{(4\pi)^2 KT_o BF_n L_s} \quad (5)$$

Where, P_t: Power radiated from transmitting antenna

G_t: Gain of the transmitting antenna

R: Range of the object from the radar

σ: Radar cross section of the target
A_e: Effective area of the receiving antenna
L_s being other losses

MMW radar is taken to be the frequency region from 40 to 300 GHz. It has an advantage of having low attenuation at certain frequencies where it is capable of penetrating into any sort of weather condition to detect presence of target. It is also able to identify targets of low RCS.

Radars are used in Air Traffic Control, aircraft navigation, ship navigation, remote sensing, detecting targets in air, on land and on sea, land use, archeology, to determine climatic conditions.

Pulse Doppler radar

It is the combination of both pulsed radar and Doppler radar. Pulsed radar is useful in detecting range of the target. Doppler affect is useful in determining the velocity of the target. A box of pulses is transmitted in such a way that there is no ambiguity in detecting of received echo. So we employ pulse repetition interval in such a way that ambiguities are avoided.

The determination of azimuth, elevation, range and velocity of the target depends on the PRF employed by the pulse Doppler radar and this dependence is shown in tabular form in Table no 1.

Table no1: Dependence of Range, Velocity and Azimuth of target on the PRF of Pulse Doppler Radar

Parameter	Range	Velocity	Azimuth
Low PRF	Good	Poor	Good
Medium PRF	Good	Good	Good
High PRF	Poor	Excellent	Good

Pulse Doppler radar is capable of selecting rejection speed, clutter rejection capability, improve SNR and able to detect missiles which fly near terrain, sea surface. In the same way there are few disadvantages of such radar which is mainly caused by the PRFs employed in detection process.

Range ambiguity occurs when the echo of first pulse is received after transmission of second pulse.

Range eclipsing is a phenomenon in which the echo of first pulse is received during the transmission of second pulse. To overcome such problems we need to employ different PRFs and sophisticated computer logic.

Linearly frequency modulation

Chirp signal is a signal in which the frequency of the signal changes linearly with respect to time. The increase in frequency is called up chirp and decrease in frequency is called down chirp (with respect to time).

Let us define a sinusoid waveform as

$$X(t) = A \sin(\varphi(t)) \quad (6)$$

As we know that instantaneous frequency can be defined as the rate of change of phase of the signal.

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \quad (7)$$

The chirpiness is defines as the frequency rate.

$$c(t) = \frac{1}{2\pi}\frac{d^2\varphi(t)}{dt^2} \quad (8)$$

The general form of LFM waveform is:

$$x(t) = A\,\mathrm{rect}\left(\frac{t}{\tau}\right)\cos[2\pi f_o t + \pi\frac{B}{\tau}t^2] \quad (9)$$

Where,
B= Bandwidth over which waveform is swept
τ = pulse width
$\alpha = \frac{B}{\tau}$ is LFM slope
f_o= carrier frequency
The amplitude of LFM $a(t) = A\,\mathrm{rect}\left(\frac{t}{\tau}\right)$
The phase modulation is the quadratic function of time $\varphi(t) = \pi\alpha t^2$

The general form of received waveform is

$$y(t) = A\,\mathrm{rect}\left(\frac{t}{\tau}\right)\cos[(2\pi f_o t + \pi\frac{B}{\tau}(t - t_d)^2) + \varphi(t)] \quad (10)$$

Where, t_d = time delay
$\emptyset(t)$ = Phase shift of LFM received wave

We know that received wave is the time shifted version of the transmitted waveform.

Focal plane array

It is an array of imaging sensors arranged in two dimensional. It helps in detecting and conveying the information that contains an image which is done by converting back-scattering coefficients of the object into voltage or current signals.

Imaging in this frequency band allow us to have a clear view of images in low visibility conditions like snow, fog, smoke, rain and even in sandstorms. It is mostly used for short range broadband communication and high resolution sensing.

Imaging is mostly done in infrared regions. As MMW also consists of few frequencies of infrared, it also got imaging feature at lower frequencies with some penetration level. We use this millimeter wave imaging for short range multiple target detection and able to differentiate one target from another.

MMW imaging is done in two different ways. Passive imaging is done by detecting the radiations emitted by the object. These emissions are detected by millimeter wave systems directly. The amplitude of the radiation depends on both temperature and emissivity of the object. Millimeter wave source is not used in this method of imaging. Active imaging is done by illuminating the scenario first and then detects the reflections from the scenario. This type of imaging needs mm wave source for illumination. Even high SNR is observed in this imaging system.

Image processing

It is the process of analysing and manipulation of raw image data to improve the quality of image. Image Processing is done in series of steps. Series of steps that are involved in image processing is shown in Fig 2.

Fig2: Block diagram of image processing

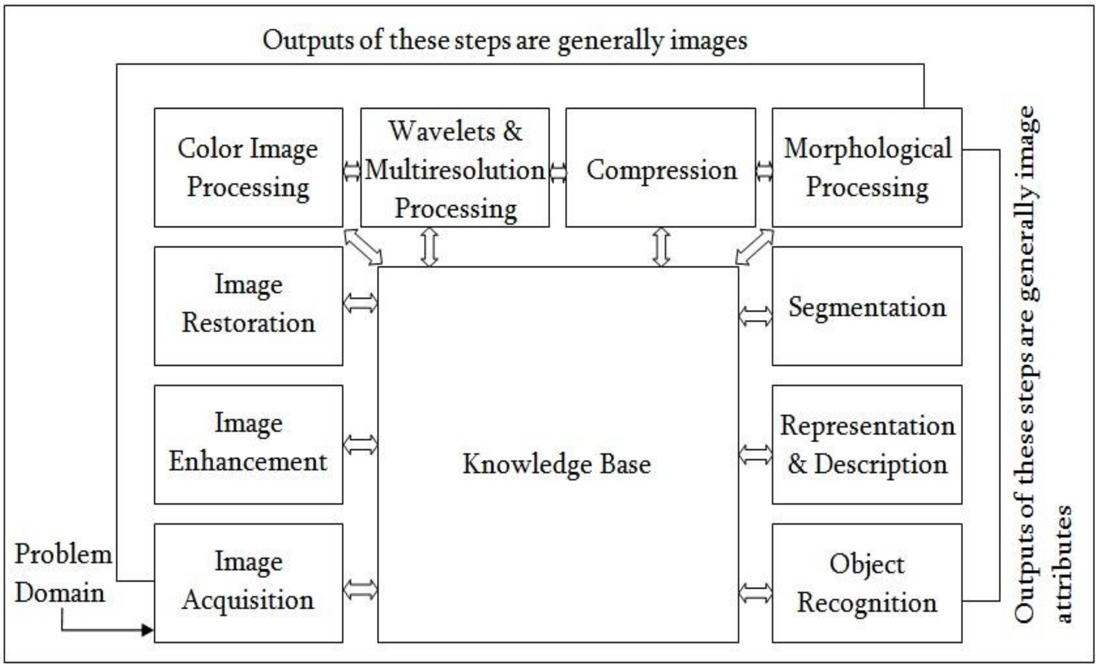


Image Acquisition is an action of retrieving an image from source, usually a hardware source for processing.

Image enhancement is the process of adjusting intensities of pixels for better assessment of image. Generally it is done by techniques like image sharpening, brightness and contrast adjustment, noise reduction, etc.

Image restoration is the process of recovering an image that has been degraded using processing techniques.

Colour image processing: Image processing that is done on colour images or indexed images or RGB images.
Image Compression: This technique is widely used to compress image data without any information lost. It is helpful in efficient use of bandwidth in communication purpose.

Morphological processing is used for extraction of image components to describe its characteristics like shape, size, etc.

Segmentation is a process in which different objects in an image can be identified by locating the boundaries of objects.

Description deals with extracting attributes that gives quantitative information of the region of interest.

II. Proposed Methodology

The motivation behind this project is to identify and classify multiple targets. Active millimeter wave imaging is used at receiver side which has a capability of penetratingin any sort of climatic condition (only at certain frequencies where attenuation is low).

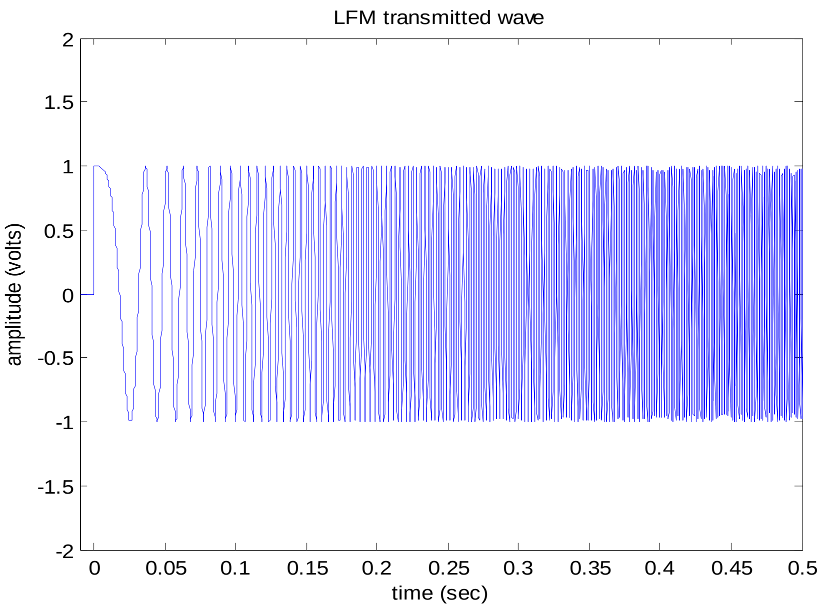
In this project, transmitted antenna element is combined with receiver elements which are the array of sensing units which form RF imaging array. This array maps the target scene into RF based image with respect to echoes received. The strength of the echoes depends on the reflectivity. For better resolution, we need more sensor elements. To develop a good imaging system we need highly sensitive sensors which can be able to detect low RCS target. Even high dynamic range of sensors is needed to identify the minor changes of reflectivity in adjacent pixels. These sensors senses the reflected signals from different direction and commensurate the reflectivity of it.

Using certain grazing angle and a narrow beam width, we scan ground and collect all echoes using a two dimensional imaging array. We use multiple PRI in order to receive accurate data. The returned signal is the combination of back-scattered coefficients of the scenario on which radar is focused and noise due to presence of clutter. This noisy received signal is fed into mixer which produces set of frequency tones which are proportional to the relative time delay between the scatterers. We limit the highest frequency obtained at the output of the mixer by using a filter and then use pulse compression techniques to improve range resolution and signal to noise ratio. Pulse compression is done by correlating received signal with transmitted signal. To process the received echoes we use digital signal processor which consists of high speed ADC, FPGA and Image Processor. Down conversion of received signal is done at ADC. Sampling and quantization of I and Q samples is done at FPGA. Altogether MN (where MxN is the size of imagery sensor array) complex correlation operations are done in FPGA over a period of 1PRI. Data from output of the FPGA is given to image processor for the reconstruction of the image. Likewise we repeat the same process for P PRIs (P is natural number) which improves the received signal strength and improves the resolution of the pixel received by the imagery sensor.

III. Simulation Results

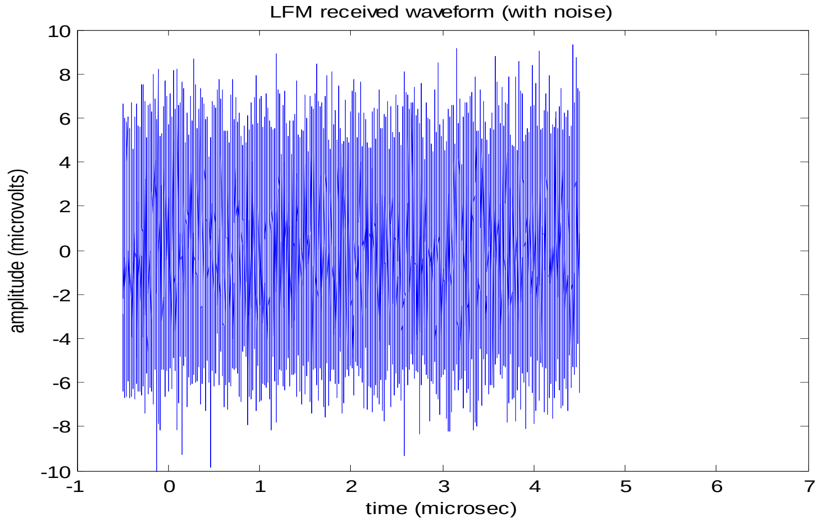
We implement above methodology by generating linearly frequency wave form as shown in Fig 3.

Fig 3: Transmitted LFM wave form



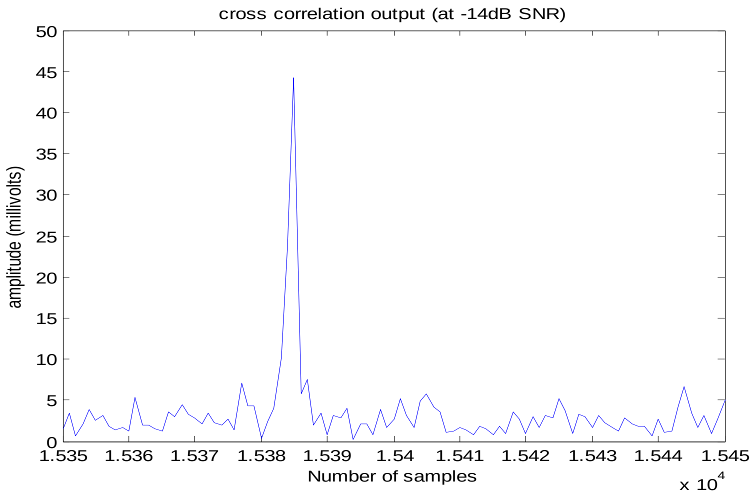
When transmitted signal hit the target, it returns back as an echo which contains the back-scattered coefficient of the targets. Echo signal gets prone to noise during its travel back to receiver. The received echo signal of complete focused area is shown in Fig 4.

Fig 4: Echo signal at receiver.



Echo received from target is fed into low noise amplifier in order to control noise levels in other systems. Output of this is fed into filter for limiting the highest frequency. Bandwidth of the filter is considered as the highest frequency of the signal. This received signal is then correlated with the transmitted signal which helps in the detection of presence of target. Output of the correlator is shown below in Fig 5.

Fig 5: Correlation output



This correlator output (raw image data) shown in Fig 6(b) and Fig 7(b);are of low resolution. This lowresolution images are fed into image processor. Image processing techniques are implemented on the raw image data for better reconstruction of the image. This raw data is interpolated to form an array of size $2^m x2^n$ (m, n ≥ 1). In this project, we interpolated raw data(by increasing values of m and n). We considered interpolated output at 256x256array where we found better image resolution. Simulations are done in MATLAB. Fig 6 and Fig 7 are the simulation results of this methodology. We considered a referenceimagesshown in Fig 6(a) and Fig 7(a) as an input and low resolution image is generated and fed into image processor to improve its resolution.

Basic method to improve resolution is by interpolating image data which can be done in three ways. Every method has its importance and different methods are used based on the requirement. In this paper, we used three interpolated methods namely;

Nearest neighbor interpolation: In this method, the intensity of the new pixel is value which is near to it as shown in Fig 6(c) and Fig 7(c).

Bilinear interpolation: In this method, the output pixel value is a weighted average of pixels in the nearest 2-by-2 neighborhood as shown inFig 6(d), Fig 7(d).
Bi-cubic interpolation: In this method, the output pixel value is a weighted average of 4-by-4 neighborhood pixelsas shown in Fig 6(e), Fig 7(e).

Fig 6: (a) Reference optical input image (b) Raw data extracted from echoes (c) nearest neighbour interpolation (d) Bilinear interpolation (e) Bi-cubic interpolation (f) reconstructed image

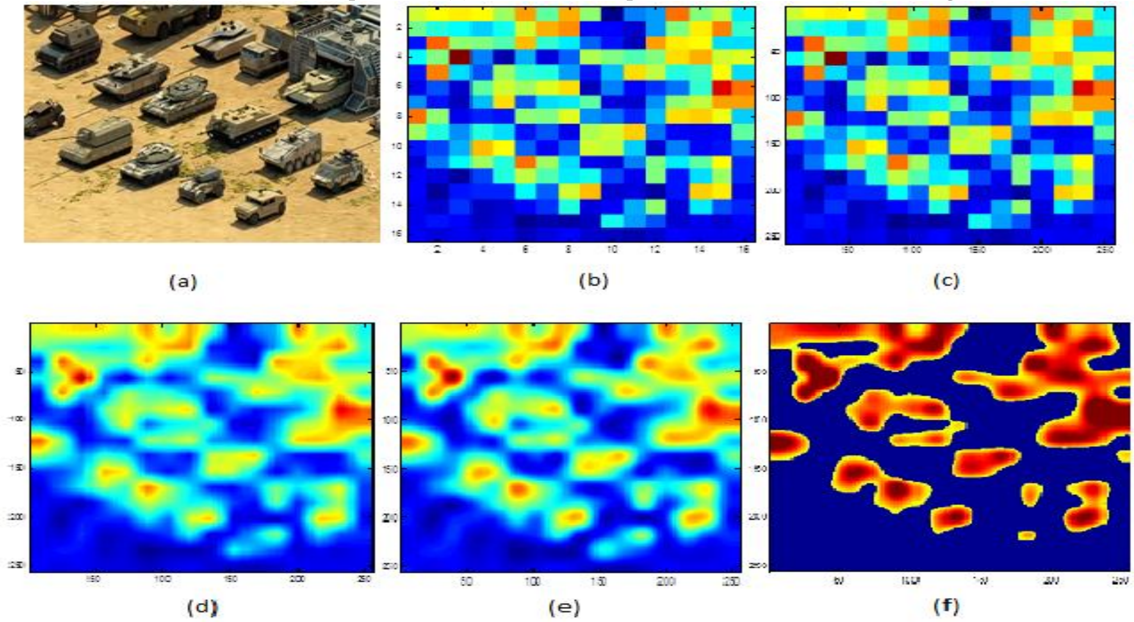
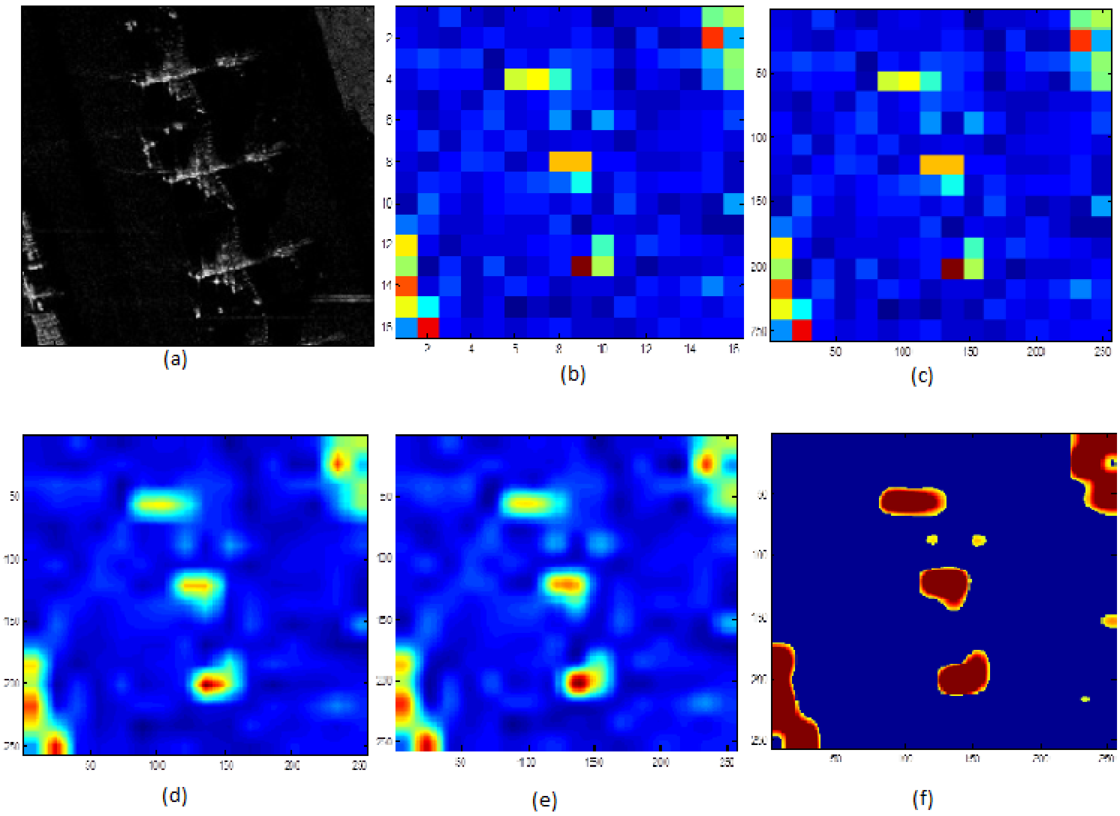


Fig 7: (a) Reference SAR input image (b) Raw data extracted from echoes (c) nearest neighbour interpolation (d) Bilinear interpolation (e) Bi-cubic interpolation (f) reconstructed image



Detection of different targets is better viewed in bi-cubic method when compared with other techniques. To identify different targets we use segmentation methods so that targets are classified and identified as shown in Fig 6(f) and Fig 7(f).

IV. Discussion

Fig 6(a) is the reference optical input image and Fig 7(a) is the reference SAR input image. As we discussed earlier, millimeter imaging technique, at certain frequencies have a property of exhibiting low attenuation to atmospheric conditions which is helpful in detection of any object even in poor visibility condition. Reference images which we considered are at different climatic scenario. Still we are able to detect them using above methodology. Better detection of objects can be done when the signals are able to penetrate into the object which gives us material properties. In order to detect target shape, size and material properties we use active imaging technique at millimeter wave frequencies. Though we are unable to construct exact shape of the image, we could still detect image. We distinguish targets from other objects by the reflections or the back-scattered coefficients of the objects. Every material has its own reflection coefficient, penetration nature which helps in distinguishing one object from other object.

V. Conclusion

Using the features of millimeter wave, we are able to detect multiple targets and distinguish them from other targets. We are also able to detect target with small RCS. It is not only able to give the geometric information of the target but also provided us with material properties of the object in the form of reflection that caused due to attenuation offered by the targets and other objects. So this technique can be used in detecting short range targets and classify them.

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