ABSTRACT
Radar and sonar are sensors which are used widely in the military domain. Research and development in these areas are normally carried out independently by different groups. While each sensor system has its own set of challenges and solutions, there are fundamental similarities in their operating principles. This article examines and compares these similarities to provide meaningful insights into the synergy between radar and sonar.

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INTRODUCTION

Radar and sonar have seen extensive military use in their primary role of detecting and identifying varied threats. Both are sensor systems which use the transmission and reception of return signals to function. Radar systems operate using radio waves primarily in air, while sonar systems operate using sound waves primarily in water (Minkoff, 1991). Despite the difference in medium, similarities in the principles of radar and sonar can frequently result in technological convergence.

Although radar and sonar operate under different environments and take on various roles, they are closely related due to fundamental similarities in function. Therefore, breakthroughs in one field can potentially provide insights and lead to the advancement of the other. This article aims to compare the two systems in order to elicit meaningful similarities between the two technologies.

BASIC FUNCTIONS OF PROPAGATION DETECTION SYSTEMS

Radar and sonar are sensor systems that use the propagation of waves to detect and localise targets. In radar, a transmitter with an oscillator is used to generate radio waves, and a waveguide links the transmitter to the antenna. In sonar, electrical energy is supplied directly to a hydrophone array which converts it to sound waves. These transmitted waves bounce off upon coming into contact with a target. The reflected waves (or the target’s inherent sound in the case of passive sonar) make their way back to the sensor system.

For radar, the received signals normally go through a low noise amplifier before being down-converted to an intermediate frequency (Skolnik, 1982). On the other hand, the received signals for a sonar go through a pre-amplifier to shape the signal (front-end conditioning) prior to being sent to the signal processing unit. Subsequent processing and analysis of the signal received enable the system to detect the target as well as determine characteristics such as range, bearing, course and speed.

TYPES OF RADAR AND SONAR

The types of radar range from those installed on large static platforms with detection ranges over 100km, to miniaturised versions installed on unmanned aerial vehicles that offer situational updates in a localised area of operations. Three distinct types of radar systems are the static early warning area surveillance platform, the targeting and fire control platform, and the battlefield reconnaissance detection and search platform. Radar detection can be active or passive, and the latter utilises the triangulation method based on electromagnetic reception or the bistatic principle.

Radar frequencies cover a wide spectrum, from the high frequency range of 3-30MHz for the purpose of over-the-horizon radar surveillance to the ultra-high frequency range of 40-300GHz – also known as the millimetre wavelength band – used for extremely high resolution and short-range imaging. Fire control and missile guidance radars operate between these two extremes, at frequencies of 8-12GHz.

The detection range of sonar installed on large shipboard platforms varies from tens of kilometres (for active sonar) to hundreds of kilometres (for passive sonar). Smaller versions of sonar are installed on helicopters and unmanned surface vehicles, and miniaturised versions are used for unmanned underwater vehicles that offer situational updates in localised areas of operations. Sonar detection can also be achieved using the bistatic principle, although this area is still in the developmental stage.

The spectrum of sonar frequency spans from a few Kilohertz or less for long-range target detection to medium range of 10-50KHz for target detection and classification.

CAPABILITIES OF RADAR AND SONAR

Radar and sonar are capable of distance measurement through the timing method, i.e. Range \( R = \frac{cT}{2} \) where \( c \) is the speed of the wave, and \( T \) is the time taken for the signal to travel to the target and back.

This method is considered more accurate, although the frequency and phase modulation of the transmitted signal vary according to time. While frequency agility in radar is established and widely available, the use of several transducer frequencies in sonar is still in the early stage of development. At this stage, some sonar transducers are capable of being modulated to operate in more than one frequency due to its larger bandwidth. However, the majority of current sonar transducers can only use a single transduction frequency. This is because the conversion of electrical energy to mechanical sound energy is done through the use of specific piezoelectric crystals which have limited frequency modulating capabilities.

Radar and sonar are also capable of measuring the speed of the target in the following ways:

- Measuring distance and recording where the target was located a set time ago
- Analysing the Doppler signal where the target’s motion relative to the transmitter and receiver produces a change in frequency (see Figure 1)

Different radar transmission types are often combined to perform a comprehensive range of functions. For instance, static platform radar may perform a wide area search to identify targets within a 360 degree arc quickly. Subsequently, it executes a precise tracking of targets previously identified for accurate fire control. When the radar tracks a target, it may vary its waveform to adapt to the target’s kinetic parameters and the environment so as to optimise its detection capability.
Lately, sonar can operate in various transmission modes to optimise its detection and classification capability for stationary or slow-moving targets as well as fast-moving ones. Besides being able to achieve omnidirectional coverage, sonar can operate in directed sectoral transmission to improve its detection capability. The incorporation of an Automatic Detection and Tracking feature in the sonar system enables continuous tracking of the target for an accurate torpedo fire control solution.

**SIGNAL AND NOISE**

The Signal to Noise (SN) Ratio is defined as the power ratio between a signal (desired reading) and background noise (undesired reading). All sensor systems which use the wave propagation have to factor in the SN ratio in order to make meaningful calculations (see Figure 2).

A high SN ratio is always desirable as it allows for higher rates of detection with a lower probability of false alarms. All wave propagation sensor systems use some form of noise limitation and signal amplification in order to improve the SN ratio.

‘Clutter’ refers to unwanted echoes in electronic systems and they occur particularly in radar. These echoes are caused by unwanted detection and interference from a variety of environmental factors, including insects, chaff and atmospheric turbulence. All forms of clutter must be estimated and factored into the equation as they lower the SN ratio significantly. Noise dominates in the absence of clutter while clutter dominates in regions of heavy clutter interference. Radar systems in these two scenarios are termed ‘noise limited’ and ‘clutter limited radar’ respectively.

Most modern radar systems are capable of varying their SN ratios to take into account the presence of clutter, be it permanent (e.g. nearby foliage and buildings) or sporadic (e.g. rain and atmospheric disturbances). The adaptive SN ratio allows radar systems to optimise the rates of detection even under adverse conditions.

The sonar equivalent of clutter is reverberation. Reverberation is caused by sound waves scattering upon contact with small objects in the sea, the water surface and the seabed. A region of strong reverberations is known as a reverberation-limited environment. Conversely, a low reverberation condition where noise dominates is known as a noise-limited environment. The sources of noise include shipping traffic, sea state and the ocean’s biological system which comprises organisms such as shrimps and fishes. Unwanted sounds and reflections can mask a desired target from detection.

**POWER GENERATION, AMPLIFICATION AND PROPAGATION**

In order to improve the SN ratio, sensor systems must also include measures to increase the power of the received signal. This is done in three main ways:

- Amplifying the transmitted signal, if any
- Increasing the directivity of both transmitted and received signals
- Collating, cleaning and amplifying the received signal

Two basic radar-transmitter configurations are the self-exciting oscillator and the power amplifier. The magnetron power oscillator is the most common type of power oscillator for radar. The klystron, travelling-wave tube and the cross-field amplifier are examples of power amplifier tubes. In the late 1990s, the solid-state amplifier started to replace the vacuum tube. The choice of transmitter depends on the radar application. For instance, power amplifiers are more stable and provide greater power at the expense of size and portability.

In the case of active sonar, transducer frequencies have undergone an innovation where multiple frequencies may be emitted, allowing optimal performance through a variety of mediums. This development may benefit military systems in the future by providing modes of detection suitable for various sea conditions.

As sound and radio waves travel, they suffer from a loss of intensity dependent on the square of the range travelled. As an omni-directional transmission system loses power quickly from a dissipation of power across a wide area, there is a need to add directivity to the transmitted waves to increase the strength of the transmitted signal. Radar systems may use a steerable parabolic dish whereas sonar systems may use a steerable beam or directed transmission. Methods of directing and steering radar and sonar beams can either be mechanical or electronic. Directivity can also be used during reception to cut down on unwanted noise interference from the surroundings.

Sonar utilises a deep sound channel occasionally, where propagation may occur with virtually no loss if the source of sound is deep and the conditions are optimal. This is due to the sound trapping in the channel with no loss at the boundaries. This phenomenon is also a well-known observation in radar, where the specific atmospheric conditions can create a confined conduit that follows the earth’s curvature, resulting in ducting. Thus, over-the-horizon detection capabilities can be achieved. However, this phenomenon can also cause problems in radar performance (e.g. gaps in radar detection or detection of unwanted clutter echoes at long ranges) as well as errors in range and angular measurements (see Figure 3).

**MATCHED FILTERING**

When receiving a signal, a matched filter option is available in some radar applications where the shape of the return pulse is known. This allows for optimal reception of the desired signal by blocking out undesired interference. Radar pulses can also be integrated, thus amplifying the signal while cancelling out random noise. Integration can either be coherent or non-coherent. Non-coherent integration compromises efficiency for the convenience of not having to preserve phase information. Matched filtering is also used extensively in coherent active sonar.
ATTENUATION

‘Attenuation’ refers to the gradual loss in intensity of any kind of flux through a medium. Both radar and sonar suffer from attenuation that results from factors such as range and environmental conditions. For example, as range increases, the signal becomes weaker until it is completely hidden by noise.

Attenuation levels vary based on the frequency of transmission and the medium through which the signal travels. It is a key factor in determining the type of detection method to be used. For instance, sonar is used by submarines as radio waves suffer severe attenuation underwater and become virtually non-functional.

By varying frequency, radar and sonar can make trade-offs between target resolution and detection range. Higher frequency radar would allow for a more precise tracking of the target at shorter ranges, while lower frequency search radar would detect targets beyond the horizon.

An example of attenuation arising from environmental conditions for radar is rain fade, as illustrated in Figure 4. Higher frequencies of radio waves (e.g. those above the range of 11GHz) suffer most from attenuation due to rain fade. Specific bands of frequency also suffer from attenuation by particular elements. For instance, the 50-75GHz bands are used rarely in radar as they suffer severe attenuation due to atmospheric absorption, especially under rainy conditions.

The attenuation of sonar wave propagation bears some similarities to that of radar. Owing to the nature of its medium, there are problems in using sonar to propagate sound waves through water mediums of different temperatures, salinity and density. Such variations cause differences in the speed of sound wave propagation.

At a depth of 30-100m in the open sea, there is usually a marked change in ocean temperatures, known as a thermocline. Thus, sonar can be hampered by the refraction of sound waves from the other side of the thermocline because of the difference in sound wave speeds at various temperatures. An analogy would be the distortion of a drinking straw when it is placed in clear water. Such variables can only be approximated during sonar calculations. This phenomenon is similar to radar propagation through different refractive layers in the atmosphere.

PASSIVE SYSTEMS

Passive sonar systems are used extensively by mines and submarines. Passive sonar is able to determine the range and bearing of an acoustic target without giving away the location of its source. Once an acoustic target has been identified using broadband detection, the sonar vessel may use narrow band analysis to identify the different frequencies making up the target’s emitted sound. Hence, the type of engine and craft can be determined.

It is most useful to reduce the vessel’s own noise. This can be achieved by employing nuclear reactors in submarines which can be cooled using silent convection, or by towing sonar hydrophones behind a ship or submarine to reduce the effects of vessel noise (see Figure 5).

The passive sonar can be compared to the use of non-cooperative emissions from commercial broadcast or communication signals in passive radar to detect targets of interest. In such a system, the receiver uses third-party transmitters in the environment and measures the arrival time difference between a signal obtained directly from the transmitter and one which is obtained via reflection from the object.

ACTIVE ARRAY RADAR SYSTEMS

Modern Active Electronic Scanned Array (AESA) radar systems as shown in Figure 6 provide great flexibility as they are capable of imitating a variety of radar antennas according to the situation (Hommel and Feslile, 2004). They are composed of several Transmit/Receive (T/R) modules which are programmed to operate in tandem.

AESA radar systems are able to generate and aim the radar transmission beam and reception path electronically through the constructive and destructive interference between the T/R modules. This eliminates the need for physical movement of the radar in order to carry out scanning, allowing the AESA radar systems to scan surroundings at a much faster rate. Conventional wear and tear is also reduced.

Through the manipulation of the T/R modules, AESA radar systems are able to transmit multiple ‘mini-beams’ to track a large number of identified targets while maintaining a wide area search beam – this eliminates the previous need for multiple radar systems (Russel, 2007).

Further advantages of AESA radar systems include low probability of detection by radar warning receivers and high resistance to jamming. As AESA radar systems are composed of multiple T/R modules, isolated failures have little effect on the entire system and this allows the AESA radar systems to attain high levels of reliability.

As the AESA radar systems continue to develop, cheaper and more power-efficient T/R modules can be expected in the market, further reducing the cost.

Sonar systems also have equivalent array used for receiving signals. The sonar array consists of multiple hydrophones which add signals from a desired direction while subtracting signals from other directions (Chapple, 2008). Hydrophones are most commonly arranged in the format of a line array and cannot be steered electronically.
SYNTHETIC APERTURE RADAR AND SYNTHETIC APERTURE SONAR

Synthetic Aperture Radar (SAR) is a type of radar which collates multiple radar images to yield a single image of high resolution. The quality of the resultant image is better than what is achievable through standard conventional means. Either a single antenna is mounted on a moving platform (e.g. an airplane or spacecraft) to illuminate a target scene or many low-directivity small stationary antennas are scattered around the target area. The many echo waveforms received at the different antenna positions are post-processed to resolve the target. Synthetic Aperture Sonar (SAS) is analogous to SAR and shares the same basic principle – the forward motion of the platform is used to synthesise a long antenna which in turn improves the azimuth resolution (Hagen and Hansen, 2008).

The differences between radio waves and sound waves give rise to a different set of challenges in SAS as compared to SAR. For example, in order for the sonar to function as a synthetic aperture, the position of the sonar at each ping must be determined with great accuracy. Hence, the underwater vehicle carrying the sonar has to be equipped with a highly accurate navigation system. In addition, factors such as electronic and ambient noise become more important as range increases, and multipath reverberation may also increase to the point that the maximum effective range of the sonar may be limited by reverberation in shallow water. While these issues are also faced by SAR, solutions such as the use of interferometry techniques have been developed to resolve multipath problems. As the engineering challenges associated with SAS processing have proven to be more difficult to overcome than those associated with SAR, the latter is now more widely used.

CONCLUSION

Despite inherent differences between radar and sonar, there are similarities in the nature of their sensor systems which lead to overlaps in their applications and technologies. Cross radar and sonar technical competencies can be seen as synergistic, and innovations in one field are likely to affect and benefit the other. Hence in DSTA, the radar and sonar specialists are put together in the same competency community to update one another with their respective system developments.

REFERENCES


BIOGRAPHY

Teo Seow Khye is Head (Sensor Systems) and is responsible for the operations and engineering support for non-platform sensor systems of the Singapore Armed Forces (SAF). He was part of the team for the Republic of Singapore Navy (RSN) Missile Corvette Project and the RSN Frigate Project which attained the Defence Technology Prize Team Award in 1990, and the Team (Engineering) Award in 2007 respectively. Seow Khye received the Public Service Commission Local Scholarship Award and graduated from the National University of Singapore (NUS) with a Master of Science (Electrical Engineering) degree in 1990. He further obtained a Master of Science (Management of Technology) degree from the Massachusetts Institute of Technology, US under the DSTA Postgraduate Scholarship in 1993.

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