EVOLUTION OF RADAR TECHNOLOGIES AND CAPABILITIES IN THE SAF – PAST, PRESENT AND FUTURE

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ABSTRACT

The roles and capabilities of radar have evolved with technology advances and novel employment concepts driven by Singapore's unique demands and challenges – limited land space, rising skyscrapers, declining birth rate and congested electromagnetic spectrum. In the early days, the Singapore Armed Forces (SAF) inherited and indigenously upgraded radars left behind by the British Forces after their withdrawal. In the 1970s, the SAF launched the first radar acquisitions to replace the inherited equipment. The late 1980s and early 1990s marked a turning point in radar technologies and modernisation. Antennas progressed from being passive reflectors to active arrays; high power transmitters shifted from relying on microwave tubes to solid-state power amplifiers; and analog computers were succeeded by digital processors. These opened up new and exciting possibilities to advance radar capabilities and applications to handle a broad diversity of threats. The SAF and DSTA promptly seized these opportunities to embark on sensor masterplanning and delivered first-of-class multi-function and multi-mission radars. Looking ahead, this article will share how future radar trends and the digital age can influence the next generation of radar development to meet the SAF's future needs.

Keywords: radar, active electronic scanning array, solid-state transmit and receive modules, digital processors, multifunction radar, multi beamforming, multi-mission radar, electromagnetic spectrum

EARLY DAYS – LEGACY 2D RADARS

Before the 1990s, radars were commonly characterised by the use of passive antenna, high power microwave tube-based transmitters, and analog receivers and processors. Reflector antennas were widely used for radar applications, and they were built in a variety of shapes that corresponded to a variety of feed systems to illuminate the reflector surface, each suited to a particular application.

Radar transmitters relied on microwave tubes such as magnetron, twystron, klystron, travelling wave tube (TWT) and cross-field amplifier. Building a high power transmitter from a microwave tube was both an art and a science – control and high voltage were keys to transmitter reliability, and not every radar vendor got it right. A typical radar construct relied on one high power transmitter, which made it a single point of failure.

A typical radar analogue processing chain comprises the following key elements:

a) Moving Target Indicator (MTI) – This helps to suppress stationary clutter, which are reflected signals from background and objects of no interest.

b) Automatic Target Detection – This relieves the radar operator from the arduous task of detecting targets from radar displays visually.

c) Extraction – This extracts range and angular estimates to convey the target position.

d) Tracking – As all the radar time-energy resource are dedicated to search, target tracking is carried out passively, thus the expression track-while-scan or track-while-search (TWS). A target track will be updated when there is a detection during the search process; if there is no detection, the target track position is predicted for reporting to allow track continuity.

In the early days, Singapore's airspace sovereignty was primarily served by two long-range two-dimensional (2D) surveillance radars – the S316 and L319 – and two height-finder (HF) radars inherited from Britain's Royal Air Force. This set-up was known as the Bukit Gombak Radar Station, and it was considered as one of the most advanced air defence systems in Asia at that time. The 2D surveillance radar's contacts appeared as blips on a screen, providing basic information on the contact's range, bearing and speed. The radar operator would then slew the HF radar antenna toward a particular contact's bearing to seek out the contact's altitude. In essence, the pairing of 2D surveillance and HF radars was employed to obtain a three-dimensional (3D) air situation picture. Figure 1 presents an aerial view of a partial setup displaying the S316 surveillance and HF200 radars.

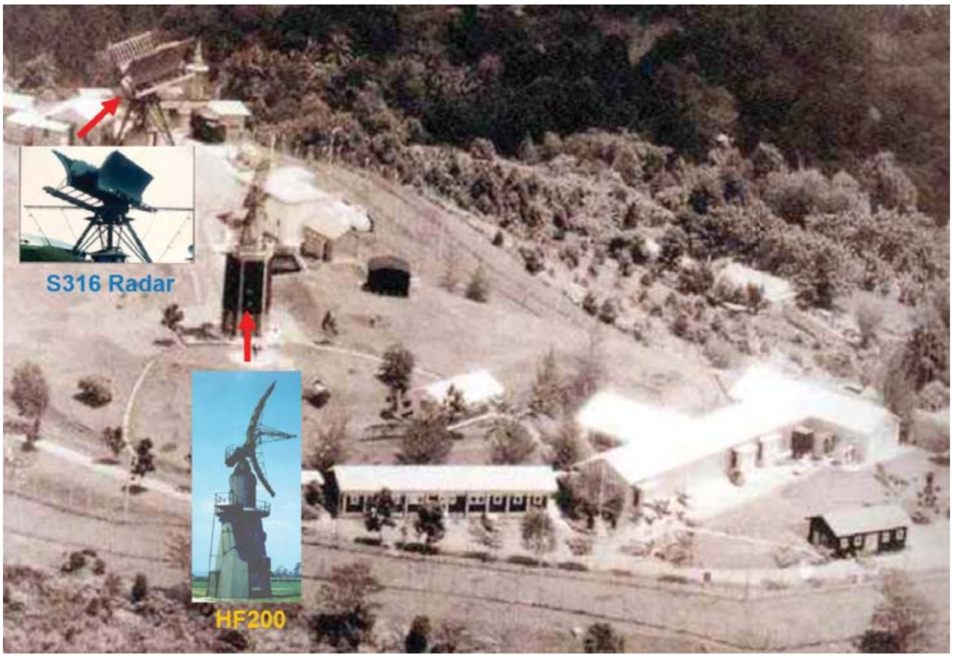

Figure 1. Aerial view of Bukit Gombak Radar Station in the 1960s (MINDEF, 2017)

The S316 comprised back-to-back systems of two reflector antennas on one rotating mount, one in L-band (23cm wavelength) and one in S-band (10cm wavelength). The combination of L-band and S-band antennas minimised the performance trade-offs of a single-frequency band system. L-band is good for long-range surveillance with minimal weather effects, while S-band is good for medium-range surveillance and tracking. The L319 was "one-half" of the S316, comprising a single reflector antenna system operating in L-band. These antennas transmitted a cosecant-square beam pattern intended for air surveillance application. This pattern is a means of achieving a more uniform signal strength at the input of the receiver as the target moves at constant altitude within the beam.

The HF200 radar had a peculiar appearance when in operation. To fulfil its height-finding role, it featured a broad horizontal beam with narrow elevation beamwidth (in contrast with a 2D surveillance radar's narrow horizontal beam with broad elevation beamwidth) that was scanned mechanically in elevation by rocking or "nodding" the antenna structure several cycles per minute. As the radar beam traversed the contacted target, echo returns were presented on a range-height-indicator display that was scaled to indicate the target's approximate altitude.

After the handover, the Bukit Gombak Radar Station was renamed as the Air Defence Radar Unit. A few years later, a pioneer group of engineers and technicians from the Ministry of Defence upgraded these radars indigenously to extend their shelf life. In particular, they introduced miniaturised and transistorised cabinets to replace bulky vacuum tube electronics.

1970s AND 1980s – NASCENT OF 3D RADARS

The process of obtaining a 3D air situation picture from a pair of 2D surveillance and HF radars was slow. The approach was also limited, particularly in handling multiple target scenarios. Thus, there was a requirement for 3D long-range radars to enhance the early warning and surveillance capabilities.

The Singapore Armed Forces (SAF) acquired its first off-the-shelf 3D radar in 1975 – the TPS43 (see Figure 2) – that was implemented as a stacked-beam radar. The TPS43 employed a multiple-horn feed illuminating a mechanically rotating reflector-type antenna to generate a stack of six simultaneous receive beams in elevation. The elevation-angle was estimated via an amplitude comparison technique, where the amplitudes of the target returns in two or more adjacent simultaneous beams were compared. This technique was also termed simultaneous lobing.

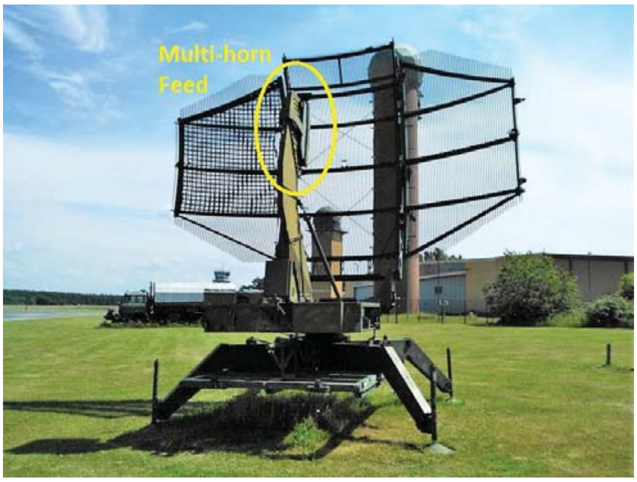

Figure 2. TPS43 (© Dirk1981 / File: Westinghouse AN TPS-43.jpg / Wikimedia Commons / CC BY-SA 3.0)

The 1980s introduced electronic scanning array (ESA) antennas to meet the radar demands for beam flexibility and low antenna sidelobes. An ESA antenna has several architecture configurations, depending on the following:

a) One- or Two-dimensional Steering – A one-dimensional ESA electronically steers in one dimension, typically elevation. A 2D ESA electronically steers in two dimensions: azimuth and elevation.

b) Frequency or Phase Scanning – In frequency scanning, the beam is steered by varying the transmission frequency. In phase scanning, the beam is steered by electronically controlled phase shifters.

c) Central or Distributed Transmitter – A passive ESA (PESA) is equipped with a central transmitter, which is typically based on microwave tube technology and located away from the antenna. An active ESA (AESA) is equipped with a distributed transmitter, which is based on solid-state power amplifiers and located within the antenna.

d) Liquid or Air Cooling – Liquid cooling, air cooling or a hybrid of liquid and air cooling is employed to dissipate the heat generated within the antenna.

The next radar acquisition was of the ITT320 (see Figure 3), which was the first ESA radar acquired. It featured one-dimensional steering via frequency scanning, PESA fed by slotted waveguide[1], and an air-cooled antenna. The 3D surveillance volume was covered by steering a series of pencil-beams in elevation electronically, while mechanically rotating in azimuth. Frequency scanning was achieved by transmitting a sequence of contiguous subpulses, each stepped in frequency. It subsequently processed a column of sequentially formed receive beams in elevation, each corresponding to a subpulse frequency. Amplitudes from these adjacent beams were then compared to estimate the target elevation angle, which was a form of the general technique of sequential lobing.

Frequency scanning radars were relatively simple and inexpensive to implement. However, frequency scanning compromised radio frequency (RF) emission control[2] measures since multiple frequency channels were required to achieve the requisite elevation coverage. Hence this put the radar at a disadvantage in terms of the performance and operational benefits of exploiting transmission frequency change or diversity.

Figure 3. ITT320 (MINDEF, 2017)

The ITT320 pencil-beam architecture has an advantage over the TPS43 stacked-beam architecture in terms of handling ground clutter and susceptibility to active jamming. Robust ground clutter handling like anti-clutter MTI and Doppler processing is essential for the lowest elevation beam, as the main lobe intercepts the ground surface, admitting ground clutter returns. In the case of a stacked-beam radar, it may also be important for the other beams in the stack, depending on the severity of the clutter. This is because the elevation patterns of a stacked-beam radar are one-way patterns, being dominated by the receiver elevation pattern. Consequently the elevation sidelobes protecting the upper beams from ground clutter (or sea clutter for a coastal radar application) are one-way elevation sidelobes. This is different for a pencil-beam radar, in which the product of the transmit and receive elevation sidelobes protects the upper beams from ground clutter.

Similarly, stacked beams are relatively easy to jam due to the multiple simultaneous receive beams, whereas pencil beams are relatively more resilient to jam due to the narrow receive beam.

In principle, the TPS43's simultaneous lobing technique is better in estimating the target elevation angle compared to the ITT320's frequency scanning technique (which is essentially sequential lobing). This is because the latter encounters amplitude fluctuations in the target return, due to different frequencies required to steer the beam in elevation and the latent effect of sequentially formed receive beams. However, the ITT320 mitigates this by transmitting several closely spaced beams to minimise these effects.

Another significant milestone was the acquisition of the E-2C Hawkeye (see Figure 4). The SAF was the first in the region to have an airborne early warning capability, which significantly enhanced Singapore's low-level and long-range surveillance. Its antenna comprised 148 dipole elements arranged in an array, and was housed in a distinctive 24-foot rotating saucer-shaped rotodome (with five revolutions per minute) mounted above the aircraft's rear fuselage.

Compared to the inherited radars, a distinguishing feature of these acquired radars was their improved sensitivity. Increasing sensitivity, however, compounded the radar clutter-handling challenge, and this was particularly compelling in the local non-homogenous clutter[3] environment. This trade-off was handled by a coherent radar – highly stable RF source for transmission in order to attain a high level of phase coherence from pulse to pulse, and coherent processing of the received signal returns. A key benefit of coherent radar is the ability to differentiate and exploit relatively small differences in velocity, corresponding to small differences in phase of the signal returns, in order to obtain Doppler[4] resolution and estimation. Radar on-site adaptations, and a radar operator's skills and experience were also critical in minimising surface clutter returns and discerning genuine target echo from clutter returns respectively.

Figure 4. E-2C Hawkeye aircraft (MINDEF, 2017)

1990s – ACTIVE ELECTRONIC SCANNING ARRAY RADARS

In the early 1990s, a sensor masterplan was initiated to establish and deliver a multi-layer suite of radars that collectively provided frequency diversity, high track quality, minimal false alarm and effective electronic counter-countermeasures. The sensor masterplan was deliberately timed to exploit the advent and maturing of AESA antennas and digital processors.

Unlike reflector-feed and PESA antennas that were equipped with a central transmitter, which are typically based on a single high power microwave tube, an AESA antenna is populated with multiple solid-state transmit and receive modules (TRM). This enables superior radar performance and availability. An AESA antenna includes the following critical technologies and building blocks:

a) TRM – Individual TRMs can be combined to provide sufficient amplification, which allows the antenna to achieve the required RF power with greater efficiency and smaller form factor.

b) Advances in RF Generation – This offers improved RF spectral purity and signal stability over a wide instantaneous bandwidth, and for coherent Doppler processing to improve clutter rejection and target detectability.

c) High Performance Digital Circuits – Ultrafast analog-to-digital converters and digital networks enable analog radar signals to be converted to digital signals with ease and speed, which made digital signal processing possible.

d) Efficient Cooling Module and Distribution – This makes it possible to achieve a healthy and stable environment within the antenna populated with active RF and electronic circuits.

Collectively, the above provides the basis of an AESA beamforming architecture and network in order to realise flexible, rapid and multiple beams. AESA no longer confined the properties that directly linked the beam's gain and width to the antenna's size. Analog beamforming was the prevailing technology of the 1990s.

The advent of AESA shifted the radar design from "power-on-target" to "energy-on-target". Previously, the focus was on short pulse widths due to the high peak power and low duty-cycle[5] offering of microwave tube-based transmitters. The attention shifted to longer pulse widths due to the low peak power and high duty-cycle associated with TRM's solid-state power amplifiers. AESA also capitalised on flexible beamforming to exploit the time dimension – radar dwell time (also known as "time-on-target") – to improve small target detection and perform target classification. The ability to achieve and exploit longer dwell time is mentioned in the later part of this article.

Once radar signals are converted from analog to digital, they are only limited by state-of-the-art in digital processing, which has seen exponential development in parallel with Moore's Law[6]. Powerful digital signal processors, commercial off-the-shelf microprocessors and multi-processing computing architectures in turn enable complex radar signal and data processing algorithms to be executed in real time. An early beneficiary was the realisation of a Moving Target Detector (MTD) concept that employed adaptive digital signal and data processing to handle non-stationary and adverse clutter conditions, which its predecessor MTI had struggled with. MTD fulfilled this task by a combination of Doppler filters, adaptive false alarm rate processing and fine resolution clutter maps. Subclutter visibility[7] is a key quantitative measure of MTD.

The FPS117 (see Figure 5) was the SAF's first AESA radar. The following presents a few key highlights and benefits that the FPS117 has over the ITT320:

a) Graceful Degradation – The FPS117's AESA antenna consists of 44 active rows of horizontal stripline linear array to steer the beam in elevation. Figure 6 illustrates a schematic diagram of a stripline array for analog beamforming. Each row is fed by a solid-state TRM located right behind it. In the event of one or few TRM failures, the antenna remains functional, albeit with a slight but tolerable beam and performance degradation. Thus, the FPS117 possesses graceful degradation and higher availability compared to the ITT320, which relies on a single TWT-based transmitter.

b) Utilisation of Frequency Band – Elevation steering of the pencil-beam is accomplished by electronically controlled phase shifters placed at individual row feeds. Phase scanning has a critical advantage over the ITT320's frequency scanning, as it allows complete utilisation of the frequency band for purposes beyond beam scanning, as well as providing independence of the transmission waveform and beam position.

c) Measurement Technique – Angular measurements are accomplished by a two-axis monopulse[8] on receive, consisting of a sum and two delta beams. This outperformed the ITT320's amplitude comparison technique that is susceptible to target echo amplitude fluctuations and vulnerable to RF interference.

Anecdotally, in the early days after the introduction of the FPS117, radar operators gave feedback that the radar screen was "too clean" and queried if the radar had malfunctioned or underperformed. It was explained that this was due to the FPS117's superior clutter handling and false alarm control compared to the older radars that the operators had been accustomed to.

Figure 5. FPS117
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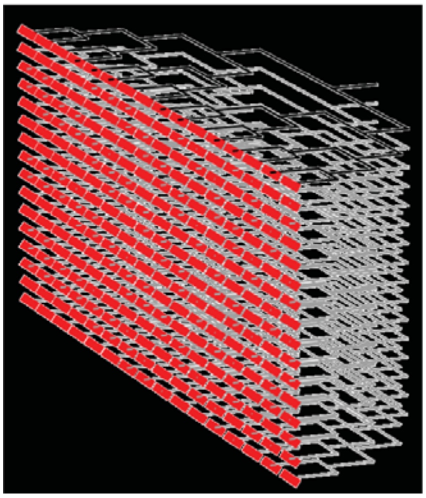

Figure 6. Stack of individual stripline array
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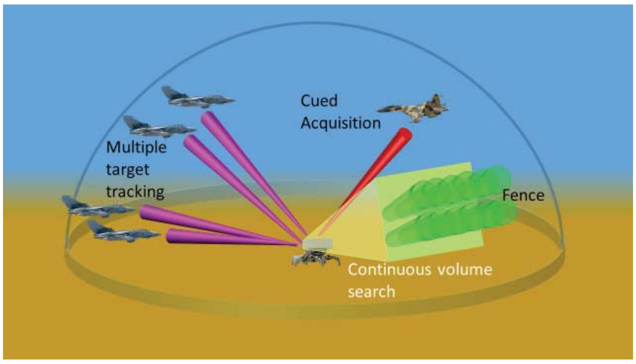

Figure 7. Various functions of a multi-function radar
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Figure 8. MFR on board the frigate (MINDEF, n.d.)

An important development arising from AESA radar technology was the opportunity to pursue a multi-function radar (MFR). A MFR is characterised by a matrix array to accomplish 2D beam steering via phase scanning – azimuth and elevation. This, coupled with smart radar resource management and optimal waveform selection, enables the interleaving of search and track functions to deliver superior quality tracking of high speed and manoeuvring targets while concurrently providing the search coverage expected of a modern 3D long-range radar. This "active" tracking presented a major advantage over the FPS117's TWS, also known as "passive" tracking. Another operational advantage was its ability to acquire the target earlier by introducing fast target confirmation on a single plot, whereas the FPS117 would have taken a few scans to confirm a target detection. Figure 7 presents the various functions of a MFR. Cued acquisition is a function where a MFR accepts a cue from an external source to acquire the target quickly, thereby avoiding the need to do its own search.

In essence, a MFR is an amalgamation of two radars: a search radar and a track radar. The Republic of Singapore Air Force was a pioneer adopter of MFR for airspace surveillance and management. This concept was later on introduced into other SAF radars, including the Republic of Singapore Navy's frigates (see Figure 8).

2000s to PRESENT – MULTI-ROLE RADARS

AESA technology continues to evolve rapidly, driven by semiconductor materials such as silicon (Si), gallium arsenide (GaAs) and more recently gallium nitride (GaN), and increasing levels of digitisation. Compared to earlier semiconductor transistors, advances in semiconductor materials have led to higher voltage handling, improved thermal conductivity and efficiency. Consequently, these enabled significantly improved RF performance – greater output power, higher operating frequency, wider bandwidth and superior reliability. Digitisation is inching towards the antenna front, eliminating analog components along the way and achieving higher efficiency and greater dynamic range[9].

Collectively, these bring about increasing levels of miniaturisation and integration in antenna architecture and beamforming, which create opportunities for game-changing benefits and radar applications. Figure 9 presents the trends in antenna architecture and beamforming, which mirror the past and present generation of radars. Compared to the past when the focus was on addressing equipment obsolescence, modern radar architectures are designed for technology insertion, performance growth and long-term sustainability.

simultaneous receive beams in azimuth and elevation. Figure 10 presents an illustration of a broad transmit beam with multiple simultaneous receive beams. The reduced transmit beam gain due to broadening is offset by a higher processing gain due to the increase in time-on-target. In essence, dual-axis multi-beamforming is a modern form of a stacked-beam radar introduced in the 1970s by exploiting AESA technology innovatively to improve radar design trade-off considerations.

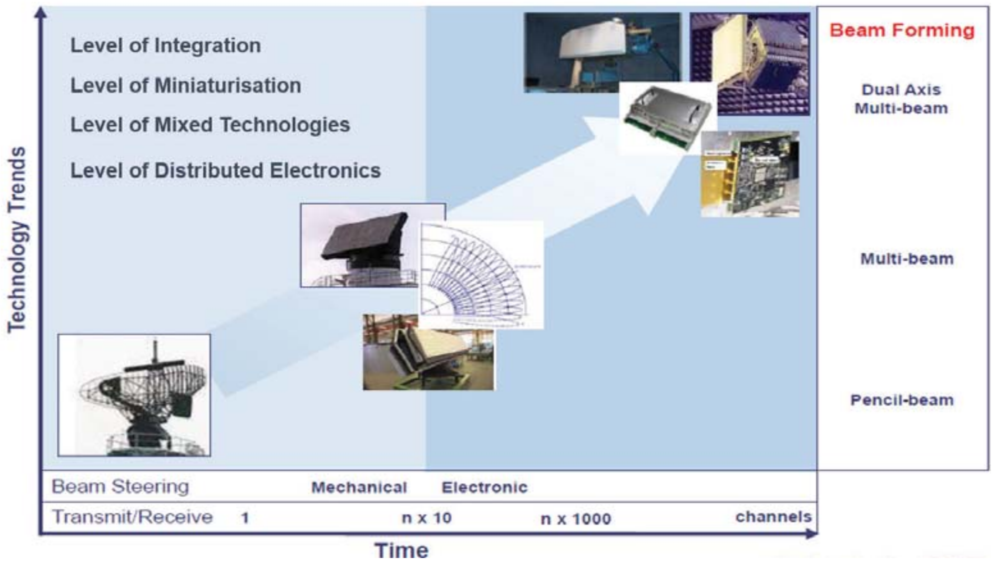

Figure 9. Trends in antenna architecture and beamforming
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In recent times, radars are relied upon to handle a broad diversity of threats, ranging from small and slow-moving unmanned aerial vehicles to very small, fast and agile missiles. Detecting these threats on top of conventional targets simultaneously with one radar imposes conflicting requirements on the radar design. For example, the requirement for a short reaction time to detect high-speed, high-manoeuvre and pop-up targets is in conflict with the requirement for a long observation time to detect slow-moving targets in a demanding clutter environment. This leads to a conflict in planning and utilising the radar time-energy budget, which hitherto has been met by introducing different radars or radar modes.

Thus, the novel solution of dual-axis multi-beamforming was introduced in order to increase the observation time without compromising the reaction time, and allow a radar to accomplish various functions and missions simultaneously – a multi-role radar. A dual-axis multi-beam comprises several

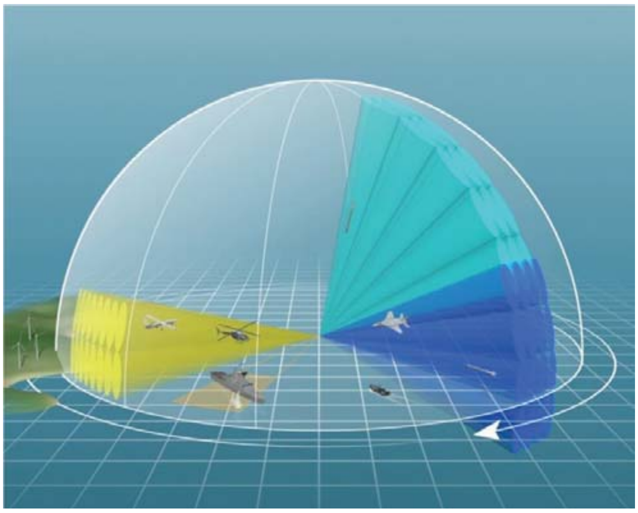

Figure 10. Dual-axis multi-beam. An individual colour illustrates a transmit beam with simultaneous receive beams
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The increase in observation time is also exploited in the Doppler domain to improve the detectability of asymmetric threats, in particular the emergence of low, slow and small (LSS) targets like drones. In the LSS space, targets of interest have to contend with birds, road and pedestrian traffic. The multi-beam's longer observation time results in higher quality returns. Instead of using the classical Fast Fourier Transform to do Doppler processing of these returns, Finite Impulse Response – powered by the latest digital signal processors – provides individual filter control to enhance detectability and extract unique features to aid target classification.

The confluence of these evolving technologies and emerging concepts gave rise to two key radar developments, namely the G550 Compact Airborne Early Warning (CAEW) radar shown in Figure 11 and the Multi-Mission Radar (MMR) shown in Figure 12. While the MFR antenna in the 1990s was populated with a few dozens of TRM, CAEW's MFR and the MMR antennas were each populated with several hundreds of TRM. Unlike the case for the E-2C Hawkeye, the antenna arrays were assimilated onto the Gulfstream G550 aircraft frame with no moving or rotating parts. It would not have been possible to install a MFR on board a business jet without an innovative antenna architecture, hardware miniaturisation and a high degree of RF-digital integration.

Figure 11. Gulfstream G550 Compact Airborne Early Warning radar (© Owen65 / File: RSAF Gulfstream IAI G550 CAEW (Conformal Airborne Early Warning).jpg / Wikipedia / CC BY-SA 2.0)

Figure 12. Multi-Mission Radar (RSAF, 2016)

The introduction of MMR was a game-changer. One MMR fulfilled multiple sensing needs – surveillance, early warning and air defence roles – to compress the Observe-Orient-Decide-Act (OODA[10]) loop. Operating a single system is a cost-effective solution compared to procuring individual sensors to serve each function. It also reduced siting and manning demands, which are particularly compelling factors in Singapore's context of limited land space and declining birth rate. DSTA conceptualised the MMR, engaged like-minded radar vendors to co-develop and were the first to deliver this capability.

LOOKING AHEAD – IMPACT OF DIGITALISATION

With the ongoing digital revolution, digital radar is the new frontier of radar. Figure 13 illustrates the evolution from analog to digital radar. In the strictest sense, a fully digital radar is one where digitalisation occurs at the antenna element level. Figure 14 illustrates this, where a transmitted signal is generated and a received signal is digitalised behind each antenna element. In principle, it simplifies the transmitter and receiver design, has few analog signals and is software-configurable for advanced and future functionalities. These translate into a maximum degree of freedom for agile and adaptive beamforming – every element is potentially a beam – and linear increase in dynamic range. However, there are engineering complexities and challenges at the antenna architecture level. A digital antenna packed with active circuits demands considerable electrical power and correspondingly generates significant heat that needs to be dissipated quickly and efficiently. For a mechanical rotating antenna, it complicates the slip-ring[11] design due to the need to transmit significant electrical power, coolant fluids and voluminous digital data generated by every antenna element. As a radar developer or user, one should consider the following:

1) Do the mission and performance requirements demand a fully digital radar?

2) Are there affordable alternatives? Would a hybrid architecture meet the increasingly challenging demands?

Novel and future demands in radar applications, concepts and antenna architectures will require increasingly smaller and highly efficient RF power amplifiers. In the foreseeable

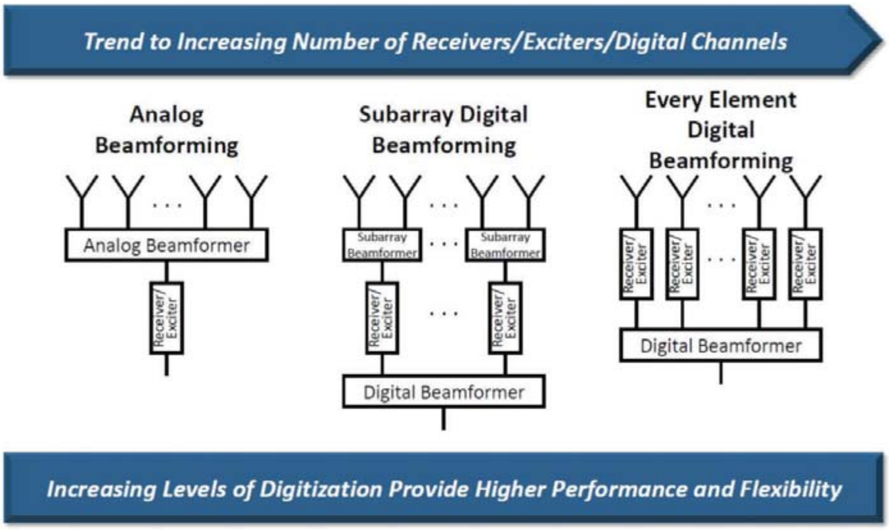

Figure 13. Trend in beamforming, from analog to digital (SAAB, n.d.)

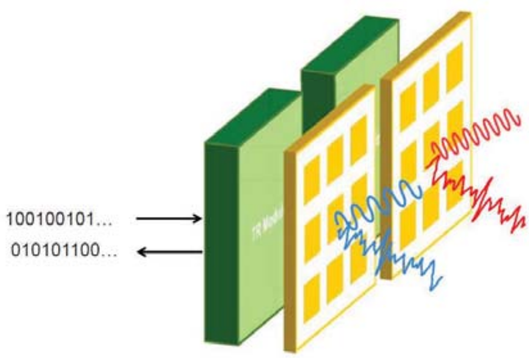

Figure 14. An antenna element (SAAB, n.d.)

future, GaN will continue to be the semiconductor material of choice for solid-state TRMs and AESA. Figure 15 compares GaN with other Si-based and GaAs materials, illustrating its superior inherent properties that translate into better and more reliable RF performance. The popularity of GaN technology and devices is evident in sustained investments in GaN-related industries and its increasing applications in cellular communications, space electronics and Internet of Things[12] (IoT) sensors, making it increasingly affordable and driving continuous innovation.

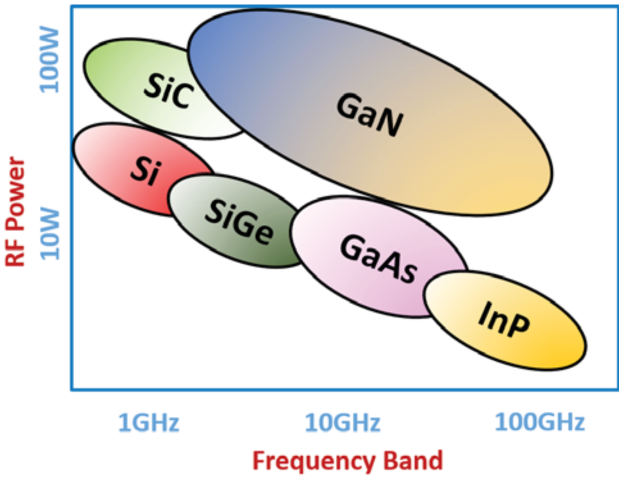

Figure 15. RF power versus frequency for major semiconductor devices

Closer to home, there are specific trends and developments that would be of interest as the SAF and DSTA strive to stay ahead of the radar capability curve.

The electromagnetic (EM) spectrum environment is increasingly congested and contested. As spectrum demands exceed availability, current spectrum allocation policies and practices such as having exclusive spectrum bands for assured access may no longer be sustainable. Moreover, actual spectrum occupancy at a given point, as a function of frequency, time, direction, polarisation and coding, may be quite low. Thus, EM spectrum co-existence may be the future paradigm in order to accommodate increasing spectrum demands. This requires real-time sensing of spectrum occupancy and control of emitted signals, in order to make it possible for multiple signals to co-exist and minimise mutual interference dynamically. It requires radars of the future to be able to instantly adapt and optimise transmission and reception to a priori knowledge in a dynamic EM environment to avoid detection or maintain high performance in a noisy EM environment. This essentially calls for a cognitive radar. Figure 16 presents a concept of a cognitive radar operating in a challenging EM environment. This requires real-time reprogrammable waveform synthesis, as it can no longer rely on pre-programmed waveform.

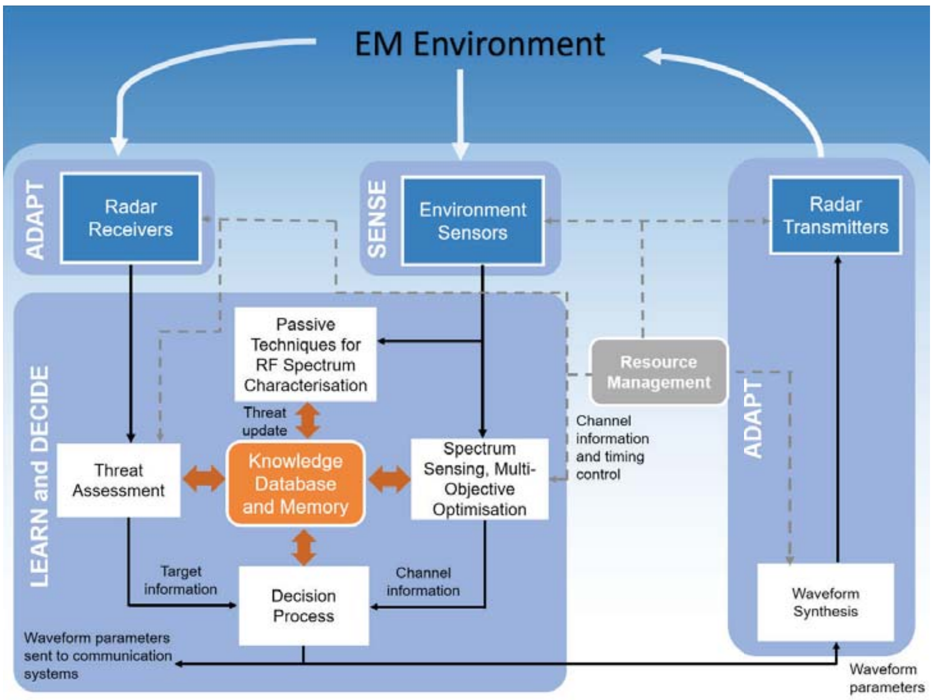

Figure 16. A cognitive radar architecture for operating in congested and dynamic EM environment

In Singapore's operating environment where there are few vantage sites and in the face of an increasingly daunting RF interoperability challenge, a multi-band radar is an interesting concept. A multi-band radar leverages the physics and inherent strengths of different frequency bands to allow one system to accomplish several missions and tasks without performance trade-offs. This is unlike the S316's two-systems-in-one concept. Capability wise, it is an extension of multi-function and multi-mission radars, which have already been delivered. However, there are technology and engineering challenges to advance this concept to a reliable capability. There are ongoing research and development of multi-band antenna arrays and power amplifiers, even faster RF digital circuits for agile front-ends and spatial diversity.

Radar signals and frequency bands are getting wider as there are increasing demands for better resolution and accuracy – these translate to voluminous real-time data. Digital radars' signal and data processors are also generating massive amounts of high-speed data. Thus, the current interest in data analytics[13] (DA) is also relevant to radar applications. Novel algorithms complemented by emerging fields in DA such as machine learning, information fusion and Big Data Analytics[14] are required to extract value from huge and seemingly uncorrelated data sets to advance automatic target classification and identification, anomaly detection, and boost equipment reliability, availability and maintainability. To name a few:

- **Automatic Target Classification, Identification and Threat Evaluation** – High-fidelity Doppler returns can help determine the dynamic properties of targets. For example, the frequency modulation of a target's returns due to its mechanical vibration or rotation. Correlated with other data sets like high-fidelity range returns and tracker's motion signatures, this enhances the analysis of target signatures for automatic target classification, identification and threat evaluation. It also aids sense-making in order to shorten the OODA loop.

- **Automatic Anomaly Detection** – In Singapore's busy airspace and littoral waters, looking out for asymmetric threats that deviate from planned routes or expected behaviours is extremely taxing for human operators. Automatic anomaly detection is particularly compelling in Singapore's context, and it can form part of a decision support system to aid radar operators to make timely decisions on the course of action. Machine learning or its equivalent can be employed to train a system continuously since an air surveillance picture is a dynamic entity changing over time, with repetitive and non-repetitive changes occurring and interacting.

- **Real-time Health Monitoring** – Customary build-in-test (or BIT) is reactive and its performance is often found lacking. This is particularly frustrating for a radar operating around the clock where availability needs to be high and downtime needs to be short. IoT sensors and DA can be applied to carry out real-time health monitoring, schedule condition-based maintenance and "just-in-time" intervention ahead of any disruptive failures. Collectively, they also aid decisions on manning and spares stockpiling and replenishment.

CONCLUSION

The local radar community has experienced the evolution of radar technologies and capabilities over different generations of radars. Radar antennas have progressed from the humble reflector-feed antenna to sophisticated arrays; bulky and awkward high power microwave tube-based transmitter that required safe handling by two operators have been replaced by miniaturised solid-state modules about the size of a book; and analog processors have been made archaic by digital processors, which continue to carry exciting prospects for radar innovation. While radar design continues to be about making trade-offs, technology and innovative applications have enlarged the trade-off space, as exemplified by the introduction of AESA antenna. Digital-based techniques have opened up many options that were previously not available in analog-based techniques. By harnessing these technologies, novel radar employment concepts were conceived and realised which led to the delivery of first-of-class multi-function and multi-mission radars.

Moving forward, the spectrum of threats, terrain and EM environment will be increasingly complex. In parallel, the revolutionary progress in RF digitisation and DA will bring exciting prospects for the radar community to exploit and to introduce innovative capabilities and applications for the SAF.

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ENDNOTES

[1] A waveguide serves as a transmission line to feed the radiating elements. In a slotted waveguide, the slots along the waveguide radiates electromagnetic waves. The shape and size of the slot, as well as the driving frequency, determine the radiation distribution pattern.

[2] Emission control (or EMCON) was introduced in order not to reveal all the RF capabilities of the radar.

[3] Non-homogenous clutter is non-uniform clutter where the amplitude of the clutter returns varies from cell to cell. This is prevalent in built-up areas.

[4] Doppler refers to the difference between the observed frequency and the emitted frequency for an object moving relative to the radar. A static object has zero Doppler.

[5] Duty-cycle is the fraction of time that the radar is in active transmission. It is the product of the pulse width and pulse repetition frequency.

[6] Moore's Law is the observation that the number of transistors in a dense integrated circuit doubles approximately every two years. Advances in digital electronics like speed and form factor are strongly linked to Moore's Law.

[7] Subclutter visibility (SCV) is a measure of the radar's ability to detect target signals superimposed on clutter returns or to "see through" clutter. To illustrate, a radar with 30dB SCV can detect a target over clutter whose signal return is 1000 times stronger.

[8] Monopulse is a measurement technique to obtain angular error information on a single pulse. In a two-axis monopulse antenna architecture, the elements in an antenna array are divided into four quadrants. Target displacement vis-à-vis the centre of the array is estimated by comparing the amplitude of the echo signal in each of the quadrants. The left-half is compared with the right-half to estimate the azimuth direction. The top-half is compared with the bottom-half to estimate the elevation direction.

[9] Dynamic range is the maximum signal-to-noise over which the receiver and signal processor operate without any saturation. If saturation occurs, undesired/spurious signals which degrade performance may be generated.

[10] The phrase "OODA loop" refers to the decision cycle of Observe, Orient, Decision and Act, developed by military strategist and United States Air Force Colonel John Boyd. Boyd applied the concept to military combat operations process. This concept has since been adopted for business and learning processes.

[11] Slip-ring is an electromechanical device that allows the transmission of electrical and RF power, data and fluid between a stationary and a rotating structure.

[12] IoT is a network of physical devices embedded with electronics, software, sensors, actuators, and network connectivity, which enables objects to connect and exchange data. It allows objects to be sensed or controlled remotely, creating opportunities for more direct integration of the physical world into computer-based systems, resulting in improved efficiency and reduced human intervention.

[13] Data analytics is a process of collating and modelling data with the goal of discovering useful information and relationships among different and disparate data sets in order to aid decision making.

[14] Big Data Analytics is a process of examining large and varied data sets – Big Data – to reveal patterns, trends and associations, where traditional data processing handling may be inadequate to deal with large and/or complex data sets.

BIOGRAPHY

Lee Chee Hoong is an Assistant Director (DSTA Masterplanning and Systems Architecting). Previously, he spent 25 years in various radar-related acquisition activities, spanning sensor master-planning, project management, system management and capability development.