# ELECTRONIC WARFARE: CHANGING OPERATIONAL CONCEPTS

**DALJIT SINGH**

Electromagnetic spectrum was first employed for military applications as a communication system by the navies more than a century ago. During the World Wars major developments in radar technology and radio navigation systems gave a distinct advantage to the armed forces by providing early warning of air attacks and accuracy in bombing targets. The opposing forces evolved techniques and tactics to defeat the radar and radio navigation advantage. This act of ensuring the freedom of friendly use of electromagnetic (EM) spectrum, and preventing the same to the adversary, added a new dimension to warfare—'Electromagnetic War', in short, 'Electronic Warfare' (EW). Since then, there has been tremendous development in exploitation of the EM spectrum and ways to deny, degrade or disrupt the use of EM spectrum by hostile forces.

With technological advances, a much wider range of electromagnetic spectrum is employed in the Armed Forces in the areas of Command, Control, Communication and Intelligence (C3I) network, sensors, weapons, navigational systems, and others. Today, almost all the operational systems, weapons and sensors employ some part of EM spectrum. It is, therefore, aptly referred to as the 'Fourth Dimension' of warfare, which needs to be dominated

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with freedom of operation. The competition between EM spectrum employment and countermeasures continues perpetually and the operational concepts continue to evolve to exploit the technological advances. Even today, the communication network is as vulnerable to intelligence gathering and disruption, as it was a century ago. There are many historical examples, where importance of EW was neglected and training suffered, resulting in operational setbacks. It is, therefore, important to examine the EW developmental process, advances in operational concepts, and consider a roadmap to achieve superiority in this field.

**WORLD WAR I PERIOD**

Radio communications were developed and matured for use by the naval ships of many countries at the dawn of the twentieth century. The communications were used to report hostile force movements or to guide indirect firing under adverse weather conditions and atmospheric obscurity. During the Russo-Japanese War of 1904, the Russian ships used to monitor the exchange of signals within the Japanese ships, and when their volume increased, it warned Russian fleets of imminent attack.[1] As the transmissions were on fixed frequency and without encryption, it was easy to monitor the signals and gainfully exploit them. Cryptography gained more importance during this period to retain secrecy of communication. Some of the nations like Austria, Italy and Britain gained proficiency in successfully decoding the important messages exchanged between the political leaders and the embassies. At present, when the technology has matured to frequency hopping techniques with encryption, Signal Intelligence (SIGINT) plays an important role in EW. But, in the year 1904, the Russian ships jammed

1. Mario de Arcangelis, *Electronic Warfare* (Poole, Dorset, UK: Blandford, 1985), p. 11.

the communication between the Japanese ships that were providing the guidance for bombarding. As a result, the Russian ships remained undamaged, and the Japanese ships withdrew.[2] Communication jamming is considered the first act of offensive EW in "preventing effective use of EM spectrum to the adversary".

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- In today's highly networked operational environment, effective communication jamming would play havoc in the Command and Control (C2) network unless it was adequately countered by redundancy, resilience and other means. During World War I, EM spectrum was employed mainly for communication between land, sea and air elements. Another major development that took place in the field of electronics was the capability of finding the direction of the originating signals. The technique of Direction Finding (DF) was based on the principle of goniometry, and it was possible to 'triangulate' the location of the signal transmitters and establish the 'Electronic Order of Battle' (EOB), which every force strives to do even today.

**WORLD WAR II**

During the intervening period, there were technological developments taking place in many countries based on the research work done on the characteristics of EM waves. The three main successful products of the research were Radar, Radio Navigation and Communications.

**Radar.** One of the most useful inventions was radar which was first employed by the Germans for detecting hostile ships through the mist or at night. On realising this advantage, the British started studying ways to neutralise and degrade radar with countermeasures. The same situation

2. Ibid., p. 12.

exists today even as much advanced technology is being applied to improve radar performance. The British also developed their own radars capable of detecting aerial platforms. As the Germans prepared to launch aerial attacks on British airfields and aircraft production industry, the British had established a chain of radars all along the coast, which proved effective in detecting and intercepting incoming raids right from the first one on August 12, 1940. The first Electronic Intelligence (ELINT) mission undertaken by the German airships failed to detect the radars for some reason. Having pinpointed the radar locations subsequently, the Germans launched a bombing mission to destroy the British radar stations with 500 kg bombs.[3] This was the first mission now known as Destruction of Enemy Air Defence (DEAD). The Germans had initially concentrated on offensive air action and did not deploy the radars even though they had developed them well. As the Battle of Britain commenced with Bombing Offensive over Europe during day and night, the Germans employed an integrated Air Defence set-up which was the beginning of the present-day multilayered Integrated Air Defence System (IADS).

**IADS and Countermeasures.** Germany had installed radars (Freya)[4] operating at 120-130 MHz with a range of 120 miles to detect the incoming raids. As the radar operated on fixed frequency, the British employed an electronic countermeasure (ECM) Jammer "Mandrel" to degrade the radar. The Germans then employed another more advanced type of radar (Wurzburg) capable of providing 3D inputs including the height, while operating at higher frequency ranges (560-570 MHz). These radars could not be jammed by Mandrel Jammer. Simultaneously, the Germans installed a radar on board their night fighters which could detect the raiders up to a limited range. As the bombing campaign intensified in Europe, the Germans conceived and employed an Integrated Air Defence System comprising one Freya Radar for initial detection, two Wurzburg radars with an Operations Direction Centre for directing anti-aircraft guns and night fighters, and searchlights. The control of the interceptors shifted

3. Abdul Karim Baram, *Technology in Warfare* (Abu Dhabi: Emirates Centre for Strategic Studies and Research, 2009), p. 84.
4. Ibid., p. 106.

from 'close control' to 'area control' which required only initial vectoring for interception by on board radar. This was the first IADS system employed successfully which imposed prohibitive attrition on the RAF. The British had no technical knowledge of the Wurzburg Radar and so they physically picked up the radar to analyse the characteristics and developed "Carpet" jammer. The Germans by then had developed multi-frequency Wurzburg radar with a much wider frequency range to counter the ECM. A similar concept of physically picking up the radars can be seen during later conflicts. The next major jamming technique employed by the British was deployment of thin metallic strips (chaff) of half the radar transmission wavelength dimension that saturated the radar screens and concealed the actual target blips. Sometime later, the Germans developed Doppler processing to discriminate between the real targets from the stationary window. The Germans reintroduced a multi-frequency Radar, "Neptune", operating at six frequencies in the 158-189 MHz Range, which was unaffected by jammers and chaff. This is the typical spiral of EW in which the countermeasures catch up with radar technology only to find the radars employing technology beyond the capability of the jammers. The radar operating frequency ranges have been increasing since then, and now the radars operate in Ku band and beyond. However, the jammers have been keeping pace with advances and are capable of much wider frequency coverage, and this spiral of countermeasure and ECM and ECCM continues all the time.

**Radio Navigation.** As early as 1933, the Germans had experimented with using electronic beams transmitting with different modulations as guidance for landing under poor visibility conditions.[5] The same principle was employed by the Germans for blind bombing at night. The main electronic beams were crossed by another beam to mark the target location. The British also developed similar means of radio navigation for night bombing. These navigational beams were interfered with by transmitting noise on the same frequency, and deception beams were transmitted that confused the pilots completely. While the present navigation has switched to the satellite-based

5. Mario de Arcangelis, n. 1, p. 42.

Global Positioning System (GPS), interference with the GPS through jamming and spoofing is a standard countermeasure which must be countered by adaptive GPS receivers.

**Radar Warning Receivers (RWR).** With development of airborne radars for navigation, tail warning radars for tail guns and air intercept radars, the Germans developed radar warning receivers which could detect radar transmissions and guide the fighters to catch the bombers "by the tail" or carry out successful interception onto the "Pathfinder" bombers equipped with Navigational Radars. Submarines were equipped with such RWRs to alert them against 'Hunter Aircraft' out to locate them. This is a good example of the defensive equipment used judiciously in offensive mode to shoot down the intruders. Ingenuity in equipment application is important to retain the upper edge in EW.

**VIETNAM WAR**

After World War II, while the EW equipment went into disuse, a propaganda campaign transmitted on Voice of America and BBC was continuously jammed by the Russians. Communications jamming continued and most of the European countries and Russia developed a chain of radars for warning against surprise air attack. Electronic espionage campaign prevalent at that time continues to this day to map the electronic order of battle (EOB) of adversaries.

During the Vietnam War, on July 24, 1965, the US F-4 Phantom fighter was shot down by the Russian built SA-2 SAM, the first SAM kill during a hot war.[6] The US had lost 160 aircraft by the end of 1965. Proliferation of SAMs during the Vietnam War changed the operational concepts drastically. While low level attacks were risky due to radar controlled Anti-Aircraft Artillery, high level missions were vulnerable to the SAMs. The US pilots studied the SAM characteristics and devised anti-SAM manoeuvres while effective ECM jammers were being developed. The Americans also developed a crystal video RWR which could compare the received

6. Mario de Arcangelis, n. 1, p. 160.

transmission parameters with the programmed radar signature and warn the pilot with audio and visual alarms. The ECM jamming technique was mainly a generation of noise, saturating the radar receiver. Having seen the effectiveness of ECM jammers, as an ECCM measure, SAM Radar operating frequency was changed from S Band (2965-3060) to C Band (5010-5090) which rendered the RWR and ECM equipment ineffective. The US later developed Anti-Radiation Missile (ARM) AGM 45 Shrike, to counter the SA-2. The ARM had an electronic seeker in the nose that homed onto the main beam transmissions of the radar and destroyed it. This induction brought in the concept of 'Wild Weasel' missions, where in a package of two to four RWR and ARM equipped packages used to precede the strike package and physically destroy the SA batteries. Later, the more compact jamming equipment was developed which could be carried externally to provide 'self-protection' against hostile surface-to-air AD weapons. This equipment now called Airborne Self-Protection Jammer (ASPJ) is a standard fit on all fighters. Heavier bombers like the B-52s were escorted by Wild Weasel missions and later ECM dedicated aircraft like EA6B which are now termed Stand-off Jammers or ECM escort jammers.

For destroying important bridges and military installations, low level strikes were planned to improve delivery accuracy, and this profile made them vulnerable to the anti-aircraft guns, and the forces suffered heavy losses. Once again, technological developments in sensor technology brought in Laser Guided Bombs (LGBs) which could be released at heights beyond the ranges of Anti-Aircraft Artillery (AAA) and provided accurate delivery on target. Gimballed designation Pods were developed to provide continuous guidance to the LGBs while the mother aircraft could continue to manoeuvre. US Navy also deployed television guided "Walleye" glide bomb for accurate delivery. Thus, Precision-Guided Munition (PGM) became a preferred weapon during subsequent operations.

The Vietnamese started deploying dummy SA-2 transmitters on known strike routes. The US Forces exhausted their ARMs on dummy transmitters before they reached the target area. While the operational concepts changed

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with advancing technology, it was the operational applications of tactics that exploited system weaknesses, which changed the endgame result. This important lesson is applicable even today.

The nearly 10-year Vietnam War ushered in many new technologies; the jammers became smarter by resorting to 'deception' jamming, programmable digital RWRs improved situational awareness, dedicated escort jammers protecting bigger bombers, PGMs were inducted to improve survivability and weapon accuracy, ARMs got inducted as DEAD weapons. All these systems kept improving as the matching technology evolved. SAM systems also improved in lethality and mobility as SAM IIIs were developed by the Russians. Due to employment of EW systems and operational concepts, the attrition rate of the US Forces, which was 14 per cent at the beginning of the war, dropped to 1.4 per cent at the termination of operations.[7] With advancement in ECM capabilities, ECCM technology kept improving and this race to counter each other continues today.

**ARAB-ISRAELI WAR 1973**

Following a well-orchestrated and well-planned surprise attack on Egypt by the Israel Air Force on June 5, 1967—during which the Israel Air Force decimated the Egyptian Air Force within two hours to achieve air superiority—Russia started rearming Egypt and Syria with better MiG-21s and supplied more capable and mobile SAMs and AD Guns. The Israelis received deception jammers which were more effective against AI radars and SAM III radars. Regular skirmishes continued after the Six-Day War of 1967, during which

7. Mario de Arcangelis, n. 1, p. 173.

the raiding teams continued to destroy the military assets of the adversaries. On October 6, 1973, Egypt and Syria launched a massive simultaneous attack on Israel when the nation was on a religious holiday. They destroyed the frontline military fortifications and installations and achieved complete surprise. Their ground troops with tanks moved in fast and deep into Israeli territory. The Israelis reacted with attacks by the Israeli fighters. However, despite being equipped with modern EW equipment, they suffered many casualties as their ECM systems were ineffective against the newly inducted SAM-6 Gainful missiles, Gun Dish radar controlled Shilka AAA, and IR-guided Strella SAM-7.[8] The Gainful Radar employed continuous wave transmissions, the Gun Dish Radar operated in Ku Band, which were beyond the capability of the Israeli EW arsenal. The SAM IIIs were mobile, and Israeli intelligence failed to update the EOB and suffered heavily. The Israelis were supplied with appropriate chaff and flares which could degrade the new systems operating at much higher frequency ranges, when deployed with appropriate manoeuvres. The weak spots of the Gainful radar were studied, and the Israeli pilots devised appropriate attack profiles which made SAMs less effective. Subsequently, new RWRs were supplied to detect CW illumination and the Ku Band transmissions.

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The lesson that clearly stood out was the need to update the EOB regularly and avoid surprises. In today's environment, the EW equipment cannot be made to tackle specific threats but should be upgradable to tackle new threats as well.

### 1982 LEBANON WAR

**The Bekaa Valley Conflict 1982.** During the intervening period after the Yom Kippur War, the Israeli Air Force modernised itself with modern fighters F-15 and F-16 with look-down/shoot-down capability, modern EW equipment that could be programmed to operate autonomously with

8. Mario de Arcangelis, n. 1, p. 190.

effective jamming techniques, Airborne Early Warning Aircraft E2C and a few advanced weapons like AGM 45 Shrike ARM, and AGM 65 Maverick PGMs. The Israeli defence industry developed a number of different types of UAVs that could "see" the battlefield in real time, act as decoy to stimulate the AD Radars and operate as SIGINT platform. The Boeing 707 aircraft was configured with EW jamming capability. The other significant technological development was networking of C2 Centres with airborne sensors and shooters. The attack commenced with launch of Remotely Piloted Vehicles (RPVs) to map SAM locations, followed by stimulating the AD Radars, SAMs and C2 Centres. The Israeli Air Force commenced electronic jamming of all radars, SAMs and communication networks. This was followed by PGM and ARM strikes to gain air superiority. The entire operation was coordinated by E2C Hawkeye Airborne control aircraft.[9] Successful Suppression of Enemy Air Defences (SEAD) operation, effective communications jamming and excellent networked and coordinated operations demonstrated the new effective way of conducting operations. This campaign changed the way wars were planned and executed post-Bekaa valley campaign. The entire world took note of the importance of Electronic Warfare, PGMs, ARMs and UAVs. The lesson from Bekaa Valley was that EW would continue to play an important role in deciding the outcome of operations. However, the competition between the SAMs and aircraft would continue unabated. Post-1982 Bekaa valley conflict, the operational concepts changed rapidly and technological advances in sensor technology, propulsion systems, computer power and networked operations brought in quantum advances in the fields of radars and EW.

**FIRST GULF WAR 1991**

During the first Gulf War, many advanced technologies for military operations were available to the US and Coalition Forces which provided a high degree of asymmetry against the Iraqi Forces. As Iraq occupied Kuwait in August 1990, the Americans employed many geostationary SIGINT satellites, missile

9. Abdul Karim Baram, n. 3, p. 374.

launch detection satellites, Imaging Reconnaissance satellites and Synthetic Aperture Radar (SAR) satellites which provided complete intelligence on the Iraqi Forces deployment and dispositions. These satellites were well networked with ground stations to provide data not only to the Pentagon, but also to the field formations. Geospatial Navigation Satellite System provided accurate navigation capability. As airborne element, E-8A Joint Strategic Targeting and Attack Surveillance (JSTAR) aircraft, deployed for the first time, had the most advanced system capable of tracking all movements of tanks, vehicles, guns and missile launchers. The JSTAR data could predict the movements by comparing the historical data and share this information with the field formations. In addition, AWACS provided a comprehensive air picture and airborne C2 capabilities. Other advanced airborne systems included the TR-1 high-altitude Reconnaissance aircraft, EC-130H EW and communication jammer and many types of UAVs. The US stealth fighter F-117 was employed for the first time in combat and with great success. All types of aircraft that were planned to cross the border were well equipped with ECM systems. The F-117, being a stealth fighter, relied mainly on its stealth capability and operated 'silently'.

The EW campaign of the coalition forces played a dominant role in achieving complete air superiority over the Iraqi Forces. Mainly, the template of the first Lebanon War was employed to achieve air superiority over Iraq and Kuwait. Comprehensive intelligence gathering campaign provided clear EOB picture of the AD systems and C2 Network. The attack campaign began by stimulating UAVs and Tactical Air Launched Decoys (TALD), while attack helicopters intruded at low level to destroy two AD radars and create a gap. This was followed by a wave of Tomahawk cruise missiles launched from the warships and the B-52s. The next wave comprised the F-117As and other fighters that were well equipped with ECM equipment and IR countermeasures. Dedicated stand-off jammer aircraft like EF 111 and EA 6B protected the strike force and other fighters employed ARMs, which were used extensively to deter and destroy the SAM sites. 'Wild Weasel' missions were undertaken by the F-4G for the last time, as they were phased out in 1995.

## CURRENT TECHNOLOGICAL DEVELOPMENTS

**Radar.** Initial development of the Radar involved HF, V/UHF Band employment with limited range capability. By the end of World War II significant developments in three-dimensional tracking capability, doppler processing and bistatic radars had taken place. Later developments took place in transmitter technology and signals processing. However, mechanically steered antennae were not efficient in tracking multiple targets and in undertaking multimode operations simultaneously. Since the 1980s, there has been significant development in radar technology as digital technology, computational processing and digital signal processing improved. The modern radars employ Active Electronic Scan Array (AESA) technology with use of array of Transmitter Receiver Modules (TRM), which facilitates electronic beam steering without any moving parts. This ensures simultaneous multiple modes of operation as the beams can be steered electronically in any direction. Airborne Interception Radars (AIR) on board fighters can operate both air-to-air and air-to-ground modes simultaneously for better situational awareness. Sharper beam steering ensures diminished sidelobes and multiple transmitters facilitate multi-frequency operations with graceful degradation. With advances in digital processing, scan rates, tracking priorities, dwell times and scan zones can be optimised as per operational scenario. Overall, AESA radars are more resistant to ECM action and have Low-Probability-of-Intercept (LPI) capability. The modern radars are now 'software defined' to operate efficiently in different operational scenarios of low Radar Cross Section (RCS), low-speed targets like UAVs as well as high level high-speed targets like fighters and ballistic missiles. With application of Artificial Intelligence (AI), cognitive radars which would self-learn from past engagements would make them tough targets for EW action. Overall frequency bands of operation of ground-based radars are so diverse that it would be extremely difficult for one ECM equipment to counter all the radars.

**Stealth Technology.** Since its development in the 1930s, radar has been the most effective means of detecting airborne objects. While active ECM has been deployed to degrade and reduce effective detection range of the radar, another means of the RCS reduction by appropriately shaping the aircraft structure gained traction during the Cold War Period, when the US deployed U2R and SR-71 SR spy planes with some stealth features. During the 1980s, the US developed F-117 'Night Hawk' stealth fighter and B-2 Bomber in complete secrecy and employed them operationally during the First Gulf War in 1991, with great success. Stealth technology aims to reduce the RCS by shaping the aircraft structure to deflect or absorb the radar transmissions and reduce the strength of beam reflections towards the radar. In fact, the USAF perceived the stealth technology as the 'Silver Bullet' which would defeat the radars without any ECM action. After retiring the EF-111 EW support aircraft, no other replacement was planned by the USAF, whereas the US Navy replaced the EA-6B Jammer with the G 18 'Growler Escort Jammer'. The stealth technology has some limitations which have now been exploited to neutralise its effectiveness. The stealth design of the F-35 class of fighters is likely to be effective against X-Band tracking radars and that too in frontal aspect. It is not as effective against low band radars operating in L band or V/UHF Bands.[10] Russia has effectively developed and upgraded low band radars like Nebo M that can effectively detect stealth fighters. The stealth technique is mainly effective in frontal aspect and not as effective in broad and rear aspect. Even though stealth features would be embedded in all future designs of all platforms, they would mainly supplement other effective countermeasures to defeat the AD systems. The current developments in counter-stealth radars operating in V/UHF bands and employing multi-static radar technology have reduced the stealth fighter advantage to a great extent.

**Sensor Technology.** With overall advances in digital technology and miniaturisation, there has been rapid advancement in the field of multi-spectral sensors. Employment of EM spectrum has spread beyond what has been employed for radar and communication systems. Electro-optical and

10. Serdar Çadirci, "RF stealth (or low observable) and counter-RF stealth technologies: Implications of counter-RF stealth solutions for Turkish Air Force", p. 97.

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infra-red sensors are now capable of detecting and pinpointing targets at much further ranges and with more clarity. Combination of EO and IR sensors provide detection and tracking capabilities in almost all types of atmospheric conditions, as wider spectrum in the IR regime covering near IR and wide IR are being employed. All modern fighters would have an array of passive sensors like Infrared Search and Track (IRST), missile approach warners, in addition to optional carriage of aircraft targeting pods like the Litening. Multi-sensors employed for terminal guidance of missiles has enhanced resistance to countermeasures. David Sling Interceptor Missile manufactured by Rafael Advance Defense Systems is known to employ multispectral sensor for jam resistant terminal target acquisition. Mica AAM has option of either IR or RF-based seeker, which improves its success against countermeasures. The main advantage of such sensors is that they are passive in nature that do not trigger any warning. In ground-based sensor regime, passive electro-optic sensors have achieved much better detection and tracking capability under adverse atmospheric environments. The Rafael manufactured Sky Spotter is a passive EO surveillance early warning system capable of detecting, identifying, classifying and tracking multiple targets at long ranges.[11] The system is also capable of detecting stealth aircraft. Such passive sensor-based systems are inherently unaffected by normal ECM actions faced by radars. From EW aspect, the EM spectrum employment has spread across many regimes including UV, Optical and IR.

**EW Technology.** Technological developments have been equally well applied to improve the performance of EW systems. In the field of ESM, application of interferometry principle has improved the accuracy in detection and geolocation of hostile radars and communication centres. The RWRs on board fighters are as good as ESM receivers in terms of accuracy in detection,

11. Sky Spotter Brochure available at www.rafael.co.il. Accessed on March 30, 2021.

classification and geolocation of radars and communication centres. The frequency coverage has been enhanced from 2-18 GHz to 1-40 GHz. With AI embedded algorithms, these programmable receivers can analyse and correlate unknown transmissions with identified transmitters. Networked ESM platforms with ESM receivers would further improve geolocation accuracies in a congested EM environment. ECM systems have also adapted the AESA technology to simultaneously jam multiple threats emanating from different directions. With more directive transmissions the ECM can pump in more EM energy. The provision of Digital RF Memory (DRFM) ensures more authentic deception techniques to break tracking locks of hostile radars. Size, weight, and power requirements of systems have been reducing, which make the ECM systems more potent to tackle hostile systems. Modern radars have much more robust ECCM capabilities as they operate with more complex transmission patterns over a much wider frequency band, frequency agility and much reduced sidelobes.

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## CURRENT OPERATIONAL DEVELOPMENTS

**Net-centric Operations.** Rapid development in computer and communication technology has led to robust, resilient, secure, and adaptive networks in military operations. Various ground-based, airborne and space-based sensors can now be networked to have a comprehensive filtered operational picture available to commanders and warriors. Commands, data, voice, and videos are exchanged online with all networked operators. Sensors, decision makers and shooters are now on the same grid to ensure a much faster decision and execution cycle. Inputs from various ISR assets can be best exploited by fusing the inputs from sensors operating on different frequency regimes. The networks can ride on terrestrial, WiFi and space-based networks seamlessly. Net-centric operations inherently ensure redundancy in connectivity, sensors, and shooters. Resilience and capability of data links would be crucial in future to ensure uninterrupted massive flow of information.

**Integrated Air Defence.** Net-centric capability has been well exploited by military forces to integrate Air Defence assets and Command and Control elements. Integration of multispectral active and passive ground-based, and airborne sensors ensures good resilience against countermeasures and graceful degradation. Multilayered Air Defence set-up ensures effective engagement of all types of threats in the entire airspace volume from ultra-low level to the stratosphere. The SAMs have much longer engagement envelopes, making the attackers vulnerable at much longer ranges. S-400 SAM system has a kill envelope extending to 400 km. These ranges push the EW Support Forces further away from the sensors to be jammed.

**Stand-off Attack Weapons.** Improvements in sensor technology, propulsion systems and precision navigational systems have ushered in a variety of weapons that can be fired from stand-off ranges of hundreds of kilometres. These weapons are capable of autonomous target engagement and they could be data linked to mother aircraft for target updates and real-time bomb damage assessment. AGM 86 air-launched cruise missiles carried on board B-52G bombers were launched aggressively during the first Gulf War in 1991. The B-52G can carry 14 missiles for independent targeting. AGM 158 B Joint Air-to-Surface Stand-off Missile was developed in the 1990s to attack high-value targets while staying out of reach of the hostile AD missiles. The missile has an effective range of 370 km with precision delivery accuracy. The IAF has acquired SCALP air-launched cruise missile which has stealth features and an effective range of more than 250 km. During the Aero India 2021 airshow, Rafael Advanced Defence System showcased SPICE 250 ER PGM with an effective range of more than 150 km and capable of attacking moving targets. Medium-class fighters can carry 16 such bombs and can independently attack 16 targets simultaneously. With this kind of stand-off ranges the mother aircraft stays outside the lethal AD envelope and, therefore, does not require active ECM to degrade the hostile sensors. However, such weapons are expensive and are available in limited quantities for high-value targets.

**UAVs.** Unmanned Aerial Vehicles have been employed in most of the wars post World War II. The Israelis pioneered the employment of UAVs as decoys, SIGINT and ISR platforms during the First Lebanon War, and the world took note of the UAV potential as integral to all types of operations. Recent conflicts in Syria, Libya and Azerbaijan are testimony to UAV destructive power at the lowest cost. UAVs are being employed as the loitering munition, airborne 'sniper' and persistent ISR and SIGINT platform. Azerbaijan inflicted heavy attrition on the Armenian Forces by effective employment of UAVs. The US Navy has planned induction of the aircraft carrier-based MQ-25A Stingray autonomous air refuelling UAV, to extend the operational range of the fighters. Employment of UAVs will continue to expand in many roles in future.

## RECOMMENDED APPROACH FOR INDIA

**EM Spectrum Management.** The EM environment will keep getting more and more congested as almost all the platforms and systems will use some segment of EM- spectrum. Net-centric operations require massive exchange of data that will generate heavy EM flow. However, the frequency bands for military operations are limited and they are required to be shared amongst the services. To ensure 'clean' operation in the EM spectrum, the first step would be to segregate operating frequencies (as far as possible) during the planned induction of radars, communication systems, data links and other sensors. For example, AI radars of all fighters generally operate in X-Band. An overlap of operating AI radar frequencies of SU-30 fighter with the Rafael could lead to interference, degrading the performance. The same is applicable to ground-based and AWACS radars. This EM spectrum management needs to be addressed at the tri-service level.

**Net-centric operations would require more robust and secure data links. Monitoring and mapping of hostile data links would provide crucial inputs on hostile activity. While own forces employ more robust and resilient and LPI data links, the nation must acquire the capability to map hostile datalinks.**

**Embedded ECM Suite.** The LCA has been inducted into the IAF without any self-protection jammer. Integrated Self-Protection Suite must be included during the platform design stage as later add-on will always have compatibility issues with other sensors. This is applicable across the board for all platforms, including the UAVs.

**Upgradable Systems.** The life of inducted ECM equipment is more than ten years. However, the threat environment would change at a fast pace and the ASPJs should be able to tackle more advanced evolving threats of the future. The EW systems should have open architecture and be upgradable as the technology develops.

**Exploit Net-centricity.** During operations, unknown hostile systems are bound to be encountered. The ECM effectiveness would be ascertained based on the engagement results. The EW systems should exploit net-centricity to upload latest and effective jamming techniques to the ECM equipment in the air. SIGINT assets when networked would improve the geolocation accuracies and resolve ambiguities.

**AI for Analysis.** The data acquired by SIGINT Platforms, AWACS, ASPJs RWRs and other EW equipment would be very large and it would be impossible for specialists to analyse it in a short time. Artificial Intelligence and Machine Learning techniques would be essential for faster data processing.

**Data Link Mapping.** Net-centric operations would require more robust and secure data links. Monitoring and mapping of hostile data links would provide crucial inputs on hostile activity. While own forces employ more robust and resilient and LPI data links, the nation must acquire the capability to map hostile datalinks.

**Multispectral Sensors.** All future airborne platforms would have some degree of stealth features. Integrated Air Defence Network must have multispectral sensors to ensure redundancy against active ECM action as also the ability to detect stealth aircraft. Induction of Passive Location systems and EO sensors capable of accurate tracking of airborne objects would address these issues.

**The satellites have communication uplinks and downlinks with ground stations for data exchange and housekeeping. These links are vulnerable to interference if security and secrecy is not planned. All such data links would require reassessment to ensure their uncompromised operation and satellite redundancy is considered essential.**

**ECM Escorts.** With dense EOB of powerful radars operating at lower frequency bands, the ASPJs would not be able to handle all threats. Modern ECM escorts would ensure better protection against such powerful and frequency diverse radars. Any degradation in detection and range ambiguity would adversely impact the composite operational picture and, in turn, the executive decisions.

**Stand-in Jamming**. With ground-based AD weapons acquiring much longer kill ranges, the ECM escort jammers would be vulnerable in these envelopes. Jamming from further would degrade jamming effectiveness. ECM action by UAVs as stand-in jammers is a viable concept as a larger number of UAV-borne jammers could be deployed at different radials to protect the incoming attack force.

**Realistic Training.** Performance of ECM equipment and effectiveness of jamming techniques need to be checked against realistic hostile emitters. General training conducted against own sensors and SAMs does not generate enough realism and confidence. An Instrumented EW Range with programmable EW emulators and simulators would provide better tools for generating effective jamming programs. Airborne EW trainer aircraft could be employed for training the SAM operators. This way the operators would be able to realistically evolve EW tactics. All the three services should train together in such an environment.

**Space Assets.** The satellites have communication uplinks and downlinks with ground stations for data exchange and housekeeping. These links are vulnerable to interference if security and secrecy is not planned. All such data links would require reassessment to ensure their uncompromised operation and satellite redundancy is considered essential.

**DEW.** Directed Energy Weapons are maturing to a stage of operationalisation. Lasers as weapons against sensors and UAVs have been deployed by many forces. India should accelerate its research in this field.

**DEAD Capability.** With other countries acquiring S-400 class of SAMs, it is imperative that own forces must have capability to geolocate and target the crucial radars from stand-off ranges. Induction of SCALP missile provides this capability; however, geolocation of the SAM site is required to attack the target. Anti-Radiation Missile (ARM) would be able to geolocate and attack the SAM sites in real time. Provision of such weapons would be good deterrence and effective counter to Long Range SAM systems.

**Cyber and EW Operations.** EW is one of the 'arrows' in the quiver which would have other arrows as well. The forces must develop as many options as possible to degrade the hostile military machinery. Application of cyberattacks along with stand-off PGMs and decoys would be a good option to achieve EW superiority.

## CONCLUSION

Electromagnetic spectrum has been exploited by military forces for more than a century. World War II saw significant progress in use of EM spectrum in radars, communications, and radio navigation. The opposing forces applied ingenuity in degrading these systems till a more robust system was fielded. The contest to retain freedom of EM spectrum use while denying the same to the adversary started right from the beginning and this fight would continue in the foreseeable future. Induction of SAMs in the battlefield changed the concept of operations and EW applications during the Vietnam War. During the Lebanon War of 1982, the Israeli Forces demonstrated the power of EW applications in paralysing and neutralising the opposing forces in all domains of operations. Nearly a decade later the Allied Forces once again exploited technological superiority in EW application to defeat the Iraqi Forces, with minimum attrition.

Today, most of the forces conduct net-centric operations and have Integrated Multi-Layered AD systems with extended kill ranges. The operational concepts of EW application are also undergoing significant changes. Employment of UAVs and their operational potential has opened up more options of their employment in the EW Role. Stand-off attack weapons, though available, would be in limited numbers to attack high-value targets. Other attack profiles with shorter range attack weapons would continue to require EW protection.

While density and congestion in the military allocated EM spectrum is increasing by the day, it is important to manage the EM spectrum usage right from the stage of platform or system procurement plan. All platforms would require integrated EW suite at the design stage itself as later add-on would always be a challenge. Data link mapping of the adversary and making own links more robust and secure requires attention as all future engagements would be in a networked environment.

Training in a realistic environment is important to validate EW tactics and jamming techniques. This requires an arena created with multiple emulators and simulators to emulate realistic hostile EOB and derive meaningful lessons. With massive data downloads collated from all the sensors, analysis by humans would be near impossible in a short time frame. AI and ML would help in this area.

EW is a highly specialised field when it comes to programming the systems and jamming techniques. The forces must nurture this specialisation to get the best out of the EW equipment. During hostilities, time is at a premium and only trained manpower would be able to perform. At the same time, the national industry should be geared to upgrade the systems in a short time to counter new threats. For this the systems need to be manufactured indigenously with open architecture and provision of upgrade. The Indian defence industry needs to catch up EW technology through collaboration with more experienced players in the world. It is quite evident that control of EM spectrum would play a decisive role in all domains of operations and national effort is required to achieve this superiority.