HIGH RESOLUTION INVERSE SYNTHETIC APERTURE RADAR IMAGING FOR VEHICULAR APPLICATION

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Abstract: RADAR images of contiguous targets like vehicles on road often suffer from side lobe enhancement due to environmental effects. This leads to false alarm in target detection and also degradation in image quality. In this paper, the CLEAN algorithms are introduced to eliminate side lobe enhancement and significantly improve the target detection performance and image quality. The effectiveness of the CLEAN algorithm is demonstrated through the results. Also the hardware results show how excellent performance can be attained by combining the correlator and the CLEAN Deconvolver. Thus signal processing methods like cross correlation, FFTs, CLEAN on range data and CLEAN on Image are incorporated on radar return signal on polyphase coded transmitted waveform. Robustness thus achieved through such signal processing in target detection and imaging, is finally tested by creating interference and multipath in the channel.

Key words: *RADAR, Inverse synthetic aperture radar (ISAR), CLEAN Algorithm, Range, Correlation, Intelligent Transport System (ITS)*

I. Introduction

ITS means addition of information and communications technology to the transport infrastructure like vehicles in order to improve safety and reduce vehicle wear, transportation times, and fuel consumption etc. To provide potential benefits of ITS applications in a national highway network, a broad range of research and development efforts are being carried over under the umbrella of ITS technology.

Lots of initiative have been taken to introduce ITS. Large scale national ITS projects began in Europe, US and Japan in the mid-1980s. The EU' (European Union) Safety initiative [1], announced in November 2002, aims to halve the number of annual traffic accident fatalities in the EU by 2010 and aim for "zero traffic fatalities" by 2020. The United States' ITS ten-year plan [2], announced in January 2002, talks about achieving a 15% reduction in the number of annual traffic fatalities by 2011. Europe takes a prime role in regional and international ITS standards activities to advance in ITS technology in the world market. The European Committee for Standardization (CEN) put focus on ITS standards issues. Many ITS standard items are developed in parallel by ISO/TC204 and CEN/TC278 [3]. Japan has been sparingly successful in translating its strengths in electronics technology into successful ITS.

This paper deals with the development of high resolution radar for vehicular application. In this paper authors have introduced ISAR processing along with some advanced signal processing tools. ISAR is proven useful for classifying and recognizing targets [4, 5]. But the performance of such a system may degrade significantly due to strong side lobe level due to congested vehicles on road. And also in this practical scenario high resolution microwave images of contiguous targets also suffer from side lobe enhancement [6]. Therefore radar target images usually suffer from strong side lobe levels (SLL) in either the range or the cross range domain. The net effect is that the dynamic range of the image is reduced. And this leads to severe problem in the case of radar imaging of contiguous targets that is the side lobes interact, causing peak misallocation and spurious peaks [7, 8]. Therefore proper classification, location identification of vehicles play important role to minimize the number of collision. In order to enhance the radar performance, authors have combine the matched filter and coherent CLEAN [7, 9, 10] algorithm.

This paper also shows the advantage of using spread spectrum in radar in the form of multipath and interference reduction. Finally all the specified techniques are used to image a prototype (toy vehicle). In the paper cited in [14], authors have discussed only about the CLEAN algorithm which can be used for sidelobe reduction. In the present paper authors have extended the implementation of the towards the hardware implementation of the same on Lab-based test-bed prior to improve the image quality of polyphase coded spread spectrum ISAR vehicular radar.

II. System Model

A. ISAR Processing

ISAR [11] is a technique for computing high resolution radar images that exceed the traditional resolution limits imposed by the physical size, or aperture, of an antenna. ISAR exploits target motion to form high resolution backscattered images of distant targets. The ISAR geometry can be represented as shown in the figure 1. The geometry is defined in terms of the target's rotational motion relative to the radar i.e., θ(t), is the instantaneous rotational angle in the XY-coordinate system with the radar line-of-sight (LOS) along the Y-
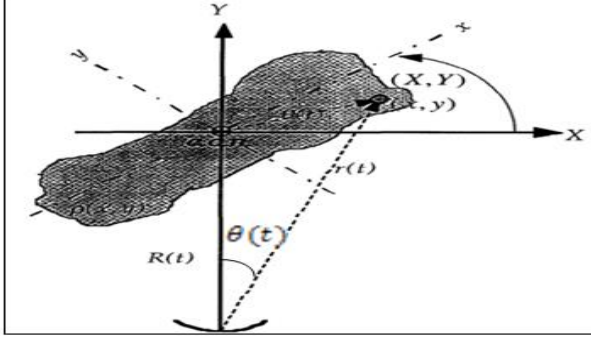
axis defining its instantaneous slant range, R(t).

Fig. 1: ISAR Geometry: Target and Scatterer at location (x, y).

The instantaneous range of the ith point scatterer at (x_i, y_i) is defined by $r_i(t)$, while the target itself is defined by its reflectivity function, p(x, y), shown in two dimensions (2D).
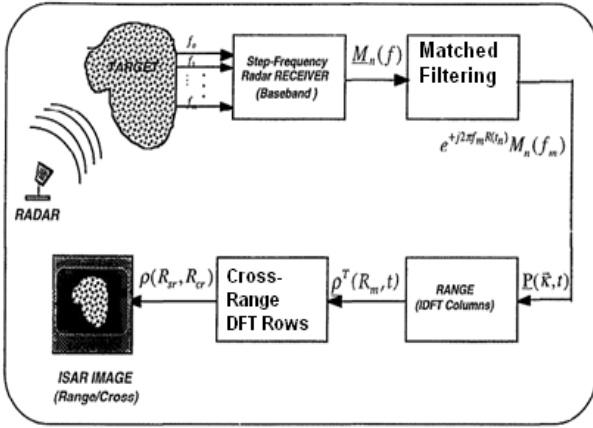

Fig. 2: ISAR Processing

Figure 2 represents the conventional signal processing algorithm for ISAR image formation. It involves 2D matrix formation based on target return. At first reflected signals for a particular angular orientation of target are collected by sweeping radio frequency followed by matched filtering (or correlation) of each signal. IDFT is performed on matched filtered output to obtain range information. The same procedure is repeated for different angular orientations and along the angular domain DFT is performed to get the cross range information of the target. Hence the final matrix contains both range and cross range data. The image thus plotted using this 2D matrix is an ISAR image.

In this paper authors have introduced one type CLEAN algorithm after matched filtering to reduce the side lobe effect to improve the range resolution. And another after having ISAR image i.e. the image data matrix again passed through the second CLEAN algorithm to have a high resolution image removing the residual noises.

B. Correlation Receiver

Because of it inherent advantage of maximizing the received signal Signal to Noise Ratio (SNR) level, correlation receiver [12] is useful to increase the radar range and target detectibility. In a radar system, the use correlation receiver will help to search for copies of a transmitted radar pulse in order to determine the presence of any target such as buildings or aircraft. The working principle of a correlation receiver is based on the correlation between delayed reference signal, and the actual target echo, the peak value of the correlation function indicates the distance to the target (the amount of time delay of the reference signal is also a measure of distance to the target). In this method, the return signal from the target is cross correlated with a time-delayed replica of the transmit waveform. The estimated value of the target range can be calculated by, $r_0 = cT_0/2$, where T_0 represents the delay in received signal corresponding to the target distance.

The correlation of the emitted and received signal can be written as:

$$R(\tau) = \int_0^{T_{int}} r(t)s^*(t - \tau)dt$$

------ (1)

Where T_{int} is the integration time. The delay T0 can be estimated as the position of the maximum. Thus

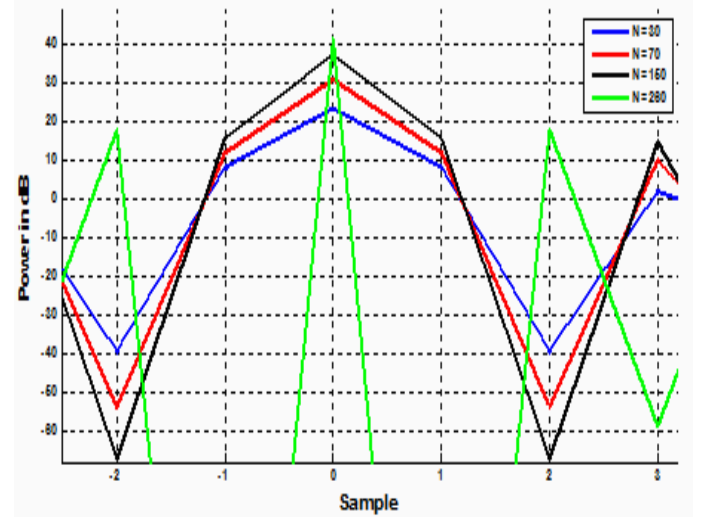$$T_0 = \max|E[R(\tau)]|$$

------ (2)

Fig. 3: Autocorrelation property of Polyphase code (P4) with different length (N).

The range resolution of radar is a function of the compressed pulse width, therefore narrow pulse width of pulsed compression radar will produce the high resolution radar.

In the hardware experiment polyphase (P4) coded spread spectrum signal is generated in baseband level. P4 code is more Doppler tolerant and good tolerance for pre-compression bandwidth limitations compared to other poly phase code such as Frank, P1 and P2 code. And it can be constructed for any length N and more the value of N, better is the compressed pulse as seen in Fig. 3. The elements of P4 code are given by

$u(i) = \exp[j\varphi(i)]$ and their phases are defined as

$$\varphi(i) = \frac{\pi}{N}(i-1)(i-1-N) \quad \text{------- (3)}$$

Let the P4 coding sequence used as radar signal is
A= {a0, a1...aN-1}   ------- (4)
where an associated to each phase sample of the P4 code.
The autocorrelation function of P4 coded signal can be written as

$$c(m) = \frac{1}{N}\sum_{i=0}^{N-1-m} a_i a_{i+m} \quad \text{------- (5)}$$

Where C_0 is the main lobe peak, which is equal to 1, and the other terms are the interfering side lobe.
The received signal before matched filtering can be represented as given below

$$Rs = \sum_{k=0}^{T} P_k(A(\tau_k)) \quad \text{------- (6)}$$

Where T is the number of point target, P_k is the received signal power corresponding to k^{th} target and τ_k is the delay associated to the kth target.
This received signal then passed through a cross correlation procedure i.e.
$$D = xcorr(A, Rs) \quad \text{------- (7)}$$

C.   CLEAN Algorithm

In the experiment CLEAN algorithm [14] is used twice –
1) As side lobe reduction technique in range domain using flow chart as in figure 4a.
2) To improve the image quality of a polyphase coded spread spectrum ISAR system using flow chart as in figure 4b.
This CLEAN algorithm, works by subtracting the normalized complex point spreading function (PSF) of target response (S) from the cross correlated value of the range domain map (D). In this approach, authors have consider only the one dimensional image (i.e., in range domain) of target after the coherent detection. PSF has been generated based on the autocorrelation of the reference signal.
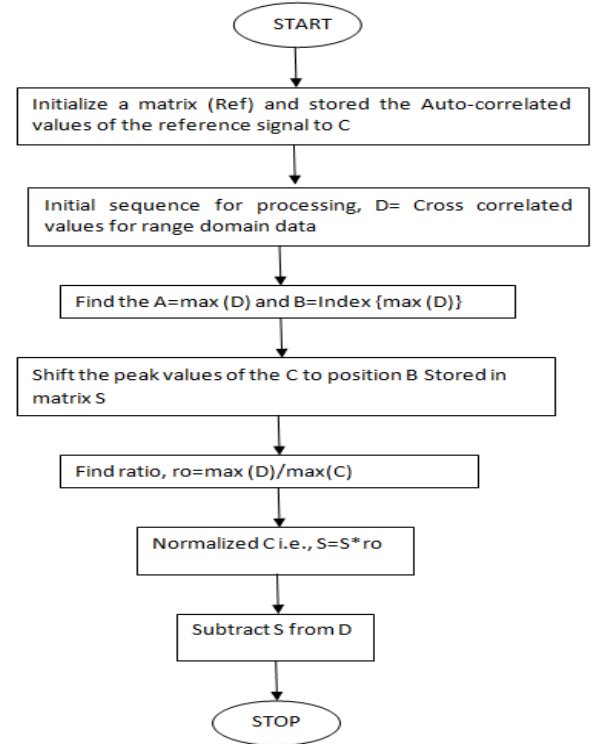

Fig. 4a: CLEAN algorithm for Side lobe reduction.

Let at i^{th} step, the cross correlated matrix (D), after the correlation between the target return data (Rx) and the reference signal (Ref), can be represented as

$$D_i(x) = \int_{-\infty}^{\infty} Rx(x) Ref(x)^* dx \quad \text{------ (8)}$$

For this target peak, apply subtraction of a fraction $r_{oi}(= \max(D_i)/\max(C_i))$ of complex PSF of target response (S) from the 1D image D_i to form the new cleaned image matrix

$$D_{CLEAN}(x) = D_i(x) - r_o S(x) \quad \text{------- (9)}$$

After the side lobe reduction, the range domain matrix is stored in a one dimensional map. Then with the angular rotation of the target, a 2D matrix has been generated involving the range and angular domain (cross range) information.
It works by identifying the brightest spot in the image map (D). The location and intensity information for the brightest spot are retained in a clean map (G). Once the brightest spot is removed from the image map (D), the procedure is repeated with the next brightest source in the image map until the remaining image map (D) is below some predefined threshold criterion. The amplitude and position of each source are noted and represent the "cleaned" image.
The idea of the CLEAN algorithms is to remove the side lobe effect by subtracting the side lobe terms in (3) directly from (5).
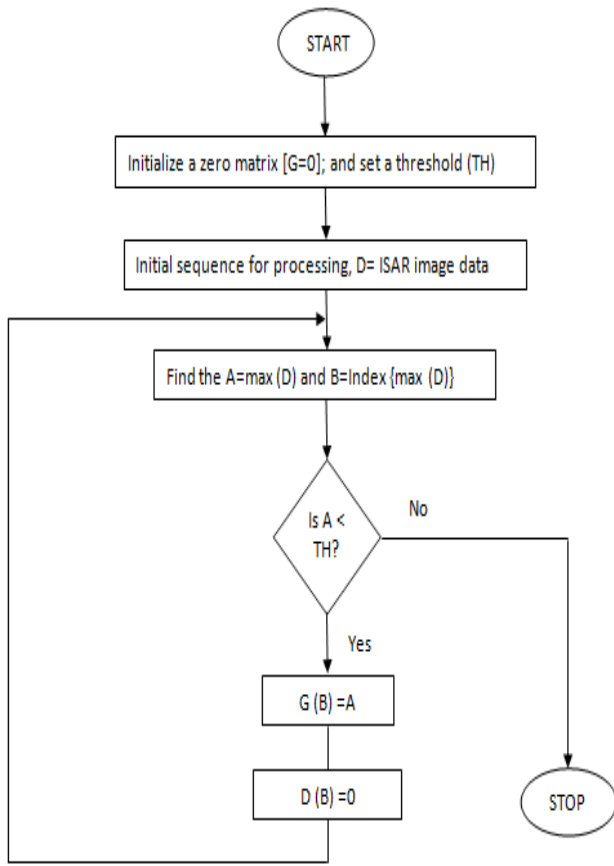
Fig. 4b: CLEAN algorithm for Image cleaning.

III. RESULTS

A. Experimental setup:-

Authors of this paper have tried to prove their concept by implementing the same at hardware level by creating different critical scenario.

Basic block diagram of the radar system is shown in Fig 5 having the following specification mentioned in Table 1.

Table 1: Radar System specification

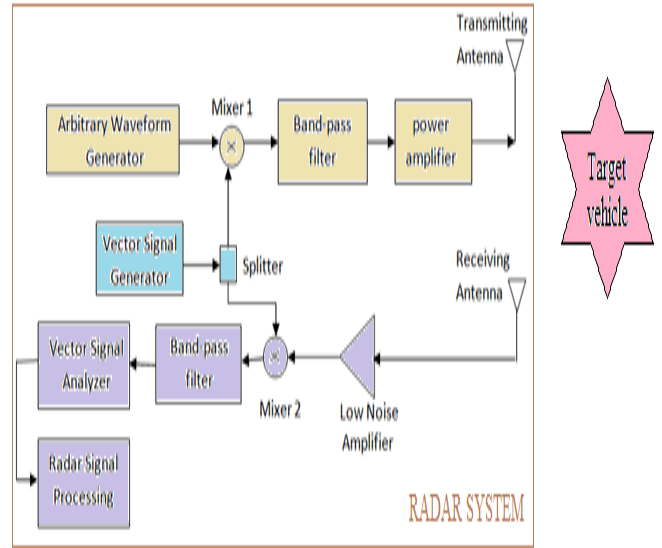| Instantaneous Bandwidth	100 MHz
Total System Bandwidth	1GHz
Code used for spreading	Polyphase (P4) code [260 Bit]
Processing Gain of Spreading Code used	24 dB
Radio Frequency	1-2 GHz (Hopped)
Duty Cycle	6%
Range Resolution	0.15m
Cross Range Resolution	0.2m

Fig. 5: Hardware Setup for polyphase coded Spread Spectrum radar.

The block diagram of the hardware setup of the radar is represented by Fig. 5. P4 code is being used as Spreading code in this Spread Spectrum radar of baseband instantaneous bandwidth of 100 MHz. The signal generation upto IF level has been carried out using Arbitrary Wave Generator (AWG). The IF signal then up-converted to Radio Frequency (RF) level (sweep range 1-2 GHz) using RF mixer and transmitted in direction of target using transmitter side antenna.

The reflected signal from target vehicle is down-converted to IF level and ported to Vector Signal Analyzer for further processing.

B. RADAR system performance:-

Part I: Signal processing

ITS is a type of system which like other systems may contain multiple number of users i.e. other vehicles having intelligent transport system installed in them. So those users will act like interferer to the particular vehicle discussed over here. Therefore, Interference rejection is one of the major concerns in actual vehicular condition. Another practical concern is the distribution of the vehicular channel whether Rician or Rayleigh etc. Thus mitigation of multipath is another issue that the authors have also taken into consideration. Following sequential steps are involved to tackle the problems just discussed:

a) *Interference Rejection :-*

Spread Spectrum has its unique property of data hiding. So application of spreading code reduces the problem of interference.

As can be seen from the Table 2 and Fig 6, radar detects target correctly in presence of interference. The received spectrum shows that the radar signal is corrupted by the interfering signal. But the correlator output still distinguishes target even when the Signal to Interference Ratio (SIR) in negative though with the decrement of the SIR, the main lobe to side lobe ratio degrades.
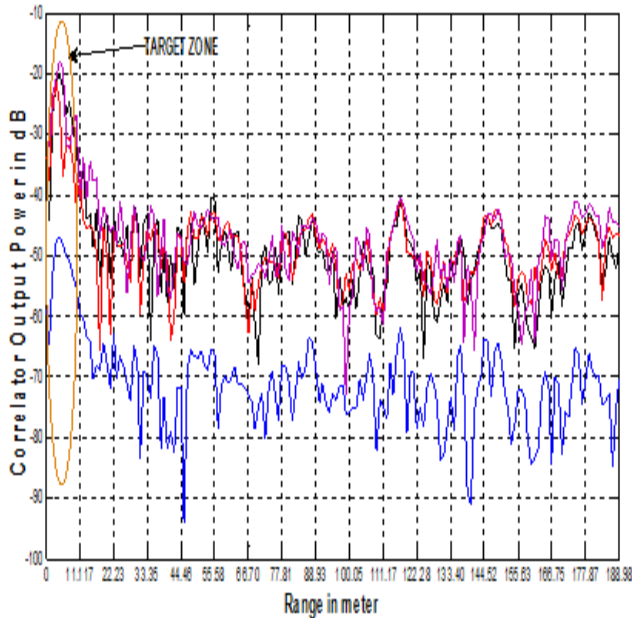

Fig. 6: Correlator Output at different Interference levels

Table 2: Performance of System at different Interference Level

SIR (dB)	Main Lobe to side lobe Ratio (dB) [from Fig. 6]	Color Indication in Graphs Above
-11.48	15.02	Blue
-4.01	19.64	Red
-3.89	21.59	Black
+1.95	22.71	Magenta

b)   Multipath rejection:-

The radar that has been constructed utilizes Spread Spectrum technology for baseband generation. So using higher length of spreading code, range resolution of radar can be increased thus resolving closely placed multipath. Once resolved, it is easier to remove by providing receiver gating. Receiver gating is basically defining a window for target zone such that window will remain open for target zone and closed for rest. Hence any multipath outside that specific zone can be easily rejected. Therefore high resolution is essential for multipath rejection.
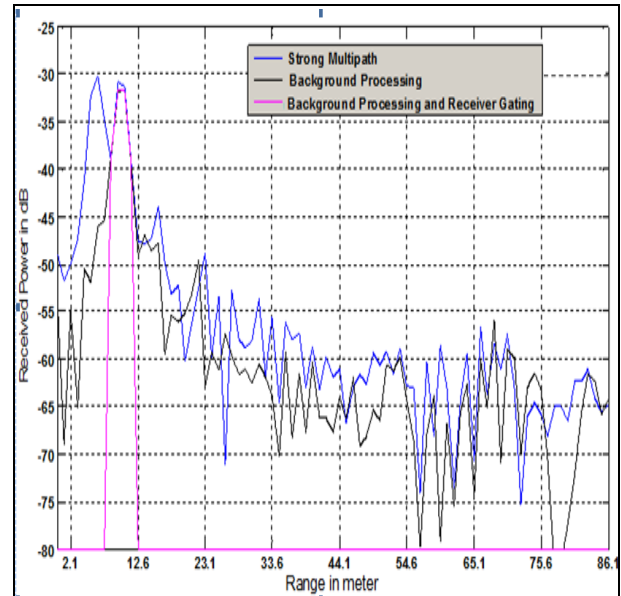

Fig. 7: Multipath Rejection using receiver gating and background cancellation

In the Fig 7, received data at three different levels is overlaid with an offset. The red (upper) graph indicates target with a strong multipath signal which is reduced to a certain level by background cancellation (indicated by Green graph). It is further reduced along with other noise by a proper gating at the target zone only (indicated by the lower graph).
Note : finds target even though peak lower than that of the multipath peak.

c)   *CLEAN algorithm:-*

CLEAN algorithm has been applied twice after range and again after cross range extraction.

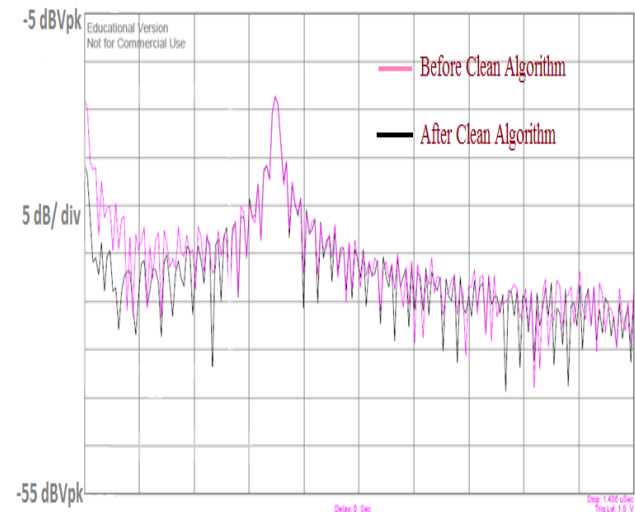*CLEANing applied in range extraction:-*

Fig 8: Output of CLEAN processor (Targets are well separated).

Figure 8 represents the performance of the CLEAN algorithm in determining the ranging data where targets are well separated. Here the effect of sidelobe rather sidelobe enhancement is not very critical as the mainlobe to sidelobe ratio is high and represents nearly like ideal condition i.e. mainlobe to sidelobe ratio of the autocorrelation of code (P4) used .
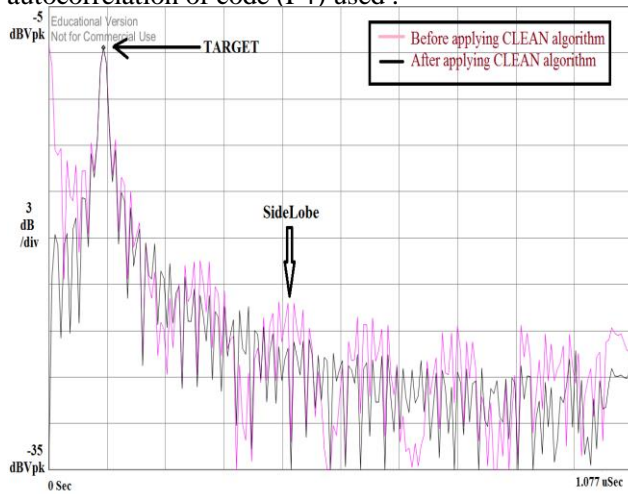

Fig. 9: Output of CLEAN processor (Targets are closely placed).

In reality there is high chance of nearby targets. The closer the targets are, higher chances of sidelobe enhancement since the sidelobe of both the targets may overlap on each other leading to the generation of the spurious peaks (i.e. false targets). Even if there is no spurious peak generation due to overlapping, small target, if present in sidelobe region, may be left out during detection.

The above results show the effectiveness of the CLEAN algorithm. In Figure 9, the mainlobe (i.e. target peak amplitude) to sidelobe ratio is 14 dB but the application of CLEAN algorithm, the mainlobe to sidelobe has increased to 17dB. So due to cleaning, there is increase in performance of the radar signal processor by 3dB. Also the ripples in sidelobe level is reduced and smoothened due to cleaning process without hampering the target peak. That means the target Radar Cross Section (RCS) will remain same with additional side lobe reduction. Also very feeble target falling in sidelobe of those other two targets can be detected thus enhancing the sensitivity of the radar. Hence in this scenario CLEAN algorithm appears to be more effective by providing 3dB increment in mainlobe to sidelobe ratio than the far away targets.

Part II: Image processing

CLEANing applied in image extraction:-

This experiment involves image formation of standard targets followed by prototype car imaging. Fig 10(a) represents radar image for 3 targets placed in both range as well as cross range. But due to the presence of high sidelobes, there are many false targets that have been created which may lead to wrong decision in any radar application. Thus clean algorithm may help in this regard by further minimizing the sidelobes and enhancing image quality.
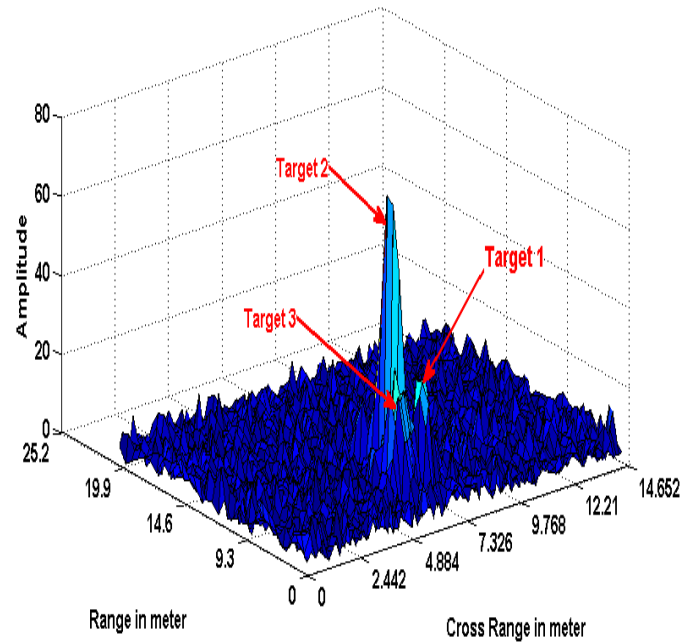

Fig. 10 (a): Image plot without CLEAN processing.

Fig. 10(b) is extracted with the CLEAN processing representing the significant improvement in the image quality due to CLEAN algorithm reducing the unwanted peaks. Everything other than the targets are removed leading to sharp definition of target thus helping in proper decision making in applications like ITS.
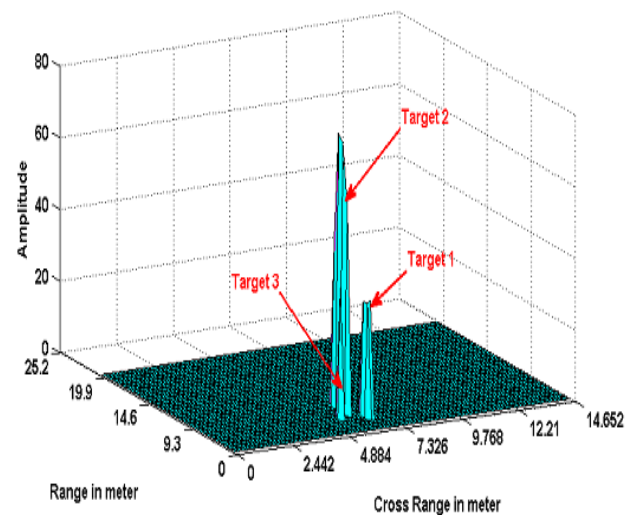

Fig. 10(b): Image plot after CLEAN processing.

Automobile Scattering center Location:-

A foil wrapped toy car (Fig. 11(a)) is used as the target vehicle. The foiled area acts as reflector (i.e. scattering centers or hot spots) and the authors have tried to image the car sidewise followed by the back-end separately and locate as many hot spots as possible. The distance of the car from radar system is 10.4 meter. Fig below shows all the hot spots on the actual toy car.
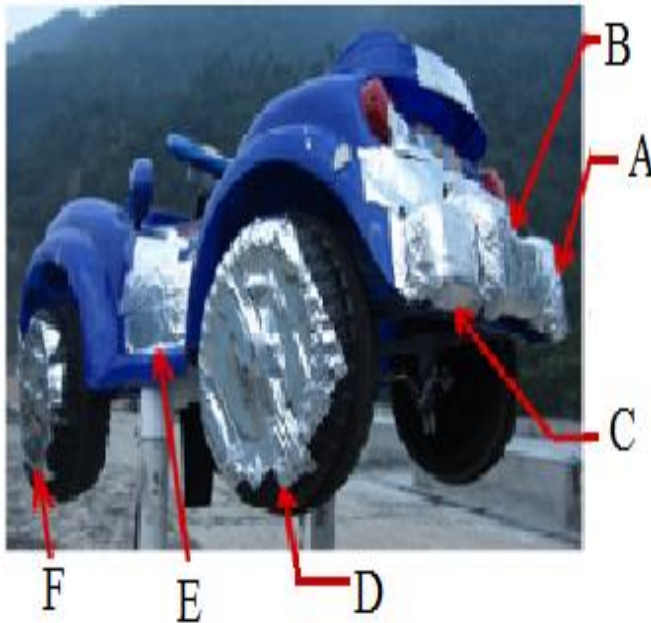

Fig. 11(a): Car with foil wrap.

After radar signal processing, the final image of car's back-end and side are shown in Fig 11(b) and 11(c) respectively. The one-to-one mapping of the hot spots in the images with the acutance is also shown.
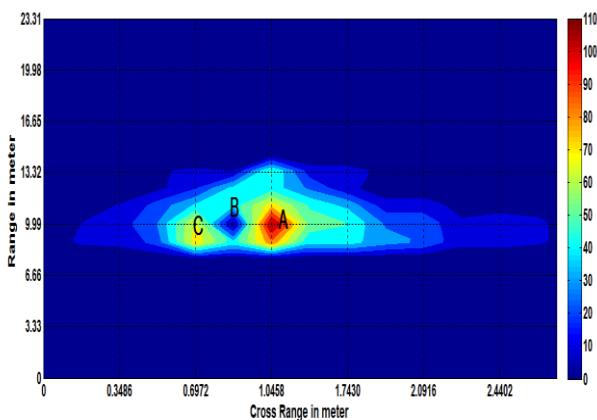

Fig. 11(b): Back-end Cross Range Image of Car.

The actual dimension of the car is 1m x 0.6m. Fig 11(b) above shows the back-end image of the car which has a continuous foil wrapping and since cross range resolution of the radar is 0.2m hence there are three hot spots that can be seen. Also the hot spots have variation in intensity implying the discontinuity in the structure of the car i.e. dents etc.

For the sidewise imaging, foils have been stuck in a way to create three equidistant hot spots having separation of around 0.3m. All the three scattering centers are clearly visible in ISAR image (Fig 11(c)) with separation around 0.4m. The error is caused due to limitation of the cross range resolution. Here also intensity varies due to the same reason as in case of the back-end imaging.
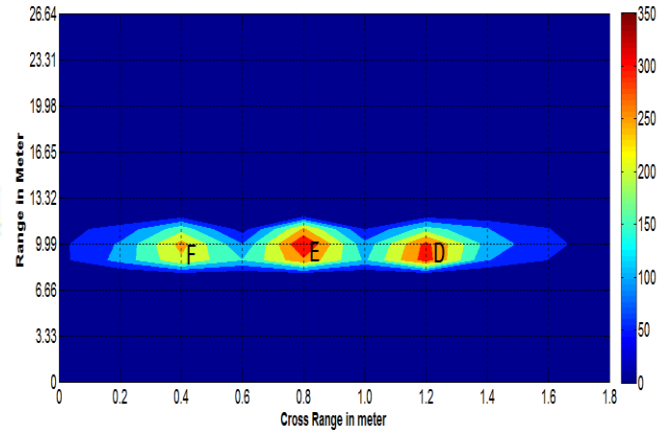

Fig. 11(c): Side-end Cross Range Image of Car.

On successful completion of cross range imaging, the authors have tried for range cross range image of the car. In this case car (i.e. target vehicle) is placed in front of the radar as if the radar system is placed on a vehicle which is chasing the target vehicle. The scattering centers of the target vehicle can be seen in Fig 12 along with the radar image.
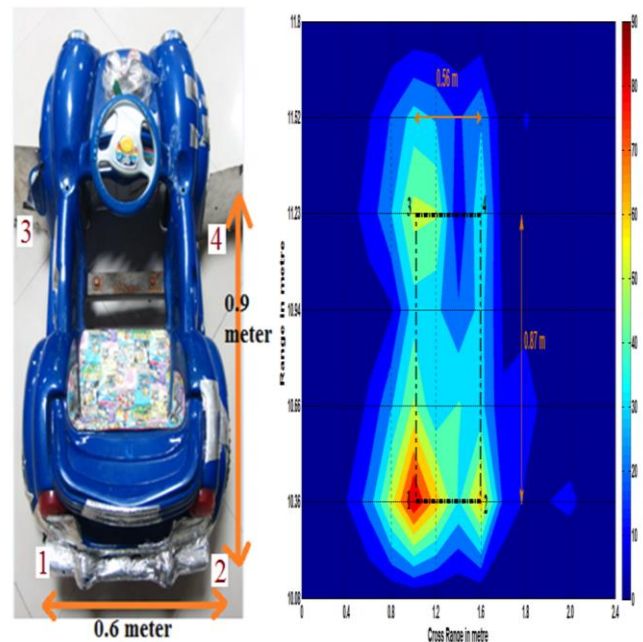

Fig. 12: Range Cross Range Imaging of Car.

Scattering centers are visible (Fig.12) at the location of the rear end [1(0.9435 m, 10.368 m); 2(1.5096 m, 10.368 m)] and the exterior rear view mirrors [3(0.9435

m, 11.2320 m); 4(1.5096 m, 11.2320 m)]. The breadth and length (From mirror location to rear end) of the toy vehicle is measured to be 0.56 m and 0.87 meter respectively. Even the intensity variations from the hot spots are clearly visible from the color MAP of radar image.

Thus, the radar, when mounted to actual vehicle, will be useful in detecting the nearby vehicle and identify the types/ dimension of vehicle from radar image.

IV. CONCLUSION

Inverse synthetic aperture radar is widely used all over the world for classifying and target recognition. It can be very beneficial in ITS as an tool for ACC (Automatic Cruise Control) where the vehicular controlling will be according to the classified targets from the image that has been formed. In this paper a hardware setup with above said technique is built and its performance under several conditions is analyzed. Authors have considered severe channel conditions and accordingly used correlation receiver as remedial measure to handle such channel rich in interference and multipath. These measures have further been extended to tackle sidelobe enhancement (due to the use of correlation receiver and its enhancement because of constantly varying channel conditions, closely placed targets etc.) which has a great effect leading to the suppression of feeble targets and lowering the target detection capability/ radar sensitivity. In this situation efficient use of CLEAN algorithm provides an extra significance in performance enhancement as represented in figures. As a result high quality imaging is possible also. Finally the main goal is looked for i.e. ISAR radar imaging. Radar imaging for standard targets followed by imaging of prototype of a vehicle is performed giving a promising result.

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