Detection of multiple moving targets in UWB TWR using digital heterodyne receiver

Damodar V Kadaba, Subhadra Singh, Abdul Subhan, Gowtham G[1], VK Bansal, L Ramakrishnan
Central Research Laboratory, Bharat Electronics Ltd., Bengaluru-560013
[1]Military Radar, Bharat Electronics Limited, Bengaluru - 560013
damodarvkadaba@bel.co.in

Abstract

In this paper a practical realization of a low complexity, step frequency continuous wave (SFCW) through wall radar (TWR) sensor for detection and tracking multiple targets is discussed. Heterodyne architecture is adopted for TWR transceiver by employing dual, PLL-based sweeping synthesizers. The reference and transmit synthesizers are separated in frequency by an amount equal to intermediate frequency (IF). Received signal at IF is filtered using narrow band, sharp cut-off band-pass filters, thus limiting noise bandwidth of the system. Measurement of phase difference between transmit and receive signals is performed digitally using oversampling technique. Reflectivity phasor, which carries target information, is compensated for varying initial phase (across stepping sequence) in the transmit chain using reference IF channel. Detection of moving human targets is accomplished using MTI (moving target indicator) filtering of digitally down converted data from successive bursts. MTI filtering effectively removes stationary clutter including wall. Due to UWB nature of the radar, human movements of the order of few tens of centimeters can be detected. A real-time display depicting history of range profiles from MTI processing chain portrays target traces, thus enabling detection and tracking of multiple targets. Techniques developed are illustrated using real data sets, and results are explained.

I. INTRODUCTION

Realization of ultra-wideband (UWB) sensor for through-the-wall surveillance applications has had to contend with multiple approaches; in particular, whether to adopt time-domain Impulse Radio Transceiver (IRT) or Stepped Frequency Continuous Wave (SFCW) based transceiver [5]. A survey of commercially available TWR systems has shown that most designs are based on IRT. This could be due to the fact that, SFCW transmitters in the past would take large amount time to step through the required bandwidth (in the order of hundreds of milliseconds for 1GHz). Large sweep time implies large data acquisition time, and hence very slow update rates for detection/decision making. Because of this limitation, frequency domain transceivers were more often used in lab environment for characterizing UWB systems, rather than building them for practical purposes such as through wall detection.

Recent advances in VLSI technology have resulted in design of fast acting, accurate digitally controlled phase locked loops (PLL) [1]. Such PLL devices when used in combination of Voltage Controlled Oscillators (VCO) can synthesize signals of large bandwidth, with precise control over quality of transmitted spectrum, while ensuring sweep times of the orders of milliseconds. Availability of digital PLL devices has resulted in development of SFCW UWB radar systems as they provide advantages of narrow band signal processing, while achieving resolutions of the order of centimeters at reasonable update rates.

Receiver structures for SFCW radars, reported in literature, are mostly based on homodyne architecture where the received echo is mixed with a copy of the transmitted waveform, followed by an analog quadrature detector. Quadrature detector generates a varying DC voltage at each frequency step corresponding to composite reflectivity indices (Real/I, and Imaginary/Q), also referred to as frequency response of the scene under illumination. Though simple in construction, homodyne receiver has the following disadvantages that hinder it's performance: I/Q imbalance due to analog quadrature detector, and poor signal to noise ratio (SNR). The received signal would need to be amplified before analog to digital (A/D) conversion is performed because of the lossy propagation medium.

When a radar return signal is mixed directly to baseband and amplified, a phenomenon known as $1/f$ noise or flicker noise exists. This noise is also amplified which is prevalent at low frequencies. It is defined by the noise-temperature ratio of the receiver mixer and varies inversely with frequency, and hence the poor SNR. The effect of flicker noise can be avoided with the introduction of an intermediate frequency (IF) at which phasor measurements can be carried out. Resulting improvement in SNR helps in better detection, and hence tracking as illustrated in this paper.

In this paper results of performance of an SFCW based TWR which is practically realized, is discussed. Signal processing techniques for mitigation of wall and stationary clutter, and enhancement of moving targets are discussed. A real-time application for signal processing, detection, and imaging of moving targets has been developed which has the capability to render through wall detections in real time on a Radargram image, which when accumulated over time can show patterns of movement that can be useful for decision making. Various detection algorithms for adaptive threshold generation for automatic detection of targets in the image, such as CA/SO/GO CFAR are available in the application.

II. HETERODYNE RECEIVER

Structure of heterodyne transceiver for SFCW radar is depicted in figure (1). It consists of two synthesizers which sweep/step through required bandwidth while dwelling at a spot frequency during each step for a required period of time. The two synthesizers use same clock source as reference, and are required to step simultaneously. One of the synthesizers is offset in frequency by an amount equal to the IF. The transmit synthesizer is amplified, and radiated through antenna, reflects off target, and received by radar. The RF signal is mixed with receive synthesizer signal, and then filtered at IF using vary narrow band (of the order of few KHz) crystal filters, thus resulting in limiting effective noise bandwidth of the system. Since the IF can be designed to be far away from DC, the heterodyne architecture minimizes the problem of temperature drift, and alleviates the problem of flicker noise [4, 6].

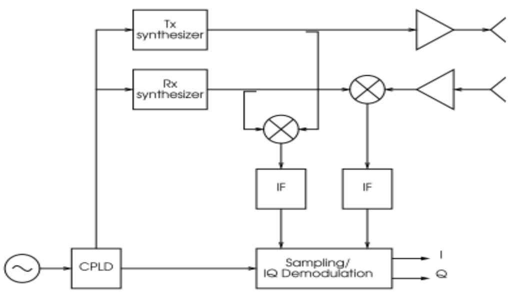

Figure (1): Heterodyne architecture

A unique advantage provided by the heterodyne system is that the harmonics generated by the synthesizers are not required to be filtered before transmission as they mix down to outside the intermediate frequency bandwidth.

It is to be noted that the phasor relation between two IF channels in the receiver can be tracked from step to step. For example, if the Tx and Rx channels are looped back using a cable of length l, the two IF channels would differ in phase by an amount corresponding to delay introduced by loop-back cable, assuming all other connecting links are matched in length electrically. Their phase relation is given by:

$$\varphi_n = 2\pi F_n\left(\frac{2l}{c}\right)$$

where, φ_n is the phase difference between reference IF channel, and echo channel, F_n is the frequency during n^{th} dwell, and c is speed of light.

This relation shows that when SFCW transceiver operates, phasor relation between the two IF signals quantify/measure complex frequency response of the scene under surveillance at different spot frequencies. An inverse Fourier transform would turn frequency response into impulse response which essentially is the range/delay profile of the received signal. This is used for detection much like the A-scope waveform in case of conventional radar.

III. THE RADAR SYSTEM

A handheld, monostatic, SFCW TWR based on heterodyne architecture has been realized using PLL based synthesizers (figure 2). Objective of design was to detect human targets at least up to 20m beyond various types of walls of more than10” thickness. A total of 1GHz bandwidth is swept through at C-band frequencies, with step size of 5MHz. The radar provides a resolution better than 15cm, and has an unambiguous range of 30m. Signal parameters of TWR under study are listed in figure (3).

Figure (2): Picture of TWR

Frequency band	C band
Sweep Bandwidth	1 GHz
Frequency step	5 MHz
Number of frequency steps	200
Time for one sweep	20 ms
Unambiguous range	30m
Number of FFT points	1024
Intermediate frequency	10.7MHz
IF filter bandwidth	1MHz

Figure (3): Radar signal parameters

A. *Signal processing*

The phase of the received IF signal is required to be adjusted to correct for the phase error introduced by the phase difference between the synthesizers. Hence, the phases of both the reference and received IF signals need to be measured. The Nyquist sampling theorem requires that the signal be sampled at a frequency greater than the bandwidth of the received signal. However, the IF signal is a narrowband signal and assuming a low radar speed, the received signal should not change for a specific radar azimuth position, as the targets will be stationary relative to the radar. Therefore the IF waveform can be sampled over more than a single period reducing the sampling rate requirements of the analogue to digital converter.

The in-phase and quadrature-phase (*I* and *Q*) values of the IF signal are usually obtained quadrature demodulation mixer and taking the DC component of the result. This process is equivalent to multiplying the IF signal with a complex sinusoid at IF frequency and taking the real and imaginary parts of the results. The result is that a simple, low cost digital signal processor can return *I* and *Q* information as shown here.

$$\begin{aligned} I + jQ &= \frac{1}{N}\sum_{n=0}^{N-1} x[n]\, e^{-j\frac{2\pi n}{N}} \\ &= \frac{1}{4}\left(x[0] + x[1]\, e^{-j\frac{\pi}{2}} + x[2]\, e^{-j\pi} + \right. \\ &\quad \left. x[3]\, e^{-j\frac{3\pi}{2}}\right) \\ I &= \frac{1}{4}\left(x[0] - x[2]\right) \\ Q &= \frac{1}{4}\left(x[3] - x[1]\right) \end{aligned}$$

To optimize hardware for the receiver, digital IQ detection is used for determining phasor relation between reference and echo channels. Only one ADC per channel is required when digital phase detection is employed.

B. *Moving target detection*

Returns from stationary objects such as furniture, pillars etc. on the far side wall overwhelm the receiver, in addition to reflection from wall, and direct signal due to antenna coupling. Attenuation of transmitted signal by wall material weaken signal scattered from targets of interest. Dynamic range of signals that the receiver has to manage for detection of useful targets is in excess of 100dB. As a result signal to clutter ratio is too low.

To detect moving targets, classical MTI filters with proper weighting are used. This can be considered as back ground cancellation used in image processing techniques for change detection. In TWR case, background is update on every pulse to pulse basis.

It is to be noted that *I/Q* data inferred by the signal processor is affected by phase noise of the Tx, and Rx synthesizers. Thus we expect MTI output to consist of moving targets, and residual clutter due to system imperfections such as phase noise, and random/multiple reflections within the radar enclosure. Hence, though MTI processing improves SCR, residual clutter may still be comparable to human target echoes.

Radar coherency relies on the synthesizers and the sampling process being synchronized to the same master oscillator. This ensures that the phase measured in the intermediate frequency channel can be related back to the transmitted signal and therefore the phase difference can be measured. In Figure (2)the separate reference channel is introduced to the system. The reference signal is generated by mixing signals coupled from transmit and local oscillator synthesizers, and sampling the bandpass filtered result. This signal will then only contain the phase error present in the received data channel [4].

C. *Rendering of target information*

A real time application for rendering moving targets is developed for display of TWR. A 2-D matrix is created by arranging data sweep-wise on a fast-time vs. slow-time axis as shown in figure (4).

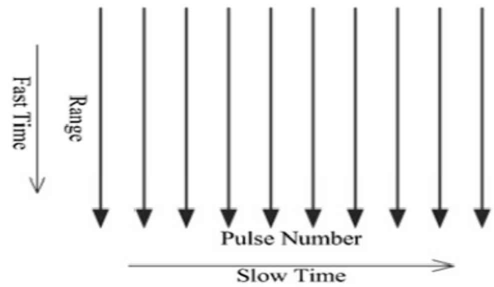

Figure (4) Radargram image matrix

Fast time axis represents A-scope data with elements mapped onto a color scale proportional to amplitude of the range cell, and slow time is the axis representing time progression, earliest being to the left, latest being to the right. It essentially constructs a time history of detections in range cells using a moving object can be identified by the traces of its position in the 2-D image.

IV. EXPERIMENTS AND RESULTS

The SFCW TWR radar system has been tested for human target detection performance under different operational conditions. Intended detection range of radar was a minimum of 20m through 10” concrete wall as benchmark. An earlier version of TWR, discussed in [3], with homodyne architecture had achieved a detection of 10-12m under similar test conditions. The radar is intended primarily for motion detection, and can provide updates at up to 20Hz.

It was observed that signal processing operations, which involve operations on complex numbers, when implemented in fixed point arithmetic in FPGA did not perform well due to loss of accuracy, and dynamic range. Hence application was migrated to floating point platform, and rendering software was developed using popular tool *Qt*. TWR software allows operator to select views of signals on the Radargram in various modes:

normal, MTI, coherent integration, adaptive threshold (via CA/GO/SO/OS CFAR methods) view etc.

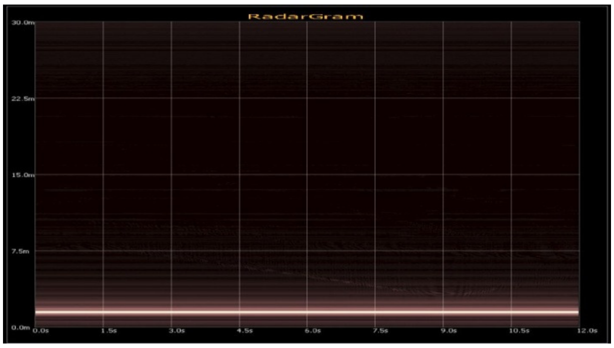

Figure (6) Radargram plot in normal mode

Radargram view in figure (6) depicts TWR display in normal mode. Test scenario for this case was the radar device looking through 12” external concrete wall. As shown in the above figure hardly anything can be inferred from the image as reflections from wall, and mutual coupling between Tx/Rx antennas overwhelms display. Radargram is optimized for viewing images in MTI mode. MTI operation can invoke an up to 5-pulse canceller for mitigating returns from stationary objects. An SCR improvement factor of better than 50dB has been achieved. Figure (7 and 8) show MTI image for the same test case sited above. It can be seen that multiple targets are detected at up to 30m through the wall in this mode. Horizontal lines at 25m are returns from an opposite wall located at that distance. Activity beyond the second wall also can be discerned. The picture is noisier at range scale of less than 3m. This is due to residual clutter caused by the phase noise of the synthesizers.

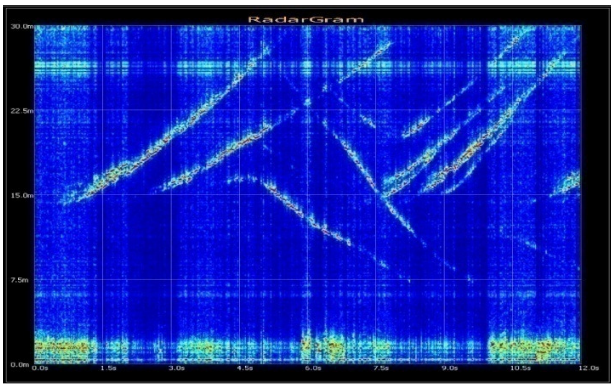

Figure (7) Radargram plot in MTI mode CRL corridor activity captured by TWR

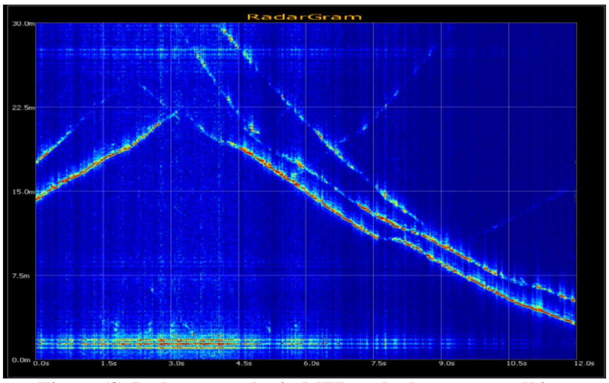

Figure (8) Radargram plot in MTI mode three men walking

Residual clutter due to various factors can be minimized using coherent integration over multiple pulses. It is assumed that target movement within integration time is negligible compared to resolution of TWR. In Figure (9) it can be seen that coherent integration does reduce noise to a large extent, and renders better images.

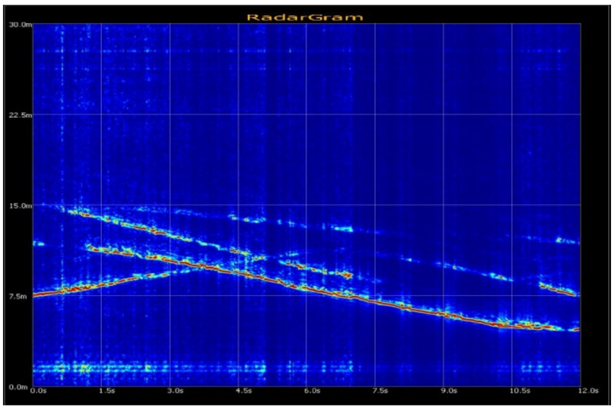

Figure (9) Radargram plot in coherent integration mode

V. CONCLUSIONS

The paper is focused on detection of moving objects. Moving targets cause time varying components in the scattered data. This data must be filtered out from the received signals and assigned to a specific target. The challenge is that a large amount of data must be processed in real-time and that the back scattering effect of moving targets is usually quite weak compared to the static scattering by walls, furniture etc. Moving people often cause a noticeable trace in the radar data as illustrated in the above experiments. TWR software provides real-time updates of detection results in an intuitive manner. Data sets generated by the software can be used for tracking of multiple targets using multi-static configuration of sensors. For detection of stationary humans through wall, changes caused in phase of returned signal by breathing and heartbeat has to be detected. The same has been achieved using this radar system through range-Doppler processing [2, 8, 9]. Image update rate in heart-beat detection mode is about 6seconds due to integration time involved. Extension of TWR for 2-D imaging (range vs. bearing) using direction of arrival (DoA) techniques is underway.

In conclusion, it is demonstrated that heterodyne receiver architecture has resulted in improving detection range of the TWR device. Future work will focus on mitigation of ‘flash’ effect using reflected power cancellation, and explore digital beam forming techniques for achieving cross range resolution.

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BIOGRAPHY

Damodar V Kadaba received B.E. degree from Mysore University & M.Tech. Electrical Engineering from IIT-Delhi. He is presently working at Central Research Lab, Bharat Electronics, Bangalore. His areas of interest are signal processing for radar systems, adaptive algorithms, parameter estimation and tracking.

Subhadra Singh, received M.E. in Signal Processing from IISc, Bangalore, and B.Tech. from Maulana Azad National Institute of Technology (MANIT), Bhopal in ECE. He is currently a Member Research Staff in ECS Group at CRL-BEL. His areas of interest are Radar data processing, Image processing & motion estimation, Video processing and real-time implementations on Linux based embedded platforms

Shaik Abdul Subhan received B.Tech. degree from JNTU, Anantapur & M.Tech. in digital in 2008. Since then he is working in radar signal processing group. His areas of interest are secondary surveillance radar reply processing, and radar imaging.

Gowtham Ganesh received B.E. degree in ECE from Malnad College of Engineering, Hassan. He is presently working with D&E group of Military Radar SBU, Bharat Electronics Ltd, Bangalore. His areas of interest are sensor signal processing and real time software development for radar systems.

Vijay Kumar Bansal received B.Tech. from FET, Gurukul Kangri University &M.Tech. in RF & Microwaves from IIT Kharagpur. Presently he is working in Radar signal processing group at Centre Research Lab, BEL Bangalore. His areas of interest are UWB radar signal processing, video extraction, hardware design for base band digital signal processing.

L Ramakrishnan obtained B.Tech (Electronics Engg) from MIT, Anna University & ME (ECE) from Osmania University. Starting his carrier at HAL, he worked in various projects including Air borne Transponders for Secondary Surveillance Radar, Airborne radar for modern fighter aircraft, Air Route Surveillance Radar, Radio Proximity fuses etc. His area of professional interest includes Design and Development of front ends for Radar, Wireless & Communication Systems. He is currently serving as Principal Scientist & Group Head at Central Research Laboratory, Bharat Electronics Ltd., Bangalore. His current areas of research interest include Ultra wideband Radars, Signal Processing Sub-systems & Radar Data Processing systems for various Radar Applications and Embedded products for military applications. He has over fifteen National and International publications to his credit. As part of the BEL team, he has been bestowed with Raksha Mantri Award under Innovation category and Bharat Electronics Limited R&D excellence awards. He is a Member IEEE and Certified PMP.