CHALLENGES OF SEEING UNDERWATER – A VISION FOR TOMORROW

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Abstract

The last decade of this millennium is experiencing a revolution in undersea technologies relevant to naval military applications. Ten years ago the single most pressing global consideration of western navies was the tracking and containment of Soviet nuclear-powered submarines in deep water. These submarines were relatively noisy by modern standards, and could usually be detected and tracked at considerable range by passive sonar at low frequencies. The US spent literally billions of dollars on the SOSUS system to implement this strategy. Now that the cold war is over, the emphasis has shifted to higher frequencies, broader bandwidths, intelligent processing and active systems as the focus has moved to littoral regions and submarines have become very much quieter. Extremely quiet conventional (even anaerobic) submarines are available from several European sources, some of which are not necessarily as discriminate as the US and its partners would like about their customers in the face of pressing need for foreign exchange. Such submarines threaten even the largest and most protected capital groups at sea. At the other end of the spectrum, the ease and low cost with which a relatively unsophisticated mine can be laid in shallow water belies the enormous damage that it can inflict. Opposing these worrying trends, the maturation of sophisticated technologies in MHz frequency and parametric sonar, acoustic signal processing, ambient noise imaging, autonomous vehicles, remote sensing, and many other component technologies has opened up a rich panoply of options for the modern navy to exploit and deploy. The challenge is in the integration of these nascent technologies to give a meaningful and co-ordinated picture.

Introduction

The title of this paper begins with the words ‘Challenges of seeing underwater…’. By ‘seeing’, we mean perceiving our environment in any way that permits images to be formed. In water, light does not travel very far. Sound, however, can travel tens of thousands of kilometres, e.g. see Munk et. al’s book on tomography[1] page 337. Underwater acoustics has therefore traditionally been considered the first choice in detecting and classifying objects underwater, although sonar was rarely used to form images as such until recently. Now we are familiar with the impressive 3-D plots of the seabed obtained from sidescan sonar, synthetic aperture sonar (SAS) and interferometric multibeam systems. Nevertheless, the displays and types of sonar used for military combat systems still do not enjoy this level of visual sophistication. At the same time, several novel technologies are emerging as promising alternatives or compliments to active and passive sonar. These include Ambient Noise Imaging, Raster scanning lidar (laser imaging), very-high frequency (VHF) active imaging systems, artificial intelligence signal processing and many more. This paper touches on a few of these developments and indicates how they might impact naval military applications in the coming decade to provide a vision for the future. Several technology areas will be presented, each in their own section. We begin with the most distant, remote sensing.

Remote Sensing

Remote sensing is familiar to us as a tool to image the earth's surface. The first sub-surface images to be obtained by satellite were of major features on the ocean seabed, thousands of meters deep, obtained by a superb and highly-accurate set of measurements of average sea surface elevation by the Ocean Dynamics Satellite (Seasat-1) satellite in 1978. Seasat was designed to provide measurements of sea-surface winds, sea-surface temperatures, wave heights, internal waves, atmospheric liquid water content, sea ice features, ocean features, ocean topography, and the marine geoid. Seasat provided 95% global coverage every 36 hours. The instrument payload consisted of

- X-band compressed pulse radar altimeter (ALT).
- Coherent synthetic aperture radar (SAR)
- Seasat-A scatterometer system (SASS)
- Scanning multichannel microwave radiometer (SMMR)
- Visible and infrared radiometer (VIRR).

This remarkable instrument brought into focus the enormous range of measurements and interpretations that could now be made from remote sensing satellites. The ridges and canyons of the sea bed were imprinted on the average sea surface as clearly as a National Geographic map.

One of the more recent satellite remote sensing capabilities to have made an impact in this regard has been the European synthetic Radar Satellites ERS-1 and ERS-2.

ERS-1 was conceived as an orbiting platform that would be capable of measuring the Earth's atmospheric and surface properties with a high degree of accuracy. It uses active microwave emissions to collect global measurements and images independent of time of the day or weather conditions. It also undertakes the measurements of many parameters not covered by existing satellite systems, including those of sea state, sea surface winds, ocean circulation and sea and ice levels. ERS-1 & 2 carry a number of instruments consisting of a core set of active microwave sensors supported by additional, complementary instruments:

- Active Microwave Instrument (AMI), which combines a Synthetic Aperture Radar (SAR) operating in image or wave mode
- Wind scatterometer
- Radar Altimeter (RA)
- Along-Track Scanning Radiometer
- Microwave Sounder (ATSR)

· Precise Range and Range-rate Equipment (PRARE)
· Laser Retroreflectors (LRR).

Although ERS-1 is now nearing the end of its life, ERS-2 is operating successfully.

With synthetic aperture radar (SAR), very slight variations in the sea surface roughness (to which radar wavelengths are very sensitive in terms of the reflectivity) can be detected and mapped. Such variations are caused by the dilation and compression of the small-scale sea-surface waves, effectively advected by large-scale surface currents caused by internal waves. As an internal wave propagates, it generates tubular convection cells that create small surface currents of alternate compressive and dilative divergence, resulting in bands of light and dark SAR images.

Internal waves are not the only cause of modifications in the sea surface small-scale roughness. A ship leaves a very long wake expression on SAR images[2]. The propeller turbulence causes a change in surface roughness that can persist for several kilometres behind the vessel. Fig. 1 shows two such vessels (bright) and their linear wakes (dark). The wakes are offset from the vessels due to an artefact in SAR processing which can be used to estimate vessel speed. Researchers at CRISP at

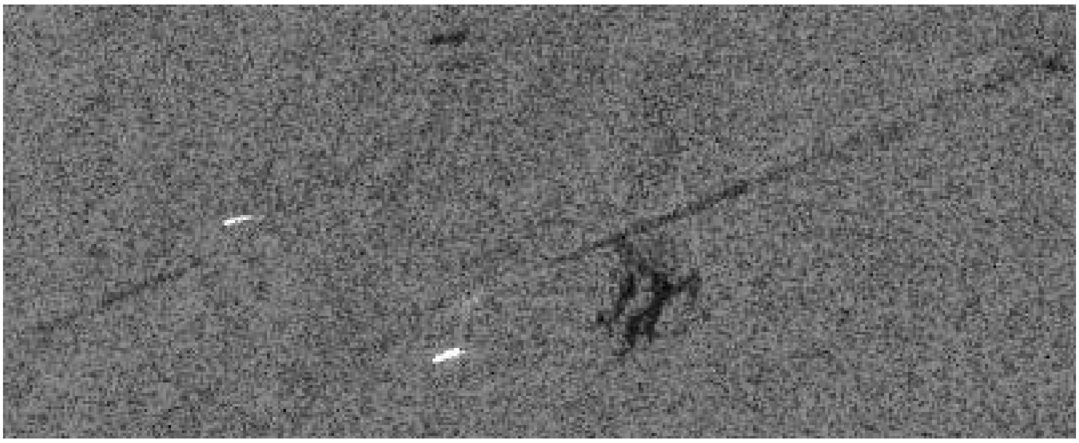

Figure 1. ERS-2 SAR image (original copyright ESA 1996) showing two ships and their turbulent wakes. The wakes are offset from the ships' headings due to SAR processing artefacts, from which ship speed can be inferred.
Image courtesy of CRISP website at http://www.crisp.nus.edu.sg.

NUS in Singapore are developing automated techniques for detecting and classifying ships from SAR wake images.

The remarkable part of this observation is that the vessel need not be on the sea surface to leave such a trail. SAR images exist that show several naval vessels proceeding in convoy, each leaving a turbulent wake signature behind. The exciting thing is that there are two more wakes than visible ships[3]. Two wakes are not terminated by a bright SAR reflective spot as expected from a surface vessel (which acts like a very effective corner reflector) but by nothing at all. The conclusion is that submerged vessels left these two turbulent wake trails, invisible by direct means.

One might expect such turbulent wake fields to be particularly evident in shallow water, where submerged vessels cannot be far below the surface and the turbulence energy is confined by the water depth.

There is now a new French satellite (SPOT) that operates in the visible EM band and which can be used to accurately measure the ocean surface colour. In regions of algal bloom and other similar biological activity, or where rivers with high suspended sediment flow into the sea, one effectively has a colour tracer in the ocean. A submerged vessel would stir up the water column and can be expected to leave a surface expression of different colour where such tracers exist.

Coming closer to earth, visual EM systems can be used to directly image dark objects below the sea surface. A hyper-spectral camera with a very high frame rate has been used with great success to image whales for the purposes of carrying out a population

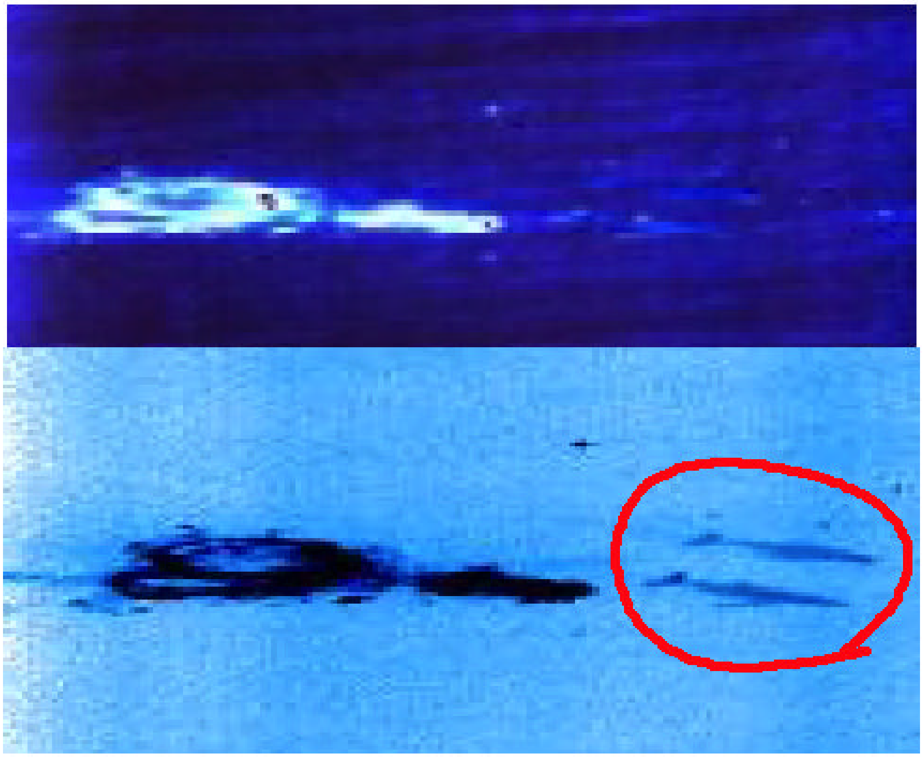

Figure 2. Upper image is raw hyperspectral data of the sea surface. Lower image is after correction to remove surface reflection. Two submerged whales are observed in the lower right area, indicated by the red pen. Figure adapted from[4]

census[4]. Although the whales do not appear on the raw colour image, special enhancement techniques (based on colour correlation differences between surface and sub-surface reflected energy) can be used to subtract the sea-surface reflection and reveal the dark objects beneath. In Fig. 2 the raw hyperspectral data can be seen in the upper panel, and the surface-reflected corrected data in the lower. A breaking wave event can be seen as a white streak in the upper panel, and appears dark in the lower. Two whales, invisible in the raw data, are clearly delineated in the processed data of the lower panel, circled in red pen.

The use of laser airborne bathymetry systems, again from aircraft, has also proven very effective for surveying depths under 50m. An Australian system has now been extensively tested and is in productive service, surveying difficult areas far more quickly and effectively than a surface vessel ever could[5]. An example image from airborne LIDAR bathymetric mapping adapted from this paper is given in Fig. 3. The high resolution (1.5m) and detail in the estuary depth contours far exceed that of

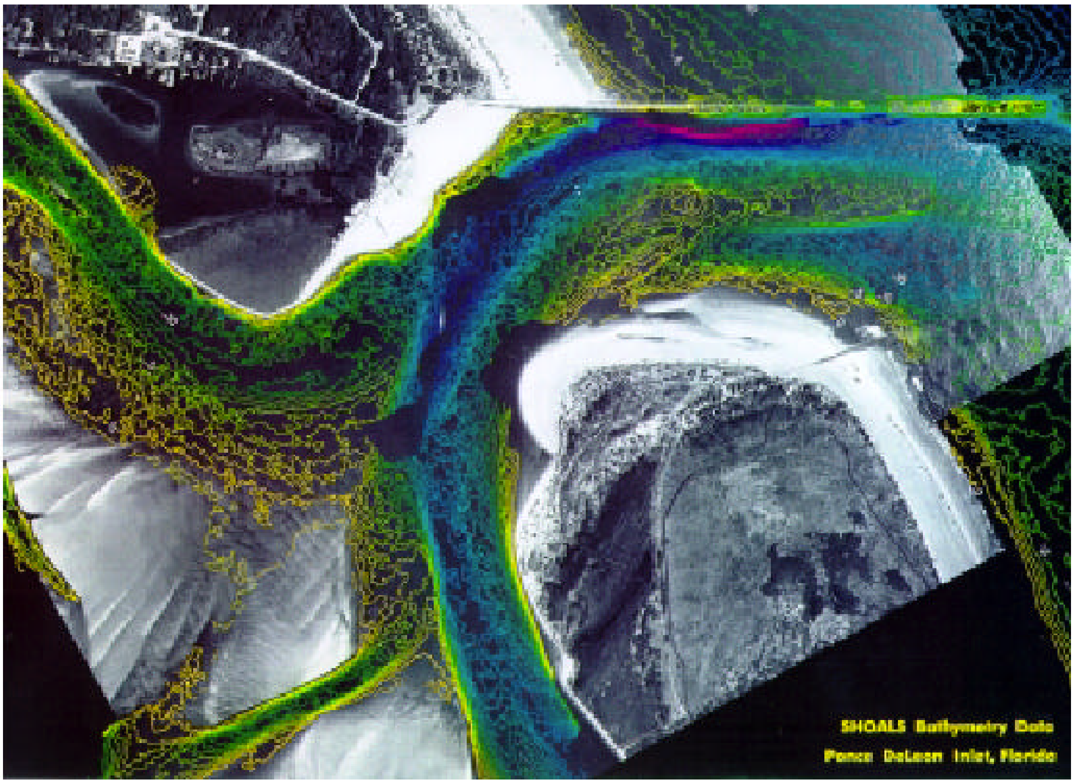

Figure 3. Airborne LIDAR bathymetric mapping of an estuary. The high-resolution (1.5 m) and consistent accuracy suggests that airborne LIDAR could be useful in shallow waters for the detection of submerged submarines.

conventional charts, suggesting that the same type of system, obviously with modified processing, could perhaps be used to detect submerged vessels and suspicious features on the sea bed in relatively shallow water.

Autonomous vehicles and probes

At the highest end of this group, and perhaps still strictly in the remote sensing category, are the autonomous automated aircraft drones. These can fly missions that can carry the type of hyperspectral cameras and radars that we have seen produce useful information when deployed from satellites and conventional aircraft. In Navy support, these drones would be capable of surveillance duties over large areas with high resolution at a fraction of the cost of piloted aircraft.

Dipping into the water itself, autonomous underwater vehicles (AUV's) have now matured, and many vehicles are now available for routine operational surveying tasks.

Figure 4. Daewoo Heavy Industries 'OKPO' Commercial AUV.
(Courtesy of Daewoo Heavy Industries Ltd)

Although government agencies still support much of the new AUV development, purely commercial companies are now beginning to produce AUV's as operational products for direct sale, such as the 'OKPO' from Daewoo Heavy Industries illustrated in Fig. 4. Combined with 'smart' mission profile interpretations, collision avoidance sonar, underwater acoustic modems and accurate inertial guidance packages, these AUV's are now able to carry out sophisticated surveillance tasks, patrolling areas to seek and map intruders and unfamiliar objects. A small fleet of AUV's can carry out patrolling and mine-detection duties over a far larger area than a single surface vessel towing a remotely-operated vehicle (ROV) and with far better coverage. The US is already using a covert AUV equipped with a periscope to penetrate hostile waters and map minefields.

In addition to the traditional, large AUV (which is still expensive, though much less so than a small surface vessel) there are now various autonomous probes appearing on the market that can carry out profiling tasks and report their findings for Rapid Environmental Assessment (REA) from a variety of support platforms. Some of these probes are expendable deployed from ships or aircraft, such as the shallow water expendable environmental profiler (SWEEP)[6]. Others can be recovered a few hours or days after deployment, such as Ocean Sensors' Autonomous Profiling Vehicle (APV) or the moored portable ambient noise data acquisition (PANDA) system developed by the ARL and PORL of the Tropical Marine Science Institute (TMSI) in NUS, Singapore. The use of such probes drastically widens the scope for multi-platform information fusion and exchange, improved systems performance estimation and tactical decision making. The ability to absorb multi-dimensional information effectively brings us to our next topic, data fusion.

Underwater laser scanning systems

Underwater laser raster scanning imaging systems have now successfully transitioned from prototypes to operational commercial products. Several companies offer commercial products, and at least one research institute in the US (Harbour Branch Oceanographic) has a specialised group that routinely builds laser scanning imaging systems to specification. Four of these systems are described in Table I, adapted from a paper by an HBOI researcher and colleagues[7].

	NCEL	USM	HBOI	Duke
Application	ROV inspection	Biological mapping	Biological mapping	Geological mapping
Range	0.5-2.0 m	10 cm	0.5 m	2.0–3.0 m
Angular Field (air)	40º x 40º	28º x 28º	28º x 28º	30º x 30º
Angular Field (water)	30º x 30º	21º x 21º	21º x 21º	22º x 22º
Accuracy	1 in 1000	1 in 200	1in 200	1 in 100
Pixel Resolution	134^2 to 800^2	200^{22}	200^2	100^2
Scan Rate	< 4 s	0.05 s	0.05 s	0.20 s
Laser Power	150 mW	10 mW	10 mW	75 mW
Laser Wavelength	532 nm	670 nm	670 nm	532 nm
Depth Rating	914 m	914 m	914 m	4,500 m
Viewports	Acrylic, dome	Acrylic, flat	Acrylic, flat	Acrylic, flat
Housing Size	57”L x 9” OD	28”L x 8” OD	29”L x 8” OD	12”&20”L x 9”$_1$ OD
Housing Material	Anodized AL	Anodized AL	Anodized AL	Titanium

Table 1. Design specifications for laser line scanners developed by HBOI (from Kocak et. al, 1999[7])

As Table I illustrates, the HBOI systems are limited in range to a few metres. Commercial systems are available which can penetrate up to 10-20 m in most waters, but in turbid water the effective range may be considerably less. Clearly, laser-scanning imaging can provide excellent resolution for close-up classification, but cannot yet fulfill the need for detection at any but the closest ranges.

Recently, several laboratories have demonstrated the use of temporal modulation and subsequent synchronous laser detection to improve imaging of subsurface objects in shallow water environments[8]. The technique relies on the synchronous detection of the reflected signal, a principle well known in signal detection theory. The advantage of this approach is that the signal return from the target is coherent with the transmitted waveform while the return produced from scattering is quasicoherent and represents noise. The idea is to achieve “processing gain’ via correlation of the transmitted and received signals against a "noise" background. If this approach can be made robust, it will extend the range of current lidar systems.

Active sonar

Active sonar is, of course, the oldest subsurface naval technology for detecting and classifying targets. This is not to say that progress and new developments have ceased. With the shift from passive to active detection of submarines following the end of the cold war and the rapid fall in radiated noise levels from (especially small non-nuclear) submarines, there has been a flurry of new developments. Three of the major new areas are in Low Frequency Active Sonar (LFAS), Parametric sonar and very high frequency imaging systems.

LFAS is a concept promoted by the US Navy to detect submarines at ranges large enough to prevent unsuspected attack. It is particularly effective in the protection of a capital battle group in deep water. I would have like to have shown a picture or drawing of LFAS in this paper, but such images are classified. The principle is to detect a submarine while still outside torpedo range, and then to scare it away or to neutralise it by dispatching a destroyer or similar vessel to deal with the threat. The sonar relies on the ability of the deep ocean to propagate low frequency sound with little loss. An ideal frequency band for propagation might be in the range of 20-100 Hz. Unfortunately, small submarines, perhaps of 6m hull diameter, have a low back-scattering cross-section at these frequencies due to diffraction. An ideal detection frequency might therefore be somewhat higher, closer to 200-500 Hz. The US LFAS system uses a number of signals spanning the range 100-500 Hz, including windowed CW and various FM chirps. Details are classified. Again, different signal modulations optimise different aspects of the detection and classification system. Hyperbolic chirps are excellent for range resolution. Windowed CW is good for Doppler speed estimates. Longer signals optimise processing signal to noise ratio by using pulse compression. The length of a signal must be optimised for the temporal coherence of the situation, which will change with location and target geometry.

In practice, the choice of a signal or signals from a library of options is made adaptively depending on the findings of previous signals, the local environment and the need to detect, or classify a pre-detected target. LFAS embodies several of the emerging technological features to be found in most leading-edge systems

- Broadband
- Adaptive
- Bi- or Multi-static
- 'Smart' processing

Gone are the days of designing monostatic proprietary systems with fixed transmit and receive characteristics. Modern systems are open-architecture, broad bandwidth and adaptive in terms of the way they can be operated at all levels. This includes every aspect from the transmitted signal to the processing of the received echo. Such systems are now routinely constructed from Commercial Off-The-Shelf (COTS) components. This both reduces the cost, increases the reliability and maintenance options and allows for more flexible growth and upgrading in the future development of the system.

The second major area of active sonar development is in the use of parametric sonar. While the LFAS system is tailored for deep water, parametric sonar is finding advocates in the area of shallow-water active sonar. The biggest problem facing active sonar in shallow water is reverberation. Shallow-water active systems are not usually limited by ambient or system noise. The difficulty is that the bottom and surface interaction is so strong that backscattering from these surfaces dominates the return echo. This effect scales with output power, so cannot be easily overcome. One way to fight this reverberation is to transmit the signal in a carefully controlled beam with little or no spatial sidelobes. Traditional beamforming requires large apertures to achieve low sidelobes, and this results in large and unwieldy transducer arrays. Parametric sonar relies on the non-linear interaction of two high-frequency signals to produce a lower-frequency beat-frequency emission. The sidelobes of the beat-frequency do not exceed those of the (much higher-frequency) transmit signals. Because sidelobes decrease as the aperture of the transducer array increases (in terms of wavelengths) the result is that a nearly-sidelobe-free transmit beam can be achieved from a compact transducer array operating at much higher frequencies than the beat-frequency emission. Relaxation processes quickly absorb high frequencies, so that in the far field, only the (desired) beat frequency remains.

Using parametric sonar, highly collimated beams can be directed into the bottom and sub-bottom to detect buried or partially-buried mines. Parametric beams can also be used to search the water column, steering the beam like a narrow torchlight through the region of interest without incurring blinding backscatter from energy which leaks into angles which interact strongly with the surface or bottom.

The reason that parametric sonars have not been developed for active-duty systems until recently is that the efficiency is extremely low, yielding perhaps only 2-4% of the input energy, due to the weakness of the non-linear interaction. Recent developments have stabilised the performance and achieved acceptable levels of efficiency. A major US sonar company has now built a parametric sonar for the US Navy Fleet. While prototype testing has revealed some shortcomings, the problems are expected to be resolved in the next year or two and we can expect the littoral US Navy to be parametric-equipped in perhaps five years from now. Another major US sonar company has built several units of a 2-D parametric sonar array for the German Navy, where it is in successful operation.

The third area of recent development is in very high frequency (VHF) imaging systems. Finding objects in turbid waters with underwater video is a problem due to the lack of visibility. High frequency acoustic signals suffer less scattering in turbid waters, so attempts have been made to produce an innovation in high-resolution underwater acoustic imaging. Until recently, it was not possible to handle the computational load associated with sonars with many (perhaps 100-1000) receiving elements at high frequency (100 kHz – several MHz). The new systems coming onto the marketplace now use sparse arrays, to reduce the number of elements, and modern DSP power to achieve real-time imaging. There are at least two systems of interest that are now newly available, or in testing and about to become available.

The first system we shall present is a tri-band imaging sonar from a Norwegian company that operates at 150, 300 and 600 kHz. The range resolution varies from 50 mm to 100 mm, and the –3 dB beamwidth varies from 0.6 degrees to 2.5 degrees, with a field of view from 25 degrees to 90 degrees, depending on the band[9]. The system has sufficient computational power to run at between 5-10 frames per second with 1600 receivers, and can image objects up to 100m range. The data rate is some 160 Mbits/s, a large number, but still only 10% of ROMANIS's data bandwidth, which we will discuss later under 'Ambient Noise Imaging'. The advantage of this system is that it can easily be mounted on an ROV to provide a 'vision' capacity in turbid waters easily capable of mine detection, pipeline following, inspection, etc. Furthermore, the system is already commercially available at a competitive cost in the region of S$500k.

Figure 5. the 'Echoscope' VHF active imaging sonar. Image courtesy of Omnitech (http://www.omnitech.no)

The second VHF active system we shall mention is an Australian single-frequency imaging system, built in conjunction with Thomson Marconi Sonar on very similar lines to the Norwegian device but operating at a frequency of about 3-4 MHz[10]. A prototype system, primarily intended for acoustic mine imaging, has been successfully tested in turbid waters and is designed to detect the difference in the slot of a straight and Phillips' head screw. The resolution at close range is of the order of 1 mm. The receiver uses a random array of sparse receiving pillars, assembled in collections in 'smart tiles' with amplification electronics bonded directly to the ceramic sensors. Although a commercial product is not expected to be available until 2001, one can safely assume that this device will have a somewhat shorter range than the Norwegian system, in the region of 5-20 m, but with higher resolution. Such a system would be capable of highly discriminate classification and inspection. Operated in tandem with other sensor systems, it could provide the closest-look highest-resolution step of a hierarchy of detection and classification processes.

Ambient Noise Imaging

In 1985 Prof. Michael Buckingham began to develop the idea of Acoustic Daylight (AD) imaging, using ambient noise in the ocean to form images of silent objects much as we use the random light around us to see objects that do not glow in the dark. In 1992 Buckingham and Potter, then at the Scripps Institution of Oceanography, obtained a US Navy research grant to develop a prototype AD system. In 1994 this prototype, named the Acoustic Daylight Ocean Noise Imaging System (ADONIS), was deployed for the first time. ADONIS was immediately successful, producing identifiable images with a resolution of 1m at up to 40m range using only ambient noise[11]. The results appeared in an award-winning paper in Scientific American in 1996[12].

Nevertheless, the images were highly variable in quality, and the statistical vagaries of ambient noise illumination resulted in many false images and unsteady detection. AD was not yet ready to transition to a prototype system. After leaving Scripps, Prof. Potter worked on the signal processing aspects of using ambient noise to image silent objects with support from the Singapore Defence Research Directorate (DRD). The result was the development of several new imaging approaches and a Kalman filter solution to the problem of how to track targets reliably through varying noise illumination. This collection of imaging techniques, which include the original AD principle but extend far beyond those simple beginnings, has been termed Ambient Noise Imaging (ANI)[13].

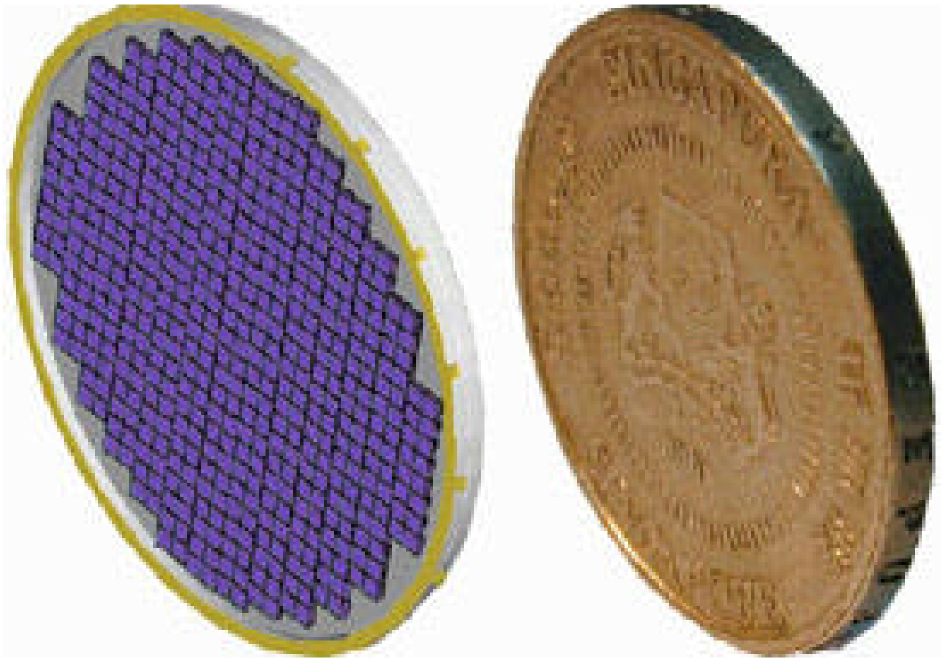

Figure 6. The ROMANIS 25-85 kHz ANI array (left) shrunk to the size of a Singapore $1 coin (right) for comparison of the form factors.
The ROMANIS array is 1.4m in diameter and some 85 mm thick.

Although ANI is not yet ready for system implementation, a second-generation research ANI imaging array is being built at the Acoustic Research Laboratory (ARL, http:/arl.nus.edu.sg) in Singapore with DRD support. This array, called the Remotely Operated Mobile Ambient Noise Imaging System (ROMANIS) will be ready at the end of 1999 and will be tested in local waters in the first half of the year 2000[14]. The ROMANIS system operates in the bandwidth of 25 – 85 kHz, much lower than the VHF imaging systems described above and has an aperture of 1.4m, larger than the VHF systems to retain good resolution. ROMANIS' angular resolution is similar to the Norwegian imaging sonar, achieved by means of the larger aperture. The data date from ROMANIS will be some 1.6 Gbit/s, 10 times that of the Norwegian imaging sonar, or any other sonar known to this author. The imaging range will also be several hundred m, up to perhaps 1 km, 10 times that of the Norwegian system. The development of ROMANIS is therefore of a technological sophistication on a par or exceeding anything worldwide. The electronic and mechanical sophistication of ROMANIS has resulted in some 500 sensors and more than 50 Pentium PC computers being connected without wiring harness and in a thin circular array with a form factor no thicker than a coin, see Fig. 6. This has become possible by the adoption of leading-edge networking protocol technologies (Fibre-channel). Again, the use of commercial off-the-shelf (COTS) technology is being used to streamline the design and keep costs down, while improving upgradability and growth paths. Because ROMANIS is fully software configured, it embodies the trend to adaptive configuration, in addition to being broad-band.

If ROMANIS performs as simulations and theoretical calculations predict, it will add a completely covert capability to the current line-up of underwater imaging systems, covering ranges from a few metres to perhaps a kilometre for the detection of larger targets. This capability will be more advanced than anything available outside Singapore, including the USA. If used as the passive receiver of an active system, ROMANIS' performance will compliment the range and resolution of VHF active systems and fill the gap between these and traditional sonars.

While the range limitations of ANI are severe compared to active sonar, the overriding advantage is that ANI is completely covert and operates against completely silent targets. This cannot be achieved with any other sonar system. Only laser scanning systems can compete in this way, and their range is even shorter, perhaps 10-20 m in local turbid waters. In general, a rough rule of thumb is that laser systems can operate at 2-4 times the range of optical vision. ANI thus offers a complimentary capability, suitable for the covert investigation of smart mines (which detect active sonar interrogations) and other intelligent targets. ANI could be used, for example, to police and patrol restricted areas without alerting intruders that they have been detected.

Covert active sonar

The division of sonar systems into active, passive, and now ANI is in fact rather artificial. As a solution to the limited range of ANI systems, Prof. Potter has suggested that a hybrid system could be developed, which we shall term covert active. The idea is to use a broadband passive or ANI receiving system and add an active capability that transmits signals, which are not readily distinguished from natural ambient noise. Potential targets would then not be aware that they were being illuminated.

These pseudo-random signals could be modelled after snapping shrimp or breaking surface waves (when high-frequency, broadband transients are useful) or more like shipping noise (when near-CW would be useful). Broadband high frequency is best for robust resolution in target classification. Lower frequency CW is best for long-range detection and Doppler estimation for target speed estimation.

The potential advantages of covert active are enormous. The transmit signals could be at very low power, substantially below the true ambient noise and thus undetectable, because the signal would be orthogonal and designed to achieve a high signal to noise processing gain by the use of pulse-compression when processed with a matched filter. Covert active detection ranges would be similar to active systems using similar frequency bands, without the disadvantage of being overt.

The ability to deploy a covert active system requires several advanced technology components, which are now coming online:

- A sufficient understanding of the local ambient noise statistical structure in space and time. This is required so that the pseudo-random signal can be effectively camouflaged. The spatial and temporal structural information can be acquired for 'home waters' by traditional long-term observation and for novel theatre areas by using REA techniques including ROV's and AUV's as discussed above.
- An ability to operate at least bistatic active and preferably multi-static active sonar topologies. Multi-static active systems require advanced processing and data fusion combined with sophisticated data link and Communication, Command and Control (C3) protocols.
- A flexible, software-configured broad-band transmit and receive capability, so that a wide range of signals can be used from a library covering all frequencies and signal types of value. Such a capability is a very new feature of sonar systems, and not yet fully available in most off-the-shelf packages.

Magnetic & electric field detectors & gravimetric techniques

The use of magnetic, electric and gravimetric field sensors to detect objects underwater has undergone a periodic 'pendulum swing' of interest over several decades. The problem with these approaches is generally that the signal is very weak and superimposed on a very high level of noise which is statistically highly variable, so that the natural environment often appears as a target signal, and targets often pass unnoticed.

Recent advances in the interpretation of the time-varying nature of both natural noise and target signatures has resulted in some gains in this regard. Additionally, helium-cooled sensors are now able to detect objects the size and mass of a paper clip at 2m range. Unfortunately, the sensitivity falls off rapidly with increasing range, so that it requires a target the size of an aircraft carrier to result in detection at a range of more than a few nautical miles.

Finally, the improved neutralisation of magnetic signatures from vessels and the use of non-metallic materials moves to negate the advances made in sensor technology and signal processing.

Data, system and platform fusion

Having briefly reviewed the maturing technologies now being brought to bear on naval combat, a number of obvious trends become apparent in future trends:

- A greater diversity in types of information (not just sonar and radar)
- A greater number of complimentary systems, working in concert
- A greater diversity in types of platforms (satellites, ships, aircraft, ROV's AUV's)
- A greater number of platforms

The information gathered from all these resources must be assimilated effectively if it is to provide improved tactical decision support. This assimilation process is complicated by two main factors:

- The source information is of many different types, spatial and temporal resolution
- The source information comes from many different platforms at different rates

The degree of difficulty increases substantially with multi-static sonar systems replacing more conventional monostatic or bistatic. The ability to process these data effectively and to fuse the result into a single tactical display is a major area of active research, going beyond but including C^3. For example, 3-D and 'CAVE' (fully immersive computational environments) are being explored at several advanced institutes, including the IHPC in Singapore, for their potential to display multi-dimensional data.

However, the task goes deeper than these issues. Effective data assimilation and fusion is but the first step. To derive the full benefit of the computational and data resources, the following assets also need to be seamlessly integrated:

- Historical databases in the form of GIS or similar architecture.
- Real-time spot-measurement updates.
- 3-D dynamic modelling of circulation and related ocean processes.

The component technologies named above are now in place. The coming decade will see the effective integration of these assets to provide a truly powerful data fusion capability, the output of which will be a dynamic and interactive, adaptive tactical display, available and custom tailored to all commanders in a group, giving as complete as possible a tactical picture of the situation and system performances. Research has already yielded encouraging results in using AUV's to survey and import data into GIS systems[15]. The use of minehunting sonar to gather environmental information for inclusion in GIS has also been explored[16].

Signal processing developments

All of the previous sections have dealt primarily with the hardware side of new technologies. While many of there require and rely on the high computational power of modern processors, they do not include the development of new signal processing schemes and approaches. The last decade has seen a number of very promising developments and applications in this regard, including:

- Wavelet and other non-Fourier transform techniques
- AI and intelligent systems processing
- Statistical and Random Processes estimation in shallow water
- Broad band processing
- Synthetic aperture and interferometric active sonar
- Shallow-water matched field and inversion algorithms

Wavelet and other transforms have proven to be extremely powerful in the extraction of critical features of many types of signals. Additionally, it is possible to select wavelet bases which maximise the inter-group separations while minimising the intra-group variability, so that a discrimination algorithm classifies suspect signals which a far greater robustness. A high degree of compression of the original data is achieved as an added bonus, permitting results to be linked via a number of communication channels, including acoustic modem. The ARL in the National University of Singapore has been very active in this area of signal processing research, and the results have been most encouraging[17],[18].

Artificial Intelligence (AI) methods have also been increasingly applied to underwater signal processing tasks, and there is a large body of literature that has been developed over the last two decades on this area. Coupled with powerful feature-extraction transforms, such as the wavelet family, AI is proving to be a very effective tool in tactical interpretation and decision-making. The ARL in Singapore is actively engaged in developing AI and 'smart' processing algorithms for imaging and decision-making.

The statistical characterisation of shallow-water environments is difficult, because of the high degree of spatial and temporal structure, but necessary for successful operation in littoral waters and the prediction of system performance. For obvious reasons, a deterministic description is not possible for many aspects of the operational environment. An understanding of statistical characterisation and estimation is therefore of great importance.

Regrettably, space does not permit further discussion of the many other interesting signal processing and propagation advances that have been made in the last decade and which will impact the next.

Conclusion

This decade has seen a powerful shift of interest from deep water, large distant target detection and classification to littoral waters, small and varied target detection and classification at closer range. Not only has this resulted in a predictable shift upward in sonar frequencies, but it has also brought to play a host of other technologies by which we may image the underwater environment. Additionally, signal processing has moved ahead in the intelligent analysis of signals and automatic classification and prediction. Computational power has continued to double every 14 months or so, and propagation models have become more complete and accurate, including many more aspects of the environment and possible mismatch. The challenge is not in identifying useful technologies, but in bringing them to bear effectively on the tactical problems of naval combat scenarios. These technologies will make their mark when integrated using the following features:

- Data will be combined from multiple data collection platforms.
- Diverse platform types (surface and submarine vessels, ROV’s, AUV’s, drones, aircraft and satellites) will be used in concert.
- Diverse sensing technologies (multi-static passive & active, ANI, covert active, VHF active, laser) will be employed in a co-ordinated search over all useful ranges, bandwidths, resolutions and degrees of covertness required to span interests and needs.
- Systems will be open-architecture and modular to facilitate growth and reconfiguration.
- Systems will employ ‘smart’ processing and AI in the detection, classification and prediction of environmental developments.
- Data fusion and visualisation will be required together with integration of historical data from GIS and similar sources, real-time spot measurement updates and 3-D dynamic modelling.

The future thus holds a rich potential for the application of advanced sensor technologies and signal processing that is already proven and ready to be integrated into systems. The challenge will be in the fusion.

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