OPERATING AND SUPPORTING THREE GENERATIONS OF WEAPON LOCATING RADARS

TAN Jit Yong, LEE Chee Hoong, CHUA Wah Seng

ABSTRACT

The SAF started deploying Weapon Locating Radars (WLR) in the 1980s. In the early 2000s, a highly mobile weapon locating system was acquired to supplement the first generation fleet of WLRs. Recently, the Army inducted the third generation of WLRs. Technological evolution in antenna, microwave and computer processors has significantly influenced radar applications and capabilities. These advances and their outcomes are evident across the three generations of WLRs. For example, the performance envelope, reliability, and supportability of the third generation WLRs based on an active electronically scanned array are unlike the first generation WLRs utilising a passive electronically scanned array. Consequently, operational and maintenance support concepts and practices have evolved. However, these advances and enhancements have their own pain points and trade-offs. This article will share the evolution across different generations of WLRs, with a focus on the operations and support aspects.

Keywords: radar, antenna architecture, processor, operations & support, built-in test, mean-time-between-failure, human-machine-interface

ROLES AND BASIC PRINCIPLES OF WEAPON LOCATING RADARS

Indirect fire weapons[1] like rockets, artillery guns, and mortars (collectively termed RAM) are typically deployed behind and fired over undulating terrain at objectives not in the line of sight of the RAM launchers. A Weapon Locating Radar (WLR), as the name suggests, is deployed to detect and locate adversary RAM units when they fire so that a swift response can be directed to take out the 'shoot-and-scoot' launchers. Commonly known as a Hostile Weapon Locating (HWL) mission, the process involves several steps (see Figure 1 and 2):

(a) Establish a search fence by electronically scanning the horizon several times per second (aka revisit time)

(b) Intercept an incoming projectile in its ascending trajectory

(c) Verify the initial detection in order to handle any false alarm

(d) Track the projectile along its ascending trajectory

(e) Simultaneously extrapolate back along the trajectory to predict and report the launch point (LP) and forward along the trajectory to predict and report the projectile impact point (IP)

Depending on the antenna elevation coverage and projectile trajectory, tracking the projectile can take several seconds, to collate sufficient track measurement points to predict the LP and IP. Thus, the entire process from initial projectile interception to LP and IP reporting can take tens of seconds. A few key indicators define a WLR capability, namely the probability of locating the launchers, LP and IP reporting accuracies, and confidence in target classification (whether it is a rocket, artillery gun, or mortar).

A secondary role of a WLR is to support friendly fire elements. When operating in a Friendly Fire Registration (FFR) mission, as illustrated in Figure 3, the WLR sets up a 'window' through which its own RAM projectile will pass through. Unlike the HWL's search fence, this 'window' is established a priori based on own fire orders. This allows the WLR to track the projectile in its descending trajectory and extrapolate forward along the trajectory to predict its impact point. This information is used to compute fire correction data for its own RAM launcher to improve firing accuracy.

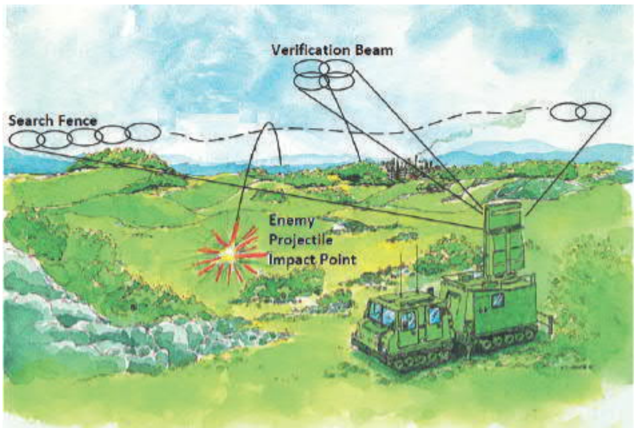

Figure 1. WLR's HWL mission

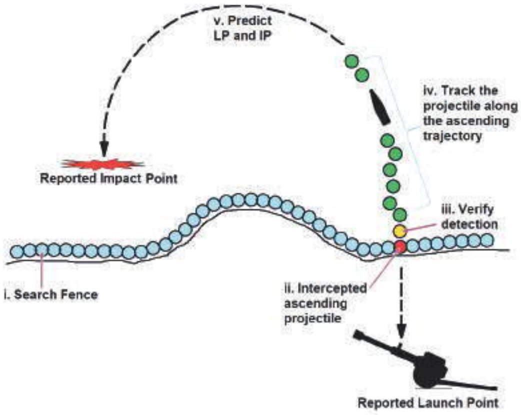

Figure 2. Search, detection, verification, and tracking process of a HWL mission

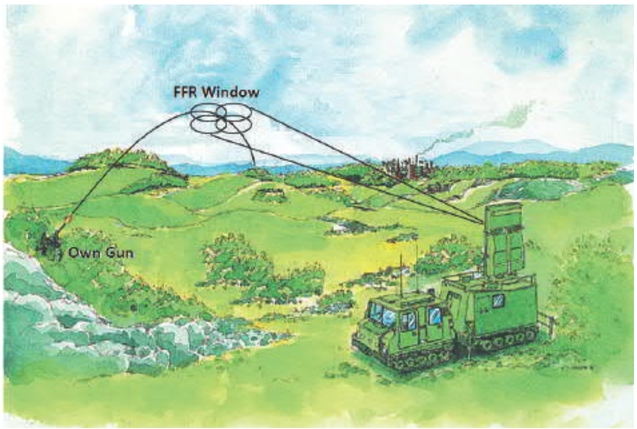

Figure 3. WLR's FFR mission

THE SAF'S FIRST GENERATION WLRs – TPQ36 & TPQ37

The TPQ36 and TPQ37, presented in Figure 4, were developed in the 1970s. The SAF acquired and fielded them in the mid-1980s and early 1990s, respectively. Back then, they were considered state-of-the-art systems because they were among the first systems to introduce two-dimensional electronically steering array (ESA) for beam flexibility. The two-dimensional ESA has an antenna beam electronically steered in both the azimuth and elevation planes, to carry out dedicated search and track of extremely small radar cross section (RCS[2]) projectiles. For example, an artillery shell has an RCS of 0.001m^2. In comparison, an air surveillance radar typically employed a one-dimensional ESA. The one-dimensional ESA has an antenna beam electronically steered in elevation while mechanically steered in azimuth, to perform track-while-search[3] of aerial targets that were more than 1,000 times larger than a RAM projectile. Those were the days before the advent of stealth aircraft and small drones.

TPQ36 and TPQ37 played complementary roles in the battlefield, with the TPQ36 covering the short-range and the TPQ37 covering the long-range. Both have a similar configuration, comprising the (a) Antenna Transceiver Group (ATG), which comprises a passive ESA (PESA) antenna and travelling wave tube (TWT)-based transmitter; (b) Operations Control Group (OCG), essentially where all the processing and controls are carried out; and (c) Diesel Generator Unit (DGU).

The key distinction between the TPQ36 and TPQ37 lies in the ATG due to the following:

(a) **Frequency band** – TPQ36 operates in X-band, whereas TPQ37 operates in S-band.

(b) **Effective Radiated Power[4] (ERP)** – TPQ37 has a larger antenna and more powerful transmitter necessary to achieve a higher ERP to fulfil its long-range role.

(c) **Transmitter** – TPQ37's more powerful TWT-based transmitter operates at a higher transmission duty cycle[5] that requires liquid-cooling. TPQ36's TWT-based transmitter operates at a lower duty cycle with air-cooling and thus has simpler configuration.

(d) **Antenna Architecture** – While both antennas are PESA technology, they differ in their electronic scanning mechanisms. The TPQ36 does phase scanning in azimuth and frequency scanning in elevation. Electronically controlled phase shifters are used to steer the beam along the horizontal plane, while a sequence of contiguous transmissions at different frequencies is used to steer the beam in the vertical plane. The TPQ37 does phase scanning in both azimuth and elevation planes, and there are phase shifters in both planes.

Figure 4. TPQ36 (top) and TPQ37 (bottom)

TPQ36 and TPQ37 use similar back-end hardware in their OCG. The first generation signal processor (SP) comprises 128 single-layer Circuit Card Assemblies (CCA). The radar computer has a 128KB RAM and software programmes residing in a 2MB magnetic tape. The human-machine-interface (HMI) comprises a rotatable map drum, a Cathode Ray Tube (CRT) monitor called the B-scope, an alphanumeric keypad and trackball. Some of these hardware are highlighted in Figure 5.

Figure 5. Inside the OCG: SP back plane (left) and HMI (right)

Operating and supporting the TPQ36 and TPQ37 was labour-intensive and time-consuming, as outlined:

(a) Each system was manned by a crew of eight men and set-up took 30 minutes. Interconnecting the ATG, OCG and DGU units required five men to lay out three cables physically, with each cable up to 50m in length and 150kg in weight. Levelling the ATG required the four legs to be manually cranked. When the transmitter was switched on, it took a few minutes to warm up, similar to the cathode ray tube television of the old days.

(b) Routine processes and controls relied heavily on hardware like magnetic tapes, LEDs, switches and map drums. Booting up or rebooting the computer required winding and unwinding the magnetic tape to load software programmes. To report the LP and IP, a computer-controlled servomotor would physically roll the map drum to the proper northing coordinates and a small light spot projected onto the map from inside the drum indicated the easting coordinates.

Figure 6. Signal tracing using circuit diagrams

(c) Troubleshooting was laborious and hazardous. Handling the bulky transmitter and its peripherals required at least two men and it was a hazardous undertaking as it involved high voltage power supply. Troubleshooting the SP back plane, where each CCA had 100 pins mated to the SP back plane pin plate and the 128 CCAs were connected via more than 10,000 wire-wrapping, could take more than an hour as it involved signal tracing over several pages of circuit diagrams (see Figure 6).

(d) The basic ops-loading list (BOLL, aka field level spares and consumables) comprised more than 500 line item types. Field test equipment included the bulky oscilloscope and spectrum analyser.

SECOND GENERATION WLR – ARTHUR

ARTHUR (see Figure 7), an acronym for '**ART**illery **HU**nting **R**adar', is a C-band radar introduced into service in the early 2000s to complement the fleet of TPQ36 and TPQ37. Unlike the TPQ's separate OCG, ATG and DGU units, ARTHUR's hardware is contained in a 10ft rear cabin of the track articulated all-terrain carrier Bandvagn 206 to meet its mobility role. Size, weight, power, and cooling (SWaP-C) were thus critical considerations in the conception, design, and equipment layout of ARTHUR.

(a) Its antenna is stowed and deployed on the roof of the rear cabin. To keep the antenna architecture simple and lightweight, it features PESA technology that carries out phase scanning in azimuth and frequency scanning in elevation to steer the beam, similar to TPQ36.

(b) Hardware count is significantly reduced as ARTHUR leverages powerful processors, multi-processing computers and software. Radar processing can be carried out with less than 10 CCAs. Software programmes and Digital Terrain Elevation Data (DTED) maps are installed in a 2GB hard disk. Its HMI comprises a LCD monitor, keyboard and mouse, which presents a pleasant user experience.

(c) An on-board generator relies on the vehicle engine and resides in the front cabin. This requires the vehicle engine to run as long as the radar was in operation.

(d) It is manned by a crew of four and is set up in less than 10 minutes.

(e) BOLL comprises less than 200 line item types.

Figure 7. ARTHUR

Though ARTHUR is significantly smaller in SWaP-C compared to TPQ37, it has a similar performance envelop by exploiting the latest technology in radar radio frequency (RF) generation and computer hardware. Advances in RF generation achieved the desired RF spectral purity and signal stability over a wide instantaneous bandwidth, which is necessary to carry out coherent Doppler processing in order to handle non-stationary and non-homogenous clutter conditions. A RF receiver complemented this with improved sensitivity and lower noise figure. Finally, it was also important that field programmable gated array processors were introduced to run complex radar signal and data processing algorithms (e.g. Doppler filtering, adaptive false alarm rate processing, fine resolution clutter maps and fuzzy logics). This will enable good sub-clutter visibility[6] in order to enhance the target signal-to-returns (clutter and noise), thus improving target detectability.

There was also ingenuity in exploiting inherent design features, which might at first be deemed a limitation. ARTHUR's frequency scanning in elevation deprives it from the performance and operational benefits of exploiting frequency change or diversity. For a given search beam position, the transmission frequency would remain the same on successive scans. Thus, if a RAM projectile happens to present a weak RCS in that position, successive scans may not improve the projectile's detectability. To overcome this limitation, an innovative feature was introduced to transmit a different frequency at the same beam position. A slight change in frequency can drastically alter the RCS, essentially changing the RCS profile. This improved the projectile's detectability and tracking accuracy.

Generally, compared with the TPQs, troubleshooting and recovery from an ARTHUR defect is quicker and less laborious, as it is largely driven by enhanced built-in-tests (BIT) powered by computers and software. With BIT, technicians and even operator-maintainers can easily identify a faulty module and replace it. There is no longer a need to carry bulky and generic test equipment for troubleshooting as most signals are monitored and reported by the radar computer.

THIRD GENERATION WLR – SAFARI

The SAFARI WLR (see Figure 8) was introduced into service in the mid-2010s to modernise the physically aging and technologically obsolete WLR fleet. It is a highly compact radar configured on a locally built track articulated BRONCO platform.

Figure 8. SAFARI

On the exterior, SAFARI looks similar to ARTHUR, but there are distinct differences in their antenna technologies that are key to the SAFARI's superior performance and availability. The first WLR to introduce active ESA (AESA) technology, its AESA antenna enjoys several advantages over the first and second generation WLRs:

(a) The SAFARI antenna is populated with hundreds of solid-state transmit and receive modules (TRM), which allows it to enjoy a high availability and graceful degradation. It can continue to operate when there are the occasional TRM failures. Primarily for this reason, mean-time-between-critical failures (MTBCF) was adopted instead of the commonly used mean-time-between-failures (MTBF) associated with a single point of failure.

(b) Its beam steering network allows it to steer the beam electronically wider in azimuth and higher in elevation to increase its spatial coverage.

(c) It employs dual-axis multi-beamforming consisting of multiple simultaneous receive beams in azimuth and elevation to increase the radar dwell time aka 'time-on-target' to detect further.

Drawing a lesson learnt from ARTHUR's reliance on its vehicle engine to draw power and to keep within the SWaP-C constraint of the BRONCO vehicle, a novel Integrated Power and Cooling System (IPCS) independent of the vehicle engine and peripherals was introduced. The IPCS supplies power to the radar and provides cooling to the cabin interiors for operator comfort and equipment well-being. Thus, any vehicle engine issues will not affect radar operations.

EVOLUTION ACROSS THE THREE GENERATIONS OF WEAPON LOCATING RADARS

A comparison between the three generations of WLRs is summarised in Table 1. It provides an outline of how technologies in antenna, microwave, and computer processors have advanced, and their positive influences on radar performance, operations and support.

The shift from PESA to AESA has been a significant game changer for radar applications. Generally in a PESA radar, the focus is on short pulse widths due to the high peak power and low duty cycle offering of microwave tube-based transmitters. It was about 'power-on-target'. Power is the defining factor in specifying and realising a radar capability. The advent of AESA, with their high duty cycle TRMs and the ability to accomplish multi-beamforming shifted the radar focus to 'time-on-target' (or 'energy-on-target'). Another advantage of AESA over PESA is eliminating the need for external RF waveguides. Depending on the length (rigid or flexible) and type of waveguides (choice of material like aluminium or copper), the RF loss between the transmitter and antenna radiating elements is significant. For

	Generation 1		**Generation 2**	**Generation 3**
	TPQ36	**TPQ37**	**ARTHUR**	**SAFARI**
Development Era	1970s		1990s	2010s
Antenna	PESA (phase scanning in azimuth; frequency scanning in elevation)	PESA (phase scanning in both azimuth and elevation)	PESA (phase scanning in azimuth; frequency scanning in elevation)	AESA (phase scanning in both azimuth and elevation)
Transmitter	Air-cooled TWT	Liquid-cooled TWT	Air-cooled TWT	Few hundreds TRM
Signal Processor	128 CCAs		< 10 CCAs	< 10 CCAs
Computer	128KB RAM; magnetic tape		2GB hard disk	64GB solid-state drive
Human-Machine-Interface	B-scope; map drum; indicator lights; trackball		LCD monitor; keyboard; mouse	LCD monitor; keyboard; mouse
Power & Cooling	Two generator sets; one air-con		One generator (relied on vehicle engine); one air-con	Integrated power and cooling system
Performance Envelope	1x	2x	2x	> 4x
Crew Size	8		4	4
Emplacement Time	30mins		< 10mins	< 10mins
MTBF	100hrs	90hrs	550hrs	810hrs[7]
MTTR	2hrs		60mins	< 45mins

Table 1. Summary of comparison between three generations of WLRs

example, the two-way RF loss of the ARTHUR waveguide is about 1dB. It also saves on the need to service the waveguides.

A complementary and critical aspect of AESA is the increasing levels of digitalisation within the antenna. High performance digital circuits (e.g. analogue-to-digital and digital-to-analogue converters as well as networks) enable ease and speed of conversion of analogue radar signals to digital signals. Once converted to digital signals, powerful digital signal processors and commercial off-the-shelf microprocessors enable complex radar signal and data processing algorithms to be executed in real time, to enhance small target detection and target classification.

On the other hand, the AESA antenna brings a high degree of sophistication that requires a corresponding level of service attention compared to the simplicity of PESA. As the antenna is ‘active’ with numerous transmitters and electronic circuits, electrical power and thermal management is critical to ensure a healthy and stable environment within the antenna. Given its importance and complexity, more maintenance time and resources are allocated to SAFARI’s AESA compared to the TPQs, where attention was mainly on the transmitter and signal processor rack.

The advancement and proliferation of computers and software also benefitted WLR operations and support. It enhanced user experience in setting up and operating the WLR. This is evident when comparing the HMI of TPQs, ARTHUR and SAFARI. In the TPQ, the operator is required to recall and enter the right function codes (there are about 50 function codes) to set up the radar. In SAFARI, the corresponding actions require a few intuitive mouse clicks.

It has also improved BIT to aid in the troubleshooting of equipment defects and ultimately enhance system availability. Paradoxically, with increasingly enhanced BIT coverage and system availability, technicians have fewer opportunities to hone their troubleshooting skills and maintain currency. It is also increasingly challenging for BIT to catch up with the industry trend of developing critical embedded systems assembled from off-the-shelf hardware and software components. The increasing levels of hardware and software dependencies have resulted in increasing ambiguities in troubleshooting and identifying where the defect lies, which then require the intervention of technicians. Therefore, there are two challenges. The first lies in providing sufficient hands-on exposure and maintaining currency. The second is the need to develop software and IT competencies in addition to the traditional electrical and mechanical expertise of the technicians.

Mobility and smaller platforms will continue to put pressure on SWaP-C. While increasing levels of hardware miniaturisation and hardware-software integration have mitigated SWaP-C constraints, an overemphasis to deliver a compact system comes with operations and support trade-offs. There may be insufficient room to incorporate redundancy of critical subsystems, thus compromising mission availability. Confined space may restrict operator movements and technician workspace. For example, the highly compact and integrated IPCS of SAFARI has limited the field maintenance scope.

FUTURE OF WLRs

Just as in the beginning with the introduction of TPQs, stringent WLR missions will continue to demand state-of-the-art technology and applications. With its inherent demands to detect and track extremely small RCS projectiles, there is potential to go beyond the classical WLR role to include supporting counter-RAM mission and detecting drones. Supporting a counter-RAM mission to intercept the incoming threat requires the WLR to increase its elevation coverage, in order to track the projectile along the entire trajectory. Detecting drones requires increased 'time-on-target' to detect and classify low-flying, slow-moving and small drones while contending with distractions like birds, road and pedestrian traffic.

To improve radar availability and optimise operator workload, there are initiatives to introduce condition-based maintenance (CbM). Radars typically rely on classical practices for its upkeep. This includes a preventive maintenance regime to carry out calendar-based activities, and a corrective maintenance regime based on BIT to recover the radar after a fault has occurred. CbM based on health monitoring and alerting will allow for early detection and identification of developing faults so that timely actions can be taken. Such initiatives can also apply to WLRs.

CONCLUSION

This article discussed how radar technologies, capabilities, as well as operations and support practices have evolved over three generations of WLRs. Compared to the first generation WLR, the third generation WLR is manned by half the crew size, more than two times capable, significantly quicker and easier to deploy and handle, and more reliable[7]. A powerful BIT makes it easier to troubleshoot and recover from equipment defects, thus enhancing system availability. However, defects are increasingly sophisticated and ambiguous due to the increasing hardware and software dependencies associated with new technologies. This requires the technicians' skill sets to expand beyond the traditional electrical and mechanical expertise to include software and IT competencies.

ACKNOWLEDGEMENTS

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REFERENCE

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ENDNOTES

[1] NATO defines indirect fire as "fire delivered at a target which cannot be seen by the aimer". The target may be beyond the horizon or at a far distance away behind a terrain and thus beyond the fire's line-of-sight.

[2] A target is ascribed an effective area called the radar cross section (RCS), which is a measure of the proportion of incident energy reflected back to the radar. RCS varies with a multitude of parameters such as transmitted frequency, target geometry, orientation and reflectivity.

[3] As all the radar time-energy resource were dedicated to search, target tracking was carried out passively, thus the expression track-while-scan (or track-while-search). A target track would be updated when there was a detection during the search process; if there was no detection, the target track position would be predicted for reporting to allow for track continuity.

[4] Effective Radiated Power is the product of antenna gain and average transmission power.

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

[6] Often target signals are masked in clutter returns that can be 1000 times or more strong. This requires good sub-clutter visibility, which is a measure of a radar's ability to "see through" clutter in order to detect weak target signals.

[7] Mean-Time-Between-Critical-Failure is used to better depict the system reliability as there is a high level of redundancy of transmit and receive modules in the active electronically steering array that allows for graceful performance degradation.

BIOGRAPHY

TAN Jit Yong is a Deputy Head (Systems Management). He is responsible for the operations and support (O&S) of a range of Field Artillery Target Acquisition equipment. Since 1995, he has been overseeing the O&S of all generations of the Weapon Locating Radars (WLR) at various stages of their system life cycles. Jit Yong graduated with a Bachelor of Applied Science (Information Technology) from Royal Melbourne Institute of Technology (RMIT) in 2002.

LEE Chee Hoong is a Radar Engineering Expert (Systems Management). Previously, he spent more than 25 years in various radar-related acquisition activities, spanning sensor master-planning, project management and capability development. He graduated with a Master of Science (Management of Technology) and a Bachelor of Engineering (Electrical and Electronic Engineering) from the National University Singapore in 1998 and 1990 respectively.

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