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Application Of Digital Signal Processing In Radar Signals

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Abstract

There has been explosive growth in Digital Signal Processing theory and applications over the years. This research explores the applications of digital signal processing in Radar. A survey on applications in digital signal processing in Radar from a wide variety of areas is carried out. A review is done on basic approaching models and techniques of signal processing for different parameters and extracting information from the received signal. The various techniques adopted at different stages of radar to obtain the target's signature, is also researched.

Keywords: Radar, Doppler, Digital Signal Process (DSP), convolution, Clutter filters, Scanning, Synthetic aperture radar (SAR), cancellers

INTRODUCTION

Flexibility and versatility of digital techniques grew in the front-end signal processing and the advent of integrated digital circuitry, high speed signal processors were developed and realized. Radar continued to grow in the recent years by keeping the future developments in mind and with better digital capability. Significant contributions in DSP in Radar have been in MTI processing, Automatic Detection and extraction of signal, image reconstruction, etc. A case study of Radar Synthetic Vision System for Adverse Weather Aircraft landing is discussed. In this report an effort is made to identify the contribution of DSP in the advancement of Radars.

METHODOLOGIES

RADAR transmits radio signals at distant objects and analyzes the reflections. Data gathered can include the potion and movement of the object, also radar can identify the object through its "signature" the distinct reflection it generates. There are many forms of RADAR – such as continuous, CW, Doppler, ground penetrating or synthetic aperture; and they are used in many applications, from air traffic control to weather prediction.

In the modern Radar systems, digital signal processing (DSP) is used extensively. At the transmitter end, it generates and shapes the transmission pulses, controls the antenna beam pattern while at the receiver, DSP performs many complex tasks, including STAP (space time adaptive processing) – the removal of clutter, and beam forming (electronic guidance of direction).

The front end of the receiver for RADAR is still often analog due to the high frequencies involved. With fast ADC convertors-often multiple channel, complex IF signals are digitized. However, digital technology is coming closer to the antenna. We may also require fast digital interfaces to detect antenna position, or control other hardware.

The main task of a radar's signal processor is to make decisions. After a signal has been transmitted, the receiver starts receiving return signals, with those originating from near objects arriving first because time of arrival translates into target range. The signal processor places a raster of range bins over the whole period of time, and now it has to make a decision for each of the range bins as to whether it contains an object or not.

This decision-making is severely hampered by noise. Atmospheric noise enters into the system through the antenna, and all the electronics in the radar's signal path produces noise too.

Major blocks of modern radar system

The major components of modern radar are the antenna, the tracking computer and the signal generator. The tracking computer in the modern radar does all the functions. By scheduling the appropriate antenna positions and transmitted signals as a function of time, keeps track of targets and running the display system.

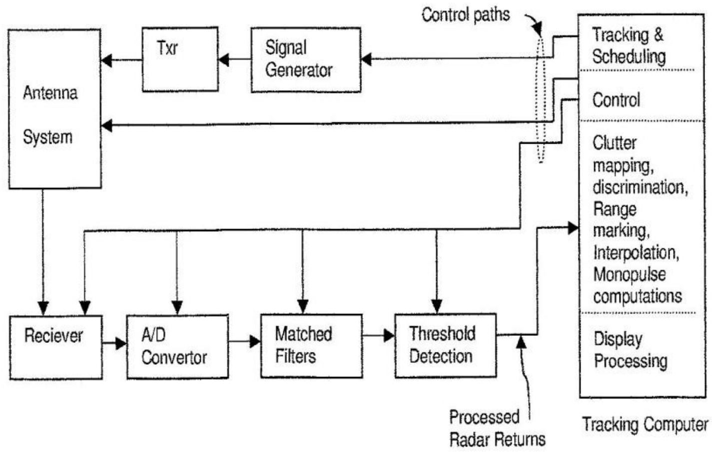


Fig 1. Block Diagram of a Modern Radar system

Even if atmospheric attenuation can be neglected, the return from a distant object is incredibly weak. Target returns often are no stronger than twice the average noise level, sometimes even buried under it. It is quite difficult to define a threshold for the decision whether a given peak is noise or a real target. If the threshold is too high then existing targets are suppressed, that is, the probability of detection (P_D) will drop. If the threshold is too low then noise peaks will be reported as targets, that is, the probability of false alarms (P_{FA}) will rise. A common compromise is to have some 90% probability of detection and a false alarm rate of 10^{-6}.

It maintains a given P_{FA} known as CFAR, for Constant False Alarm Rate. Rather than keeping the threshold at a fixed point, CFAR circuitry inspects one range bin after the other and compares the signal level found there with the signal levels found in its neighboring bins. If the noise level is rather high in all these (e.g. because of precipitation) the CFAR circuit will raise the threshold accordingly. Further tasks of the signal processor are:

- **Combining information:** Secondary surveillance radars like those located on airports can ask an aircraft's transponder for information like height, flight number or fuel state. Pilots may also issue a distress signal via the transponder. The ground radar's signal processor combines this data with its own measurements of range and angular direction and plots them all together on the appropriate spot on the scope.
- **Forming tracks:** By correlating the data sets which were obtained in successive scan cycles, the radar can calculate a flight vector which indicates an aircraft's speed and expected position for the next scan period. Airport radars are capable of tracking hundreds of targets simultaneously, and flight safety depends heavily on their reliability. Military tracking radars use this information for gun laying or guiding missiles into some calculated collision point.
- **Resolving ambiguities in range or Doppler measurements:** Depending on the radar's pulse repetition frequency (PRF), the reading for range, Doppler or even both are ambiguous. The signal processor is aware of this and selects a different PRF when the object in question is measured again. With a suitable set of PRFs, ambiguities can be eliminated and the true target position can be determined.
- **Ground clutter mapping:** Clutter is a collective term for all unwanted blips on a radar screen. Ground clutter originates from buildings, cars, mountains etc, and a clutter map serves to raise the decision threshold in areas where known clutter sources are located.
- **Time and power management:** Within a window of some 60^ox40^o, phased array radars can instantly switch their beam position to any position in azimuth and elevation. When the radar is tasked with surveying its sector and tracking dozens of targets, there's a danger of either neglecting part of the search sector or losing a target if the corresponding trace record isn't updated in time. Time management serves to maintain a priority queue of all the tasks and to produce a schedule for the beam steering device. Power management is necessary if the transmitter circuitry runs the danger of overheating. If there's no backup hardware then the only way of continuing regular operation is to use less power when less power is required, say, for track confirmation.
- **Countering interference:** Interference can be a) natural or b) man-made. Natural interference can be heavy rain or hail storms, but also varied propagation conditions. Man-made interference, if created on purpose, is also called jamming and is one of the means of electronic countermeasures.

Detection of Signals

Detection is the process by which the presence of the target is sensed in the presence of competing indications which arise from background echoes (clutter), atmospheric noise, or noise generated in the radar receiver. The noise power present at the output of the radar receiver can be minimized by using filter, whose frequency response function maximizes the output peak-signal to mean-noise (power) ratio is called matched filter. We shall discuss the application of digital filtering to matched filters.

Fast Convolution Filter Implementation

(a) Dual pipeline FFTs matched Filter

In this system, FFTs are pipelined and both the forward and reverse radix-r FFTs are implemented in hardware. Initial recording of the data is done using input buffer (IB) memory and it takes 'N/r' clock pulses to read N data points and 'r' input rails. The amount of time 'N/r' is called as one epoch. It requires three epochs for the first data to be completely filtered, and is delivered by one epoch thereafter. In the dual FFT systems arbitrary data is filtered sequentially with arbitrary reference functions selected from reference memory.

Drawback

In many applications the same data set be filtered with several different filters, in this case only one forward transform is performed followed by several inverse transforms, it is possible to eliminate one of the pipeline FFTs. This is desirable since it would save a large amount of hardware.

(b) Single forward FFT matched Filter

The data is first transformed and the result stored in the temporary storage memory (TSM). The data is then multiplied by the filter function and inverse transformed. This allows multiple readouts of the forward transformed data for the TSM and multiple filtering of the same data set; the output of each filter will appear sequentially.

Drawback

The data at the output of the forward FFT are in digit reverse order, it is then corrected by reading the data out of the TSM in digit reversed order. The second FFT is performed the output is placed into an output buffer, and to be read in a bit reversed order from the output buffer.

It requires five epochs for the first data to be completely filtered, and is delivered by one epoch thereafter.

(c) Single inverse FFT matched Filter

A single inverse FFT is employed and the data is read from the input buffer in digit reverse order. The data is transformed and stored in TSM in normal order, and then read out in bit reserve order.

Drawback

Complex conjugation must be performed after each transform and stored. The digit reversed access to the IB is required and the IB maybe quite large compared to TSM and may be difficult to implement.

(d) Reconfigurable FFT matched Filter

The FFT subsystem switches the inter-stage delay lines to realize both forward and reverse transforms.

Forward transform: by routing the data through the inter-stage delay memories (IDMs) in decreasing order.

Inverse transform: by sending data through the IDMs in the increased order of size. The total memory of each stage is the number of delay lines memories.

Comparison of 4 matched filter systems

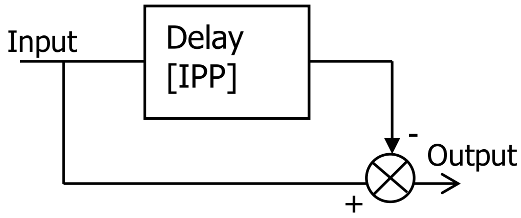
The relative performance of dual pipeline matched filter is fastest but requires two complete pipeline FFTs hence more hardware is required. Single inverse transform matched filter has better performance over single forward transform matched filter and also doesn't require a double buffered output memory. Reconfigurable FFT matched filter is preferred and chosen most of the times, it doesn't require digit reserved to the IB and also doesn't require digital recording of TSM.

Doppler processing

Doppler processing is used to filter out clutter and thereby reveal fast moving targets. Such filters are implemented digitally, FFT or a set of transversal filters. Cancellers and few optimized methods are some of the clutter rejection techniques.

Cancellers

Clutter rejection filter amounts to the design of FIR digital filter with stop-bands to reject the clutter frequency component. A simple filter is a two-pulse cancelor.



A two-pulse canceller is used if the clutter component (assuming DC only) remains constant in a given range bin and can be eliminated by subtracting the output from two successive pulses. The transfer function of two-pulse canceller is equal to $1-Z^{-1}$. And is equivalent to FIR digital filter with magnitude response sin ($\omega/2$).

In practice, the clutter has a power spectrum that covers frequencies above DC. The two-pulse canceller will attenuate low frequency components but may not totally reject clutter. A three-pulse canceller with its transform function equivalent to FIR filter is $0.5+z^{-1}+0.5z^{-2}$. This attenuates further the components near DC.

Implementation of Clutter Filter

The returns from the same range bin over several pulses are linearly combined to form the output per IPP, each delay of Δ can be realized using shift register.

a. The direct implementation of the optimum linear processor with N points requires N multiplications per output point. Since a different optimum processor is designed for each Doppler channel, the filter tap weights are different for each channel.
b. A simpler Suboptimum Processor is obtained by cascading a three-pulse cancellor with a bank of band-pass filters (implemented by a sliding FFT). N-point FFT requires $N\log_2 N$ multiplications; only $\log_2 N$ multiplications are required per each Doppler Channel. Thus significant hardware simplifications are possible with this scheme provided its performance is adequate.

E.g. moving Target Detector

MTI Signal Processing

A major task in moving target indicator (MTI) radar is to obtain a time-domain filter, with the introduction of digital technology, these are achieved using digital transversal filters, recursive filters and filter banks.

Adaptive Thresholding and Automatic Detection

Digital processing permitted the reference level to be generated/internally from the observations themselves, thereby permitting more sensitive and faster thresholds. Most of the Radars employ automatic detection circuits to maintain, ideally, a constant false alarm rate (CFAR) by generating estimates of the receiver output. Automatic target detection for a search radar can be achieved by comparing the processed voltage in each cell to:

1. A fixed threshold level.
2. Threshold levels based upon the mean amplitude of the ambient interference.
3. A level computed on the basis of partial (a priori) knowledge of the interference distribution.
4. A threshold level determined by distribution-free statistical hypothesis testing that assumes no prior knowledge of statistical distribution of the interference.

In first case a detection decision is made if the processed signal r_o, is equal or greater than a present threshold. That is, if $r_o \geq T_p$, a detection is declared.

The second and third cases represent adaptive threshold CFAR processors. In these processors, estimates of the unknown parameters of the known distribution of the processed interference are formed. In the second case can achieve CFAR when the distribution of processed interference is completely described by its mean level. The third case forms estimates of the unknown parameters of the known (a priori) distribution.

The fourth case are called nonparametric CFAR processors. These distribution-free process form a test variable whose statistics are independent of the distribution of the input (non-processed) interference.

A. Adaptive Threshold CFAR Processors

The adaptive threshold CFAR processors is applicable to situations where the distribution of the processed data (in the no-signal case) is known generally and unknown parameters associated with the distribution can be estimated. It is often implemented as moving or sliding window through which estimates of the unknown parameters of the interference are formed.

B. Distribution free CFAR Processors

These provide CFAR characteristics when the background return has an unknown distribution. These processors remain insensitive to variations in the distribution, and generally experiences additional detection loss their CFAR properties make their application advantageous.

1. Double Threshold Detector
2. Modified double threshold Detector
3. Rank order Detector
4. Rank-sum double quantizer Detector

C. Scanning Radar Application

The optimum processor for a pulsed, non-coherent waveform on n pulses is a square law detector followed by a n pulse non-coherent integrator that uses equal weighting of each detected pulse. The integrator must not only be realizable in practical sense but also

1. provide a small detection loss as possible
2. provide a means of minimizing losses associated with integration sample window and scanning beam straddle of the target
3. In track-while scan applications, permit accurate measurements of the target angular position.

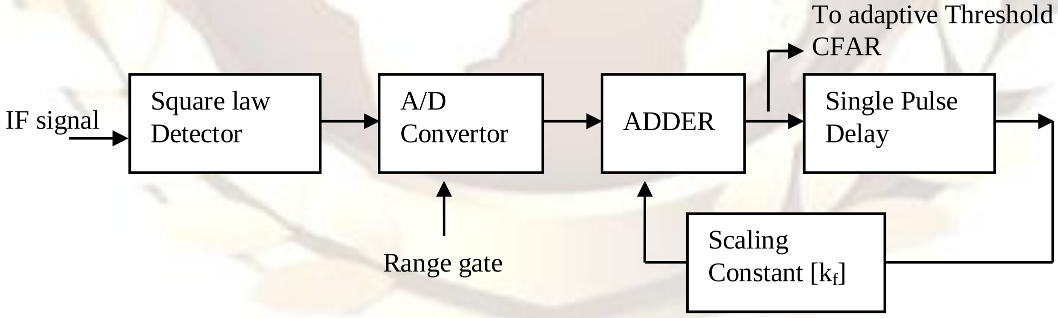


Fig.3 Square law detector

Integrators that are typically configured are sliding window. And this requires the storage of data for n inter-pulse periods. The single-loop processor requires storage of data for the single inter-pulse period. Of course, if data memory is somehow restricted and if performance is acceptable the feedback approach is preferred and single feedback loop is shown below.

Signal Processing in Synthetic Aperture Radar (SAR)

Digital processing has also permitted increased capability for extracting target information form the radar signal. High resolution SAR provides an image of a scene. Radars are used to recognize one type of target from another, with the aid of digital processing, inverse SAR (ISAR) produces an image of a target good enough to recognize from other classes of targets by extracting the spectrum of a target echo signal. Interferometric SAR, which uses two antennas spaced vertically with a common SAR system, can provide height information to obtain 3D image of a scene. Greater flexibility and real-time operation suggest digital signal processing in SAR.

SAR exploits the probability density of the clutter to detect man-made features by modeling the clutter by a family of densities and picking the density that best describes the clutter on local basis.

Fourier based methods are used for detection of stationary and moving target detection and identification in reconnaissance SAR. The computational time of the time domain correlator (TDC) is overcome in the frequency domain. Here digital spotlighting principle is used to extract the target's coherent SAR signature.

Step 1

Coherent matched-filtered SAR reconstruction of the scene in the presence of foliage is developed by exploiting the angle and frequency from the target's coherent SAR signature.

Step 2

With the help of Fourier-based method the three dimensional statistic representing the moving target coordinates and speed is used for moving target detection.

Strip Mapping SAR

On the incoming data, the pulse compression matched filtering is done to obtain Range resolution and stored prior to azimuth processing. Data are processed one row at a time to perform the azimuth compression, since large amount of data are collected large memory space is required. For each range resolution cell different azimuth compression filter is required.

Assuming range azimuth resolutions are to be equal and total range is mapped to Δ_z then each memory column has M samples and $2\lambda z_1 / L^2$ samples (niquist rate sampling) in each row.

The total storage requirement is

$$Memory = \frac{2\Delta_z}{L} \circ \frac{2\lambda R_{\max}}{L^2}$$

Total calculation is that required for the operation of M azimuth pulse compression channels in parallel. So the total computational time using direct convolution is upper- bounded by

$\frac{2M\lambda R_{\max}}{L^2}$ multiplications

By using FFT for high speed convolution together with parallel parallelism reduces the speed requirement significantly.

Spotlight mode SAR

Stretch processing is adopted, i.e., the azimuth resolution is obtained from different Doppler shifts of the individual targets. Let x_1 and x_2 are the two targets both at same range z_1 then the received signal $r(t) = e^{-j\frac{\omega_o}{cz_1}(vt-x_1)^2} + e^{-j\frac{\omega_o}{cz_1}(vt-x_2)^2}$ is the sum of two chirps.

$1 + e^{-j\frac{\omega_o}{cz_1}[2x_1-x_2)vt-x_2^2-x_1^2]}$ will be the signal of x_1 is considered as a reference point and is called dechirping. The discrimination between the two targets are performed analyzing x_1 at zero frequency and target x_2 analyzed as frequency $2\omega_o v(x_1 - x_2)/cz_1$. Signal processing of the multiplier of dechirping and FFT is carried out. Since this approximation is done near to x_1 the FFT processing is limited to small region around the reference point. Also it is advantageous to band-limit the dechirped azimuth signal to the frequency range of interest and do FFT. To avoid aliasing low-pass filter is chosen whose impulse response is a rectangular window and the frequency response is $\sin {}^{N\omega}/_N \sin \omega$. The high frequency-domain sidelobes of the rectangular window is overcome by using a different window or an optimal low-pass filter.

Thus this signal processing tends itself to a spotlight mode of SAR. Small areas of central reference point are imaged individually and a large map is constructed by piecing together several sub-maps.

The key feature to be considered to discriminate the man-made structure and the foliage is the characteristics of SAR signature of a man made metallic cylinder are different from the nature objects such as tree with the same size of low frequencies in the UHF band.

Why not shape information to distinguish targets?

The resolutions of the reconstructed SAR images are poor at UHF frequencies. The SAR magnitude reconstruction of both man-made targets of foliage will appear as blobs. Thus, there is no much discrimination about the information. By the process of Digital spotlighting the procedure to extract the coherent SAR signature of a target is done.

Target detection and identification

a. Matched Filter Reconstruction

Based on the SAR principles governing the variations of the gain and phase of target's coherent radar cross section with respect to the signal frequency and relative speed, angle, we have a general expression for the two-dimensional matched filter that is capable of detecting a specified target in the presence of foliage.

The measured signal $S(k_u\omega)$ is passed through a bank of *N*, two-dimensional matched filters, and it is passed through SAR wave front reconstruction algorithm.

b. Digital spotlight detection and identification

The image filtered reconstruction requires image formation for all possible target types followed by a search algorithm to detect the targets. The targets are identified by search method, extract the coherent signatures, and then perform matched filtering on the signature of these suspected targets. The extraction of coherent signature from the coherent reconstruction image is done and process is called digital spotlighting.

Digital spotlighting is a computer based process that isolates the target or a target region in a SAR scene. To detect and identify targets, digital spotlighting the reconstructed image $f(x,y)$ is the reconstruction domain. A stationary target's signature is fairly focused and once the target signature is spotlighted, it is transformed into any domain of the SAR signal for identification.

Detection of targets in foliage

Three different target detection techniques for UHF SAR were discussed in this research. These techniques are brief out.

a. Baseline approach

It consists of 3 stages with high resolution, Ka-band SAR DATA. The first stage, a simple two-parameter constant false alarm rate (CFAR) detector, is a computationally simple prescreening algorithm that rejects most natural clutter. A target detection is declared if the CFAR algorithm evaluation ratio exceeds CFAR threshold. This algorithm is followed by a clustering algorithm, which combines multiple detections occurring in a target-sized area into a single detection. The combination of these two algorithms is considered to be the baseline algorithm.

b. Adaptive change detection

The adaptive filters used are two-dimension extensions of Widow Least mean Squares (LMS) filter, used as joint process estimators for noise cancellation. Each makes use of two images, a primary, D [presumed to have targets] and a reference x [without targets]. The clutter of the reference image is convolved with the weight matrix, W, to predict the corresponding clutter in the primary image. This primary image is subtracted from the primary to yield an error image, and the difference is used to adoptively tune each element of the weigh matrix by an approximation. At each iteration, the sign of the gradient is measured. After consecutive sign changes, and scaling, the deviation is found. By using two-pass change detection with the adaptive filters, the target-to clutter ratio is increased.

c. Multiple aperture detection

It takes off both the UHF SAR and the angular diversity of target returns. In order to achieve a high cross range resolution with a SAR operating at FOPEAN frequencies, it is necessary to process the data over a large integration angle. By splitting the integration aperture, multiple images are formed. It is then applied to two-dimensional adaptive filters used for change detection to these multiple images. This had an advantage with the different responses of clutter and targets with aspect angle. Clutter returns were expected to show less aspect angle dependency than targets, this property allows angle dependency than targets, and clutter can be removed by change detection algorithms. This technique has two distinct advantages over traditional change detection the multiple aperture targets are perfectly co-registered and only one flight pass is required over a given scene.

CONCLUSION

In this research a brief overview of application of digital signal processing in Radar is presented. Matched filter implementation, echo cancellers and automatic detection and tracking are discussed in separate sections. In most of the modeling, Fast Fourier transform is a very commonly used technique for analyzing and filtering digital signals. Different techniques of detection of targets in foliage are discussed for SAR. The recent advances in signal processing are blended with many more algorithms to present an up-to-date perspective and can be implemented in Digital Signal Processor because of their flexibility and the ability to attain high precisions.

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