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Recent Advancements in Naval Surveillance Radars

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***Abstract*: The Surveillance Radars with improved technology are increasingly deployed to enhance the detection capability and improve the reaction time available to tracking Radars for better guidance of the firepower of the platforms. Harnessing of distributed low power transmitter technology and increased receiver sensitivity coupled with Digital Beamformer to effectively steer transmit and receive beams, Pulse Doppler processing and Electronic beam stabilisation has evidently helped in leapfrogging of Radar performance. The solid state based TR modules have invaded the front end of the Radar with resultant planar array antenna & thus improving the efficiency & reliability of the Radar system. Advanced pulse compression, Doppler techniques & signal processing implemented on a digital platform deployed above-deck, riding piggyback on the front end has made the erstwhile complex RF & waveguide rotary joints redundant. Convergence of technology modules evolving rapidly with communication technology is becoming evident in the form of deployment of Fibre Optic media; Server based data processing, Data Distribution Services for real time operation of the system.**

Index Terms: Firepower, low power transmitter, Pulse Doppler processing, main beam clutter, Electronic beam stabilisation, Multi-Objective Evolutionary Algorithm, fibre optic media, Quality-of-Service, data distribution services

I. INTRODUCTION

The Radar designers are exploiting the advances in electronics technology and computer science to achieve the accurate detection of low RCS targets in a diverse environment of Clutter, interference and jamming. Classical Radar is defined by its ability to detect presence of targets and determine the range of that target. The technological advances have brought other dimensions such as determination of angle to a target (both azimuth & elevation) which is based on radiation pattern of its antenna. Also, the early Radars had no means of measuring target velocity directly. The Doppler shift measurement techniques evolved subsequently has enabled the current Radars to estimate the radial velocity of the targets instantaneously. Pulse Doppler processing entails coherent integration of several pulses with a high degree of integration efficiency leading to a significant processing gain.

All contemporary and future Radars road map is to move towards multi dimensional detection configuration. The conventional 2D Surveillance Radars used to provide the target information only in Range and Azimuth, and provide this information to tracking Radars for target designation. Tracking Radars in turn used to scan in elevation for target of interest to engage weapons if required. For achieving long ranges, high power transmitters and associated extremely high voltage components and engineering challenges are being overcome in new 3D Radars through advanced TR modules, waveform generation and pulse compression techniques. To extract and provide the elevation information of the target, the conventional parabolic antenna is being replaced with planar array antenna with beam forming technique aiding in providing the elevation information of the target to Radar controller. With TR modules and beam forming located at rear side of antenna electronics, there is no requirement of waveguide rotary units, which are being replaced with high speed fibre optic rotary joints. Most of the Radar signals are digitized above deck, the signal processing at above deck and data processing is carried out at below deck on latest available multi core servers.

The Section II elaborates new technologies of various Radar building blocks of 3D air surveillance Radars. And conclusions are presented in Section IV.

II. ADVANCEMENTS IN 3-D RADARS

Emerging technologies being exploited in terms of dual polarization and Digital Beamforming techniques for providing an integrated solution essentially required for Multi-function Radars like simultaneous air surveillance and weather sensing. Multifunction Radar is a complex Radar system which combines the previously isolated tasks of searching volumes of space, tracking targets and guiding missiles. When looking at the operational efficiency of this type of Radar system is to schedule the Radar jobs effectively. These jobs take the form of a coupled task which consists of two distinct operations that require processing in a pre-determined order and at a specified interval apart. In the Radar scenario, each job is cyclic in nature with its own due date and processing time. The need for an on-line scheduler restricts the Radar controller to use heuristic methods.

The phased-array panels function together coherently to radiate and receive pulses of Radar energy that can be used to detect, locate, and track aircraft and weather targets as depicted in Fig 1.

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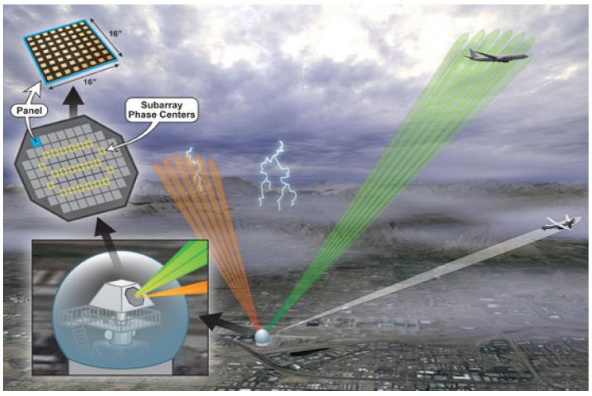

Fig 1. Multi-function phased-array Radar panel provides a solution for simultaneous aircraft surveillance and weather sensing

Multiple receive beams in modern radars are used for improved performance in volumetric surveillance, reduced beam shape loss, improved performance in extreme clutter environments and angle estimation. Signal processing for multiple receive beams to find detections from the individual beams and estimation of target parameters. Implementation of multi beam detection combining and Maximum likelihood angle estimation algorithm is required. Compared to conventional single beam radars performance improvement in target detection and better angular accuracies and resolution are achieved. Multi-beam radar handles the digital video data received from the beams focused at different angles at the same time, which makes the surveillance volume by single dwell much larger than those of the conventional single-beam radars by the number of beams as shown in Fig 2. Although due to the advances in processing technology handling such multi-beam data is not so complicated nowadays, but combined processing of these beams for detection and target parameters estimation brings other challenges.

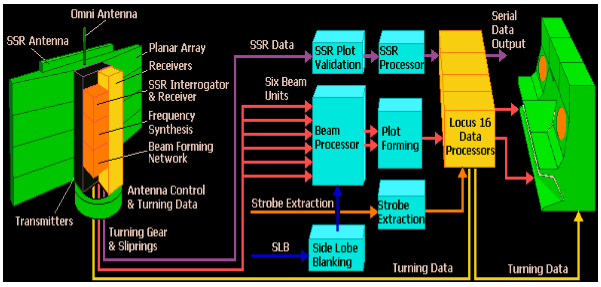

Fig 2. Block diagram of a typical 3D radar

A. ANTENNA

Traditional 2D surveillance Radar antennae were parabolic, cassegrain, slotted waveguide antenna, these antennae are being replaced with phased array antenna with individual multiple elements or row of antennae. The elements are dipole, patch antenna, Vivaldi antenna etc. This element configuration is enabling addition of RF signals in free space rather than handling high power RF combiners / components. In this configuration, even if few antenna elements fail, still Radar system operates, which enables graceful degradation. This requires antenna element or group of elements to be excited by individual transmitters is addressed through low power solid-state based transmit modules.

B. TRANSMITTER

The solid state modules have very high MTBF values and hence highly reliable transmission and high Radar availability. Currently most of the Solid state transmitter modules are based on LDMOS or GaN based technology. These Transmitters being in many numbers and have provision to control individual elements gain and phase, based on Radar configuration, can have various modes of operation in combination of antenna and beam former.

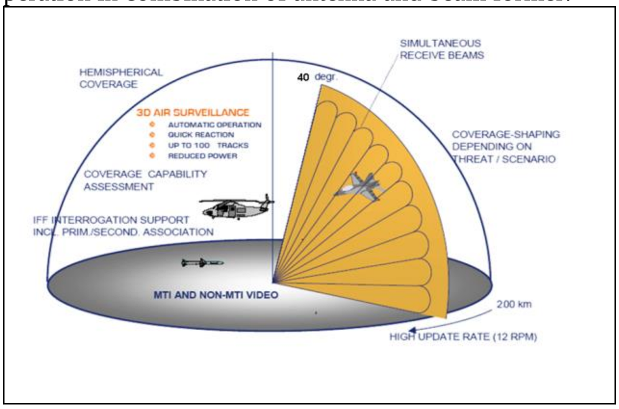

Fig 3. Multiple Elevation Beam Formation

By having planar array antenna and exciting the transmit modules with different phases, different transmit patterns can be achieved, by means of which multiple elevation beams are being formed and hence the capability of 3D Radar, as shown in Fig 3.

Multiple beams or beam steering is possible by means of planar array antenna. There are various ways beams are formed to cover elevation, and the most popular methods are, switched beam or simultaneous multiple beams or combination of both. Again these are being formed either in digital domain or analog domain. The beams formed by analog means are phrased as analog beam formers, where as other type is called as Digital Beam Former.

C. RECEIVER

Just the same as transmitters, the receivers also have shrunk in size and the combined package has emerged as TR module widely accepted in modern 3D radars. As the receivers are very close to antenna elements, the noise figure of the overall radar is improving and also resulting in improved dynamic range of the receivers. Being individual and multiple receiver elements, failure of few elements won’t have significant impact on Radar operational performance and hence enables graceful degradation of the system.

The need for high power rotary joints has vanished by having transmitter and receiver being part of antenna on above deck. The rotary joints now are required to carry high density digital data, which are being addressed by fibre optic rotary joint. Multi Channel Fibre optic related modules and accessories are becoming part of Radar

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building blocks. This fibre optic module uses Serial Front Panel Data Port (sFPDP), Aurora and 10G Ethernet protocols to provide higher data rate with low loss for long distance communication.

D. BEAMFORMING

Beamforming is a digital technique that focuses the radar transmitter and receiver in a particular direction. The side to side direction is commonly referred to as the azimuth and the up and down direction as the elevation. Beamforming can be used to focus the radar over both azimuth and elevations.

Early airborne radars, and many ground and naval radars used the more familiar parabolic type antennas. The parabolic shape focuses both receive and transmit energy in the direction of the antenna. The antenna may be rotated to search in all directions or aimed in the azimuth and elevation of interest. In order to search across the area of interest, the antenna must mechanically be aimed or rotated to steer its beam in the desired direction. In many military applications, this function is often performed electronically, using active electronically scanned array (AESA), which is an electronically steerable antenna. This allows very rapid steering of the radar beam, which is particularly useful for military airborne radars. This technique is known as "beamforming", which references the electronic steering of the main antenna lobe or beam as depicted in Fig 4.

An AESA is built from many small antennas or individual elements. Each antenna element has a transmit and a receive module. Therefore, each element can individually vary the phase and amplitude of both receive and transmit signals. These changes, particularly in phase, provide for steerable directivity of the antenna beam over both azimuth and elevation. Only when the receive signal arrives in-phase across all the antenna elements will the maximum signal be received. This provides the ability to "aim" the main lobe of the antenna in a desired direction. The process is reciprocal, meaning that the same antenna lobe pattern will exist on both receive and transmit (assuming common frequency for receive and transmit).

Each antenna element must have a delay, or phase adjustment, such that after this adjustment, all elements will have a common phase of the signal. If the angle $\theta = 0$, then all the elements will receive the signal simultaneously, and no phase adjustment is necessary. At a non-zero angle, each element will have a delay to provide alignment of the wave-front across the antenna array. Once each antenna element input is down converted to baseband by a common clock and local oscillator, each antenna input is delayed by the correct amount so that the wave front arriving from a given direction is aligned. This delay can be digitally implemented by phase rotations, or multiplication by $W_i = e^{j\theta}i$. For better side lobe control, the amplitude can also be varied, by using $W_i = a_i * e^{j\theta}i$. By adaptively changing W_i for each antenna input, the beamforming can be accomplished. The transmit direction works in the same manner. The advantage is very rapid steering, which can allow fast searching as well as tracking of objects. Mechanical movement and motors can be eliminated. Using a technique called "lobing"; the radar beam can be rapidly steered on either side of a target. By noting where the stronger return is, the target movement can be more accurately tracked.

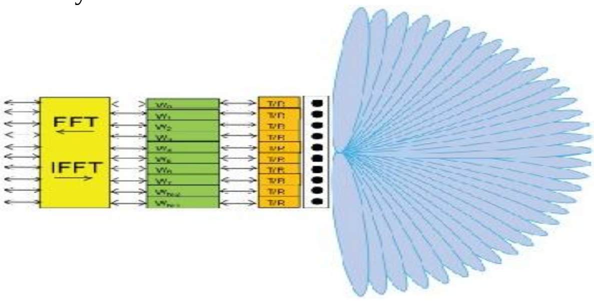

Fig 4. Beamforming on elevation

Digital beamforming can also be used in another capacity. In some systems, it is desired to receive and transmit separate signals in different directions simultaneously. This can be accomplished by using the FFT algorithm. Normally, FFTs are used to take a time domain signal and separate it into its different frequency components. In this case, the FFT will separate the incoming signal into its different spatial components or angle of arrival components. The input signals are sorted by the FFT into bins corresponding to different angles of arrival, as shown in Figure 3. Similarly, in the transmit direction, a signal fed into each FFT bin input will be transmitted in a specific direction, corresponding to a specific antenna lobe. If the input to a FFT bin is zero, no energy will be transmitted in that direction; the transmit lobe will be "missing". These beam former also addresses the Roll & Pitch stabilization requirement by electronically stabilizing the beams as compared to erstwhile hydraulic / mechanical stabilised systems.

E. SIGNAL PROCESSOR

It is feasible today to put the data converters at IF stage and all the baseband processing digitally. The time delays that create the interference patterns between antenna elements can be done digitally in a beamforming network at baseband as well, eliminating the need for analog phase-shifters or delay lines on each antenna element. This partitioning allows DSP designers to decompose transmit and receive paths into discrete functions—multipliers, filters, FIFOs for delay, and adders—model them in MATLAB, and implement them from libraries. The most demanding functions can go into purpose-built ASICs, FPGAs, or perhaps GPU chips, while less-demanding operations can be grouped into code on DSP chips or accelerators as shown in the following Fig 5.

Advanced systems add another dimension to the array processing. By subdividing the antenna into sub-arrays, the system can transmit a number of beams simultaneously, and then set the receiver to listen using the same many-lobed antenna pattern. Or alternatively, the system can scan the beam through beamforming.

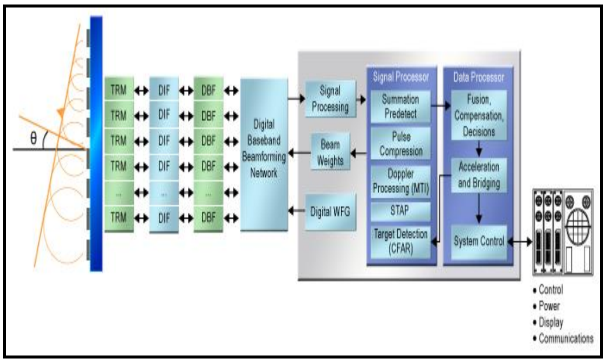

Fig 5. Hardware scheme of 3D active phased array Radar

Now, when binning the compressed pulses, the system can create a three-dimensional array of bins as shown in Fig 6. Now for each pulse we have two- or three-dimensional array that represents range, direction and representation of physical space. This arrangement of memory is the starting point for space-time adaptive processing (STAP).

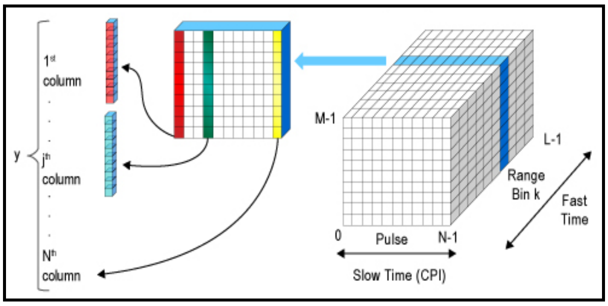

Fig 6. Three dimensional array processing

Increasing demand on efficiency of the radar with employment of low power transmitters, there is a need for increasing the average power by some way of modulating to achieve the long range surveillance requirement of the radar without compromising the resolution. Hence the Pulse compression technology, where in transmission is a wide pulse with less peak power, modulations like Linear Frequency Modulation (LFM), Barker code or Polyphase code and compress the signal on receive and have good resolution too with very good sidelobe levels.

Also there are different Pulse waveforms and PRF generation because of extensive use of FPGA's. This calls for new waveform and exciter technology based on latest FPGA's with combination of RF modules integrated in same package. The latest trend of PRF generation is based on coincidence algorithm, which addresses both range and Doppler ambiguities. PRF can be derived for optimal target detectability using Multi-Objective Evolutionary Algorithms. This evolutionary algorithm (EA) will deduce near-optimal PRF sets efficiently from the vast number of possibilities. This algorithm generates the PRF sets with low level of range, velocity blindness and maximizing range and velocity decoding as indicated in Fig 7. The "quality" of each set is based on Radar model and associated main beam clutter (MBC), so each PRF set is application / scenario specific.

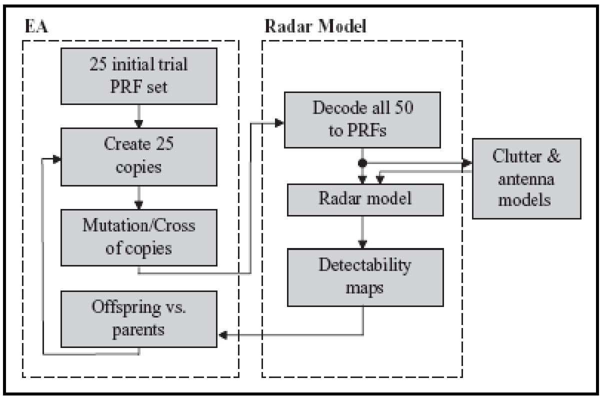

Fig 7. Flow chart of PRF generation by EA algorithm

Contemporary Signal Processing has to handle pulse compression, Doppler processing, followed by Coincidence Algorithm or Chinese remainder theorem for range and velocity decoding, in addition to Moving Target Detection (MTD), Constant False Alarm receiver (CFAR), data processing, centroiding etc. The traditionally used LFM waveform is having very weak Peak Side Lobe Ratio (PSLR) of -13.2 dB which may not be sufficient to discriminate nearby targets. Even though Windowing techniques improve the PSLR, but at the expense of widening the main lobe of the autocorrelation function thereby reducing the range resolution. Non-linear FM and Polyphase coding techniques prove better in terms of fine range resolution, superior Signal to Noise Ratio (SNR) through side lobe reduction up to -30dB, as shown in Fig 8.

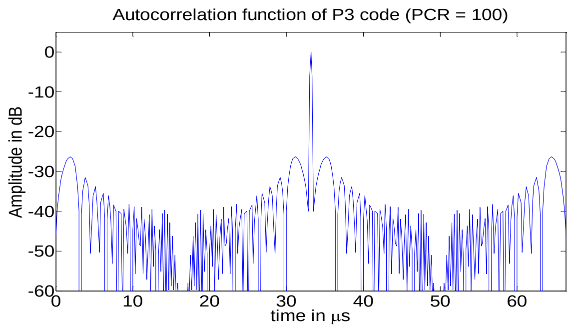

Fig 8. PSLR of Polyphase (P3) code

Polyphase waveforms can be generated through the principle of phase variation of linear frequency modulation techniques, categorized as P1, P2, P3 and P4 codes. Polyphase waveforms are analyzed in terms of range resolution, SNR, Doppler tolerance and pre-compression band-limiting properties. Since 3D Radar has multiple channels on azimuth and elevation, the signal processing has to process very high speed data with time synchronization. As the data transfer is asynchronous between the modules, Time stamping is very crucial. Signal processing task becoming multi dimensional in range, followed by processing by burst / dwells, and multiple elevation channel processing. Signal Processor becoming distributed system between above and below deck for data transfer and thus signal processor firmware is turning out as heart of the 3D Radars. Most of the advanced radars are operating at medium PRF, the traditional raw video presentation on PPI are being replaced with synthesized videos, tracks, over laying of maps of the terrain dynamically with GPS interfaces. The Advanced PPI is more user friendly with more graphical user interfaces and presentations embedded with target classification.

F. DATA DISTRIBUTION SERVICES

Gradually, Data Distribution Services which is a communication middleware fabric for scalable and extensible Systems-of-Systems (SoS) is entering into radar domain as well. During the past several decades, techniques and technologies have emerged to design and implement distributed systems effectively. The challenges for system of systems are unique when compared to traditional systems since their scale, heterogeneity, extensibility, and evolution requirements are unprecedented compared to traditional systems. Typically in SoS, the computational and communication resources involved are highly heterogeneous, which yields situations where high-end systems connected to high-speed networks must cooperate with embedded devices or resource-constrained edge systems connected over bandwidth-limited links. Moreover, in SoS it is common to find multiple administrative entities that manage the different parts, so upgrading the system must be incremental and never require a full redeployment of the whole SoS.

Since its inception, DDS has experienced a swift adoption in several different domains. The reason for this successful adoption stems largely from its following characteristics:

- DDS has been designed to scale up and down, allowing deployments that range from resource-constrained embedded systems to large-scale systems-of-systems.
- DDS is equipped with a powerful set of Quality of Service (QoS) policies that allow applications fine-grain control over key data distribution properties, such as data availability, timeliness, resource consumption, and usage.
- DDS is equipped with a powerful type system that provides end-to-end type safety for built-in and user-defined types, as well as type-safe extensibility.

As a result of these characteristics, the DDS standard is the most advanced data distribution technology and is evolving as a key building-block to be deployed on the current and future radar systems.

III. CONCLUSION

The need for long range surveillance capability coupled with short range high precision, quick reaction tracking requirement is increasingly being demanded by the user. The trend is towards convergence of technologies evolving in the defence application such as 4D including Range, bearing, Elevation and Doppler for velocity with real time processing. Surveillance radars play a major role with advanced technology to enhance the detection capability and improve the reaction time available to tracking radars for better guidance of the ballistics of the platforms. Also convergence of technology modules evolving rapidly with communication technology is becoming evident in the form of deployment of fibre optic media. It is also an additional demand for containing the life cycle cost is driving the modern Radar technology.

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