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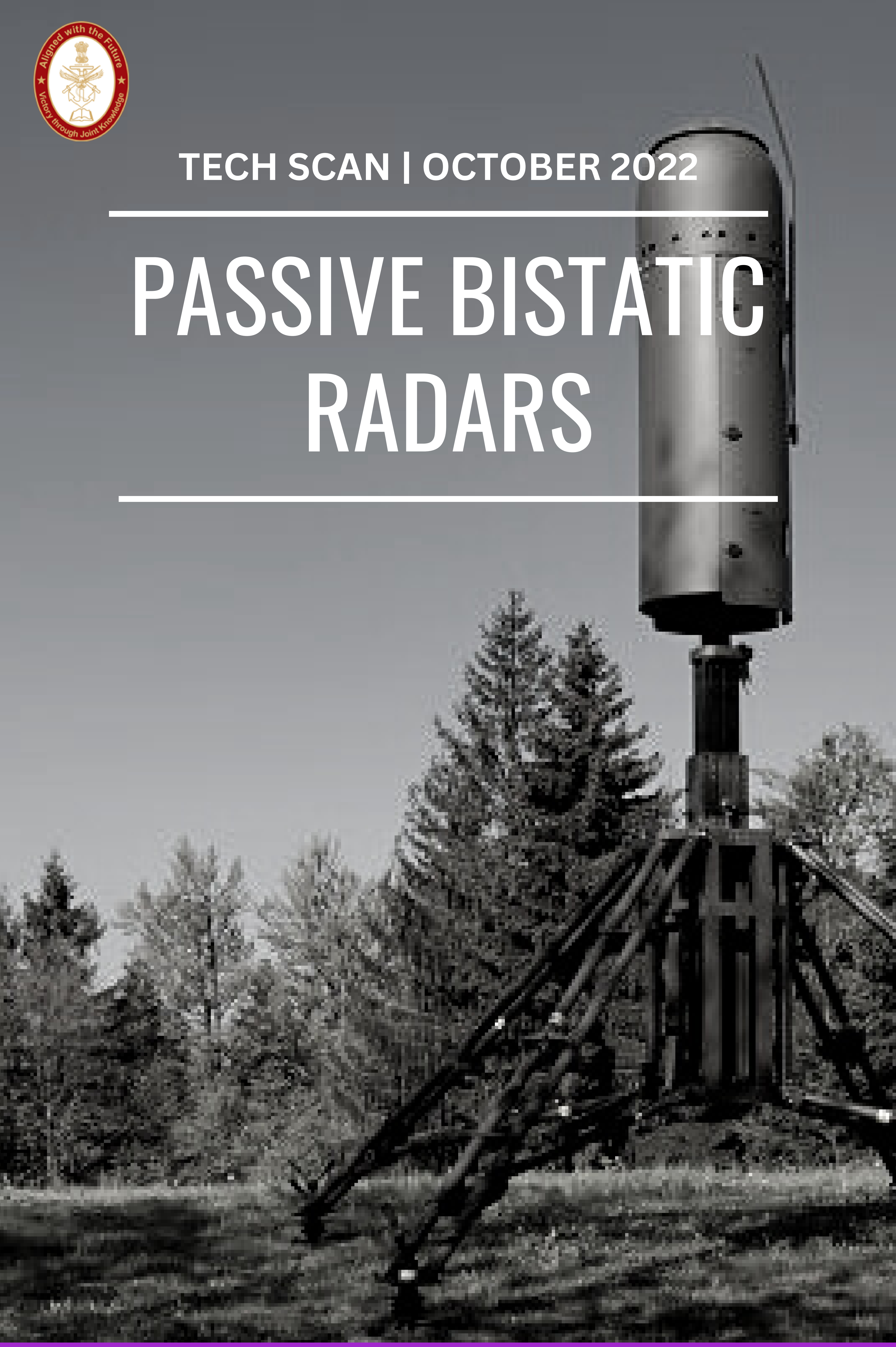
PASSIVE BISTATIC RADARS



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TECH SCAN

PASSIVE BI-STATIC RADAR

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ABSTRACT

Conventional monostatic radars have a dedicated transmitter and use the same antenna for transmission as well as for receiving the reflected signal. The effectiveness of these radars is limited because the Earth is not a perfect sphere and has irregular terrain features like mountains and valleys. On the other hand, a Passive bistatic radar (PBR) does not emit any energy by itself. Instead, it relies on the energy emitted by illuminators of opportunity (IO), such as radio and television transmitters, to catch targets as far away as 200km and even more. Ground-based passive radars are relatively well-developed and the technology has matured. Monostatic radars, being a radiation source, they very easily get detected by radar warning receivers and become easy targets for anti radiation missiles. On the other hand, passive radars remain covert unless optically observed. Even when detected, their operating frequency remains unknown. Since the enemy does not know which emitter is used as an illuminator by a passive radar installation, it faces a challenge to devise an effective electronic countermeasure against these PBRs. As of today, with the advent of stealth aircraft and drones, the exploitation of PBRs will gain greater importance, as they can be effectively used in conjunction with conventional radars to provide a comprehensive air picture. [1]

Introduction

In early 1944, Britain's defence encountered an intriguing observation in reconnaissance imagery along the Northern French coast. It spotted six enormous antenna constructions of a new type. These antennas did not appear to generate any radio-frequency (RF) emissions. So, it was presumed that they were part of a newly developed German long-range radar. The puzzle was not answered until a German radar operator, captured in the autumn of that year, revealed that these were Passive Bi-static Radar (PBR) designated as “Klien Heidelberg” (KH) Early Warning Radars. The PBRs were unique; as they did not emit any RF energy. These German PBR installations could provide early warning of the impending British air attacks by using the emissions of the British "Chain Home" (CH) radars.

The broad characteristics of the PBRs are:

- Passive radars are almost undetectable since they do not emit any signal.
- The PBR receiver is far less vulnerable to electronic countermeasures (ECM).
- The bi-static radar operation has inherent counter-stealth properties.
- Passive radar systems do not need a dedicated transmitter and hence are cheap, have low maintenance cost and very low power consumption.
- Passive radar systems may be made highly portable and mobile.
- Passive radar systems extensively utilise the emerging low-cost Software Defined Radios and abundant computational power.
- The disadvantages of these radars are that they require complex processing algorithms and their receivers are power-hungry due to multi-channel data processing systems.
- Other factors affecting the performance are the non-coherence between received signals and decreased spurious free dynamic range (SFDR) of the receiver.

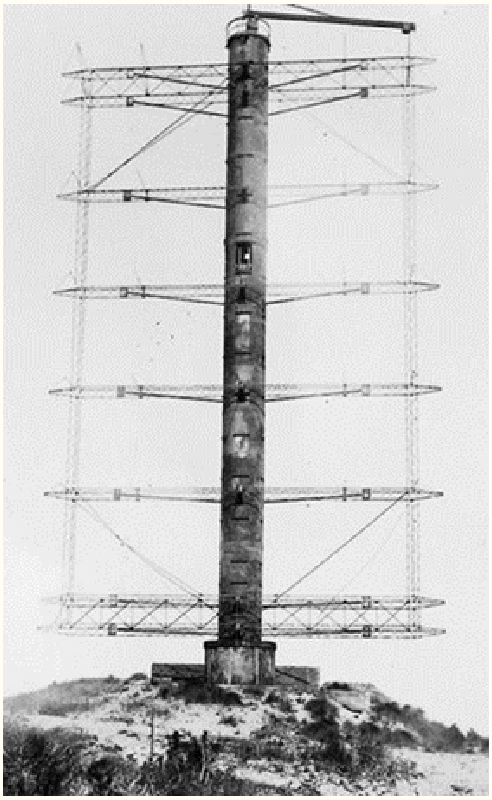

Figure 1: Klien Heidelberg Radar

How do the PBRs Operate?

A PBR , also known as Passive Coherent Location (PCL) Radar relies on signals emitted by IO rather than using its own transmission to illuminate targets, such as radio or television or cellular or GNSS transmitters, which are reflected by targets and are then received and processed at the PBR's receivers. PBRs, which depend on external transmission, can complement active radars in less critical functions like providing a more comprehensive air situation picture, where PBRs' extended capabilities like enhanced ranges and anti-stealth features are exploited. For a passive radar system to function reliably, a constantly illuminating signal is required, which illuminates a usable volume, and has favourable modulation. FM Broadcast (analogue and digital radio broadcast), widespread in developed and developing nations, is an excellent candidate as an IO for the PBRs.

Additionally, for a PBR, it is also anticipated that for a given antenna size, there would be a significant amount of illumination above the horizon, which is required to detect airborne targets. Militarily speaking, a country may deactivate its broadcast or communication signals (IO) to counter the deployment of PBR systems. Therefore, PBRs must utilise an always-present illuminator. FM broadcast, viewed as the final resort for mass communication and propaganda distribution due to its simplicity, low cost, and prevalence in most homes, is the favoured IO candidate for PBRs.

In addition to the FM Broadcasts, TV, HDTV, GSM, Cellular and L-band transmissions from Inmarsat satellites, which provide more coherent signals for longer wavelengths, are also valuable illuminators of opportunity for passive radars. PBR has at least two receiving channels. One channel performs as a dedicated receiver channel which monitors the direct & strong signal received from one or more transmitter(s). It is used as a reference signal in radar processing.

The second channel is connected to an antenna which receives the echo of the same transmitter(s) reflected from the moving targets. The accuracy of the target position measurement mainly depends on the bandwidth of the utilised signal and the receiver antenna beam width. The receiver measures the time difference of arrival (TDOA) between the direct and echo signals. The radar processor calculates the time delay and frequency shift by correlating the reference and echo signals. The system can localise the target in the Cartesian coordinates by combining the delay and frequency shift measurements from multiple transmitter-receiver pairs. Passive radars are good at intercepting UAVS, whose sizes are getting smaller and smaller and are made of non-metallic materials, making their detection difficult as they can rise to small heights and navigate at low speeds, thus avoiding being captured by conventional radars.

Software Defined Radios have helped in low processing frequencies used for radar, thus allowing wavelengths the size of the UAV to be obtained, thus expanding the radar cross-section. In addition, the integration times are more extended, thus offering a higher resolution of the Doppler effect and thus improving the processing of these signals. The target's range is calculated by measuring the time difference between the arrival of the signal from the transmitter and the much weaker version created by reflection from the target. On the one hand, each target's location, heading and speed are accurately calculated in PBR systems using the Doppler shift and the reflected signal's arrival direction. On the other hand, the altitude coverage of a PBR is usually limited since most illuminators radiate their RF energy at relatively low elevation angles.

The Forward Scattering Radar (FSR) is a particular case of PBR configuration, where the target crosses (or is very close to) the line of sight between the IO and the passive receiver. In this case, detecting a target is done by the EM "shadow" that the target casts on the receiver rather than its reflection. Notably, targets with stealth design are inherently 'Radio-opaque' rather than radio-transparent. This makes FSR particularly useful against targets with low reflectivity, as their "shadow" depends on the target's silhouette and is independent of its material. As a result, passive radar can be effectively used to track moving targets of higher stealth, which conventional radars may not be able to detect. The use of active, low frequency band radars, combined with passive radarscovering the lower tier, provide an ideal combination against air threats – independent of their shape or coating.

To remain covert, a passive radar must avoid betraying its location by emitting any other form of detectable energy. Since it does not incorporate a transmitter for target detection, a passive radar will have a relatively low thermal signature and would be hard to detect using an IR sensor. However, using an RF communications link by the PBR system could give itself away as an easy target for hostile electronic intelligence (ELINT) systems. Similarly, the PBR's local oscillator and superheterodyne receiver must be well shielded to prevent its output from leaking-out at detectable strength levels.

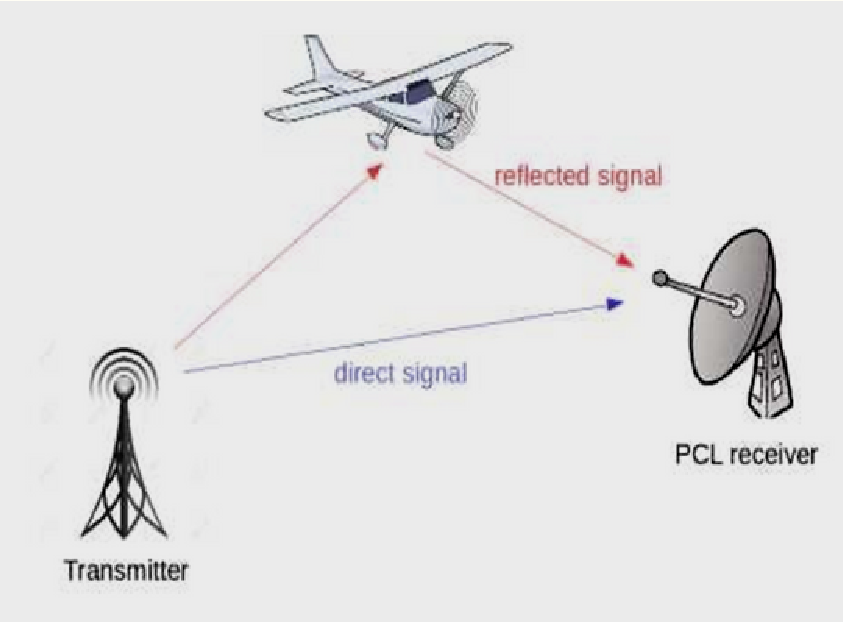

Figure 2: Sketch of the PBR geometry

Passive bi-static radar system scan exploits television, radio, audio broadcasting and mobile communication transmissions as illuminators of opportunity (IO). However, a directive antenna provides only limited angular coverage for radar surveillance instead of a desirable wider field of view. PBRs use antenna arrays composed of Omnidirectional elements to mitigate this limitation instead of a dedicated directive surveillance antenna. Despite all these benefits, which make passive radar appealing for various applications, they still have to deal with non-optimised waveforms and a solid direct signal from the transmitter of opportunity, which generally works in continuous wave (CW) mode. Therefore, PBR systems must effectively cancel this severe disturbance and clutter/multipath reflections received from stationary obstacles like buildings and hills.

Directive antennas, having a high Front-to-Back Ratio (FBR), are usually employed to attenuate the direct signal from the reference transmitter. A directive pattern may be created by simultaneously processing the signals received at each element as long as the elements are sufficiently spaced apart. This also enables the electrical steering of the beam in all directions or, better yet, the generation of a group of directed beams that span the entire air space of interest. The availability of numerous coherent receiving channels would be necessary for this. In this instance, however, the same array might be utilised to gather the sent signal by synthesising a beam directed at the opportunity emitter. This represents a viable solution if several dispersed illuminators of opportunity need to be exploited. However, one of the significant challenges in passive radar technology is installing passive radar on moving platforms, which includes aeroplanes, satellites, ground vehicles, UAVs and ships. While generally ***having more processing challenges than active radars, PBR systems offer an attractive monitoring solution due to their lower operational cost and no requirement for a separate frequency allocation.***

Emitter Location System (ELS)

Although the **hostile asset** may not be visible at night, in the presence of fog or smoke, camouflaged, or beyond the line of sight, ***the location of its active transmitters*** reveals its physical location. An analysis of the signals transmitted from that location can ***usually identify the type of asset*** (weapon, military unit, aircraft, ship). ***These are different from classical PBRs. Passive radars using ELS technology can exploit many other high-frequency transmissions from the hostile flying objects, at which stealth technologies may prove less effective. China has developed an ELINT system to monitor F-22 stealth aircraft*** by monitoring its radio communication, satellite communication, IFF transponder and radar emissions by using three different sensors to locate the source of electromagnetic radiation emissions using an instrument that measures wavelengths by comparison of interference patterns through an interferometric detection system.

Some of the examples of ELS are:

- China uses Passive Radars like YLC-20 and YLC-29 radar. YLC-20 Passive Surveillance Radar can operate as an individual unit and in a network as an interferometer. China’s CETC DWL0002 Passive Detection System, which has an interferometer-based detection system.
- Russia has Moskva-1Passive Radar system which can classify a signal into aircraft or missile and can effectively guide air defence systems to the target with a range of up to 400kms. [2]
- In 2013, Czech Republic's ERA, also known as the Multi Static Primary Surveillance Radar (MSPSR), was designed with the capacity to 'exploit' FM transmissions. Pakistan has been using VERA-E and VERA-NG Passive Radars for Electronic Support Measure role [3].

Applications

There is a close working relationship between SIGINT, Air Defence, Artillery and EW, which has been so evident in Russia-Ukraine Conflict which commenced on 24 Feb 2022. Recent exploitation of Western HARM anti-radar missiles have proved extremely effective. Hence, using passive radars in conjunction with other sensors operating in cellular communications, radar, IR, and optical domains can aid in the ***optimal exploration of Air Defence denial strategies.*** Timely and accurate identification and location of threats supports the following military activities:

- Warning of an imminent attack. By locating a hostile weapon platform (aircraft, ship, artillery unit) the direction from which the weapon would approach.
- Threat avoidance. If one knows where the threat systems associated with the transmitters are located, own plans can leverage threat avoidance.
- Selection and implementation of electronic countermeasures. The location and identification of a threat would help decide ***time-sensitive countermeasures.***
- ***Comprehensive e-ORBAT (Electronic Order and Battle).*** Knowing the location and identification of hostile assets and their recent movement history facilitates location of the emitter.

Ground-Based PBRs

Most passive radars are stationary ground-based systems, and the technology is relatively mature and well-exploited. Nowadays, stealth technology is widely used in military aircraft design and plays a significant role in military affairs. Systems using passive radar are inherently anti-stealth. Since there is no transmission at higher altitudes, such systems can only provide coverage up to medium heights (up to 10000 – 15000 feet). Using active, low-frequency band radars and passive radars covering the lower tier would provide an ideal combination against stealth threats. As the frequencies are relatively low, the corresponding wavelengths become comparable to the target-aircraft structural parts (wings, empennage, stabilators etc.) so that resonance phenomena appear, triggering scattering modes that increase the target's echo. Moreover, Radar Absorbent Material (RAM) coatings are less efficient at lower frequency bands.

Consequently, hiding an aircraft from a passive radar becomes much more challenging. Modern self-defence or countermeasure systems simultaneously identify emitters across a broad frequency range, usually employing radar warning receivers (RWRs), alerting the pilot of the probable enemy radars and suggesting effective jamming or decoy techniques. Passive radar systems are not detectable by RWRS, can't be tracked and cannot be jammed/ or interfered with because they don't emit radiation. They can also not be targeted by an anti-radar weapon (such as an anti-radiation missile).

A few key products developed for ground-based passive radars are covered as under:

- Silent Sentry of Lockheed Martin was introduced in 1998 that exploited the output frequency of Frequency Modulation radio and analogue TV transmitters.

- In the UK, Roke Manor and BAE systems teamed to develop a CELLDAR system to exploit the signals from 900 MHz mobile phone base stations with a range of 60 km.

- In the 2007 Paris air show, HOMELAND ALERTER was showcased, which could detect and track air threats at low and medium altitudes. The AULOS radar was launched in 2012 by Leonardo, which uses FM band transmissions and Digital Video Broadcasting terrestrial sources. Another breakthrough was using Hensoldt's TWINVIS, which picks up rudimentary transmissions such as FM, digital, and television.

- SPYGLASS is a European project conducted by the University of Birmingham. Universita di Roma La Sapienza has run trials that could pick up transmissions from the constellation of Galileo navigation satellites (GNSS) that would detect surface ships. Similar trials in the US were carried out to highlight the efficiency of 5G networks in providing signals to passive radars.

- Australian MAVERICK M series was given to the Australian Army to develop ground-level capabilities and evaluation activities.

- Taiwan's National Chung-Shan Institute of Science and Technology (NCIST) has created a vehicle-mounted 'Mobile Passive Radar System', which has an 'advanced phased array' structure that could quickly identify China's Chengdu J-20 stealth fighters.

- In the Middle Eastern region, Saudi Arabia's SAMIT, developed by the Prince Sultan Defence Studies and Research, can exploit Digital Video Broadcasting-Terrestrial (DVB-T) up to 250 km.

- ERA has unveiled a new passive multistatic primary tracking device - known as SICORRA [**SI**lent **CO**Rrelation **RA**dar] - that receives ambient signals that bounce off an aircraft, but the aircraft is not emitting signals itself. The signals received do not have to be from the aircraft, like VERA, but can be reflected FM signals from sources such as cell phone or television towers.. Not only is it "invisible" like VERA-NG, but it can even see "silent" aircraft that do not transmit any electromagnetic signals. [4]

Air Borne Application of PBRs

Airborne Passive Bi-static Radars (APBR) are the latest and fastest evolving application of Passive Bistatic Radar. Airborne passive bi-static radar system is cheaper to construct, easier to cool, lighter, and requires less power than a traditional active radar system. These characteristics make it perfect for mounting even on a light aircraft or unmanned aerial vehicle (UAV), especially for the next generation of Low Observable (LO) UAVs, which would complement the platforms' LO design with an inherent Low Probability of Intercept (LPI) air-to-air and air-to-ground sensing capability. PBR fitted UAVs are promising military systems for flying surreptitiously in enemy airspace. Firstly, because it is portable, the receiver may be placed anywhere needed to provide the appropriate air and ground coverage. Secondly, the system's relative motion can be taken advantage of. Ground pictures and Airborne Early Warning can be produced using synthetic aperture radar (SAR) and inverse synthetic aperture (ISAR) imaging techniques, which would be a valuable addition to the current onboard active systems.

Sea Borne Application of PBRs

Seaborne passive radar using nearby digital radio or digital television transmitters can detect airborne targets of different kinds. This allows the system to monitor the airspace over coastal areas. However, as regards the maritime targets (such as smaller boats and vessels), the detection is not easy as they are slow, and the target echo is inseparable from the clutter. Hence, clutter removal is more complicated than in the case of ground-based radars.

Furthermore, the clutter characteristics will change depending on the geometry of the transmitter, clutter, and radar, which should be considered when the algorithm for clutter cancellation is designed. [5] Nevertheless, there is a potential for the surveillance of coastline and maritime infrastructures, such as harbours and ports, and surveillance of large areas. This can be done by having more than two receiving elements and adapting the algorithms for multi-array processing to improve clutter suppression and target detection further.

Space-Based Passive Bi-Static Radar

Space-based sensors perform ISR roles that contribute to the battle space awareness in all domains ranging from Electro-Optical, Infra-Red, Synthetic Aperture Radar, SIGINT (ELINT & COMINT) and Hyperspectral. While the traditional choice for passive radar configurations is exploiting terrestrial illuminators (FM, Cellular and TV signals), over the last few years, new ideas about passive radar applications relying on satellite transmitters have emerged. A suitable solution is represented by Global Navigation Satellite Signal (GNSS) constellations. For many years, the remote sensing community has known their opportunistic exploitation for passive SAR applications. More recently, their alternative utilisations for passive coherent locations have also been explored by many countries.

Other noteworthy options are represented by communication satellites such as Iridium and Inmarsat and broadcast systems such as DVB-S transponders. These communication satellites in geosynchronous orbit are increasingly broadcasting digital signals with high bandwidth and power, which can be used as IO. These signals are well suited for surveillance by a passive bistatic synthetic aperture radar. The concept is passive because it re-uses transmissions intended for a different purpose and is bistatic. After all, the transmitter and receiver are in different places (on separate satellites). The receiver will collect the scattered transmitter signals, and if correctly synchronised, the data can be used to form synthetic aperture radar images.

The wide bandwidths adopted by current SAR missions (from tens up to a few hundred MHz) enable range resolutions comparable to or even better than the size of several targets of interest, such as aircraft, ships or ground vehicles, sensibly reducing system sensitivity to clutter echoes. The challenge with GEO satellites are weaker signals.

Selecting an instrument mounted on a GEO instead of an LEO satellite can guarantee continuous signal availability over a large area. LEO platforms are visible from a given geographic area for a limited time, and a constellation of satellites would be needed to assure temporal continuity of the coverage, with the further issue represented by the handover [6]. As computing power increases, passive bistatic radar concepts will become increasingly feasible.

Unmanned Hostile Assets- Increasing Relevance of PBRs

Unmanned aerial vehicles (UAVs) and autonomous drones have made air power, which once was the domain of highly developed militaries, now accessible to a broader range of countries. A significant interest of the radar engineering community has been focused on PBR architecture due to the rising number of civilian users. UAV monitoring has reached the level where a small UAV target may be detected up to 100m away from the receiver using the Fractional Fourier Transform (FrFT) to enhance detection. [6]

These new weapon systems, which go by many other names, including suicide drones, loitering munitions, and kamikaze drones, are the next-generation threats. Drones fitted with explosives for kamikaze attacks are often termed loitering munitions, such as the Switchblade 300, and Ukrainian forces have used Phoenix Ghost weapons. [7] With the help of recently introduced Iranian drones, Russian troops have damaged Ukrainian positions. The Iranian drones typically fly in pairs and identify their targets before slamming into them. Tackling UAVs requires real-time decision-making, as detecting small and low-altitude targets is challenging. UAVs can be tracked through both active and passive radars. Active standard radars enable the system to detect any UAV using radio frequencies, but Passive Bistatic Radar uses radio, acoustic, air visual surveillance posts, etc., to determine the presence of the UAV and can trigger other EW systems to jam the UAV or carry out hard kill using kinetic weapons. The growing deployment of fifth-generation (5G) broadband cellular networks with large number of base stations,particularly in urban areas can provide illumination needed to detect and track UAV threats. Texas based Cobalt solutions has been contracted by US Home security to provide PR 1000 sensor against drone threats.

Emerging Threats

Success in a future conflict will depend significantly on the ability to disrupt the ***adversary's operational mobility by exploiting air superiority***, especially in the context of nuclear-armed states. **Stealth technology and Countermeasure System**s are critical elements in the effectiveness of fighter aircraft that can radically change the outcome of military operations. The emerging threats in our neighbourhood are:

- China's J-20 5th generation Stealth fighters now operate in all five theatre commands. A variant of the twin seater J-20 is also being developed to allow it to take on more complex electronic warfare missions and missions involving drones. [8]

- The FC-31 Gyrfalcon, a twin-engine aircraft in the prototype stage, is China's second fifth-generation fighter aircraft, under development, which would essentially include features such as the ability to use drones, artificial intelligence, advances in stealth, and omnidirectional sensors. It would also mean an exponential reduction in signature and exponential acceleration in processing power, as well as the ability to iterate in terms of available mission systems to reprogram at the speed of relevance.[9]

- To **project China's growing interests** in the Indian Ocean and maintain the security of its strategic sea lanes, the Chinese navy will maintain or even strengthen its presence in the Indian Ocean. [10] Chinese NOSS (Navy Ocean Surveillance Satellite) triads, use interferometers for signal detection.

- The High-speed Anti-Radiation Missiles (HARM) that destroyed Russian radar, has become a "critical factor" in Ukraine's recent success after it secretly armed their jets. [11] ***PBRs help obviate the dependence on vulnerable monostatic radar systems.***

PBRs Bolstering C4ISTAR Function

Data fusion combines information from several sources to enhance the original data's potential values and interpretation capabilities and create high-quality images. Situational awareness can be improved by integrating OSINT, HUMINT, SIGINT, IMINT, ELINT, SAR, ISAR, and cyber and PBRs with reliable communication linkages employing geospatial technology. Even for emerging anti-drone systems and stealth platforms, it will be a good solution. ***This combination of sensors in the command & control system will indeed be revolutionary.*** In addition to the FM channel, ***there is a need to exploit the GNSS and GSM network***, especially the **5G network, by installing the antenna along the border to exploit these radars.**

Conclusion

Even the best conventional Radar Sensor Networks (RSNs) have gaps, because of terrain features like mountains and valleys- and simply because the Earth is not perfectly round. These RSN aim to maximise surveillance coverage and **minimise both interferences between single nodes and the total power consumption** of the RSN. However, as recent conflicts demonstrate, RSNs are vulnerable. The a***bove analysis underscores the need to minimise the usage of active radars by maximising the usage of PBRs in the RSN,*** which is also preferable for covert operation scenarios in military applications. ***PBR systems are attractive due to their cost-effectiveness and covert operational capability.***

However, efficient deployment of PBRs is relatively complex due to their dependence on IO and use in urban and hilly terrain where highly directional transmission gains are required to optimise transmission patterns owing to topological and urban requirements.

Furthermore, an ***AI neural network comprising the sensor to shooter weapons will be needed to generate a super-fast kill web.*** Proliferation of technologies, like the Internet of Things, would result in the Internet of Weapons being held by adversaries. Hence, *the side which strikes first will gain ascendancy in the conduct of the battle during the opening hours of a conflict.*

A PBR, rather than using its transmissions to illuminate targets, leverages signals from IO that are reflected by targets and then received and processed at the PBR's receivers. A PBR will have a **relatively low thermal signature** and would be hard to detect using an IR sensor. Passive radars sift through a host of signals of opportunity, such as low-frequency FM radio broadcasts and **offer the same probability of detection as by conventional mono-static terrestrial and aerial radars.** PBRs can't be tracked and, therefore, ***cannot be neutralised unless its network signature is compromised, which is rare.*** If a PBR is to remain covert, it must use a much smaller antenna that inevitably has a lower gain, a wider main lobe, and more potentially troublesome sidelobes which reduces detection range and multipath problems.

Small drones and stealth platforms pose a significant threat to both military and civil infrastructure. Stealth aircraft are designed to be invisible to conventional radar sensors. ***PBRs can detect both; small UAVs as well as stealth aircraft.*** PBRs are an alternative to the gap filler radars often needed to complement conventional RSNs. A ***3D air picture generated by a multi-static passive radar can seamlessly provide the same kind of information as a conventional RSN.*** By combining conventional radars with passive radars, we can generate s a more comprehensive air picture without worrying about the sensors being used. New ***PBR systems are being developed on satellites, UAVs, small aeroplanes, ships and other moving platforms.***

There is a need to re-assess threat perceptions, future battlefield scenarios and consequent effects on force structuring and capability development. The takeaways for our Armed Forces are:

- PBR-fitted autonomous UAVs are promising military systems for operating surreptitiously in contested airspace.

- Similarly, the developments in exploiting satellites using satellites and ship-borne PBRs are underway to exploit the electromagnetic spectrum for a credible C4ISTAR against new potent threats like Unmanned systems and stealth platforms.

- India must install and exploit the network of IO in critical border segments and use LEO and GEO satellites as IO to leverage optimal exploitation of PBRs during peace and conflict.
- A significant challenge in PBR technology is installing it on moving platforms, which includes aeroplanes, satellites, ground vehicles, and ships. AI and ML will need to be exploited for overcoming processing challenges.

Endnotes

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