STUDY ON DEVELOPMENT OF RADAR TECHNOLOGY AND IT'S FUTURE

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Abstract: Radar basically is an electromagnetic sensor used for detecting, locating, tracking, and recognizing objects of various kinds at considerable distances. It has changed over the years as technology has developed, both in terms of its function and its capabilities. During the World Wars, radar was brought into the open due to technological need. Many countries started their path toward building the radar around the 1930s. In spite of its limitations, it changed the course of World War II. Radar displayed extensive evolution every now and then as the field is not matured at all. Initially it displayed only the presence of ships. However, to fulfil the modern-day needs, it went through many revolutions. Analog computers were replaced by digital processors, high power transmitters switched from depending on microwave tubes to active arrays of antennas, and antennas went from being passive reflectors to active arrays. Thus, this paper examined the evolution of radar from its embryonic stage to modern age. In order to fulfill the demands of the future, this paper also look at the upcoming radar trends and possible solution.

Key words: Radar, cognitive radar, RF, plug-and-play**,** transistor.

Introduction

1. RADAR stands for Radio Detection and Ranging and this is an active transmission and reception method in the microwave GHz range. Radar sensors are used for contactless detection, tracking, and positioning of one or more objects by means of electromagnetic waves. It is a technical marvel that has transformed our ability to see and understand our surroundings. Radar, which was first developed as a military instrument in the early twentieth century, has grown into a ubiquitous and flexible technology with uses in a variety of industries. Radar is an electromagnetic sensing device that uses radio waves to detect, locate, and track things. The core approach includes transmitting radio frequency pulses that bounce off things in their route and then analyzing the reflected signals to learn more about the targets. This capacity makes radar extremely useful in industries such as aviation, meteorology, defense, navigation, and even automobile systems. In aviation, radar is vital for air traffic control, guiding airplanes safely through the skies and averting crashes. Weather radar helps meteorologists monitor and anticipate atmospheric conditions, allowing for more timely and accurate weather forecasts. Military radar systems offer early warning and surveillance capabilities, which contribute to national security. Radar technology continues to advance, with developments like phased-array antennas, synthetic aperture radar, and millimeter-wave radar pushing the limits of performance and precision.

2. The radar antenna emits a signal in the form of radar waves, which move at the speed of light and are not perceivable by humans. When the waves hit objects, the signal changes and are reflected back to the sensor, likewise to an echo. The signal arriving at the antenna contains information about the detected object. The received signal is then processed in order to identify and position the object using the data collected. In a second step, it is possible to emit a pulse to trigger a reaction. In addition to its front end (microwave component with antenna structure), a complete radar sensor consists of units for signal conditioning and signal processing. These elementary components may also be supplemented with a radome, housing, lens, and a component carrier. Through the antenna design, the front end plays a key role, as it comprises the sensor in itself and sets the parameters for subsequent functions. Signal conditioning and processing analyze and interpret the signals provided by the front end. This is necessary in order to give the individual, raw radar detections a comprehensible meaning for users through the assignment of units of measure and references. The radar front-end transmits and receives the electromagnetic microwaves. These resulting signals are then forwarded to the signal processing component. To protect the antenna and electronic components, the radar is usually equipped with a housing. Technicians call an antenna cover a radome. Besides protecting the front end, this also is used to secure the antenna.[1] Some radar products also have a special lens used to focus the radar beam. Another component of radar is the interface necessary for radar information to be output and forwarded to other technical products.

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3. Today's 3D radars have several transmitting and receiving antennas. Every transmitted signal can be received by any antenna. The special arrangement of multiple antennas improves the spatial resolution and reduces susceptibility to interference. As compared to 3D radar, usually 4D radar also has several offset antennas in the elevation and can thus separate detections in the elevation angle. This enables localization in a 3D environment..The fundamental theoretical framework of radar was first developed in the late nineteenth century, and the first part of the twentieth century established its firm footprint. Despite its limited capabilities, it proved to be a game-changer in World War II. Around the 1930s, many nations began their journey toward developing the radar[2]. However, only the USA, UK, and Germany were able to deliver the required operational impact[3]. China, a modern day radar hub, started its journey in 1950s[4]. It's interesting that every nation ended up with a radar system that is essentially the same. Initially, the only aim was the long range detection of ships and aircrafts[5]. Later on, after the Second World War, when the world's geopolitics got stabled, it witnessed an upward curve in terms of development. Even in the modern world, this technology is ever evolving and trying the serve the mankind as per the era's demand.

4. In future to reduce cost and development risk, radar systems will inevitably require a standards-based open radar architecture and reusable **plug-and-play** reconfigurable sub-systems not only in the domain of embedded SP boards but also for the RF and microwave building blocks. However, this article is organized as follows. Firstly, it discussed the basic inspiration of radar from nature. There it discussed about bat's natural echolocation system. Later, this article oversaw the technological development of radar upto the breakout of WW-II. In next part, this article discussed the shortfalls of radar technology upto that time. On completion of that, it oversaw the modern day radar challenges, requirements and possible solutions. Finally the paper concludes with the future day demand on the radar technology.

Background History and Chronological Development of Radar Technology

5. Before the nineteenth century, radar was still a very much dream. By taking the inspiration from bat, people thought that someday they will be able to make something alike. In pursuant to such dream, in the last part of nineteenth century, renowned scientists like Faraday and Maxwell started their theoretical endeavor. Following the wake of them, people could form basic radar just before the second WW. Rests of the journey of radar are as follows:

a. Between the years from1940 to1945, the advancement of ground based radar was the first priority. Meanwhile magnetron was also introduced within this timeframe.

b. Between the years from1945 to1960, civil application of the radar was flourished. In addition, CW radar was also invented. To get the velocity and range information, continuous wave was required instead of short pulses. The same timeline also witnessed the turning up of the concept of phased array radar from theory to reality. Invention of this radar has abolished the requirement of the mechanical antenna movement. It also offered faster scanning, improved accuracy and better target tracking.

c. Between the years from1960 to1980, the concept of SAR was the main point of discussion. For digital imaging, this radar was a timely need. In the same timeframe, OTH and AESA radar was also came into the daylight.

6. The navigation of bats served as the primary source of inspiration for the development of new technology like radar. Because of their incredible capacity to use echolocation to navigate and find objects in total darkness, bats are frequently referred to as "natural radar"[6]. Bats use a biological sonar system called echolocation in which they produce high-frequency sound waves (ultrasound) and listen for echoes that are reflected back from nearby objects. Different bat species can produce noises at different frequencies. Typically, the hertz (Hz) range of their ultrasonic calls is between 20,000 and 200,000. The echolocation system of bats functions as per the following procedure[7]:

a. Emitting Ultrasound. Bats use their mouths or noses to produce high-frequency sounds. Most of the time, humans cannot hear these sounds.

b. Echo Reception. These sound waves become echoes when they strike nearby objects in the surroundings.

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c. Analysis of Echoes. Bats have extremely sensitive ears that are built to detect these echoes. Bats can gauge the distance, size, form, and texture of the objects they come across by examining the timing and strength of the returning echoes.

d. Navigation. Bats utilize this knowledge to find their way in the dark, discover prey (such insects), avoid dangers, and find places to rest.

7. Bats can successfully "see" their surroundings, even in complete darkness, by continuously producing sounds and deciphering the reflected sounds. This unusual trait enables them to be expert hunters and aids in their survival and growth at night, when other animals may be hindered by poor visibility. Human are yet to produce a radar like bat, the current buzzword is the cognitive radar is nothing but the bat[8].

Theoretical and Technological Development of Radar

8. By taking inspiration from bat, human also felt that they can capitalize this idea. However, it took long time to convert dreams into reality. The development chronology of radar is as follows:

a. Establishing the Theoretical Possibility. Faraday and Maxwell established the theoretical possibility of electromagnetic field in 1985[9]. In next year, Hughes demonstrated the existence of electromagnetic field at radio frequency[10]. Hertz demonstrated that the radio wave behaves similar to the light wave in terms of propagation and reflection[11]. He also noticed that the radio waves feel interference by the surrounding objects. He also identified that radio waves are being reflected by the metallic objects. He had provided the experimental verification of Maxwell's theory of electromagnetism.

b. Use of EM Wave's Reflection Principle. In 1900, Tesla suggested that to determine the relative position, course and speed of a moving target, electromagnetic waves may be used. He has contemplated that the concept of radar can be explained using wireless system. Later, Marconi suggested the same by proposing the possible application of radio waves in navigation by the use of reflected rays[12].

c. Telemobiloskop: First CW Radar- Forefather of Modern Radar. In 1903, Huelsmeyer advocated using continuous waves as an anti-collision technique for ships traveling in dense fog. He invented Telemobiloskop[13], a CW radar relying on the Doppler effect, to avoid collision at sea during fog[14]. He also had the patent of this innovation. However, he was far advanced in thinking in comparison with his counterparts and thereby failed to catch the eyes of the decision makers[15]. Later, Loewy developed the radio object detector in 1923 by applying the Fizeau principle. However, none of them could solve the problem of the long distance between the transmitter and the receiver[16].

d. Detection of HF Radio Communication's Propagation Path. HF radio communication's propagation path between transmission and reception was accidently detected by Taylor and Young in 1922. This chance discovery served as a shield from other ships infiltrating naval troops during night and fog. They demonstrated a 60 MHz VHF propagation in the same year. It is possible to detect any target using this frequency. Later on, Breit, Tuve, and Taylor showed in 1926, following Swann and Frayne's concept, that the radio wave could be used to determine the height of the ionosphere by keeping track of its relative flight time.

e. Accidental Findings Leading to the Radar Innovation.In 1933, it was discovered that the radio waves emitted from Daventry radio station were being reflected from aircraft and produced echo. This echo, after being amplified, could be displayed in the cathode-ray oscilloscope. This one gives the real hope for the foundation of radar[17].

f. Establishment of Radar Range Equation. In 1935, UgoTiberio, an Italian navy officer, later on professor at the University of Pisa, first established the radar equation while studying on the detection of objects by electromagnetic waves[18]. The radar range equation is important for the following reasons:

(1) Assessing the technical requirement to procure a new radar.
(2) Understanding the trade-offs for designing a radar
(3) Assessing the performance of the radar.

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The radar range equation for tracking radar is:

$$R = \left(\frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 (SNR) k T_s B_n L}\right)^{1/4} \dots\dots (1)$$

Here, P_T denotes peak power (in MW), $G_T G_R$ denotes antenna gain (in dB), λ denotes the wavelength, σ denotes the radar cross section, L denotes the various losses, $kT_s B_n$ is constant and R denotes the range in meters[19].

To get the maximum range of the radar, this can be rewritten as

$$R_{max} = \sqrt[4]{\frac{P_S G^2 \lambda^2 \sigma}{P_{e_{min}} (4\pi)^3 L_{ges}}} \dots\dots (2)$$

Here, $P_{e_{min}}$ is the smallest received power which can be detected by the radar. In addition, L_{ges} denotes different types of losses[20]. This equation also denotes that, if one quadruples the antenna gain, the maximum range will be doubled.

$$R_{max} = \sqrt[4]{\frac{P_S}{k}} \dots\dots (3)$$

This equation denotes that, in order to double the range, the transmitted power needs to be increased by 16 times.[21]From this equation, SNR can be measured as well. SNR is the standard measure of radar's ability to detect a given target at a given range from the radar. The SNR equation for tracking radar, (when the target is known) is as follows:

$$S/N = \frac{P_t G_T G_R \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L} \dots\dots (4)$$

The minimum detection range of radar can be found from the following equation:

$$S_{min} = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4} \dots\dots (5)$$

For the search radar, this equation is slightly different, where instead of peak power; the value of average power is required. The equation is as follows:

$$\mathrm{S/N} = \frac{\mathrm{P_{av} A_e t_s} \sigma}{4\pi \Omega \mathrm{R}^4 k \mathrm{T_s L}} \dots\dots (6)$$

Here, P_{av} denotes average power (in MW), Ω denotes the solid angle searched, $\mathrm{T_s}$ denotes the scan time for Ω, σ denotes the radar cross section, L denotes the various losses, kT_s is constant, $\mathrm{A_e}$ is the antenna area and R denotes the range in meters. The above mentioned equation can be written as:

$$P_{av} = \frac{4\pi R^4 \Omega k T_s L (S/N)}{A_e t_s \sigma} \dots\dots (7)$$

This equation denotes that, the power requirement of radar is independent of wavelength, a very strong function of R and a linear function of everything else.

g. Invention of Pulse Radar. To get the simultaneous range and bearing data, pulse radar was the crying need.

(1) Historical Background. Rudolph Kuhnold at the NVA (NachrichtenmittelVersuchsanstalt – Naval Signal Research Office), combined pulse transmission with a higher frequency to determine the target range and improve resolution. Later, with the collaboration with GEMA, Kuhnold experimentally detected an airplane[22]. On the other hand, following the advice of Young, Page created a transmitter output of 60 MHz with a 10-us pulse gap of 90 us to detect an airplane at a distance of one mile which was the first pulse radar. Based on the above contributions, in

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1935, an anti-collision radar was fitted onboard SS Normandie by Dr. Henri Gutton which was capable of detecting coastlines at distances of up to 12 kilometers. Admiral Graf Spee was the first warship equipeed with a full-fledged radarhaving wavelength of 80 cm, a carrier frequency of 350 MHz, a transmit power of 8 kW and a pulse length of 3 μs. The resulting target range was 220 km[23].

(2) Block Diagram.

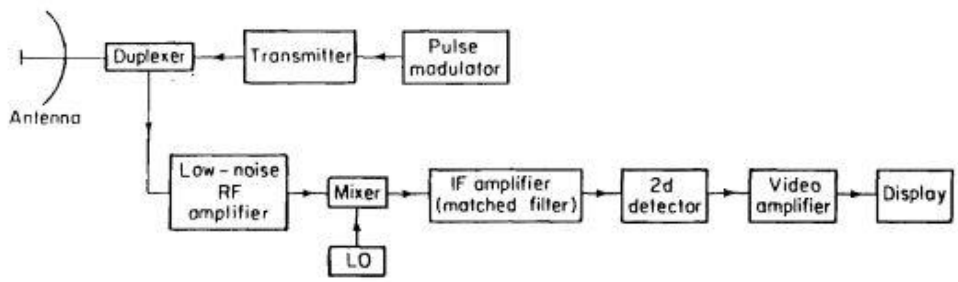

Fig 1: Block diagram of a pulse radar

(3) Working Principle. As per the basic block diagram, the transmitter generates short pulse signals as packet of radio waves and radiates as a narrow beam through the antenna. Inside the transmitter, there is oscillator. The oscillator produces the super high frequency of electromagnetic wave. The operating cycle of the oscillator is initiated by the trigger. This operating cycle determines the PRF. The pulses are shaped in the modulator. The modulator determines the pulse length. Then the pulse passed to the magnetron. The magnetron converts the energy into the radio waves. It determines the radar frequency. When this packet of radio wave hits a target, it gets scattered and a small portion of the transmitted wave comes back. The radar antenna collects this reflected wave and sends it to the radar receiver. Radar receiver amplifies this received signal and sends it to the signal processor. The signal processor extracts and process the desired information from the received signal and display the information via radar display. The major difference between the Pulse radar and CW radar is that, CW radar has better range resolution with poor maximum range. For pulse radar it is vice versa. Pulse radar has blind spots as well.

h. Chain Home Radar: The First Operational Success of Pulse Radar Technology. The renowned Chain Home radar detection station was built in 1937 using pulse radar technology[24] which found very effective during the Battle of Britain by providing early information regarding enemy air attack. These stations operated in the 20-30 MHz Bandwidth.

9. Despite having early successes in radar innovation, before the outbreak of WW-II radar for ships was largely impractical, despite the above mentioned efforts. The main reasons are as follows:

a. Need for the Microwave Radar. The chain home radar was efficient for surveillance role. However, it was felt that, the support of radar can be taken for anti-aircraft naval guns. For this function, high angular resolution was needed, which could only be achieved if the narrow beam is used. To make the beam narrow, wavelength needs to be smaller. To fulfill the need, conventional triode was invented which could produce power at wavelength upto 50 cm, however, it was not enough. The radio wave's beam should be as narrow as possible to achieve the best accuracy. The frequency increases as the beam becomes narrower. High frequency generation was therefore crucial. The same bandwidth can also be obtained from a smaller antenna thanks to the higher frequency.

b. Modification Requirement in Antenna.

(1) Duplexer. The early radar systems needed separate transmission and reception antennas. In addition, it was very difficult to move those antennas. To overcome such difficulties, the ultimate solution was the duplexer.

(2) Downsizing the Antenna Length. Because of the relatively long operating wavelengths, enormous antennas were required, which would have been too much top-hamper for any but the largest warships. In spite of

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this, the majority of radiation patterns resembled floodlight illumination rather than pencil beams, and direction-finding frequently required "tuning" a receiver-antenna array with goniometers to determine the target's direction.

(3) Need for the Motor Driven Antenna. A sweeping time-base on a cathode ray tube had to be deflected by the feeble reflections in order to detect the target, which was a laborious manual process with a slim chance of success.

c. Modification Requirement: Power and Noise. Earlier radar had very little detection range. To increase this range, substantial increase of transmission power and substantial decrease in receiver noise is the ultimate requirement.

10. To offset the above-mentioned shortfalls, following steps were being taken:

a. Introduction of Cavity Magnetron: Evolution of Centimetric Radar. In pursuant to the need of smaller wavelength, cavity magnetron was invented. Initial cavity magnetron could generate pulses of 500 kw at 10 cm. Later, it could generate pulses of 100 kw at 3 cm[25]. Randall's invention of the multi-cavity magnetron in 1938 made it possible for compact, rotating antenna to provide all-around coverage. It was having the capacity to operate at much higher power and frequencies (3.3 GHz), thus allowing much shorter wavelengths (9.1 cm), suitable for small antennas of airborne radars. Its narrow beam also allowed for higher bearing accuracy[26]. Randall improved the multi cavity magnetron in 1940 by adding liquid cooling and a stronger cavity, which multiplied the power output by 100[27]. By linking different cavities inside the magnetron, the frequency instability of the magnetron was also eliminated[28]. With the innovation of cavity magnetron coupled with necessary fine tuning, centimetric radar was innovated which changed the full complex of the WW-II.

b. Invention of TWT. Power amplifier is the heart of radar's transmitter. Travelling wave tube (TWT) amplifier was the next move in the radar world in terms of transmission[29]. It was able to produce the large quantities of coherent microwave power. Radar systems rely on traveling wave tube (TWT) amplifiers because they offer high-power amplification, broad frequency coverage, low noise figures, and other crucial properties. This amplification capability is crucial for increasing the radar's range, enhancing target recognition, and ensuring that the radar works in a variety of settings, such as for surveillance, military defense, and weather monitoring.

c. Invention of Phased Array System. Radar systems have been transformed by phased array radar technology, which provides electronic beam guiding, quick target tracking, and adaptability to a variety of applications. To meet the requirement of signal delay, phased array system was introduced. Its widespread use in the sectors of meteorology, aviation, maritime, and defense has enhanced safety, surveillance capabilities, and performance in demanding and dynamic conditions.

d. Invention of PPI. The need for the display arose when it was determined that having bearing and range information on the same display would allow the operator to obtain the information without having to perform any calculations. Cathode-ray tubes provided the quick fix. This technique comprised deflecting a ray trace from the middle rather than from one edge, slaving the angle of deflection to the pointing angle of an antenna, and intensity-modulating - rather than merely distorting - the trace when echoes were detected. This change gave rise to the Plan-Position Indicator, or PPI.

f. Innovation of Tracking Radar. When the generation of higher frequency became available, in that time the special type of narrow beam was developed. This narrow beam was useful for gun laying radars. It was the mother of tracking radar concept.

11. Due to military requirements, radar developed quickly in the 1930s and 1940s. Due to a lack of funding in 1941, the UK transferred to the USA the 6W magnetron technology while the USA could produce 10W using klystrons. Since then, the USA has made a name for itself in global technology by developing cutting-edge radar technologies. Radar history saw a turning point with the opening of the Radiation Lab at MIT[30]. Radar played the pivotal role in WW-II. Many operational lessons were learned in the war years, in how the technology could be used to meet military needs, the limits of its reliability, and how to ameliorate its many quirks and shortcomings. Some of those lessons translated into new development, those are appended below:

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a. Improvement of Hardware. Radar today has different requirements than it did in the past. In the past, feed was provided via passive reflector-type antennas in a variety of designs. In the past, each feed was created for a specific application. Active array is the antenna type utilized in contemporary radar. Older radar had large microwave transmitter tubes like magnetrons, CFA, TWT, etc. Solid state power amplifiers took their place. The radar's analog processor was replaced by a digital processor.

b. Support for Marine Fleet. From the perspective of marine safety, 1945 saw a military workforce that was mostly adept at adjusting and utilizing radar data; nevertheless, the start of peace caused a serious hemorrhaging of this expertise as the personnel progressively demobilized. Governments prioritized other requirements before engineering progress because of this. However, gradually, commercial pressures took hold, and slowly, radar started to appear in global mercantile fleets.

c. Innovation of OTH Radar. All of the radars mentioned in this paperpreviously wereonly limited by radio horizon. First OTH radar, Veyer, was developed by Soviet Union in 1949[31]. The advance in signal processing made this effort successful[32].

d. Innovation of Transistor. Innovation of Transistors by Bell Labs in 1948 was one of the most prominent step for the advancement of radar[33]. By enhancing the functionality, dependability, and adaptability of radar systems, transistor technology has completely changed the radar industry. This invention significantly increased the capabilities of radar and broadened the range of applications it can be used for, including in the navigation, aviation, meteorology, and defense industries. This marked the advent of solid state electronics, which drastically decreased the size and power needs of earlier electronic tube-based devices. Through the use of compact, low-power electronics and ultimately affordable integrated circuits, this changed the electronics industry and ultimately helped usher in the information age.According to some, it was the most significant invention of the 20th century.

e. Reduction of Noise Figure. Reduction of noise figure was also a daunting task. Second WW S band radar used to be fitted with superheterodyne receiver[34] which had the noise figure of 18 dB. After 30 years of fine tuning, Schottky-barrier mixer diode reduced the noise figure up to 5.3 dB. The reduction of noise figure is a continuous process.

f. Vessel Traffic Management Support. The most compelling development in this process occurred in 1951[35], when European countries started testing radar technology for vessel traffic management, first in their ports and then — as confidence grew — in their seaways. Frustrated by their challenges in running port facilities effectively in bad weather, and in desperate need of the US aid being shipped eastward under the Marshall Aid Plan. Thus, a new era of radar technology dawned.

g. System Cooling Arrangement. The 1960s radar designs were big and heavy, frequently requiring specialized cooling services (some magnetron designs were water-cooled), and always required that a major portion of the equipment be below mast-head. Radar repair by ship's radio officers required intensive training and logistical assistance, and downtime was nearly always present. However, when transistors and later transistor-based microprocessors gradually took the place of diode- and triode-tubes, designs got more compact and dependable, and much of the hardware moved upward, toward antenna systems, leading to improvements in sensitivity and performance.

h.. Commercialization of Marine Radar: Plug and Play. By the late 1980s, manufacturers had started to advertise marine radars that simply featured the display system below the masthead, and maintenance instruction had started to disappear from the curriculum for aspiring marine radio officers. Today's systems are so small and dependable, and they're so cheap (some go for as little as $1500 in 2011 prices), that sometimes it makes more sense to replace them than to repair them.

j. Innovation of Electronic Scanned Array (ESA) Radar. To avoid the mechanical rotation of the antenna, in 1980, Electronic Scanned Array (ESA) came into the picture. It offered beam flexibility and low antenna sidelobes. The central transmitter for passive ESA is a single, high-power microwave tube that is located distance from the antenna. The technique used is simultaneous lobing. A distributed transmitter and several solid state power amplifiers are located inside the antenna of an active ESA, on the other hand. In solid state transmission modules, which could control individual element gain and phase, LDMOS or GaN-based technology was used. Additionally, the average power must be raised in order to improve low power transmitter efficiency. LFM modulation, a unique pulse compression technique, is used to do this without sacrificing resolution. One of the most recent developments in this field is the evolution of packaging technologies, such as GaN, MMIC, and the MMIC design[36].

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12. With the above mentioned conceptualization, planning, upgradation and integration, the modern era has provided the society with the following radars:

a. <u>MTI/Search Radar</u>. To suppress the stationary clutters, MTI radar[37] was introduced. Later, the search radar was evolved. The first search radars were 2D and could estimate range and angle. These angular estimations were based on the antenna's radiation pattern. Consequent square beam patterns were employed in 2D search radar. With the target moving at a constant altitude within the beam, the goal was to achieve more uniform signal strength. A height finder is used to determine the altitude. To collect the altitude data, the antenna of HF radar was oriented towards a specific bearing obtained from 2D search radar. The height finder featured a wide elevation beamwidth but a low horizontal beamwidth. The pairing of this pair was discovered to be extremely sluggish. However, the combination of this duo found very slow. In addition, for multiple target scenario, their performance was not up to the mark. Thus, it was felt that 3D search radar is necessary.

b. <u>3D Search Radar</u>. Advanced waveform creation, pulse compression, and TR modules were features of the 3D radar[38]. Instead of the Parabolic antenna used in 2D radar, phased array antenna and beamforming technology was utilized in 3D radar to obtain the elevation angle. The phased array technology is faster but more expensive than mechanical scanning, which is inexpensive but slow. In 3D search radar, high speed fiber optic rotary joints were used in place of waveguide rotary units to convey high density digital data. A stacked beam radar with a reflector antenna andnumerous horn feeds was the first 3D radar. Simultaneous lobing, an amplitude compression technique, was used to estimate the elevation angle.

c. <u>Coherent Radar</u>. We have so far talked about inherited radar. The next development was coherent radar[39], which used coherent processing to increase sensitivity. It can take advantage of quite minor velocity changes, which translate into minor phase differences in the signal returns. Its RF source for transmission is extremely steady. From pulse to pulse, there is a high amount of phase coherence.

d. <u>Active Electronically Steerable Antenna (AESA) Radar</u>. Active electronically steerable antenna (AESA) made their debut in 1990. This allows for the independent control of each module's output phase and amplitude. It delivers effective EW countermeasure, good track quality, low false alarm rates, and frequency diversity. It has multiple solid state TRM, which increases efficiency while achieving required RF power in a smaller form size. To excite the antenna element or collection of elements, these solid state devices require little power[40]. Coherent Doppler processing built into the AESA antenna helps enhance target detection and clutter rejection. It has enhanced signal stability and RF spectrum purity. It has an effective cooling system and a high performance digital circuit.

<u>Modern Technologies and Features Adopted in Radar</u>

13. After the gulf war in 1991, the use of radar became extensive both in military and civil fields. Thus, for optimum use of radar, following modern technologies were adopted and integrated to the radar:

a. <u>Introduction of Solid State Technology and Pencil Beam</u>. Today, as frequency rises, so does resolution. The ability of signal processing has greatly improved since the introduction of solid state technology[41]. Marine radars have undergone numerous other, more significant developments as a result of the transistor's invention, particularly in the areas of target information processing and display. Later, pencil beam[42] technology replaced stacked beam[43] because of its improved ability to handle ground congestion and shield against active jamming. The elevation pattern of a stacked beam was linear. It can be jammed more easily because it has numerous simultaneous receive beams. Conversely, the pencil beam employs a sequential lobing frequency scanning approach.

b <u>Component Level Digitization</u>. So far the radars were completely analogue in terms of components and techniques. The components were transmitter, antenna, receiver and signal processing unit. These components results output as analogue inputs to a video display. In modern trend, compact and lower cost digital equivalence is very much possible.

c. <u>Shift of Architecture: From Power on Target to Energy on Target</u>. The radar's architecture was changed by AESA from power on target to energy on target. Due to high peak power and low duty cycle, short pulse width was formerly the main focus. All of these were sent using a microwave tube. Due to its low peak power and high duty cycle, TRM solid state power amplifier radar has a large pulse width nowadays. To take use of the time dimension, it incorporates flexible beamforming. For accurate Doppler processing and extremely accurate elevation calculation in this situation, the radar dwell time, also known as the time on target, must be extended.

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d. Innovation of MTD. Due to its adaptive digital signal and data processing, MTI was followed by MTD. Doppler filter, adaptive false alarm rate processing, and fine resolution clutter maps are all combined in MTD. In this case, even if one TRM fails, the entire system will still degrade gracefully. The entire frequency band is utilized during phase scanning.

e. Transition from AESA to MFR. The radar community's next step was to transition from AESA to MFR. Radar that combines search and tracking is known as MFR. Phase scanning is used to provide 2D beam steering using matrix array. It uses active tracking, which enables early target acquisition.

f. Innovation in Semiconductor. The exponential expansion of downsizing will result in smaller and faster hardware, according to Moor's law. The usage of semiconductors is essential in this regard. GaAs was replaced by GaN in the semiconductor industry in order to create the RF power needed for radar transmission. GaN can provide 5–10 times more power than its forerunners[44]. Additionally, it can deliver higher working voltage while also having better thermal conductivity and efficiency, which enhances RF performance. GaN can offer a high output power, a higher operating frequency, a wide bandwidth, and greater reliability when utilized as a semiconductor in AESA radar. Monolithic microwave integrated circuits (MMIC), which are GaAs-based integrated microwave circuits, have been developed, allowing for the construction of active electronically scanned arrays (AESAs) that are more affordable, lighter, smaller in volume, and more reliable. MMIC makes it possible to build AESAs for applications that weren't previously practical.

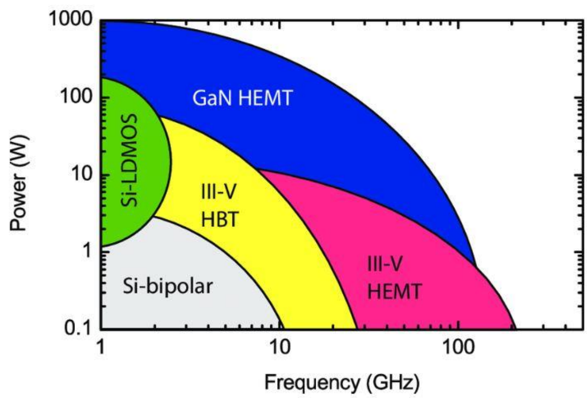

Fig 2: RF Power vs frequency for major semiconductor devices[45]

Modern Day Radar Solutions

14. The potential strategies for future radar are as follows[46]:

a. Intelligent signal coding, e.g. OFDM, CDMA

b. MIMO Radar - multiple transmit and receive antennas

c. Digital beamforming for a higher angular resolution withwide coverage without mechanical moving parts

d. Array imaging - efficient systems of reduced size and cost

15. Keeping the above mentioned strategies, modern day radar solutions are as follows:

a. Digital Array Radar (DAR). The digital radar is the next step for the radar community, where digitization starts at the level of the antenna element. The received signal will be digitalized behind each antenna element, which is the main concept. In digital radar, A/D converter is placed behind every receiver element[47]. It will make the transmitter and receiver design simple. There will be the greatest degree of flexibility for agile and adaptive beamforming with such a radar. Every component in this situation has the potential to be a beam, increasing the radar's dynamic range. The digital array radar (DAR) design has considered all commercially available (COTS) component technologies, including: (1) the low-cost and

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dependable digital electronics transceiver technology created for wireless digital telephony using the GaAs microchip; (2) the backplane communication technology using established fiber optic wires with precise laser clock; and (3) the arbitrary waveform synthesizer in terms of binary bits or direct digital synthesizers (DD)[48].

b. Phased Array Radar. Over the past 55 years, phased array radar systems have advanced from the early 1960s until now[49]. It is the new form of digital array radar. Phased array radar is a significant technological advancement in radar systems, providing a varied and advanced approach to surveillance, tracking, and target recognition. Unlike typical radar systems, which use a single fixed antenna to scan, phased array radar uses an array of separate antennas, each with its own phase shifter, to dynamically adjust the direction and form of the radar beam. This breakthrough has numerous benefits, making phased array radar an important participant in modern radar technology. Some significant features are rapid beam steering, adaptive beamforming and faster PRF. Phased array radar is also known as active electronically scanned array (AESA) radar[50]. Phased array radar can be either SIMO or MIMO radar.

c. MIMO Radar. Multiple-Input Radar with multiple outputs (MIMO), is one kind of phased array radar. MIMO radar has changed the complete gamut of radar performance including enhanced spatial resolution, target discrimination, tracking performance, and interference resistance[51]. As a result, MIMO radar has found use in a variety of industries, from the maritime and automotive to the defense and aviation. This has improved safety, situational awareness, and performance in challenging conditions[52]. Traditional radars that broadcast from a single phase center are unable to take advantage of the spatial diversity of the transmit phase center that is present in MIMO beamforming. Although a MIMO implementation[53] normally requires more processing than a conventional radar system, it can allow the array to have fewer elements and smaller physical size for a given angular resolution, which enables reduced system cost and/or size. MIMO radar range equation is as follows[54]:

$$R_{max}^{\mathrm{MIMO}}(K) = \left(\frac{MNP_0 G_s^2 \sigma_0 \lambda^2}{(4\pi)^3 F_n SNR_{min} N_i} D(K)\right)^{1/4} \quad \ldots\ldots (8)$$

Here if the integration pulse number is K, the D(K) is the integration gain, M is the transmission array element and N is the receiving array element.

d. Cognitive Radar. It is not possible to totally rely on pre-programmed waveform in the modern world. Real-time reprogrammable waveform synthesis is now required. The demand for instantly adaptable optimization of transmission and reception in the current crowded and contested EM spectrum is prompted by spectrum allocation policy and EM spectrum coexistence, and can only be met by cognitive radar[55]. The idea of cognitive radar was introduced for the first time by S. Haykin in 2006 [56].Cognitive radars use the perception-action cycle of cognition to perceive the environment, gather important information about the target and backdrop, and optimize the radar sensor to achieve the desired aim[57]. The echo-location system of a bat, which may be seen as a physical representation of cognitive radar (although in neurobiological terms), contains all three of these components. These cognitive technique can be fed to the phased array radar[58]. The radar world has witnessed substantial work in this field in last few years[59].

(1) Functional Components. The functional components of cognitive radar are three: 1) intelligent signal processing, which builds on learning from interactions between the radar and its surroundings, 2) feedback from the receiver to the transmitter, which facilitates intelligence, and 3) preservation of the information content of radar returns, which is accomplished by the Bayesian approach to target detection through tracking[60].

(2) Novel Concepts. There are many novel concepts and technologies used in radar i.e. software defined radio (SDR), digital signal processing (DSP), arbitrary waveform generation (AWG). Integration of such technologies provided the opportunities of real time optimization. To exploit these degrees of freedom several cognitive inspired concepts and algorithms have been proposed which is under thorough scrutiny now. Cognitive-inspired techniques in radar mimic elements of human cognition such as the perception-action cycle[61], learning, anticipation[62]and the used of external knowledge[63].

e. Photonic Radar. Radar technology is moving in a positive direction with photonic radar, which has the potential to perform better and be more flexible in a variety of applications. Radar systems can now get around some of the drawbacks of conventional radar technology because to its incorporation with photonics, which is why it is still being researched and developed in both civilian and military contexts. The wide band, high speed, parallelism, and high integration requirements of the next-generation radar are exactly the four salient features of photonics. Future radar systems may take an

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interdisciplinary approach to solving bottleneck issues in the microwave realm by utilizing optical techniques, concepts, and technical aspects, namely by building microwave photonics-based radar systems[64].

f. Synthetic Aperture Radar (SAR). Synthetic aperture radar is a modern-day requirement for all-weather wide-band, high-resolution imaging. Synthetic aperture radar refers to a particular implementation of an imaging radar system that utilizes the movement of the radar platform and specialized signal processing to generate high-resolution images. The Doppler effect allows targets to be separated in the along-track direction based on their distinct Doppler frequencies. This technology was originally called as Doppler beam sharpening but was later renamed synthetic aperture radar (SAR). The major difference between SAR and a real radar is that how it gets the azimuth resolution. While the range resolution and radar equation developed before for a real aperture radar are still applicable here, the along-track imaging method and resulting along-track resolution change significantly between real and synthetic aperture radar cases.

In terms of the physical antenna sizes, we can write this expression for a real aperture radar as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^3 R^4} \frac{\lambda R}{L} \frac{c\tau_p}{2\sin\,\theta_i} \sigma_0 \quad (9)$$

where , the pulse lenth is τ_p , the angle of incident is θ_i and the normalized backscattering cross section is σ_0. This equation may be reduced into

$$P_r = \frac{P_t W^2 L c \tau_p \sigma_0}{8\pi\lambda R^3 \sin\,\theta_i} \quad (10)$$

In a real aperture radar, with the antenna length, the received power increases linearly. Thus, real aperture radar has longer antenna size. For this reason, SAR is the modern day need.

Extensive Uses of Radar

16. We know that one of the core uses of Radar is to send and receive valuable information in the form of waves. RADAR is helpful in detecting incoming signals during war and also used by a geologist for earthquake detection. Archaeologists use this technology for detection of buried artifacts. It is also used to understand the environment and climatic changes. RADARs have a wide range of usage in military operations. They are used in Naval, Ground as well as Air defence purposes. They are used for detection, tracking and surveillance purposes also. Weapon control and missile guidance often use various types of RADARs. Law enforcement, especially highway police, has extensive use of RADARs during a pursuit to measure the speed of a vehicle. Due to bad weather conditions, when the satellite cannot get a clear image of traffic and barricades, RADARs are used to get the desired results. RADARs in satellites are used for remote sensing. RADARs are used to track and detect satellites and spacecraft. They are also used for safely landing and docking spacecraft.[65]

17. Just like various types of waves are received by an antenna, this technology is also used to detect weather conditions of the atmosphere. It is also used for tracking the motions of planets, asteroids and other celestial bodies in the solar system.[66] Ground mapping and weather avoidance RADARs are used in aircraft to navigate them properly. This technology enables an aircraft to ensure the location of obstacles that can threaten the flight plan. Ships are guided through high resolution RADARs situated on the shores. Because of poor visibility in bad weather conditions, RADARs provide safety by warning threats. These ships often use this technology to measure the proximity of other ships and their speed on the water. RADARs are used to safely control air traffic. It is used to guide aircraft for proper landing and take-off during bad weather conditions. These RADARs also detect the proximity and the altitude of the aircraft. However, radar sensors have been an integral part of applications such as automatic door opening, driver assistance systems, alarm systems or evene radar trap since many years.[67]

Can GPS Replace the Radar

18. There are many talks around that radar may be replaced by GPS in future. GPS is a tiny device in comparison with radar which can be a cheaper option. However, there are lot of cons for which GPS will not be the best fit in the place of radar. Some of those are as follows:

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a. Real-time Object Detection. Radar systems actively emit radio waves and detect their reflections off objects, allowing real-time detection of nearby obstacles, targets, or aircraft while GPS is a passive navigation system that provides information about the device's position based on satellite signals but does not actively detect objects in real-time.

b. Obstacle Detection. Radar is effective in detecting physical obstacles, such as buildings, mountains, or other aircraft, providing real-time awareness of the surrounding environment. GPS does not directly provide information about obstacles; it focuses on determining the device's location, speed and direction.

c. Weather Conditions. Radar can penetrate various weather conditions and provide information about precipitation, storms, and atmospheric phenomena. GPS signals may be affected by adverse weather conditions, such as heavy rain or dense cloud cover, potentially limiting its accuracy.

d. Resolution and Detail. Radar systems can offer high resolution in tracking moving objects, providing detailed information about the size, shape, and composition of targets. GPS is primarily focused on providing accurate positioning but has limitations in terms of detailed object characteristics.

Thus, the ideal option for GPS is not to replace the radar, but to integrate with it to accomplish maximum efficiency.

Future of Radar

19. For Radar applications, having direct access to the data at each array element provides flexibility and real time re-configurability not possible with conventional architectures. The flexibility and re-configurability could and should extend beyond the design stage of the radar system, enabling dynamic operational modes and configurations that can be adopted as the operational situation evolves. The evolution from ESA RADAR to DAR RADAR can be facilitated by using open standard systems and COTS boards. Already today ESA RADAR systems are implementing OpenVPX and COTS boards which allow radar designers to improve or reconfigure the mission without drastic changes to the system background. In the domain of embedded systems, standards such as VPX have made enormous steps in providing commonality between products of various vendors, as well as reducing cost. Unfortunately no such situation exists yet in the RF and microwave domain.[68] The entire radio interface remains almost fully proprietary and also fixed once the design has been implemented. Actually, giving similar system requirements to different contractors for the development of a new radar system will almost always result in different type of systems while essentially serve the same missions.

20. In order to enable fast technology refresh while lowering the cost of new radar systems, there have been initiatives by DoD in US and European Defence Agency (EDA) to create open radar architectures and reusable plug-and-play subsystems to facilitate the use of COTS components from a broad array of vendors. As an example, Interoperable Modular Architectures (IMOSA) approach represents a core innovation addressed in the EDA CapTech. IMOSA allows the division of systems into Building Blocks (BB) that can be developed separately through different and disruptive technologies. Moreover these BBs are defined through standard interfaces which allow easy integration in complex systems. In 2012 Defense Advanced Research Projects Agency (DARPA) launched the development of so called RF-FPGA to enable a common hardware architecture that facilitates reutilization of the same set of RF front-end components across different applications through programmability of the transceiver chain. The core objective of the RF-FPGA is to eliminate redundant and costly hardware development required for the adoption or recognition of a new wireless function or waveform in other words, RF standardization. The Hardware resulting from the program should be dynamically-programmable analog and RF blocks similar in purpose to a digital FPGA.[69] It aims to demonstrate working blocks of reconfigurable components and programmable transceivers capable of configuring for a variety of wireless applications while maintaining near optimal performance.

21. Already in 2004, the Swedish Defence Research Agency (FOI) identified the need of such RF standardization. An approach called programmable microwave function array PROMFA was developed. The objective was to develop reconfigurable, and in certain respects completely new RF front ends having the ability to adapt in real time to perform a new task or function supporting various operational requirement. Such ability requires new class of circuit and system architecture easily adaptable with multifunctional properties. A proof-of-concept, generic building block, has been demonstrated. The concept is based on an array of generic cells, in which a number of different functions can be realized. Each PROMFA cell is a four-port circuit, and several cells can easily be connected together in larger arrays similar to DARPA or RF-FPGA.[70] The future of radar holds exciting possibilities as ongoing technological advancements continue to shape and refine this critical sensing technology. Several trends and developments are expected to influence the future of radar across various domains. Here are some key aspects that may define the future of radar:

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a. Integration with Emerging Technologies. Radar is likely to integrate with other emerging technologies, such as artificial intelligence (AI) and machine learning. By leveraging these technologies, radar systems can enhance their capabilities in terms of target recognition, classification, and decision-making, leading to more intelligent and autonomous systems.

b. Millimeter-Wave and Terahertz Radar. The use of higher frequency bands, including millimeter-wave and terahertz frequencies, is gaining attention[71]. These frequencies offer improved resolution and sensing capabilities, making them suitable for applications like imaging, security screening, and advanced driver-assistance systems (ADAS) in autonomous vehicles.To get the high Doppler shift, high carrier frequency is required. Such carrier frequency helps to obtain high bandwidth. Additionally, because non-metallic objects reflect terahertz frequencies, contrary to lower frequency signals, the radars are now enabled to detect and image objects that were previously invisible to them. Given all of the above, and also due to recent advancements in terahertz technology, new security applications of mm-wave and terahertz radars have quickly begun to emerge[72] and are a strong focus of the radar community's attention at present[73].

c. Space-Based Radar. Advances in space technology may lead to the deployment of more sophisticated space-based radar systems. These systems could provide global coverage for monitoring activities such as maritime traffic, environmental changes, and disaster response[74].

d. Digital Radar. A radar architecture is described in which RF pulse waveforms are generated digitally in the transmitter and target returns are digitized without analogue down-conversion in the receiver, thereby eliminating most of the analogue components found in typical radar systems. This architecture, which has a number of important advantages over conventional radar systems, which has already implemented by using broadband digitization technologies developed recently for the communications industry and it will be modernized further in future.[75]

d. Quantum Radar. Quantum radar, an emerging field of research, explores the potential of using quantum entanglement and superposition to improve radar sensitivity and detection capabilities. While still in the early stages of development, quantum radar holds promise for applications requiring ultra-sensitive detection and stealth[76].

Conclusion

22. Radar witnessed much technological innovation in last one century. Keeping pace with the modern technology and innovative modern day requirement is really arduous task. But radar community is trying to adapt with all the modern updates. Basic CW radar has successfully changed the whole gamut of WW-II, it depicts how powerful the technological prowess is. The future of radar is characterized by a convergence of technologies, increased intelligence, and expanded applications across diverse fields. As research and development continue, radar systems are poised to become more capable, adaptive, and integral to emerging technologies and societal needs.

23. The modern day needs are even more challenging. Thus, there is no shortcut to update our knowledge as per the modern day requirement. The domain of radar is ever spreading. Only the upgradation of knowledge in the subject matter and applying that knowledge in practical field is the absolute remedy to keep updated with modern day challenges. Low cost digital radar and finally quantum radar is the ultimate future. Advances in RF and digital electronics are making digital arrays an attractive possibility not only for radar but also communication and electronic warfare. We need more initiatives in this direction are necessary to make RF and microwave blocks to find their way into embedded systems to achieved signal processing, single board computer and other functions. The RF and microwave industry, as those are more connected to defense systems, should benefit from the government initiatives to accelerate the transition from today's restrain situation where there are no constraints on RF architecture in the backplane and thus little progress in achieving greater modularity to an open and standardized approach for cost effective digital radar systems in future.

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