

Modern Radar Techniques for Air Surveillance & Defense

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Abstract.

During the last sixty years Radar systems have evolved from auxiliary electronic devices to the heart of every modern weapon system on the ground, sea, air and space. In the course of their evolution the Radar systems started with a few simple, but extremely useful, capabilities for providing ranging of remote objects and radio-location, while continuous advances of the Radar technology added many more capabilities like precise navigation, targeting, guidance, mapping, imaging, target recognition, target identification & classification and more yet to come.

The evolution of the Radar Technology has caused the birth and development of a new field of science, the Electronic Warfare, whose main objective is to provide countermeasures to the Radar threats. Moreover, responding to the threat of detection by Radar, the targets started becoming more elusive by incorporating 'stealth' techniques in their design.

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.

The modern radar techniques are focused in the fields of: adaptive antenna arrays, receiver sensitivity and real-time digital signal processing. Also, the advances in computer science that can now provide immense processing power, has allowed the emerging of new Radar configurations beyond the classic mono-static case: The passive and poly-static Radar systems. Although, these new configuration are still in the experimental phase, they have already showed interesting properties, especially at the detection of low RCS targets.

In the present article, the modern techniques in the design of new radar systems, as well as the upgrade of existing systems are presented and their performance and prospects are analyzed. It is considered that Radar will remain the centerpiece of all new Air Surveillance & Defense systems in the 21st century and will continue to evolve following the advances of science and technology and responding to the requirements of the modern warfare.

Keywords: Radar, Jamming, RCS, Clutter, Signal Processing

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1. Introduction

The last few decades radar has become the main component of every major military system and frequently the overall military value of the system is dependent on the performance of its radar. This fact is not coincidence because radar has actually replaced the sharp vision and the fast reflexes of the traditional warrior, only now the radar vision allows the detection of the enemy at hundreds of miles away in day and night at any conditions and can provide precise guidance to the weapons within milliseconds.

Having understood the value of superior radar performance, militaries of the world keep pressure on the radar manufactures for even more enhanced radar capabilities as they know that at the battleground the better radar will define the victor. Radar, being a set of electronic components, has tied its evolution to the technological advances in electronic engineering and computer science. Also, as radar systems are actually high value items costing from a several thousand to millions of Euros, it is not uncommon for radar systems to be upgraded several times during their lifespan before they are replaced.

Apart from radar upgrades and the development of new radar systems, the advances in the fields of real-time signal processing, software and data networking have given the radar developers the opportunity to explore the performance of novel radar architectures and configuration which although were known in theory for decades, they could not be practically implemented due to restrictions posed by technological limitations at the above fields. The Passive Coherent Locator (PCL) or better known as passive or multi-static radar is an example of such a system which will soon be fielded by the militaries as a complement to the existing “classical” radar configurations.

In this paper, we will explore the components of the air-defense radars that can be upgraded by use of modern technology in order to optimize their performance in the modern battlefield, we highlight the radar sub-systems where the explosion of computer power has provided the capability to introduce novel solutions to old problems and finally will introduce the concept and the characteristics of the passive radar systems that will soon find their place in the future arsenals.

2 Advances in Radar Technology and Performance Optimization

2.1 Phased Array Antennas & Electronic Scanning

Although the classic parabolic reflector remains the most popular air surveillance radar antenna due to its simplicity, robustness and low-cost, it can only serve 2D radar systems as the produced beam is broad in elevation and cannot be used to distinguish the air targets altitude. However, modified parabolic reflector antennas using multiple horn-feeds had been able to produce multiple receive beams stacked in elevation. This has been the first attempt to produce 3D radar systems using the conventional reflector antennas. Unfortunately, the height calculation accuracy of these systems although adequate for early warning purposes, has not been precise enough for tactical operations as interceptor or missile guidance.

The breakthrough that permitted the manufacturing of high precision 3D radar systems has been the development of the phased array antenna, which is composed by a large number (many hundreds or thousands) of small radiating elements (typically dipoles or waveguide slots). This type of antenna has the capability to focus the radar's radiation into high energy pencil-beams which can be guided electronically in space without the need of any physical movement of the antenna structure. By the use of phased array antennas the radar system can schedule the transmission and reception beams according to specific operational modes such as: long range detection (low beams), detection in clutter (multi pulse beams), ballistic missile warning (high beams) etc

The key element of the phased array operation is the use of the phase shifter, a microwave technology component that can adjust the phase of the electromagnetic wave that feeds every radiating element (or groups of elements). Through appropriate phase adjustment the beam pointing and focusing (beamwidth) can be adjusted according to the operational mode of the radar. (See Figure 1)

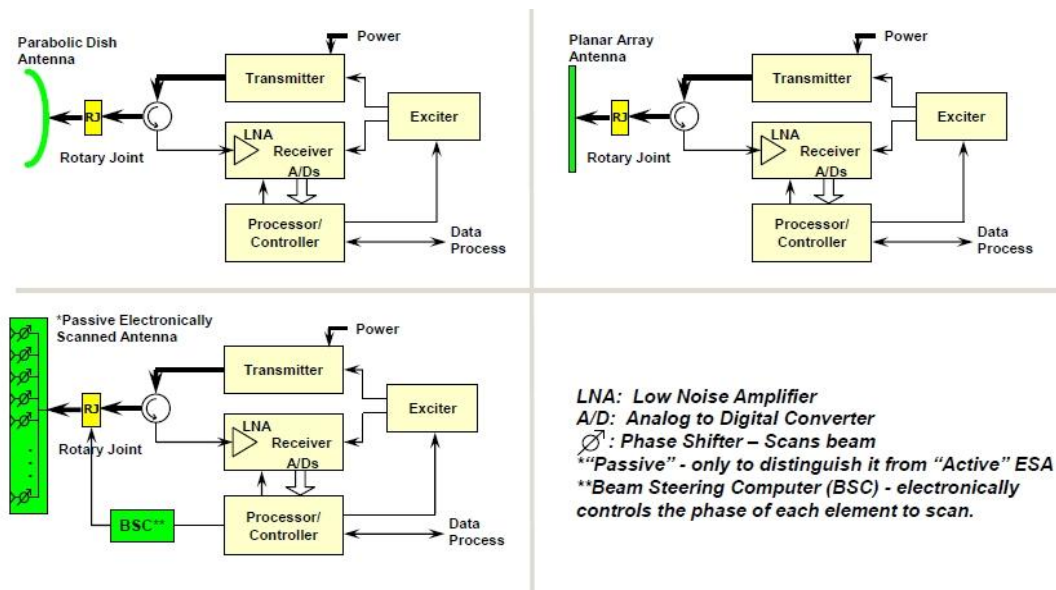


Figure 1. Configurations of Radars using passive antennas with mechanical or electronic beam steering (Source: Northrop Grumman)

During the 1990's has been common practice for the radar manufacturers to migrate their systems from parabolic reflector type antennas (2-D or multi-feed 3-D) to the phased array type in order to take advantage of the advanced features and operational capabilities. Such an example is the Westinghouse AN/TPS-43 radar system that of the 1970's-80's that evolved to the AN/TPS-70 in the 1990's by the introduction of a new phased array antenna.

2.2 Solid State Modular Transmitters

The component that allowed the development of practical radar applications has been the microwave tube, which has been used as the centerpiece of the radar transmitters both as oscillator (Magnetron type) and as high power amplifier (TWT, Klystron, Twystron, CFA type). These tubes have provided for decades the very high electromagnetic (EM) power that is needed for the detection of small targets in long distance.

Although over the decades the tube transmitters have evolved in maturity both in performance and reliability, they have shown some disadvantages: their limited life-cycle a few thousand hours, the requirement of very high voltage of operation (30-100 KVolts), liquid-cooling requirements, very high price, phase instability and

others. During the 1990's radar manufacturers started investigating the possibility to replace the tube transmitters by using solid-state transmitter modules that use transistors in place of the tubes. The main issue at this case has been that each transistor cannot exceed the power output of 200-300 Watts of microwave energy while several Kwatts or Mwatts are required for most radar applications. In that respect the transistors had been bundled in small groups called Transmitter Modules that can deliver output power of about 1 KWatt. Then, depending on each particular application, several tens or even hundreds of transmitter modules are coupled together using microwave power combiners to produce the final required output power.

The main advantage of the solid state transmitter is its inherent self-redundancy that allows it to remain operational with slight performance degradation even if 10% of its modules are out of operation due to failure. Moreover, the modules operate at low DC voltage, do not require liquid cooling and, if properly designed, can operate for many thousand hours without failure. Finally, the repair, test and alignment of the transmitter modules can be performed at simple workshops using ordinary test equipment and general electronics training, as opposed to tube repair and test that can be performed only at the manufacturer facilities at extremely high cost.

The introduction of transmitter module in radar application followed the manufacturing of the respective high-power microwave transistors: Started with the L-Band radar frequencies (1-1.5 GHz) in the 1990's and continued with the S-Band (2.5-3.5 GHz) systems in the 2000's. Today, power transistors are available both at C-Band (5-6 GHz) and X-Band (9-10 GHz) providing the option for radar designers to produce all-solid state transmitters. However, despite their high cost, tube transmitters (and especially) TWTs continue to be used in the modern radar systems.

The last decade, following the technology trend, almost all radar manufacturers have started adapting the radar designs by providing models options with solid state transmitters, while offering upgrades of older tube transmitters to solid state. Such upgrades are the replacement of EADS L-Band MPDR-90E double-triode transmitter amplifier by 16 solid-state modules and the replacement of the BAE SYSTEMS S-Band AR-327 TWT transmitter by solid state amplifiers mounted on the back of the phased-array antenna.

2.3 High Sensitivity Receivers

The receiver is the radar component that is tasked to amplify the extremely low power of the EM wave that has been reflected on distant targets and has been collected by the antenna receive beam. Typical levels of target echo returns are in the range of -90 to -120 dbm and thus amplifiers with very low inherent noise injection (very favorable noise figure) are required. This special type of amplifiers is called Low Noise Amplifiers (LNAs) and their commercial version that is used at the satellite TV receivers is known to the public as LNB (Low Noise Booster).

Apart from the high gain, flat frequency response across its operating bandwidth and low noise figure, a very crucial characteristic of an LNA is its durability to high input power that assures its operational reliability. Bursts of high input power that may destroy or degrade the performance of the LNA is leakage of the radar transmitter power during transmit time, intentional or un-intentional receiver jamming, atmospheric high voltage discharge during thunderstorms and others. The protection of the high sensitive LNAs has also been a field of study for the radar manufactures who have been exploring solutions of fast microwave switches in place of the older solution that employed the use of radioactive T/R tubes.

In sort, the radar developers are exploiting the capabilities of the new lower noise, higher gain and more durable LNAs to optimize the performance of the radar systems. A lower noise figure receiver can detect small RCS targets at further distance that was otherwise “buried” into the noise and clutter. Finally, the modern trend in radar design is to locate the LNAs are close to the antenna as possible (actually mount them on the antenna) instead of the traditional approach that located them close to the receiver/down converter unit.

2.4 Pulse Coding & Pulse Compression

Almost all modern radar receivers comprise a function that is called ‘Pulse Compression’. The purpose of this function is to ‘compress’, meaning shorten the length, of the received pulse echo. This function provides several advantages:

1. The shorter pulse length enhances the range accuracy of the target, as every uSec of pulse length corresponds to 150m of range. Commonly, the compressed pulse widths are below a microsecond and thus provide sub-100m range accuracy.

2. As the pulse width shrinks at the pulse compressor, its amplitude and consequently its power increases and thus maximizes the signal-to-noise ratio that facilitates target detection at later stages of the reception process.

3. In order for the pulse compressor to successfully shorten the width and increase the amplitude of the pulse, the pulse itself should have some sort of modulation in its frequency or at its phase. This means that only the correctly frequency-coded or phase-coded pulses will receive the signal-to-noise boost, while the 'other' pulses (from interference or jamming sources) at the same frequency will not be compressed and thus will be severely attenuated. Consequently, the pulse compression unit acts as a selective filter that allows only the radar's 'own' pulses to be processed for target detection.

The pulse frequency modulation scheme may involve linear or non-linear frequency increase or decrease, which is commonly called frequency 'chirp'. Thus, a system may employ linear or non-linear up-chirp (frequency increase during the pulse width) or down-chirp (frequency decrease during the pulse width). The pulse compression devices are commonly constructed of special type or crystals, called SAW devices (Surface Acoustic Wave) and their operation is based on the principle of transforming the E/M wave to mechanical disturbance on the crystal (acoustic wave) and then back to E/M wave.

The pulse phase modulation is implemented through 'phase reversals' along the pulse width. Usually 3 to 7 phase reversal according to the 'Barker' Codes are commonly used. The implementation of phase coding is easier through the use of delay line networks, but usually cannot achieve the performance of the frequency-coded Chirp waveforms.

2.5 Real-Time Signal Processors

The Radar Signal Processor (RSP) is the 'intelligent' part of the Radar which discriminates the desired type of targets out of various types of echoes that are of no interest to the system operator. RSP functions are implemented by the use of signal processing algorithms whose task is to classify radar echoes according to power and spectral (Doppler frequency) properties.

The signal processing algorithms are implemented by Digital Processor microchips at the digital domain, which means that after the receiver unit, the radar echo signal is digitized by very fast Analog-to-Digital converters so that all the processing can take place in microprocessor and digital memory circuits. In order to retain both the power and spectral characteristics of the target echoes, just before sampling and digitization, the received signal (at IF level) is routed through a balanced mixer where it is split into two components: the In-phase component (I) and the Quadrature component (Q). Both I and Q components of the received signal are sampled and converted to digital. The two components collectively contain the power and spectral identity of the original signal.

First, the spectral characteristics of the received signal are extracted from the digitized I/Q data and are processed by specially programmed microprocessors. Generally, the search radars employ two types of processing:

1. *MTI (Moving Target Indicator)*: It was the first type of target spectral processing that was used, because it can be implemented with relatively simple electronics like analog components, even tubes. As its name indicates, its primary purpose was to discriminate the moving targets by suppressing (eliminating) the zero-speed fixed objects (like ground, mountains etc) by taking advantage of the different Doppler frequency of the respective echoes. Modern implementations of the MTI using digital processors have the capability to suppress unwanted echoes (Clutter) of several non-zero speeds like sea waves, rain, clouds, chaff etc. This function can be implemented by the realization of special digital filtering algorithms.

2. *MTD (Moving Target Detector)*: It is a modern type of target spectral processing. It is much more processing intensive and thus it can be technically implemented only using modern very high speed digital processors. It has the ability to classify the spectral characteristics (Doppler) of each echo into eight or more Doppler regions. Then according to the Doppler region that each echo falls into, the processor determines if the particular echo will be classified as possible target and be further processed or if it will be dropped as clutter.

Several modern search radars use other special purpose algorithms like STAP (Space-Time Adaptive Processing). STAP is an extremely processing intensive

algorithm and can be implemented only by ultra-fast digital processors. It processes echoes both in time (consecutive echoes of the same location in space) and space (correlation of echoes in spatial proximity). This complex processing allows the detection of slow moving targets even in the presence of jamming or interference. It is particularly effective for the radars that are mounted on moving platforms like aircraft or ships.

After the Doppler processing of the target signals (echoes), follows the signal amplitude processing. First a mean noise baseline is established which at older radar systems had been universal and was applied at all the search volume of the radar, however the extensive memory of the modern processors has allowed the signal processors to maintain hundreds or thousands of noise levels for every small volume in the search area. This capability allows the establishment of dedicated noise baseline that is relevant to each particular condition that applies for every small area of the search volume. The establishment of the noise level, or more correctly, of the Noise+Clutter level allows the calculation of the Signal-to-Noise Ratio (SNR) of every possible (candidate) target echo that has passed successfully the criteria of the spectral (Doppler) processing.

Finally, the calculated SNR of each candidate target echo is compared to a (detection) threshold value that if exceeded the echo is declared as valid target, as it complies both with the spectral and power detection criteria. In all modern Radar Signal Processors, the detection threshold level is not fixed but is continuously adjusted in order to keep the number of false target detections (False Alarm Rate) below a certain level. Several schemes (algorithms) have been developed for the determination of the optimal threshold level that allows the detection of all real targets while rejects the maximum number of false targets (Maximize Probability of Detection & Minimize Probability of False Alarms). These schemes are generally referred in Bibliography as Constant False Alarm Rate (CFAR) mechanisms-algorithms. (See Figure 2)

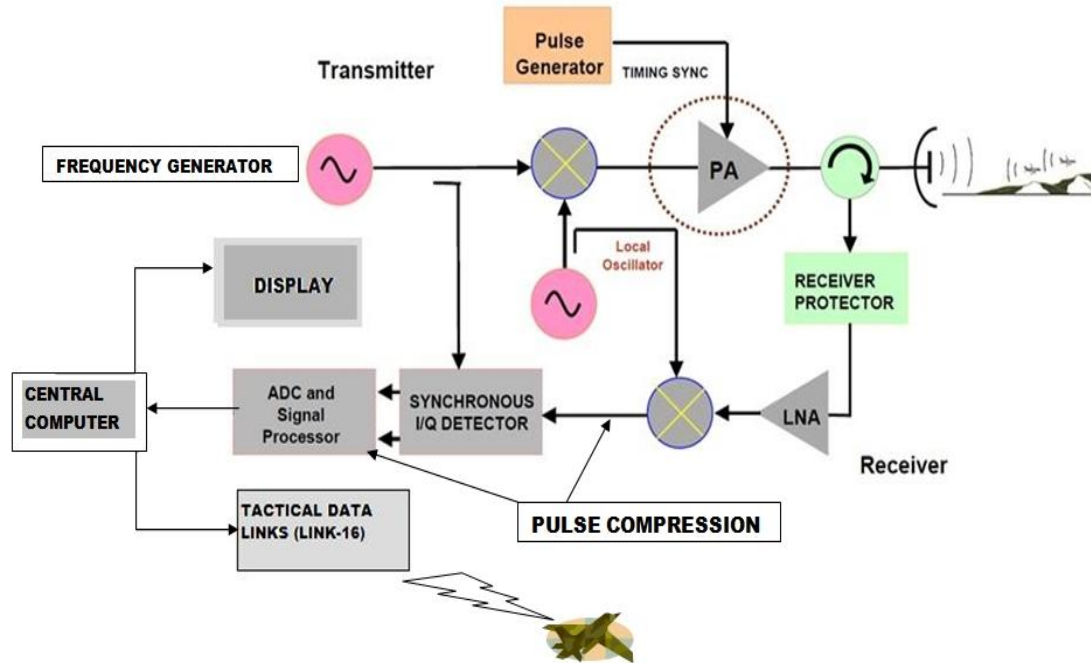


Figure 2. Block Diagram of modern coherent Radar

2.6 Tracking Computers

Following the Doppler and Amplitude (CFAR) processing at the signal processor, all the signals that have qualified for targets are being forwarded to the Radar's Computer (RC) where the last phase of processing takes place. The most basic function that takes place at the RC is the Target Tracking. Tracking is the function of correlation of targets across successive scans of the search volume. This function has a dual purpose: First it works as a filter that eliminates false targets that occasionally manage to comply with the signal processor (Doppler & Amplitude) criteria but fail to pass the scan-to-scan correlation test at the RC due to their random nature that make them appear and disappear at random positions inside the radar search volume. Second, the tracking function provides the capability to determine the velocity vector of the real targets (direction of movement and velocity). Moreover, by exploiting the velocity information of the targets, the RC can predict the possible future positions of each target and manage to maintain their tracking even if the target detection is missed at several scans in cases of marginal target S/N or intense clutter. It must be pointed out that the tracking functions are implemented by software code which must be coded in an efficient way and run on high-power computers in order to satisfy the requirement of near real time processing of the radar target data.

In several radar systems the RC, it is also used to host the functions that coordinate the overall function of the radar system such as the scanning of the radar beam, the user interface (system control), the target data display, the radar system synchronization etc.

2.7 AESA Radars and Digital Beam Forming

The most recent radar designs tend to incorporate the receiver and transmitter into the antenna. This type of antenna is called Active Electronic Scanning Array (AESA) and is becoming the standard Radar design architecture of present and the future. The AESA-type radar systems are composed of several hundred to a few thousand Transmit-Receive Modules (TRM) each of which is connected to an elementary antenna (usually a dipole or printed patch). Most importantly each TRM includes a phase shifting device which can control the phase of the transmitted and received signal. Controlling the phase of each individual TRM the radar's operational S/W can produce, focus and steer pencil beams to specific locations in space and thus cover the surveillance area through electronic beam scanning.

At the receive side the presence of thousands of individual receivers provides unprecedented capabilities as they can be grouped into sub-arrays (via Beam Forming Networks- BFNs) that perform many different functions simultaneously. Moreover, the modern advances in microprocessor technology that has allowed the management of vast amounts of data in real-time applications have enabled the realization of Digital Beam-forming. (See Figure 3)

Instead of combining the received signals of the hundreds/thousands TRMs at BFNs before digitization, the individual receiver signals are digitized at each TRM and they are combined by software at DSP processors where the actual received beams are formed. This approach opens a whole new array of application as the S/W now performs functions that used to be performed by H/W. Most notably, the radar system can easily be reconfigured, updated and upgraded just by downloading new S/W to its processors. At the same time, the number of simultaneous functions that can be performed is only limited by the processing power of its processors and the ingenuity of its programmers. A characteristic example of digital beam forming application is the ability to counter active jamming by putting a receiver null gain at the direction of the jammer.

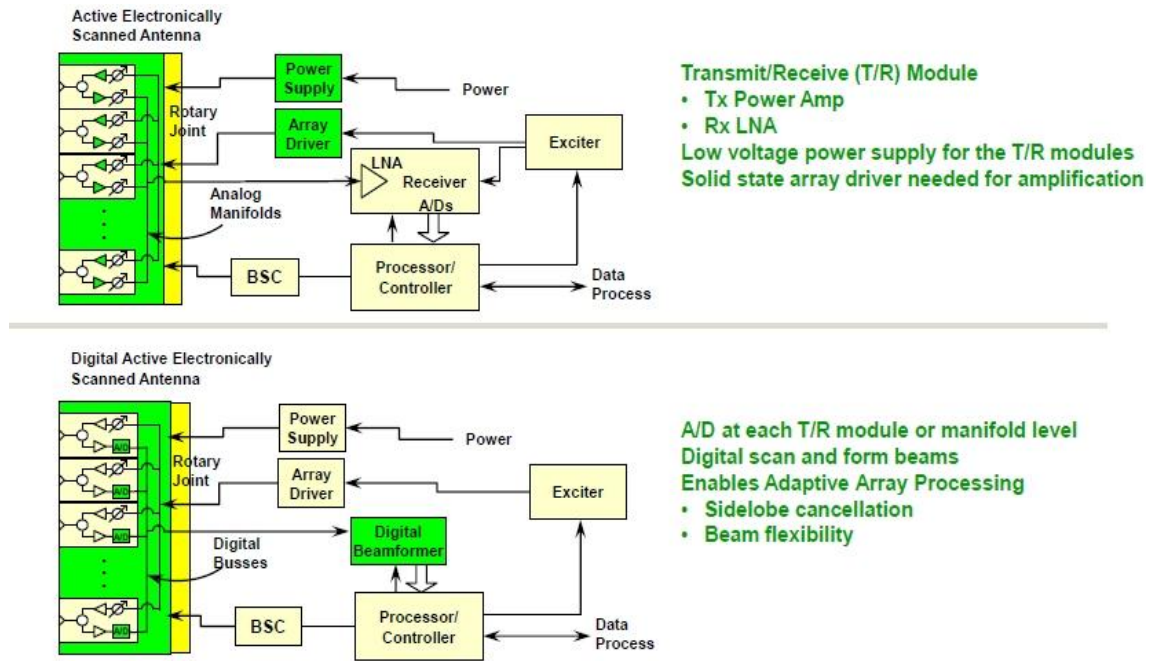


Figure 3. Configurations of Radars using Active Electronic Scanning Antennas with electronic beamforming capability (Source: Northrop Grumman)

AESA radar systems applications have first appeared a few years ago at large ground-based missile defense systems and airborne multi-mode radars of fighter aircraft. Their ability to perform simultaneously several functions (search, tracking, ground mapping etc.) and the advanced ESM capabilities (jamming immunity) have rendered them ideal for advanced defense applications, especially at mobile platforms. (See Figure 4)

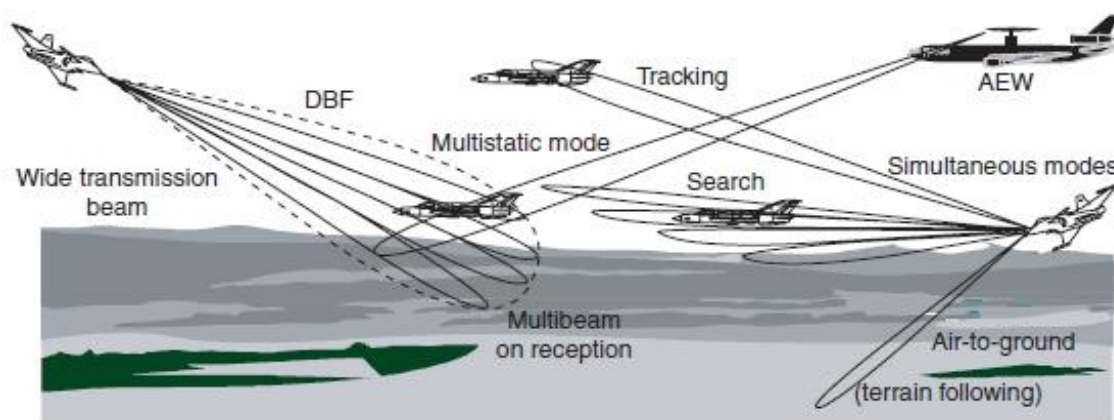


Figure 4. Functions of a multi-mode airborne radar using AESA technology (Source: Northrop Grumman)

2.8 Radar Displays

The final product of a radar system is the presentation of the detected targets along with the relevant data about their kinematic condition to the radar operator on special displays. Following the evolution of the radar, the radar displays started from simple oscilloscope-type A-Displays (Range- Signal Amplitude display) and primitive PPIs (Plan Position Indicator – Circular-type Range-Azimuth display) that projected the raw (unprocessed) received target echoes to elaborate color computer displays that project special target symbols along with the relevant target data (speed, altitude, signal strength etc).

The modern displays are fully configurable and programmable in order to present to the operator the target information in the most suitable format according to the mission of the radar system. The radar displays continue to evolve following the evolution of the computer technology.

Moreover, new forms of Human-Machine-Interfaces (HMIs) such as Helmet Mounted Displays and Touch-Screens have been used by the radar designers for a more convenient and effective presentation of the processed radar data.

2.9 High-Bandwidth Secure Data-links

The rapid evolution of the data-networks that has been the key factor for the exponential spread of the commercial networks, while the Internet has been ported into the military arena with the introduction of Virtual Secure Networks both wired and wireless. The wired communications are being secured by special crypto-devices while the challenges of the wireless networks are more complex as they have to fight against enemy jamming and eavesdropping.

The ground based radars transmit the detected targets into secure data networks that may be implemented as encrypted IP networks or other type of proprietary protocols. However, the key challenge is to include into the radar data distribution the mobile platforms such as fighting vehicles, missile systems, combat ships and fighter aircraft in order to increase their situation awareness and provide them with a strategic advantage. The above mobile platforms can also be radar data sources as they may also carry radars whose targets they need to share with their tactical & strategic commanders.

For the above reasons, over the last decades, secure wireless networks have been developed based on the Spread Spectrum Technology (Frequency Agility), Time Division Multiplexing, CDMA, as well as efficient encryption and synchronization algorithms in order to implement secure multiuser, single-cast, multi-cast and broadcast secure networks. The standard secure wireless network system that is being used across the western military inventories is the Link-16 Secure Wireless Network that is being implemented by special encryption H/W that is known as MIDS Terminals. Link-16 can transmit a variety of Data messages that include all types of radar targets as well as encrypted (secure) voice.

3 Target RCS and Stealth Targets

A key design feature of all modern military aircraft (and vessels) is the reduction of the radar-wave reflection, which is known as Radar Cross-Section (RCS). The RCS value of a target is a measure of its actual reflectivity and represents its 'size' as it is seen by the radar. It is obvious that a lower RCS target is much harder to detect, a fact that provides a significant advantage for the aircraft, but poses a challenge for the radar that attempts the detection. In general terminology, the modern aircraft designs that incorporate RCS reduction techniques are also known as '*Stealth*' aircraft.

RCS reduction techniques that are known to be employed are the use of radiation absorbing coatings and the 'stealth' airframe design. The radiation absorbing coatings are composed of special Radiation Absorbing Material (RAM) that have the property to absorb (or trap) a portion of the incident electromagnetic (E/M) energy instead of reflecting it. On the other hand, the stealth airframe design focuses into the principle of deflecting the incident E/M wave to directions other than its source where the radar is located, in that respect the search radar will fail to detect the target echo. The stealth designs tend to eliminate vertical stabilizers and avoid the use of curved surfaces in favor of steep and rectangular shapes.

On the radar side, the designers have been boosting the detection performance by introducing new efficient processing algorithms that optimize the target's Signal-to-Noise Ratio (SNR) making possible the detection of low RCS targets in the

background of noise, jamming, interference and environmental clutter signals. This efficient processing is being assisted by the introduction of ultra-fast processors that allow the real-time processing of large amounts of data through complex processing algorithms both at the time and frequency domains.

4 Passive and Multi-Static Radars

Another approach to the solution of the stealth target detection has been the introduction of the Bistatic/Multistatic Radar Concept. This type of radars implements a distributed architecture, where the transmitter and the receiver are located at different positions. Although, the particular concept is not new, only the advent of ultra-fast signal processors have made possible the actual implementation of the complex calculations that are required for the bistatic target detection.

The key element of the bistatic detection concept is that the receiver uses two channels: one is constantly receiving the source signal directly from the transmitter (Reference Signal) while the second channel is scanning the surveillance volume for targets (Detection Signal). The detection processes is based on the correlation of the Reference and the Detection signal whose relative delay reveals the position of the target. The Transmitter, on the other hand, can either be a co-operative system that transmits a known waveform or can be a Transmitter of Opportunity operated by another Service such as GSM telephony, DVT, FM Broadcast etc. (See Figure 5)

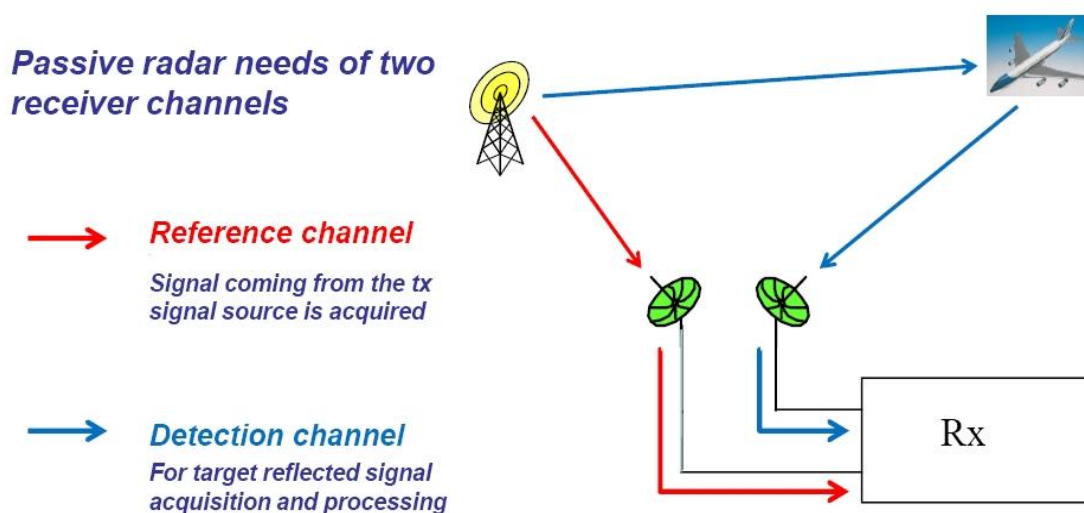


Figure 5. Bistatic Radar Topology

Although, the principle appears to be simple, there is great number of practical problems at the actual implementation. The most important are the relative low gain of the antennas that provide simultaneous 360 deg coverage, the processing of the bistatic clutter, the absence of high power illumination transmitters at particular areas of the search volume (especially at the high-altitude).

Despite its drawbacks, the bistatic radars pose as a prospective solution for the detection of the stealth aerial targets as their distributed nature eliminates the advantage that is provided by the stealth principle: the dispersion of the incident EM wave to directions other than its source (the transmitter location). Therefore, the bistatic RCS of the Stealth Designed Airframes is considered to be several orders of magnitude larger than the monostatic one.

The above reasons have renewed the interest for the development of Bistatic/Multistatic and generally passive radar systems and several corporations and research organizations are investing in the Research and Development of such systems. Apart from the obvious military applications of these systems, there is also a significant field for civilian applications as the passive operating principle does not 'pollute' the environment with additional E/M waves and is thus consistent with the Green Development as environmental friendly systems.

5 Conclusions

Summarizing, the trends that guide the development of the modern radar systems are the following:

1. Development of Active Electronic Scanning Antenna (AESA) arrays using 1000s of TRM modules and Digital Beam-forming.
2. Exploiting the advanced properties of the AESA antenna, Radar systems can perform simultaneously many functions (Detections, Tracking, Mapping, Weapons Guidance etc).
3. The Received signal is digitized at the earliest possible stage (IF or even RF) and almost all the processing takes place in ultra powerful Digital Signal Processing (DSP) modules.

4. Smart and effective DSP functions are being developed for enhancing the performance of the Radars especially at environments with intense clutter, interference and jamming.
5. Development of special algorithms for the detections of ultra-low RCS targets for systems that are using the classical monostatic configuration or passive/ multistatic configuration.
6. The Radar sensors are integrated into secure wireless networks using Tactical Data Links in order to enhance the operational awareness of the fighting and command units at the battlefield.

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