A Game Of Hide And Seek

Anti-ship missiles have evolved more rapidly than most navies' electronic warfare and ship protection systems, which gives vessels very little time to respond in the event of an attack. Remaining undetected against a more complex threat requires electronic warfare systems with the capability to detect, recognise, identify and assess low-power, wideband emissions.

By Ioannis Vagias

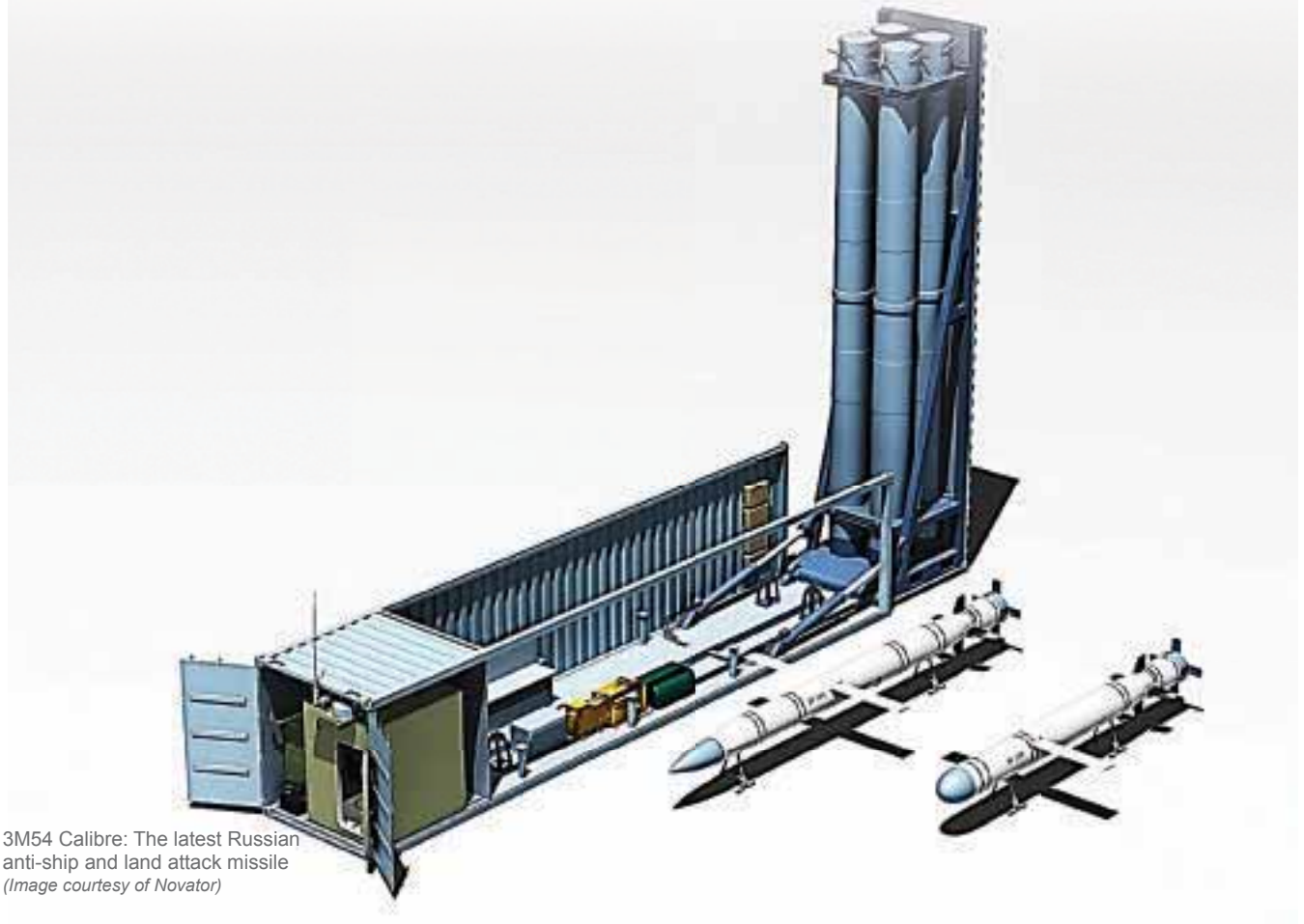
Anti-Ship Missiles (ASM) were introduced in the 1960s and have proved to be a valuable tactical and strategic weapon. Along with short-range ballistic missiles, they can shape the battlefield reality and foreign policy, since they can either damage or take out of action major surface units that are seen as a static force projector.

Nowadays, these two capabilities have great commonality and have been merged into a single system capable of precision attacking both static and moving, land and maritime targets in layered and congested air defence, and in an electromagnetically saturated environment. Today, an ASM is designed in a modular concept for long storage times. The capabilities of an ASM are driven by four parameters:

- Range and velocity: This determines the choice of the propulsion system (rocket motor, turbofan, ramjet or ram-rocket) and the shape of the lifting and control surfaces for optimum lift to drag ratio. Minimising the flight time means maximising missile cruise velocity, thus maximising the probability the missile will find a moving target in the predicted or assumed position. This parameter is crucial for time-sensitive targeting.

Also the missile will be able to pull more lateral acceleration (latax), thus making interception by shipborne missile air defence systems that use proportional navigation more difficult.

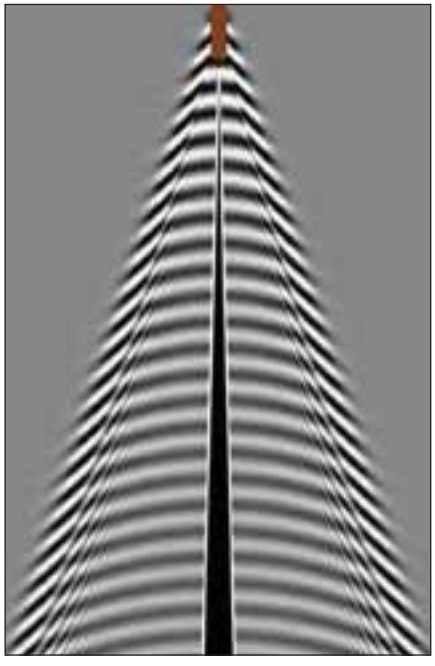
- Accuracy and target discrimination: The missile has to navigate to the target area. As this method will project position errors, it can be aided by GPS/Global Navigation Satellite System, celestial, terrain reference navigation, image scene matching, or a combination of the above for redundancy. This enables the weapon to accurately reach a target within a predefined time and begin its terminal attack. During this phase, the



3M54 Calibre: The latest Russian anti-ship and land attack missile
(Image courtesy of Novator)

missile can weave, sea skim or increase its velocity to supersonic to kinetically defeat air defence. It is in this domain that electronic warfare (EW) systems operate to either saturate the missile's receivers and/or electro-optics; deceive the missile regarding the location of the target (range, velocity and angle); radiate false targets in range and velocity; deploy decoys that can mimic the target's behaviour, signature and/or transmission of a non-combatant target.

- Susceptibility and survivability: The missile has to penetrate a layered air defence ranging from medium and short-range missiles using hybrid guidance mechanisms (command, autonomous and semi-autonomous homing, command-via-missile) and sensor-guided guns that might employ fragmentation effects. All of these, together with the employment of laser directed energy weapons are listed as hard-kill mechanisms and are the last means of defence to a ship. Long before they are deployed, however, the ship will use both coherent and non-coherent techniques for interfering with the missile's radar seeker and RF fuse, satellite receiver, radar altimeter, as well as laser dazzling the missile's electro-optics. Countermeasures (RF and IR) can also be launched to mask the ship's RF and IR silhouette and lie about the existence of the ship in a tracking gate.



Ship wake SAR image
(Courtesy of Gregory Zilman and Touvia Miloh)

A laser weapon system aboard USS Ponce
(Photo courtesy of US Navy)

- Lethality: The missile's final goal is the delivery of a warhead into a ship. Different warhead design and initiation will allow for structure penetration, collapse and incendiary effects, all of which are designed to put a naval unit out of action. The missile must be able to signal process the optimum point of impact and warhead initiation to maximise effect. However, the shape of the target can be distorted through the use of repeated electronic deception, use of corner reflectors and IR countermeasures.

COUNTERING VINTAGE AND CURRENT ANTI-SHIP MISSILES

Current electronic attack techniques have matured enough to provide adequate probability of the ASM missing or disengaging and re-attacking. Some of the techniques used and the way the ASM can neutralise them include:

- **Noise Jamming:** The ship can either transmit barrage, spot or swept spot noise on the missile's bandwidth that is recorded accurately by the ES system. The ES has to receive and record all the pulse information required, scan pattern, frequency hopping and pulse modulation schemes.
- **Deception in Range and Velocity:** Range Gate Pull Off and Velocity Gate Pull Off are well-established techniques against radar trackers, very efficient when implemented with Digital Radio Frequency Measurement (DRFM) and performed together with countermeasure dispense. The ship's jammer can digitally record, reproduce the intercepted signal and couple it with deception in angle, range and velocity, mimicking the ship's movement and radar cross-section (RCS). The missile could counter this by going wideband (frequency hopping and pulse phase modulation) and lowering its transmitted power to decrease the probability of intercept, increase the time to first intercept and the time between intercept. The goal of the ship's ES is to track the missile's transmission by binning every pulse, since each pulse will be unique. This, however, might deny the missile velocity information.
- **Deception in Angle:** Once the missile acquires and tracks the ship, it changes radar mode by transmitting very short, low power, phase modulated pulses to hide from the ship's ES. This transmission strategy is usually coupled with a change in flight dynamics, an increase of velocity to high subsonic or even supersonic, weaving and manoeuvering. Angle deception is the preferred solution during the missile's end phase. It includes techniques that:

  – Take on an ASM scan pattern (sequential tracking) through inverse gain modulation of the incoming signal;

  – Techniques (image frequency jamming, skirt jamming and cross-polar jamming) that take on the design flaws of the ASM's radar and require detailed knowledge of the RF seeker, usually obtained through intelligence;

  – Techniques (cross-eye, terrain bounce and collaborative jamming) that distort the wavefront of the incoming RF signal and do not require detailed information of the ASM emitter.

Active phased array technology coupled with DRFM—which steals the radar's automatic gain control, range and Doppler gates—has made cross-polar and cross-eye jamming very effective against ASMs that utilise mechanically-steered arrays. The best attack profile for an ASM is slant as it enables both down-range and cross-range profile information. Another engagement feature is sea state. In rough seas a sea skimming missile

would have to fly higher, but Close-in Weapon Systems would pitch and roll with the ship making tracking and engaging the missile difficult. Active Electronically Steerable Arrays do not need to be stabilised as the beam can be controlled electronically, thus making cross-eye, cross-polar and terrain bounce techniques very easy to implement and very efficient.

CO-OPERATIVE TECHNIQUES

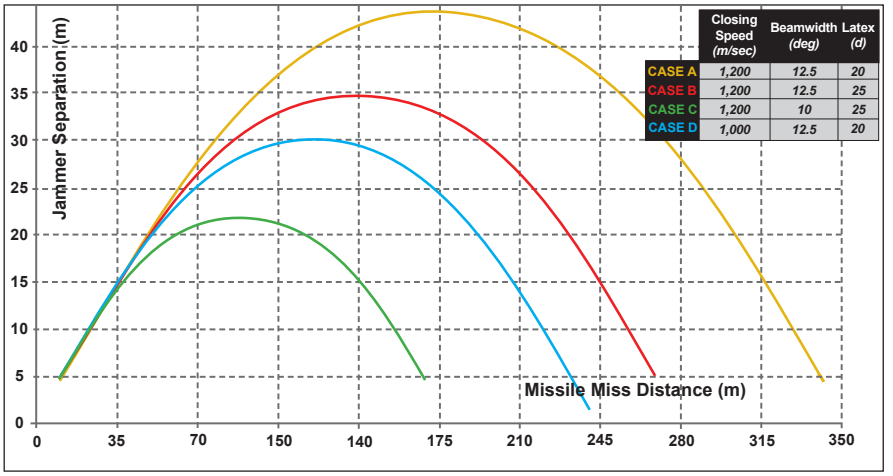
Co-operative jamming can be performed either by two or more vessels or by a vessel and one or more active decoys. The platforms have to be synchronised: This is usually performed through GPS/GLONASS/GNSS timing. This technique consists of multiple platforms noise jamming intermittently to force a missile to weave and home on jam (HOJ). Co-operative (simultaneous) jamming will force the missile to either fly through the emitters or engage one of them, while blink jamming engages the antenna scanning through servo saturation. For optimum implementation of these techniques the emitters have to be displaced by a certain distance and the ASM velocity, available latax and beam width must be known. If any of these techniques fail then the ship has to defend using missiles, guns and directed energy weapons, such as high-powered lasers.

DETECTING LOW PROBABILITY OF INTERCEPT EMITTERS

ASM RF seekers operate usually at X-band (8-12 GHz). Given the extreme scenarios of engaging from fast attack crafts or littoral combat ships, to large surface units such as frigates or destroyers, the missile's seeker operates in medium PRF schedule (MPRF, 0.3-3 kHz), transmitting very short pulses (several tens of nsec). This will allow the selection of sufficient Fast Fourier Transform (FFT) size for adequate SNR and velocity resolution, which will enable the selection of a low power transmitter.

Typically values range from 10 W to 1 kW, depending on:

- The ship's size (corvette, frigate or destroyer)
- FFT size; depending on the seeker mode (surveillance, acquisition and track)



Co-operative jamming effectiveness (miss distance) vs. jammer separation, against an ASM of varying radar beamwidth, latax and closing velocity *(Graph courtesy of Cranfield University)*

- Antenna diameter (from 35 cm up to 100cm)
- False alarm rate (several minutes) and probability of detection (90%)
- Detection range; the radar horizon depends on the flight altitude of the missile and the height above water of the ship's RCS centroid

The missile's top priority before commencing an attack on a ship is to conceal its existence. This is performed by:

- Controlling its RF emissions (RF seeker, radar altimeter and two-way communication link)
- Controlling its RF signature using RF absorbing coatings, frequency selective surfaces, faceting, blended wing-body, tilted radar antenna and concealment of flat plates such as the turbofan compressor and turbine
- Controlling thermal signature through subsonic coast to minimise skin friction drag, the use of heat dissipation coatings to lower heat signature during supersonic flight and conceal hot spots such as exhausts

ASM Active and Passive RF Seeker *(Photo courtesy of AGAT)*

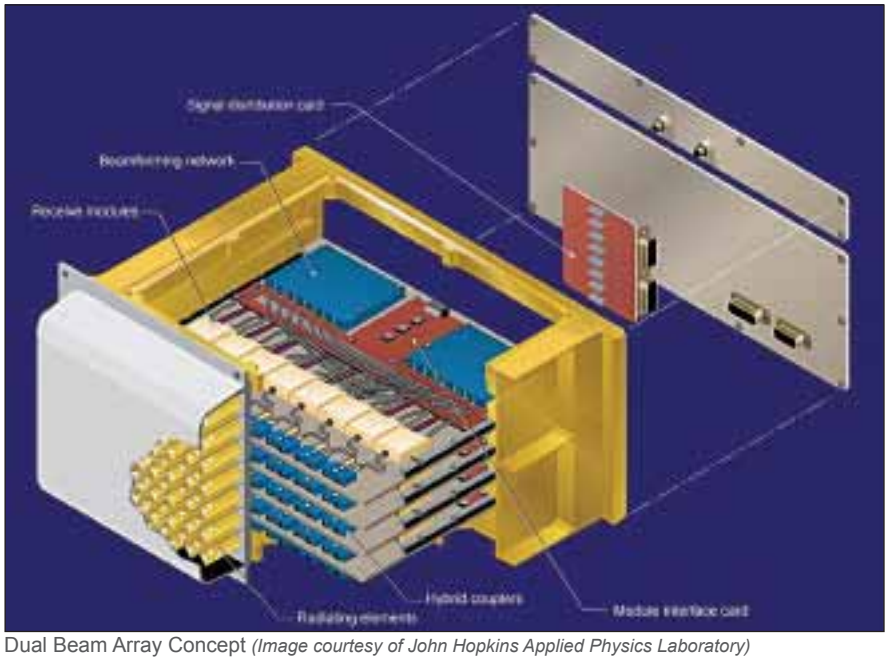
- Controlling the illumination pattern and dwell time on target

Ships of war are usually equipped with thermal imagers as an extra means of surveillance and tracking to minimise electromagnetic (EM) transmissions, and thus being detected and jammed, and to track small targets with a weak RF footprint in a clutter-rich environment such as the sea. It is very difficult for a missile to cover its existence simultaneously in all spectrums (visible, RF, IR and UV). So coupling sensors operating at different wavelengths always help. Regardless of the efficiency of IR sensors, they cannot alert the presence of a radar-equipped attacking ASM at long ranges because of atmospheric attenuation, thermal noise from the sea and sea spray. The sensor of choice for long-range detection of sporadic and wideband transmissions is a ES receiver.

CONCEALING EMITTED SIGNAL INTO NOISE

The most common technique for the ASM radar seeker to suppress the emitted spectrum under the noise floor is phase coding, also known as phase shift keying. Instead of transmitting very short, unmodulated pulses, the radar now transmits longer pulses that are phase coded. Within a single code interval the signal is phase shifted several times with different phase shift and a certain shifting period, which is equal to the pulse width of the transmission.

Vintage ES receivers such as the



Dual Beam Array Concept *(Image courtesy of John Hopkins Applied Physics Laboratory)*

Crystal Video Receiver (CVR), Super-Heterodyne Receiver (SHR) and Instantaneous Frequency Measurement (IFM) receiver do not fulfil the sensitivity criteria for:

- Detection of wide bandwidth, low-power spectral density and very brief waveforms from the main and side lobes
- High-fidelity parameter measurement (frequency, bandwidth, beam width, bearing, polarisation)
- Discrimination of simultaneously arriving pulses
- High-fidelity parameter measurement for signals at the edges of the dynamic range

CVR fulfils the open bandwidth criterion, SHR the sensitivity and IFM the fidelity without fulfilling the ability to measure simultaneous incoming signals. Note that the IFM receiver can be implemented using digital technology. These issues are better depicted in Tables 1 and 2 below.

The answer to this capability lies with the selection of channelised and digital receivers. In the first receiver type, the band is folded several times through the use of several mixers to provide adequate frequency resolution. The receiver has excellent sensitivity, is wide open in frequency and can sense simultaneous incoming signals.

The digital receiver heavily utilises analog-to-digital converters and allows flexibility in post-detection signal processing because of its ability to digitally store incoming RF signals. Depending on the bandwidth and the duration of the incoming signal, digital receivers can regulate their sensitivity, dynamic range, resolution and parallel signal processing capability. Given that these advantages can be exploited in a threat-rich and electromagnetic-dense environment, digital receivers are an investment that pays off immediately. They also require little operator input and are open architecture, which allows for continuous upgrades.

Multiple signals are discriminated in frequency even if they arrive at the receiver simultaneously. If the emitter hops in frequency or changes its PRF, the receiver will sense these changes, update the emitter's characteristics in the emitter database and track this emission. This information is valuable for intelligence, update of jamming techniques and weapon cueing.

THE WAY AHEAD

There are several things a ship can do to improve its combat effectiveness and survivability against anti-ship missiles. At the same time the ASM can employ different attack strategies and capabilities to counter the ship's advantages.

- The ship's main concern must be to remain passive: transmit a signal only when is absolutely necessary. The ship must rely on digital ES receivers and electro-optics to detect, acquire, identify, assess, track and engage. Radar active sensing should only be used intermittently for early warning, for correcting the ES receiver in range and thus monitoring what the ASM transmitter is doing, and ultimately for weapon cueing. This is possible with active phased array technology since both the dwell time on the target and the transmitted waveform can be regulated and coded effectively for the emitter to remain undetected if the missile is equipped with a passive RF seeker mode. The ship's tracker can be fed with information from the primary surveillance radar (PSR), the multifunction radar, the secondary surveillance radar, the EO surveillance and tracking system, the ES system and the data link (V/UHF, Satcom) to build up tracks.
- Apart from utilising ES systems and monostatic radar for target detection, a squadron of ships could utilise bi-static and multi-static configurations to detect bi-static RCS, which might be much larger than monostatic. This technology is currently used in semi-active radar missile guidance without providing, however, range information. Ships can communicate each other's position and transmission data through data links and synchronise with GPS. The same principles can be used for passive target detection using emitters of opportunity. This is, however, more difficult since the ship has to establish a line of sight with the emitter of opportunity.
- A squadron of ships can utilise blink and co-operative jamming with or without using active decoys to combat the missile flight and antenna dynamics (latax).
- The ASM has to minimise its electronic signature. The technologies available to do this are wideband transmissions (phase coding, pulse compression and frequency hopping) and passive geolocation (using the radar as an ES receiver). The missile also has to minimise its RCS, its dwell time on the target, EO sensing and reception of target updates through data links. Furthermore, the missile is forced to have low side lobes to avoid being detected and must rely on passive means for target detection. Once the target is detected, the missile can

TABLE 1 – ES RECEIVER'S CHARACTERISTICS

Receiver	Advantages	Disadvantages	Applications
CVR	Simple Cheap Instantaneous response High POI (point of impact)	No frequency resolution Poor sensitivity Poor signal discrimination	RWR (Radar Warning Receiver)
SHR	High sensitivity Good frequency resolution Good signal discrimination	Slow response Moderate POI Poor against frequency agility	RWR Shipborne ELINT (Electronic intelligence)
IFM	Simple Good frequency resolution Instantaneous High POI Inexpensive	Poor signal discrimination Poor sensitivity Expensive	Shipborne ELINT Self-protection and Stand-off Jammers SIGINT (Signals Intelligence)
CRx	Wide bandwidth Near instantaneous Moderate frequency resolution	High complexity Expensive Poor reliability Limited sensitivity	Self-Protection and Stand-off Jammers SIGINT
Compressive	Near Instantaneous Good resolution and dynamic range Good signal discrimination	High complexity Limited bandwidth No pulse modulation info Critical alignment	SIGINT
Acousto-optic	Near Instantaneous Good frequency resolution Good signal discrimination High POI	High complexity Immature technology	SIGINT Communications intelligence

employ a different strategy using its RF seeker to get a better fix on the target. Dropping the side lobes widens the beam width, which facilitates Synthetic Aperture Radar (SAR) modes so the missile can project the shape of the ship and thus strike at a predefined point, whilst rejecting active or passive decoys and false targets.

Another important feature that facilitates SAR and resolving stealth targets is detecting in co-polar and cross-polar mode. This is facilitated by the use of wide bandwidth (6-12 GHz) co-polar and cross-polar modes.

- If a ship is attacked by a swarm of ASMs rather than a single missile, the hit probability is greater. Multiple hits increase the probability the ship is put out of combat effectiveness. To increase their effectiveness ASMs can use different attack profiles and co-ordinate their attack through data exchange via data links. Moreover, the missiles' active RF seekers can operate either in bistatic mode, continuous or switched. In continuous mode, only one missile is emitting and the remaining missiles of the swarm receive, while in switched mode, the transmission can be switched between the missiles in a staggered or random fashion to minimise detection or in an optimum fashion to maximise SNR through better RCS visibility. This methodology can work in co-polar or cross-polar modes or in both modes simultaneously. Operating in this fashion, it is very unlikely that blink or co-operative jamming will be an effective way of defending the ship. Therefore, the ship must rely on hard-kill mechanisms (missiles, guns and laser).

EPILOGUE

Current anti-missile ship protection is technologically up to date to counter ASMs that have been engineered and produced between the 1970s and 1990s. Advances in antenna design and digital processing has made coherent jamming very efficient. This technology has matured. To enhance protection in saturated air defence environments against attacking fast jets and missiles, ships also employ expensive hard-kill systems in the form of missiles, guns and lasers, which need sophisticated trackers and optics to correct atmospheric distortion and losses.

However, ASMs have evolved twice compared to shipborne EW and ship protection weapon systems. They now use fused navigation to attack littoral and land targets, low probability of intercept waveforms and short dwell times, passive and bistatic seekers to remain undetected, as well as low RCS and high-speed airframes to saturate vintage servo-powered trackers,

TABLE 2 – ES RECEIVER'S PERFORMANCE OVERVIEW

Signal Type	ES Receiver Type					
	CVR	SHR	IFM	CRx	Compressive	Acousto-Optic
CW	Special design	Yes	Interference with pulse reception	Yes	Yes	Yes
Pulsed	Yes	Yes	Yes	Yes	Yes	Yes
Multiple Frequencies	No	Yes, but won't recognise as same source	No	Yes	Yes	Yes
Frequency Agility	Yes	Yes, but needs passband filter	Yes	Yes	Yes	Depending on read out time
PRF Agility	Yes	Yes	Yes	Yes	Imprecision in TOA	Depending on read out time
Chirped Frequency	Yes	Yes	Yes	Yes, but with reduced sensitivity	Depending on scan rate	Yes
Spread Spectrum	Yes	No	Yes	Yes, but with reduced sensitivity	Yes, but with reduced sensitivity	Yes, but with reduced sensitivity

which give the ship a very short time to respond.

The answer to staying alive for both surface vessels and missiles is remaining undetected. Both platforms have to use passive means for surveillance, tracking and acquisition. So radar, EO and ES receivers have to be integrated into a single combat system. To defend during the end game, the ship has to rely on jammers and missile systems due to their unrivalled long-range capability, and further down range, use sensor-driven guns and lasers as a last means of defence. However, the top priority when modernising a ship's sensors must be upgrading the EW system, particularly its capability to detect, recognise, identify and assess low-power, wideband emissions. Once the ship's company know early on what is sensing them, they can use their most effective system to deceive and engage it and at the same time evaluate the results. ■

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Ioannis Vagias is a radar lecturer at the Centre for Electronic Warfare, Cranfield University, Defence Academy of the UK, Shrivenham. He started his career in the Hellenic Air Force (HAF) where he worked as an avionics engineering officer. In 2010, Ioannis was awarded the Military Merit Medal, 3rd Class, elected member of the Royal Aeronautical Society and qualified as a Chartered Engineer. In 2011 he was knighted into the Order of the Phoenix, receiving the Golden Cross. He took up his current position at Cranfield University in 2013.

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