10_Sonar

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Development and Applications of Sonar and Array Technologies

- **Historical Development of Sonar and Array Technologies**
  - Sonar and array technologies have evolved over the past **100+ years**.
  - This paper focuses on **recent advancements** in these technologies while highlighting earlier sonar types.
- **Demands and Advancements in Sonar and Arrays**
  - The paper discusses **current demands** placed on sonar and array systems.
  - The **state-of-the-art** includes advancements in:
    - **Single-beam and multi-beam sonar**.
    - **Side-scan sonar** and **synthetic aperture sonar**.
    - **Acoustic Doppler Current Profilers (ADCP)**.
    - **Sonobuoys** and **variable depth sonar**.
- **Array Types**
  - Technologies such as **SURTASS-LFA** (Surveillance Towed Array Sensor System Low Frequency Active sonar) and **towed arrays** are emphasized.
- **Applications of Sonar and Arrays**
  - **Underwater activities** leveraging sonar:
    - **Seafloor excavation**, **cable and tube laying**, **off-shore oil, gas, and mineral production**.
    - **Hydrography**, **bathymetry**, **underwater archaeology**, and **fishery studies**.
    - **Naval applications**:
      - **Anti-submarine warfare (ASW)**, **mine and torpedo hunting**, and **wreck investigations**.
      - **Study of underwater structures** in harbors.
- **Threats and Countermeasures**
  - The paper discusses **current threats** in **harbors and waterways**.
  - It also highlights **countermeasures** and **technologies** related to **WaterSide Security**.
- **Parametric Acoustic Array Sonar**
  - The paper concludes with a brief overview of the **state-of-the-art in sonar** based on **parametric acoustic array principles**.

Development and Applications of Sonar and Array Technologies

- **Electroacoustic Transducers and Sonar Development**
  - The **twentieth century** witnessed rapid growth in **electroacoustic transducers**, a trend that continues into the **twenty-first century** due to increasing underwater applications.
  - The **SONAR** concept originated during **WWII**, standing for **Sound Navigation and Ranging**.
    - **Passive sonar**: Detects objects by receiving sound emitted from them.
    - **Active sonar**: Uses **echo-ranging** to locate objects by receiving reflected echoes.
  - The need for **sonar technology** grew from the **nineteenth century** and was accelerated by events like the **Titanic disaster** and **WWI submarine activities**.
- **Recent Developments in Sonar and Array Technologies**
  - The paper focuses on **modern advancements** in **sonar** and **array technologies**, with a historical overview of early **twentieth-century** developments.
  - Special attention is given to **applications in WaterSide Security** and **Parametric Acoustic Array technology**.
- **Sonar and Array Requirements Based on Application**

- Key features of sonar and array systems are **closely linked** to their **specific applications**:
  - **Carrier frequency**: Ranges from **below 50 Hz to above 500 kHz**, influencing the range of application.
  - **Pulse length**: Varies from **microseconds to milliseconds**, impacting **axial resolution**.
  - **Bandwidth**: Measured by **mechanical Q-value**, ranging from **below 2 to above 10**, affecting **resolution** and **power level**.
  - **Dual-frequency use** (e.g., **12 kHz/24 kHz or 200 kHz/400 kHz**) improves **range** and **resolution**.
  - **Directivity patterns**: Vary from **below 1° to omnidirectional**, influencing **image quality** and **resolution**.
- **Key Factors Influencing Sonar and Array Performance**
  - **Transmitting and receiving responses**:
    - **Transmitting** (dB // 1µPa/V @ 1m) and **receiving** (-dB // 1V/µPa) responses affect **sonar quality**.
  - **Power handling capabilities**: Ranges from **below 50 W to several tens of kW**, determining the need for **battery** or **cable power supply**.
  - **Operating depth**: Sonar and array types are classified based on their operational depth, ranging from **a few meters to over 6000 meters**.

Single-Beam Echo Sounders (SBES)

- **Overview of SBES**
  - **Single-Beam Echo Sounders (SBES)** have been a foundation for sonar systems for many years and are still **produced and sold** by several companies.
  - An SBES consists of **transmitting and receiving parts**, which have been modernized in terms of **hardware**, **firmware**, and **software**.
- **Basic Operation**
  - A **sinusoidal pulse**, controlled by a **master clock**, is amplified through a **power amplifier**.
  - **Acoustic power** is determined by the **water depth** and **carrier frequency**.
  - **Receiver processing**:
    - The signal is **time-gated** to prevent direct reception of the transmitted signal and to avoid the influence of **transmitter ring-down**.
    - The signal passes through a **band-pass filter** to remove **ambient noise** and **ship's self-noise**.
    - The signal is then processed through **Time-Variable-Gain (TVG)**, where amplification is adjusted based on the **received signal amplitude** from different depths.
- **Modern SBES Features**
  - Many **SBES models** now allow **raw data output** for **processing and display** via a **PC**.
  - **Frequency bands**:
    - The **carrier frequency** can be tuned in **1 kHz increments** within a specified frequency band.
    - **Echo sounder resolution** is determined by the **carrier frequency** (typically **10 kHz to 600 kHz**) and the **pulse length**.
    - **Short pulses** for hard bottoms (e.g., rock), and **longer pulses** for soft bottoms (e.g., mud).
- **Additional Features and Operational Considerations**
  - **Automatic Gain Control (AGC)** ensures that the received echo stays at an **acceptable level**.
  - The **ship's speed** over the seafloor must be factored in when selecting **screen speed and scale**, especially at depths over **100 meters**, as the ship's speed determines **SBES coverage**.
  - **Ship's motion** and the position of the **sonar projector** relative to the environment

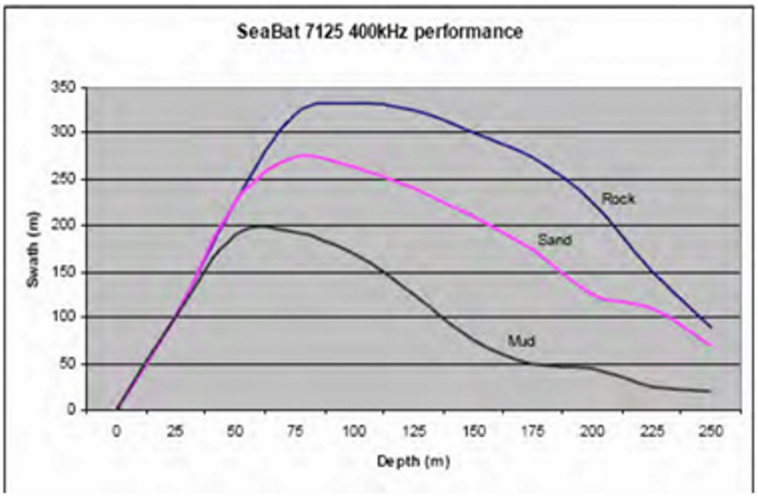
can affect **data quality**.
    - **Tide and heave** (vertical movements of the ship) can introduce **errors** in depth measurements, which must be removed via **post-processing** to avoid **artificial waves** in the seafloor data.
- **Side-Looking-Sonar (SLS) Option**
    - Some **MBES** systems are equipped with **Side-Looking-Sonar (SLS)**.
    - **SLS** should not be confused with the capabilities of **real Side-Scan Sonar**.

Multi-Beam Echo Sounders (MBES)

- **Advantages Over SBES**
    - The **Multi-Beam Echo Sounders (MBES)** overcome many of the inherent limitations of **Single-Beam Echo Sounders (SBES)**, including:
        - **Reduced resolution**.
        - **Limited swath coverage**.
        - **Longer and more expensive operational time**.
        - **Lower data reproducibility**.
- **MBES Operation**
    - MBES operates by emitting a **fan of single beams** with **small individual beam widths** and **narrow separation angles**.
    - The **best MBES systems** today use beam widths between **0.5° and 1°**, covering **more than 800 beams**.
    - **Hydrographic applications** benefit from a **wide swath coverage** with a **theoretical maximum swath width** of about **7.5 times the water depth**, utilizing a **150° total fan angle**.
- **Increased Soundings and High-Density Footprints**
    - **Equi-distant beam forming** and **equi-angle beam forming** technologies are used to increase the number of soundings per square meter and form **high-density footprints**.
    - For **equi-angle spacing**:
        - The **number of beams per degree** stays constant as the **beam steering angle increases** from nadir.
    - For **equi-distant spacing**:
        - The **number of beams per degree increases** as the steering angle increases, providing higher beam density toward the edges of the swath.

MBES Beam Spacing and Performance Considerations

- **Beam Spacing and Footprint Area**
    - As the **steering angle increases**, the **center-to-center spacing** between each beam's intersection with the seafloor **decreases**.
    - This effect is due to the **beam footprint area** being defined by the **cone created by the half-power beamwidth** of the beam in the beam fan.
    - To maintain **uniform sounding spacing**, the **beam center-to-center spacing** must **decrease**, which requires **increasing the number of beams** in the **equi-distant mode**.
    - For example, in the **RESON SeaBat 7150 operating at 24 kHz**:
        - **256 beams** are formed in the **equi-angle mode**.
        - **880 beams** are formed in the **equi-distant mode** to achieve more uniform beam spacing.
- **Variable Swath for Increased Data Density**
    - A **variable swath** is needed to increase **data density** and detect smaller objects.
    - **Swath width** is influenced by:
        - **Water depth** and **sonar frequency**.
        - **Seafloor materials**:
            - A **hard bottom** like rock leads to a **broader swath width**.

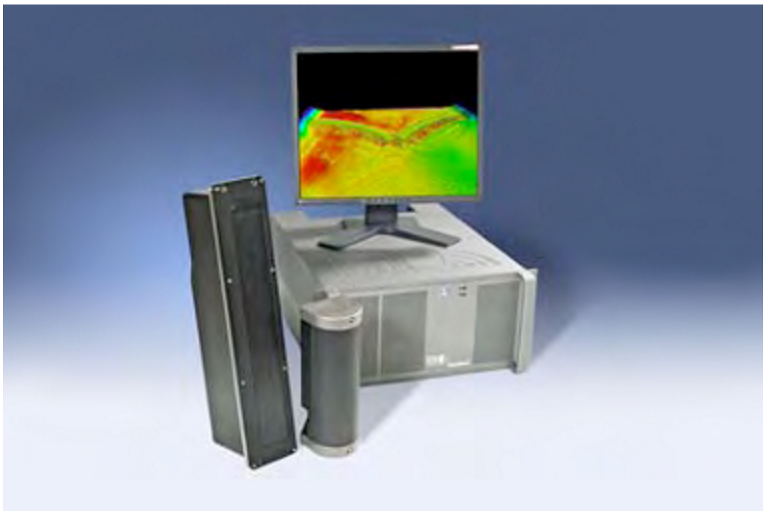


- ▫ **Mud** results in a **narrower swath width** due to **lower reflection** and **higher sound attenuation** (Figure 2 shows this for the **SeaBat 7125 at 400 kHz**).

- **Environmental and Installation Effects on Performance**
  - **Environmental factors** such as **salinity**, **temperature distributions**, and **sound attenuation** can degrade **MBES performance**.
  - **Installation conditions** also significantly affect performance:
    - **Bubbles**, **water flow**, **propeller noise**, **engine vibrations**, and **bulkhead vibrations** may:
      - ▫ **Reduce the swath width**.
      - ▫ **Lower the resolution** of sonar images.

Platform Motion and Sonar Image Quality

- **Influence of Platform Motion**
  - The **motion of the sonar platform** affects **sonar image quality** and **reduces the swath width**.
  - **Compensation for roll and heave** is implemented in modern sonar systems to counteract these effects.
  - **Pitch movement**:
    - The **platform's pitch** (its inclination in the longitudinal plane) influences **seafloor coverage**, particularly in **intermediate and deep-water surveys**.
    - To keep the **transmit beam vertical**, **motion sensors** with **pitch steering** are used, allowing the transmit beam to be steered **up to ±10°** from vertical.
- **Receiver Unit Components in MBES**
  - The **receiver unit** of a MBES includes:
    - **Receiving transducer array**.
    - **TVG (Time-Variable Gain)** facility.
    - **A-D conversion electronics**.
    - **Filters** and **demodulation facility**.
    - **Beam former** with **steering electronics** for swath coverage.
- **MBES Performance Characteristics (RESON SeaBat 7125)**



- **Resolution** of **RESON SeaBat 7125** (Figure 3):
  - **Along-track receiving half-power beamwidth**:
    - **27°** at **200 kHz**.
    - **27°** at **400 kHz**.
  - **Across-track receiving half-power beamwidth at nadir**:
    - **0.5°** at **200 kHz**.
    - **1°** at **400 kHz**.
- **Challenges in Deep-Water Systems**
  - Several factors can degrade **swath coverage quality** in **deep-water systems**:
    - **Noise on outer beams**: Beams at the highest **fan angles**.
    - **High-amplitude second return signals**: These may come from **structures in the seafloor**.
    - **High-amplitude nadir return signals**: These signals are due to **multi-beam signal specular reflections**.
  - These factors may **saturate the receiver** and cause **abrupt signal drops** (up to **40 dB**) in the backscattered signals from directions other than nadir.
  - To mitigate this, **TVG facilities** are used to manage **signal variations**.

Modern Multi-Beam Echo Sounders (MBES) and Side-Scan Sonar (SSS)

Optimizing Data Collection with MBES

- **Quality Filter**:
  - Many modern MBES are equipped with a **quality filter** to enhance the selection of **good quality data**, improving the **data collection-to-processing ratio** and reducing the **operation time** required for data collection.
- **Autopilot for Sonar Parameters**:
  - Some MBES systems feature an **autopilot** that **automatically adjusts major sonar parameters** (e.g., **range scale**, **transmitted power**, **pulse length**, and **receiver gain**) to adapt to varying **environmental and bottom conditions**, reducing the need for operator intervention and **improving efficiency** and **cost savings**.
- **Data Collection Options**:
  - Modern MBES systems can also provide **side-scan sonar** data, **backscattering snippets**, and **raw data** for **post-processing** on a PC.

Side-Scan Sonar (SSS) for Seafloor Visualization

- **Purpose**:
  - **Side-scan sonar (SSS)** is used to **visualize the seafloor** and objects located **on or above** the seafloor, creating **2D high-resolution images** of insonified structures.
- **Transducer Setup**:
  - The **sonar transducer** can be mounted on a variety of platforms:

        - **Bottom of a surface vessel**,
        - **Pole over the side of the vessel**, or

        - **Towed body** (see **Figure 4**).
- **Single or Dual Transducer Setup**:
    - A side-scan system can have **one transducer** radiating sound to one side or **two transducers** to cover a **broader seafloor region**.
- **Multi-Row SSS**:
    - Some systems may include **multiple rows (staves) of transducer elements** to form a **multi-row side-scan sonar**, which uses **interferometry** to improve **data quality**.

SSS Beam Characteristics

- **Beam Orientation**:
    - The **axis of the transducer beams** is tilted **downwards towards the seafloor**.
    - The beams are **narrow in the horizontal (azimuthal) plane** and **wide in the vertical plane**, allowing the system to insonify a **swath-like portion** of the seafloor.

Operational Benefits of Near-Seafloor Deployment

- **Towing and Speed**:
    - When mounted on a **towfish**, the side-scan sonar is typically **towed at slow speeds** close to the seafloor, providing **high-frequency echo ranging** at **low grazing angles** with **high sampling rates**.
- **Increased Range and Vertical Resolution**:
    - **Shorter distances** between the sonar and the seafloor allow for the use of **higher frequencies**, which improves both **range resolution** and **vertical resolution** of the seafloor surface profile.
- **Reduced Influence of Sound Velocity Profile**:
    - The **sound velocity profile** has less influence on **sound propagation** when the SSS operates near the seafloor compared to when it is mounted on a surface vessel.

Applications and Resolution of Side-Scan Sonar (SSS) and Synthetic Aperture Sonar (SAS)

Applications of Side-Scan Sonar (SSS)

- **Detection and Identification**:
    - SSS is used to **detect and identify underwater objects** and **bathymetric features** for the creation of **nautical charts**.
    - It helps distinguish between **different seafloor materials** and their **textures**.
    - SSS detects **hazardous items on the seafloor** that could be dangerous to shipping, and identifies **exposed cables and pipelines** that are vulnerable to ship anchors.
    - It is also used to locate **objects of interest in marine archaeology**.
- **Additional Applications**:
    - **Environmental studies**, **dredging operations**, **fishery research**, and **naval mine**

detection.
    - In **confined areas** like **ports and rivers**, where towing a platform is impractical, SSS can be **hull-mounted** or **mounted on a pole** over the side of a **surface vessel**.

Resolution in Side-Scan Sonar

- **Transducer Elements and Frequency**:
    - The **length of transducer elements** and the **operating frequency** determine **horizontal resolution**.
    - **Longer transducer elements** and **higher frequencies** provide **higher resolution** but at **shorter ranges**.
    - Higher frequencies also result in **reduced swath width** due to **sound attenuation**.
    - There is a limit to how **long a transducer** can be on a **towfish** or **AUV**, meaning **acceptable along-track resolution** is only achievable **near the transducer**.
- **Improved Resolution with Synthetic Aperture Sonar (SAS)**:
    - **SAS** improves **along-track resolution** at greater transducer distances by using the sonar transmitter to **continuously illuminate a target** while moving along a known path.
    - This motion **increases the effective length of the receiver aperture**, making the aperture appear much longer than its **real physical length**.
    - **Signal processing** coherently combines received pulses to form an **image with significantly improved resolution**, offering an **order of magnitude** improvement in resolution.
    - The **synthetic aperture technique** is adapted from **radar technology**, where **Synthetic Aperture Radar (SAR)** has been extensively used.

Synthetic Aperture Sonar (SAS) and Resolution Enhancement

Virtual Broadside Array in SAS

- **Array Movement and Target Illumination**:
    - The **virtual broadside array** formed by the **SAS** illuminates the same target on the seafloor with **multiple pulses** as the sonar moves along its trajectory.
    - The **SAS length** is determined by the **positions where the target is illuminated** by the sonar beam within its **-3 dB beamwidth** during the movement.
    - A shorter **transmitter array** improves **along-track resolution**, but **reducing array length** can negatively impact the **transmitter/receiver array speed**, affecting **range resolution**.
    - **Range resolution** is proportional to the **receiver array length**, as to avoid grating lobes, the **receiver array must move less than half its length** between consecutive echoes.

Advancements in SAS Technology

- **Navigation and Stability Requirements**:
    - Previously, a **very stable platform movement** and **accurate trajectory determination** (better than **1/8 of a wavelength**) were required.
    - **Recent advancements** in **electronics** and **signal processing** have allowed the development of **attitude sensors** for more accurate **navigation**.
- **Autofocusing and Motion Estimation**:
    - **Phase Gradient Autofocus (PGA)**, originally developed for **SAR** (Synthetic Aperture Radar), is now applied to **SAS** to improve **image quality**.
    - **Sonar micronavigation** and **inertial navigation** systems enable corrections for **sound velocity errors** and **SAS array movements**.
- **Resolution Improvement**:
    - **Nearfield beamforming** and **appropriate motion estimation** can increase **along-track resolution** of SAS by a factor of **10 to 100** compared to traditional **SSS**.

Global Developments in SAS

- SAS development is ongoing in several countries, including:
    - **Italy**, **Japan**, **USA**, **France**, **New Zealand**, **Norway**, and **Sweden**.

Other Sonar Types and Their Applications

Acoustic Doppler Current Profilers (ADCP)

- **Applications**:
  - **ADCPs** are used for measuring:
    - **Water current velocities** at various depths.
    - **Wave motion** on the sea surface.
    - **Vessel speeds** across the seafloor.
- **Doppler Effect**:
  - The **Doppler effect** produces a **frequency shift** proportional to the **velocity**, allowing for measurements of flow and motion.
- **Vessel Mounted ADCP**:
  - An **ADCP** mounted on a vessel can act as a **Doppler Velocity Log (DVL)**, using **seafloor echoes** to monitor the **speed of the vessel or subsea vehicle**.
- **Correlation Log**:
  - A **DVL development**, where the **ratio of the distance between two sonar array elements** with maximum **cross-correlation** and the **time delay between seafloor echoes** provides **vessel speed over the seafloor**.

Acoustic Transponders

- **Increased Use**:
  - The use of **acoustic transponders** has grown significantly for:
    - **Accurate positioning** of surface and subsea vehicles.
    - **Positioning of divers** and **underwater interventions**.
- **Positioning Systems**:
  - **Long Baseline (LBL)**, **Short Baseline (SBL)**, and **Ultra-Short Baseline (USBL)** systems have been developed using **transponders** mounted on vessels and/or the seafloor for **precise positioning**.

Sonobuoys and Variable Depth Sonar (VDS)

- **Sonobuoys/VDS Use**:
  - **Sonobuoys** or **Variable Depth Sonar (VDS)** are used to:
    - **Penetrate below the sea surface thermocline**, avoiding **acoustic shadow zones** created by downward refraction of sound waves due to **negative sound velocity gradients** near the surface.
    - Improve **acoustic reception** by positioning sonar at different **depths**.

Sonar Arrays and Towed Arrays

Types of Sonar Arrays

- **Purpose of Arrays**:
  - Arrays are formed by **single element transducers** arranged to improve:
    - **Signal directivity**.
    - **Acoustic signal power**.
    - **Beam forming**, **beam steering**, and **shading**.
- **Common Array Types**:

  Line Arrays: Includes both **discrete elements** and **continuous elements**.
  Planar Arrays: Includes **circular**, **quadratic**, and **rectangular** arrays with various geometries.
- **Array Directivity**:
  - Individual array elements are typically **omni-directional**, but the array itself exhibits **substantial directional properties** normal to its extension or surface.
  - The **directivity function (D)** of an array and its **directivity index (DI)** are related by **DI = 10 log D**, though further discussion is beyond this scope.
- **Signal-to-Noise Ratio**:
  - Arrays, especially arrays of **hydrophones**, provide a significantly improved **signal-to-noise ratio (s/n)** compared to using a **single hydrophone**.

Towed Arrays

- **Development and Use**:
  - The **towed array** has undergone significant development, influenced by **oil prospecting** and **military applications** during the **Cold War**.
  - **Naval applications** require **passive listening** at **low frequencies** with **enhanced directivity**.
  - **Oil companies** require higher **sensitivity** and **dynamic range** (greater than **120 dB**), leading to the development of **moveable arrays**.
- **Structure of Towed Arrays**:
  - **Hydrophones** in towed arrays are typically **cylindrical**, **spherical**, or **disc-shaped piezoceramic elements**.
  - The **hydrophones** are arranged along a **flexible plastic or rubber hose** filled with liquid, and the hose's **diameter** typically ranges from **< 25 mm to > 100 mm**.
  - **Number of Hydrophones**: A typical towed array can have **several hundred to nearly 2000 hydrophones**.
  - **Size of Hydrophones**: The hydrophones are **small** compared to the **wavelengths** to be measured.
- **Noise Reduction**:
  - To minimize **self-noise** from **turbulent flow** along the hose surface, modern towed arrays use **reduced outside diameters** and incorporate **fibre optics**.
- **Active and Passive Systems**:
  - **Active Towed Arrays**:
    - The **sound source** could be a **sonar transducer** (e.g., **flextensional type**) or an **airgun**.
  - **Passive Towed Arrays**:
    - Used for **listening** in sonar systems.
- **Improving Bandwidth**:
  - To cover several **octaves** in **passive towed arrays**, **nesting higher octave bands** within **lower octave bands** is useful for creating **broadband arrays**.

Surveillance Towed Array Sonar System (SURTASS-LFA) and Mills Cross Sonar Arrays

Surveillance Towed Array Sonar System – Low Frequency Active (SURTASS-LFA)

- **Function and Design**:
  - **SURTASS-LFA** is designed for **long-range detection** in the **100–500 Hz frequency band**.
  - The system uses a **vertical line array** of **up to 18 projectors** suspended below a vessel.
  - The **sonar beam** is **omni-directional in the horizontal plane** with a **narrow vertical beamwidth**, allowing for **steering** above or below the horizontal plane.
- **Source Level and Array Performance**:
  - Each **projector** operates like a **point source** with a **source level of 215 dB//1μPa**.
  - The **effective array source level (SL)** when all 18 projectors are operational is:
    - **SL = 215 + 20 log 18 = 240 dB//1μPa**.
- **Receive System**:
  - The **receive part** consists of an array of **hydrophones** towed **horizontally** behind the vessel.
  - The array is towed at a **depth of 150–500 m** at a speed of about **3 knots** to maintain horizontal motion.

Mills Cross Sonar Arrays

- **Array Configuration**:
  - A **2D planar array** can consist of two **discrete line arrays** mounted **perpendicular to each other**, forming a **Mills Cross**.
  - The **beam pattern** of the Mills Cross is identical to that of a **rectangular array** with equivalent dimensions as the two line arrays.
- **Directivity Index (DI)**:

- If the two line arrays contain **N >> 1** and **M >> 1** transducer elements, with **element spacing** equal to half a wavelength, the **directivity index (DI)** of the Mills Cross is:
  - **DI = 10 log NM**, which is the same as a rectangular array.
- **Advantages of Mills Cross**:

  - Sonar systems based on a Mills Cross, such as **RESON's SeaBat 7150** (Figure 6), are **lightweight** and **lower cost** compared to full rectangular arrays, due to the **reduced number of transducer elements**.
- **Trade-offs**:
  - The **Mills Cross structure** leads to **lower sensitivity** and **AG-values**.
  - However, with higher **signal-to-noise ratios**, these trade-offs may not be significant when **directivity**, **weight**, and **price** are the most important factors.

Directivity and Beamforming in Sonar Arrays

Directivity and Spatial Selectivity

- **Influence of Directivity**:
  - The **directivity of arrays** significantly affects the spatially received and transmitted signals.
  - The array acts as a **filter for spatial information**, with its **beam patterns** determining the areas of focus and coverage.
- **Spatial Selectivity**:
  - Achieved through **adaptive** or **fixed transmit/receive beam patterns**, which can be **tailored** for specific applications.
  - This process is part of **beamforming**, which can include both **array steering** and **array shading**.

Beamforming Process

- **Objective of Beamforming**:
  - The main goal of **beamforming** is to **improve the signal-to-noise ratio (SNR)** for echoes coming from different directions in an **omni-directional noise field**.
- **How Beamforming Works**:
  - **Beamforming** controls the **phase** and **relative amplitude** of the signal at each **array transducer element**.
  - This results in **constructive and destructive interference** in the acoustic wave front, leading to a **preferred radiation pattern** in the received signal.
- **Signal Reception**:
  - Information from the array's different transducer elements is **combined** to form a **specific radiation pattern**.

Beam Steering and Array Shading

- **Beam Steering**:
  - By introducing **phase or time delays** in series with the array elements, the **main and side lobes** of the beam are adjusted.

    - This procedure allows for **beam steering**, enabling the **narrow main lobe** to be directed at any **desired angle** to the array's extension.
- **Time Delay and Frequency Independence**:
    - **Time delays** are **independent of frequency**, making them useful for **broadband receiving systems**, such as **passive sonar**.
- **Phase Shifts for Narrow-Band Systems**:
    - In **narrow-band systems**, **phase shifts** in the reception channel of individual array elements are particularly useful.
    - The time delay is equivalent to a **phase shift**, and the **small phase shifts** from element to element create a **phased array**.

Beamforming Techniques and Adaptive Arrays in Sonar

Transmit and Receive Beamformers

- **Weighting in Beamforming**:
    - In both **transmit** and **receive beamformers**, the signal from each array element may be **amplified** by individual **"weights"** applied to its measurement channel.
    - By applying **different weighting functions**, a **desired sensitivity pattern** for the array can be achieved, allowing precise control of the **beam's** properties.

Controlling Array Characteristics

- **Control of Main Lobe, Side Lobes, and Nulls**:
    - It is possible to not only control the **main lobe** of the beam, but also to adjust the **side lobe levels** and **nulls** between lobes.
- **Array Shading and Directional Listening**:
    - **Array shading** uses **weighting functions** to improve signal reception in **pre-selected directions**.
    - This is especially useful in situations where **directional noise** or **attempted jamming** affects the reception.
    - The primary goal of **array shading** is to **reduce the side lobe levels**, which enhances **range** and **bearing resolution**.

Conventional vs. Adaptive Beamforming

- **Conventional Beamforming**:
    - Conventional beamforming uses a **fixed set** of **time and phase delays** and **weighting functions** to combine the signals received by individual array elements.
- **Adaptive Beamforming**:
    - **Adaptive beamforming** is more **flexible** because it combines information about the **element location in space**, the **wave direction**, and the **characteristics of the signals** received by the array.
    - Adaptive arrays can **reject unwanted signals** in the **time** or **frequency domain** and are typically able to **automatically adapt** to **changing reception conditions**.
    - The **adaptive beamforming process** is computationally demanding due to the **fast changes in response requirements**.

Real-Time Data Processing and "Wet End" Hardware

- **Computational Requirements**:
    - Adaptive beamforming requires **high computational power**, but **modern array systems** are capable of **real-time data processing** due to **advancements in computer capabilities**.
- **Shift to Wet End Hardware**:
    - With the increased data processing capabilities, there has been a shift towards the **"wet end"** of sonar beamforming hardware, which refers to the equipment **closer to the sonar elements** (typically mounted on the underwater components of the system).

Shading Functions and Side Lobe Reduction in Sonar Arrays

Impact of Array Shading

- **Side Lobe Reduction and Main Lobe Broadening**:

    - **Shading** or **weighting** functions reduce the **side lobe levels** but cause a **broadening of the main lobe** and a reduction in the **transmitted power level**.
    - The **degree of beam broadening** depends on the specific **shading (weighting) function** applied.

Shading Functions

- **Common Shading Functions**:
  Several **shading functions** are commonly used, including:
    - **Rectangular**
    - **Gaussian**
    - **Hanning**
    - **Hamming**
    - **Dolph-Chebyshev**
- **Dolph-Chebyshev Shading Function**:
    - The **Dolph-Chebyshev shading function** is one of the most frequently used in **underwater acoustics**.
    - It optimizes the balance between a **narrow main lobe** and **low side lobes**.
    - The side lobes are typically reduced to between **40 and 80 dB below the main lobe level**, which is considered highly effective for minimizing interference and maximizing directivity.

Applications of Sonar and Arrays Across a Broad Frequency Range

Frequency Spectrum for Sonar and Arrays

- The **spectrum of interest** for sonar and array applications ranges from approximately **1 Hz to more than 1 MHz**.
    - This broad frequency range reflects the **wide variety of applications** in which sonar is used.

Hydrography and Bathymetry

- **Hydrography** and **bathymetry** are essential for producing accurate **sea charts**, both in paper and electronic formats.
    - Sonar systems like **SBES**, **MBES**, and **SSS** are used for mapping the **seafloor** in **littoral waters** and the **deep oceans** (more than **360 million square kilometers**).
- **Seafloor Mapping**:
    - In addition to charting, sonar is used for **searching wrecks** of ships and airplanes.
    - It also helps in locating **lost items**, such as **containers**, **deck loads**, and **dropped materials** like **chemical agents** and **bombs**.
    - **Frequency Range**:
        - **10 kHz** is used for **deep waters**.
        - **450–500 kHz** is used for **shallow waters**.

Route Selection and Underwater Construction

- Sonar plays a critical role in **route selection** for the **laying of cables and tubes** on the seafloor.
    - It is also used for **dumping rocks** over the cables and tubes after installation to prevent **entanglements** with **anchors** and **fishing gear**.
    - **High-resolution sonar** is required for these tasks.

Offshore Activities and Sonar Use

- **Offshore activities** like **construction**, **platform positioning**, **prospecting**, and **oil, gas, and mineral production** all rely on sonar across a broad frequency band (from a few **Hz** to several **hundreds of kHz**).
    - Signal **amplitudes** can exceed several **MPa** when **airguns**, **boomers**, **sparkers**, and **underwater explosions** are used as **signal sources**, producing **reflections** and **backscattering** captured by **hydrophone arrays**.

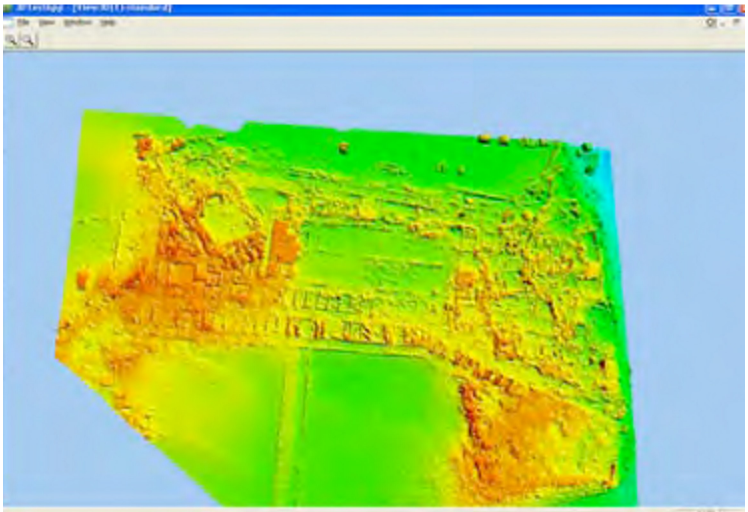
Marine Geology

- **Marine geology** uses sonar systems for:
    - **Seafloor mapping** and **sub-bottom profiling**.

    - Low-frequency **parametric sonar** is commonly used for these tasks.

Underwater Research and Environmental Studies

- **Underwater research** includes studies of:
    - **Ambient noise** and **marine life** in **coral reefs**.
    - **Pollution** from sources like **oil spills** and **waste dumping**.



    - **Marine archaeology**, including the search for **historical objects** and the study of **sunken cities** (Figure 7).
- Sonar used for these studies typically operates at frequencies **above 100 kHz** to improve **resolution**.

Sonar Applications in Fisheries, Oceanography, and Environmental Studies

Fishery Studies

- **Fish Detection and Biomass Estimation**:
    - Sonar is used in **fishery studies** to estimate **fish types** and the **biomass** of **fish schools**.
- **Control of Fishing Process**:
    - Acoustic sensors are placed on **trawls** for **real-time control** of fishing operations.
    - Sonar systems allow for **communication between control systems onboard the fishing vessel** and the **sensor systems on the trawls**, indicating:
        - **Fish school position** relative to the **trawl opening**.
        - **Trawl movements** and **proximity of the trawl bottom** to the seafloor.
        - **Size of the catch** in the trawl.
- **Efficient and Protective Catching**:
    - Sonar systems enhance **efficient** and **protective catching operations**.

Physical Oceanography

- **Studies of Oceanographic Phenomena**:
    - Sonar systems are essential in studying **oceanographic phenomena** on various scales:
        - **Small-scale local variations** in **temperature** and **salinity** in **shallow waters**, which affect **sound propagation**.
        - **Larger-scale phenomena** like **ocean fronts** and **eddies**, and **basin-scale temperature distributions**, which influence **climate change**.
- **Tomographic Studies**:
    - **Shallow water studies** (distances below **100 km**, depths below **30 m**) use frequencies ranging from **1–10 kHz** for **acoustic tomography**.
    - **Ocean acoustic tomography**, involving distances of **thousands of kilometers**, has recently gained interest in studying:
        - **Acoustic signal propagation** influenced by **changing acoustic duct**

    - **parameters**.
    - **Pollution**, **oceanic variability**, **weather forecasts**, and the **greenhouse effect**.
  - Notable example: The **ATOC project** (Acoustic Thermometry of Ocean Climate) used **frequencies below 60 Hz**, a **bandwidth of 14 Hz**, and a **source level of 206 dB//1µPa** at **1 m**, transmitting over **18,000 km** in the ocean to study climate-related changes.

Naval and Underwater Sonar Applications

Passive and Active Sonar Systems

- **Passive Sonar Systems**:
  - Ranges from a **single hydrophone** to **several hundred hydrophones** arranged in various array geometries.
  - Used for **detection**, **tracking**, and **identification** of underwater objects in **naval applications**.
- **Active Sonar Systems**:
  - Include systems such as **dipping sonar** (lowered from helicopters), **hull-mounted sonar** on vessels, and **towed sonar arrays**.

  - These systems are essential for a range of naval applications, including **Anti-Submarine Warfare (ASW)**, **mine and torpedo hunting** (see **Figure 8**), and **anti-collision** measures.

Underwater Monitoring and Navigation

- **Monitoring Underwater Regions**:
  - Sonar is used for the **monitoring of important underwater regions**, helping in strategic military and environmental operations.
- **Underwater Navigation**:
  - Sonar systems play a critical role in the **navigation of ROVs (Remotely Operated Vehicles)**, **AUVs (Autonomous Underwater Vehicles)**, **swim divers**, and **surface vessels**.
  - Sonar is also used for **measuring vessel speed** across the **seafloor** and the application of **Doppler logs** to track movement.

Recent High-Resolution Sonar Applications

- **Harbor and Pier Wall Inspections**:
  - A more recent application of **high-resolution sonar** is the **investigation and control** of **harbor** and **pier wall damages**.
- **Sediment Motion Control**:
  - Sonar systems are also employed to **monitor sediment motion** in **narrow waterways**, helping maintain navigability and preventing issues such as siltation.

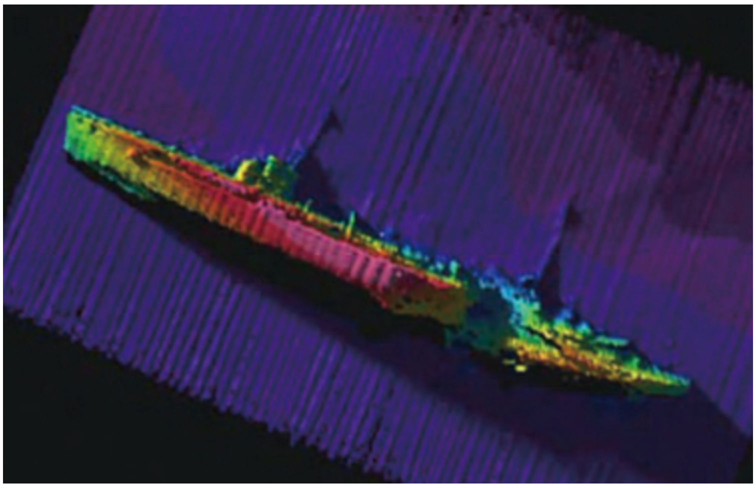
Sonar Applications for Wreck and Artefact Detection

Sonar Advancements and Wreck Detection

- **Technological Improvements**:
  - Recent improvements in **hardware**, **firmware**, and **software** for sonar systems have led to **extensive use** in the detection and study of **wrecks** and **artefacts** from various historical periods.
- **Interest in Wrecks**:
  - Wrecks are of significant interest for **historical reasons**, the potential discovery of **treasures** or **hazardous materials** on board, or simply because a wreck might obstruct **safe sea transport**.

Examples of Sonar-Based Wreck Imaging

- **German Battle Cruiser "Brummer"**:

  - **RESON's SeaBat 8125** was used to produce an image of the wreck of the **WWI German battle cruiser "Brummer"** at the **Scapa Flow** naval base, where the **German High-Sea Fleet** was scuttled on **21st June 1919** (**Figure 9**).
- **Dutch Steamer "Breda"**:

  - **RESON's SeaBat 7125** was used to create a visualization of the wreck of the **Dutch steamer "Breda"** at a depth of **30 meters** in the **Sound of Mull**, West Scotland, in **February 2010** (**Figure 10**).

Sonar Techniques for Enhanced Imaging

- **Target Coverage and Sounding Density**:
  - To improve imaging of the wreck, the **swath angle** was reduced to the **minimum required** to cover the target, which allowed for an **increase in the across-track sounding density** and the **ping rate** to maximize the number of soundings.
- **Technical Setup**:
  - **256 beams** at **0.5°** were used in the **equi-angle mode** to ensure high-resolution

data capture.
    - The **PDS2000 software** in the **MBES** system, combined with **ADUS's 3D interactive software (WreckSight)**, produced **detailed imagery** of the wreck.

Applications in Salvage and Engineering

- These advanced sonar systems have proven useful for:
    - **Salvage companies** during **wreck and cargo removal operations**.
    - **Engineers**, **naval architects**, and **sport divers** for **studying wrecks** and conducting related activities.

WaterSide Security (WSS) and Harbour Protection

Importance of WaterSide Security (WSS)

- **WaterSide Security** (WSS) involves the protection of **harbours** and **waterways** from threats like **terrorism** and **piracy**.
- The significance of WSS has grown due to **terrorist acts** in harbours and the increasing activities of **pirates at sea** worldwide.
- **Protection of harbours and ports** is a key element in WSS, with the goal of preventing **unlawful acts** that could threaten public safety and disrupt the economy.

Challenges of Harbour and Port Protection

- **Variety of Harbours**:
    - Harbours vary greatly in terms of **functions**, **location**, **accessibility**, and the **physical conditions** for surveillance.
    - They involve a wide range of **actors**, including **operators**, **passengers**, **authorities**, **ship crews**, and **workers**.
    - They also contain a **complex system of facilities**, including **installations** and **vessels** of various sizes, making harbour protection a particularly difficult task.

Historical and Recent Attacks on Harbours

- **German Submarine U47 (1939)**:
    - **U47**, commanded by **Lieutenant-commander Günter Prien**, managed to infiltrate the **British naval harbour at Scapa Flow** on the **Orkney Islands** on **October 13, 1939**, sinking the British battleship **Royal Oak** and killing **833 men**.
- **USS Cole Attack (2000)**:
    - A more recent terrorist attack occurred on **October 12, 2000**, when a **small surface craft** equipped with **200-350 kg of explosives** detonated against the hull of the **USS Cole** in the harbour of **Aden**.
    - The attack killed **17 sailors** and injured **39**.

Emerging Threats in Underwater Attacks

- **Underwater Threats**:
    - Modern threats include attacks from **manned mini-submarines**, **midget submarines**, **diver delivery vehicles**, and **divers equipped with re-breather equipment** or **open cycle SCUBA gear**.
    - Attacks from **unmanned vehicles** are also a growing concern, as such technology is available from various sources around the world.

Technological Risks and Criminal Use

- The increasing availability of **advanced technologies** to **terrorists** presents a growing **risk** that these technologies may be used for **criminal acts**, particularly in harbours and waterways.

Sonar Systems for Underwater Surveillance in Harbours

Active Sonar for Harbour Surveillance

- **Most Frequently Used System**:
    - **Active sonar** is the most widely used system for **underwater surveillance** in harbours.
    - However, the **detection range** of active sonar can be significantly reduced due to:
        - Changes in **sound propagation conditions**, such as **temperature variations** or mixing of **freshwater and seawater**.
        - **Ambient noise** interference, which can degrade signal clarity.

Passive Detection and Combined Sensor Systems

- **Passive Listening**:
  - **Hydrophone arrays** are used for **passive listening**.
  - **Electromagnetic** and **IR sensors** are also employed for detection, often in combination.
  - Combining different sensor types allows for the detection of different properties, reducing the likelihood of **false alarms**.

Protection Systems and Deterrence

- **Role of Protection Systems**:
  - Protection systems in harbours can either **deter** or **stop** an attacker.
  - While **deterrence** is preferred, **non-lethal deterrence technologies** are being developed in response to more extreme actions driven by **misunderstood religious ideologies**.
  - This has prompted advances in **non-lethal response technologies** and **tactical measures** in several countries.
- **International Security Codes**:
  - **SOLAS (Safety of Life at Sea)** convention and the **International Ship and Port Facility Security Code** (2005/65/CE in the EU) provide **international security codes** for **ships**, **ports**, and **port facilities**.
  - **Handling captured terrorists or pirates** remains an unsolved international issue.

Challenges in Harbour Environments

- **Acoustic Detection Challenges**:
  - **Harbour environments** present several challenges to sonar use:
    - **Temperature and salinity variations** that change **sound propagation conditions** over time.
    - **Quays and piers** act as strong **reflectors**, scattering sound and increasing **reverberation levels**.
    - **Shallow water depths** in harbours can cause **multi-path propagation** of sound signals.
    - **Noise** produced by **vessels** and **activities** in busy harbours further complicates detection.
- **Need for Specialized Systems**:
  - These challenges necessitate the use of **specially adapted**, **high-resolution sonar systems** and **advanced signal processing** to accurately monitor **harbour environments** and track moving objects.

Recent Developments in Harbour Protection

- **Advancements in Sonar Technology**:
  - In recent years, **sonar systems** and their applications for **harbour protection** have been developed by **military organizations**, **companies**, and **universities** across various countries.

Underwater Acoustic Imaging and Sonar Adjustments for Harbour Surveillance

Acoustic Video Images and Sonar Comparisons

- **Advanced Mosaic Technique**:
  - **Underwater acoustic video images** of a **wharf** and a **ship's hull** were compared with **sonar images** from the same locations.
  - These images were then **merged using an advanced mosaic technique**, creating a **seamless composite image** of port facilities.
  - The results demonstrated the **applicability of acoustic video imaging** for **underwater inspections**.

Adjusting Sonar for Changing Sound Propagation Conditions

- **Impact of Changing Sound Conditions**:
  - When **sound propagation conditions** change over time in a harbour, it is essential to **adjust the position** of the **sonar transmitter and receiver** to maintain optimal performance.

Automatic Detection of Underwater Intruders

- **Study in California**:
  - A study in a **marine research facility** in California focused on the ability to **automatically detect** an **underwater intruder** at long range, track the intruder, and **classify** it as a **diver** rather than a **marine mammal**.
  - The study highlighted the importance of adjusting the sonar **depth** according to the changing **sound propagation conditions** for better **detection, tracking**, and **identification** of **SCUBA divers** and **divers equipped with re-breathers**.
  - **Numerical predictions** and **experimental results** emphasized the need to adapt the sonar setup based on **environmental conditions**.

Sonar Beam Width and Steering Angle Considerations

- **Vertical Beam Width and Steering Angle**:
  - The study found that the ability to vary the **vertical transmit beam width** and **steering angle** is less critical when the sonar is **mounted in the water column** compared to when it is **mounted on the harbour bottom**.
- **Key Conclusion**:
  - The **detection range** in most cases is primarily determined by **sound propagation conditions** rather than the **sonar system** itself.

Automatic Target Detection and Tracking in Harbour Environments

Challenges of False Alarms in Harbour Environments

- **Sources of False Alarms**:
  - Real harbour environments present numerous sources of **false alarms**, making the **automatic detection** and **tracking of targets** a challenging task.

Development of New Detection and Tracking Techniques

- **Collaboration Between University of Tokyo and RESON A/S**:
  - A **new and efficient automatic target detection and tracking technique** was developed through a collaboration between the **University of Tokyo** and **RESON A/S**.
- **Interferometric Procedure**:
  - The technique is based on an **interferometric procedure**, which calculates the **phase difference** of the **split-beam information** from each **sonar channel**.
  - This approach allows for the detection of **"true" moving targets** and the separation of these signals from:
    - **Noise**,
    - **Reverberation**, and
    - **Return signals from static objects**.

Performance and Results

- **False Alarm Reduction**:
  - The new technique significantly **reduces the false alarm rate**, improving detection accuracy.
- **High Detection and Tracking Performance**:
  - The technique has proven effective in maintaining high levels of **automatic target detection** and **tracking performance**, even under conditions of **low signal-to-noise ratios** and **signal-to-clutter ratios**.

Applications and Developments of the Parametric Acoustic Array (PAA)

Westervelt's Pioneering Work and Concept

- **Foundational Work**:
  - **Westervelt's pioneering work** on the **Parametric Acoustic Array (PAA)** introduced the concept of **"scattering of sound by sound"** as the basis for the theoretical approach.
- **Applications**:

    - Since then, several **applications** of the **beam qualities of the PAA** have been suggested and tested in both **laboratory** and **field tests**. These applications include:
        - **Sub-bottom profiling**.
        - **Mine detection**.
        - **Marine archaeology**.
        - **Swimbladder resonance absorption spectroscopy** in fish.
        - Basis for a **medical echoscanner**.

Beam Qualities of the PAA

- **Narrow, Nearly Sidelobe-Free Beams**:
    - The PAA produces **narrow** and **nearly sidelobe-free** beams at **low frequencies** achieved through the **mixing** and **nonlinear interaction** of two **high-frequency sound waves**.
- **Broadband Characteristics**:
    - The parametrically produced signals have a **very broad bandwidth**, spanning more than **2 octaves**.
- **Low Conversion Efficiency**:
    - The conversion efficiency from the **high-frequency primary waves** to the **low-frequency difference-frequency (secondary) wave** is **low**, resulting in a sound pressure level about **40 dB below** the average pressure level of the primary waves.
    - This low conversion efficiency has limited the PAA's applications in certain fields, despite its excellent beam qualities.

Underwater Applications and Advancements

- **Major Field of Use**:
    - **Underwater acoustics** has become the **major field of application** for PAA, largely due to the need for **improved sonar directivity at lower frequencies** without requiring very large and expensive sonar systems.
    - The PAA's ability to improve **sound beam penetration** into the seafloor, especially for **sub-bottom profiling**, has been particularly valuable.
- **Sub-Bottom Profilers**:
    - The **TOPAS 18** and **TOPAS 40**, manufactured by **Kongsberg Defence Systems** in Norway, are successful **sub-bottom profilers** that use PAA technology. These systems are known for their **high-resolution** and **high-penetration** capabilities, offering effective solutions for **seafloor studies**.

Limited Commercial Success

- While several companies have produced PAA systems, the **sales** have been **modest**, and the primary applications remain focused on **underwater acoustics**.