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# Observing using sound and light – a short review of underwater acoustic and video-based methods

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**Abstract**

This paper is a review which briefly describes a selection of acoustic observation techniques and certain aspects of underwater video technology suitable for observations in an underwater environment. The review is divided into two sections, one for each subject, where each section concludes with a discussion of the current challenges within the respective fields.

The acoustic section of the review covers bathymetric and geometrical measurements, imaging sonars, subsurface penetrating profilers, positioning methods, acoustic underwater communication and sensor networks, and water speed measurements. The section ends by considering temperature measurements by ocean acoustic tomography and passive acoustic monitoring.

The underwater video section initially deals with questions of acquisition including underwater visibility, the type of platform, and video formats, image sensors and specialized cameras. This is followed by notes on processing techniques including mosaicking, stereo video, structured light, recording and transmission, image enhancement techniques and ends with a short discussion of underwater holographic cameras.

## 1 Introduction

This review is concerned with underwater acoustics and video, two subjects which may seem on the surface to be unrelated. However, as demonstrated by the number of techniques available, sound and light are the most suitable ways to create an understanding of the geometry and appearance of the underwater environment. Both underwater acoustics and underwater video are mature research fields, which can not be covered in their entirety in such a short report and therefore the selection of techniques and methods described below are subjective and will always be a matter of dispute.

The text is divided into two sections; acoustic methods and underwater video. Both sections are concluded with examples of some of the remaining challenges.

Sound is the wave type that propagates best in water. In conductive, turbid sea water most forms of electromagnetic waves, such as light or short radio waves, are attenuated below possible detection levels after tens or some hundreds of meters, whilst on the other hand, it is known that sound can propagate across oceans.

Animals such as cetaceans and certain turtles have evolved high performance sonars (Curtis and Barnes, 1989) to exploit the propagation characteristics of sound underwater, and already by 1490, Leonardo da Vinci had described a rudimentary passive sonar (Urick, 1983). It has also been demonstrated that humans can easily learn to discriminate between different objects using frequency transposed sound from dolphin mimicking sonars (Fish et al., 1976). It is therefore not surprising that with a more developed technology, acoustic waves have been used for a multitude of purposes, from passive use in warfare to acoustic cameras that produce moving pictures.

On the other hand, an obvious advantage of light and optical imaging, including video, is that when interpreting the result one is using our most developed sense, the visual perception. In contrast to underwater acoustics, the colors, shapes etc. in optical images (mostly) are perceived in a natural manner, whilst the interpretation of acoustic images can sometimes be confusing and at times even misleading. A recent and comprehensive state-of-the-art paper, covering several different imaging methods including acoustic imaging and video, is to be found in Kocak and Caimi (2005).

## 2 Acoustic methods

### 2.1 Introduction

A historical essay on the development of underwater acoustics covering the period up until 1950 can be found in for example Lasky (1977).

Around 1925 the principles of the echo-sounder, or fathometer, were firmly estab-



lished in the field of engineering. The separate field of marine acoustics was slowly evolving, and an interest in the physics of the medium itself was established, in particular the role of temperature layers on sound propagation within the ocean was already understood.

Significant achievements in modern underwater acoustics were made during World War II. A large group of scientists were summoned to the National Defense Research Committee. One of the twenty-three groups in this enormous effort was Division 6 – Sub-Surface Warfare. This group published a report of great importance shortly after the war, the Physics of Sound in the Sea (NDRC, 1980) which summarized four years of intense research on sound phenomena in the sea, including sound generation, transmission, reflection, reception and detection.

Post war development of marine acoustics was directed towards a more thorough understanding of the physical phenomena involved. In particular, developments in radar technology and signal processing influenced sonar technology, as well as progress in electronics and computer technology.

Underwater acoustics arrays were first adopted in the 1950s and utilized in the context of radar twenty years later. By the early 1970s, a review article mentions the use of towed, hull mounted, beam steered from end-fire to broadside, synthetic aperture and side-looking sonars as well accepted, understood and largely implemented concepts (Hueter, 1972).

The materials used in the transmitting and receiving devices, the transducers, have evolved immensely over the years. Early electrostrictive quartz transducers were replaced by magnetostrictive transducers based on nickel. In the late 1940s, ferroelectric materials were introduced, and by the mid 1950s, the first lead zirconium titanate, PZT transducers were in use. Today this material, and variants, are the dominant material used in the manufacture of sonar transducers.

Also during the late 1950s, purely theoretical reasoning lead to the prediction of the parametric sonar (Westerveldt, 1957). Basically, parametric sound is created by nonlinearities in the medium, through the interaction of high intensity, high frequency wavefields. Parametric sonar can produce narrow highly directional, almost sidelobe free, sound sources of small size. However it does so at the cost of low efficiency. The parametric effect was experimentally verified in the early 1960s (Bellin and Beyer, 1962). The generation of a narrow beam is of particular advantage in shallow waters, where the use of wide beam sonar can be limited by the effects of reverberation.

### 2.2 Existing technology

As previously mentioned, the applications of underwater acoustics are many. Some of the most common are listed in the following section, together with a short description and associated references.

As also stated earlier, given that the the field of underwater acoustics is very large, the applications and techniques described below are only a selection. For general background, there are a large number of monographs on the subject of underwater acoustics, two such classical texts are Urick (1983) and Clay and Medwin (1977). In addition, The International Hydrography Organization has created an extensive bibliography (IHO, 2001), that may be helpful, although it is inclined towards the needs of the hydrographer.

#### 2.2.1 Measuring geometry including bathymetry

One of the most widespread applications of underwater acoustic sensing is bathymetry (measurement of the depth of bodies within water) using single beam echosounders. Almost any vessel of significant size today has one or more of these devices. Echosounders measure the depth indirectly via the time from the transmission from a projector to the reception of the reflected signal by a hydrophone. In practice, the projector and the hydrophone are usually the same device unit, and therefore rely on the reciprocity of the material (McCollum et al., 1992).

In general, the characteristics the reflection are dependent on the angle of incidence of the sound wave, (grazing angle), the smoothness of the sea floor (roughness),



the sea floor composition (e.g. acoustic impedance), and the frequency of the sound (Hamilton, 1980). For bathymetry only the time-of-flight of the reflection is used, which is then converted to distance/depth by using a known or assumed sound velocity.

When a single transducer (i.e., a point source) is used, a rather large portion (footprint) of the seabed is insonified. This can create ambiguities in the time/depth measurements, since only the first return of the reflection is used in the depth calculation. The remedy for this problem is to insonify a smaller area, this can be achieved by using an array of transducers which either, concentrates the sound energy into a beam or uses the array to increase the receiver's sensitivity in a given direction; using a concept known as beam-forming (Nielsen, 1991).

The prevailing form of beam-forming technology is the phased array, originating in WWII radar research. The method relies upon a number of transducer elements, configured either as a strip (line array) or across a two-dimensional surface (plane array). Each element can be either excited (i.e., acting as a projector) or used to record (i.e., acting as hydrophone). Formal descriptions of the operation of phased arrays can be found in for example Urick (1983), however, here we limit ourselves to an intuitive overview.

In short, for a transmitting array, a given firing pattern will create interference between the particular sound fields of each transmitter, so that the intensity of sound will be a function of the (solid) angle relative to the acoustic axis of the projector. This can for example be used to create a sound field that is narrow in one direction and wider in another. If the timing or the phase of the transmitted signals are varied, the beam can be dynamically steered in different directions. The general term for such techniques is active beamforming.

Alternatively, the sensitivity of the receiving array in a given direction (directivity) can be controlled, by, comparing the phase information between the different hydrophone elements.

If the waveforms received by the individual hydrophone array elements are recorded individually, the sensitivity pattern of the receiving array can be changed, simply by changing parameters in the processing of the recorded data. That is, the same set of data (i.e. the same array) can be steered to observe any of a (large) number of angles. This can be used to probe the echoes from many different directions, from a single transmitted signal.

This approach is utilized in the Multi Beam Echo Sounder (MBES), which is routinely used today for bathymetric surveys. In doing so, the projector array transmits a beam pattern that is wide athwartship but narrow fore and aft. The receiver array is beam-formed to receive in as many as 500 or more individual beams (e.g. Kongsberg, 2008 or Reson, 2008) that are narrow atwhartship but wider fore and aft. As the platform (ship) moves forward, a three-dimensional bathymetry is measured in a swath, which can cover a width up to 5–8 times the water depth, but often limited to less (Augustin and Lurton, 1998).

MBES appear in different configurations, differing in frequency, number of beams, etc. Oceanic depths (up to 11 km) are measured with relatively low-frequency (12 kHz) systems, while shallow waters (say 10–50 m) are measured with frequencies around 100–500 kHz.

The resolution for a survey grade echosounder can be on the centimeter level with an accuracy around 0.5%. However, to calculate the "true" depth (optionally linked to a geodetic reference) a number of factors must be considered, such as platform stability, errors in measured platform coordinates, subsurface material composition, errors in sound velocity estimates, etc. In practice, the accuracy of a bathymetry survey is therefore rather on the decimeter scale, depending on the intended use.

The International Hydrographic Organization IHO has created a number of standards that are relevant for bathymetry measurements, in particular the S-44 (IHO, 1998), which acts as a useful introduction to the problems.

The characteristics of the reflections from the bottom can be used to classify and map the seabed, making it possible to discriminate between different sea bed characteristics. Commercial post-processing equipment which perform this discrimination include the Roxann (Burns et al., 1985) and the QTC (Prager et al., 1993). These con-



cepts have also been applied to beam-formed sonars (e.g. Preston et al., 2001) and side-scan data (e.g. Preston et al., 2004).

In the classification of seabed materials (geoacoustics) there are mainly three basic models used to determine the mechanical parameters of the materials; the frequently revamped Biot-Stoll theory originally published in the mid 1950s (Biot, 1956a) (Biot, 1956b) (Stoll, 1970), later (1970s) the empirically based and less complex Hamilton model (Hamilton, 1980) and a more recent theory described by Buckingham (1997).

### 2.2.2 Acoustic imaging

Sound can be used to produce a map of reflected intensities, known as a sonargram. These images often resemble optical images, and the level of detail can be very high. However, when deployed in other forms of environment, the sonargram can be utterly confusing, and it takes significant experience before it can be interpreted correctly (Fish and Carr, 1991).

Sonargrams are created by devices which emit beam-formed pulses toward the seafloor or the object being imaged. The beams are narrow (typically around tenths of a degree) in one direction (horizontal) and wide (typically around 45°) in the other (vertical) direction, directed down from the transducer. The intensities of the acoustic reflections from the seafloor or objects on it of this "fan-shaped" beam are recorded. As the beam is moved, the reflections will depict a series of image lines perpendicular to the direction of motion. When stitched together "alongtrack", the lines will produce a single image of the seabed or object.

The necessary movement can be achieved by rotation of the transducer array, as in sector scanning sonars for remotely operated vehicles (ROVs), where they are used as navigational aids much as conventional ship-radars. However, more often, the array is towed on a cable behind a ship (tow-fish), and since the lines imaged are perpendicular to the ship's length axis, this configuration is known as side-scan sonar.

Originating as a military mine-hunting technique in the 1950s, civil commercial side-scan systems were introduced around 1960, and were initially used for finding shipwrecks and marine archaeology. Today, side-scan sonars are also routinely used for marine geology, pipeline monitoring, search-and-rescue and many other purposes (Fish and Carr, 1991).

The long range GLORIA sidescan sonar was developed in the 1970s, to survey large oceanic areas, and operated at relatively low frequencies (6 kHz) and was used to produce images of continental shelves world-wide (Rusby and Revie, 1975). Today it has been superseded by the 30 kHz TOBI multisensor (Towed Ocean Bottom Instrument). There are several types of side scan sonars for ocean use as well as for shallow water. A table showing the performance of a selection of sonars is found in (Blondel and Murton, 1997).

The along-track resolution which is achievable by an imaging sonar is proportional to the length of the array, measured in wavelengths. To achieve a higher resolution, it is thus possible to either increase the frequency (which soon limits the range due to attenuation of the sound) or to increase the number of elements (or length) of the transducer array, which is expensive.

A third method which also increases the resolution of sidescan sonar is to move a sonar array along a line with known or estimated coordinates, and subsequently insonify the same spot on the seabed with several consecutive "pings". This will produce a synthetic array, with a length equal to the distance traveled (Cutron, 1977). Using signal processing techniques originally used for processing of airborne radar (Kovaly, 1976), an image with high resolution can be obtained, which is up to an order of magnitude better than is achievable by conventional sidescan sonars. A critical factor is the positioning and stability of the array. In contrast, to Side Scan Sonar (SSS), the resolution of a Synthetic Aperture Sonar (SAS) is also independent of range. An update treatment of the subject can be found in Hayes and Gough (2004).

### 2.2.3 Acoustic cameras

For almost 40 years, there have been numerous attempts to design an acoustic camera. One of the first successful was the EWATS system created by EMI in the mid



1970s (Brown and Galloway, 1976) which had 200 lines of resolution and maximum of 10 m range (Milne, 1980).

Today, a well known commercial product is DIDSON (Soundmetrics, 2008), but others exist, for example, the Echoscope (CodaOctopus, 2008) or (very similar to an acoustic camera) the BlueView (BlueView, 2008). A comprehensive paper describing imaging sonar techniques in general and three-dimensional imaging in particular, is Murino and Trucco (2000).

### 2.2.4 Subbottom penetration

When a sound wave insonifies the seabed, some of the energy penetrates into the seabed itself. The amount of sound energy that propagates into the sea floor is highly dependent on the frequency of the sound, the bottom composition and the angle of incidence. As a rule of thumb, for a typical sea bottom (containing no gas and consisting of soft materials), frequencies above 10–12 kHz are reflected. Therefore signals from a typical side scan sonar, or a standard echosounder, typically operating in the range 100–500 kHz will not penetrate significantly.

Sound with a frequency in the frequency range 1–10 kHz can penetrate to a depth of several meters, and 100 Hz–1 kHz sound can penetrate tens of meters or more. The trade-off between the high frequency required for high resolution and the low-frequency required for penetration depth, can to some extent can be overcome by signal correlation techniques (Schock and LeBlanc, 1990).

Seismic methods, operating below a few hundred Hz, are routinely used for 3D-mapping in hydrocarbon exploration. Repeated 3D-surveys (4D mapping) for reservoir management is now a standard procedure (Yilmaz and Doherty, 2001). In oil exploration, seismics is the dominant method and hence much effort has been spent on research and development of such techniques. Below 100 Hz, sound waves (such as those generated by earthquakes) have been detected traveling at various depths in the earth's crust around the globe (Shearer, 1999).

Depending on the number of channels and the frequency used, bottom penetrating devices can be tentatively classified as shown in Table 1. The distinction between seismic and subbottom profilers may be made based upon the number of receiving channels, multiple channels implies the use seismic processing techniques. However, the term single channel seismics is also often used.

### 2.2.5 Positioning and navigation

Sound can also be used for the purpose of underwater positioning, in which typical applications are navigation of subsurface vehicles or divers and station-keeping in offshore platforms. Outdated in terms of the equipment described, but still useful, as an introduction to the subject is Milne (1983) alternatively a less detailed overview can be found in Vickery (1998b).

The principle for the most common systems (baseline systems) is that an acoustic pulse (know as a "ping") is transmitted from a base station (e.g. a ship or an underwater vehicle) at a known time. The pulse activates a transponder, which after a known delay responds with another ping, often at another frequency, which is then in turn received at the base station. Sometimes when electrical cables can be used, the remote ping is triggered by an electrical pulse, it is then called a responder. The time between transmission and reception of the ping is recorded and corrected for the delay. Knowing the velocity sound in water, a distance (known as the slant range) to the transponder can then be determined.

If more than two transponders are present and their positions in three dimensions are known, the position of the base station can be calculated. In practice, the greater the number of transponders which are used, and the more frequently the depth of the target is measured, the better is the accuracy of the system.

In one form of the system, the transponders are fixed on the seabed, and separated by up to a kilometer or more, depending on the water depth and task. The position of the (moving) base station is calculated by finding the intersection of the spheres with radii equal to the respective slant ranges, and centered at the transponder positions. This type of underwater positioning system is called a Long Base Line system (LBL).



Recent development includes integration with GPS (Thomas, 1998) and inertial navigation systems, to minimize the number of base stations deployed (Larsen, 2000). LBL systems are mainly used in the offshore industry for station-keeping or ROV navigation.

Another configuration, the Short Base Line system, SBL, uses one transponder and three (or more) hydrophones, separated by 10–20 m and fixed to a rigid vessel or platform. Again, the response times are measured and the position for the transponder is calculated, using the calculated slant ranges. These systems are today less common, although a recent implementation for ROV navigation has been reported (Bingham et al., 2005).

A third method, based on the assumption that the acoustical wavefront is planar at the base station, is the Ultra Short Base Line system (USBL), sometimes called Super Short Base Line (SSBL). Again, a set of hydrophones is used, but in this case they are separated by only half a wavelength of the transponder frequency. By measuring the phase difference between the arrival of the response at each of the hydrophones, an angle of incidence can be determined. As before, the slant range is calculated, and the position of the transponder can be estimated. The hydrophones in a USBL system are typically built into a single assembly.

Other systems, based on the principle of hyperbolic navigation have been proposed for the use in AUV navigation (Leonard et al., 1998). Since the positioned platform is passive (i.e., it only receives signals from the beacons and does not transmit), this approach therefore saves the energy of the platform and makes it harder for others to locate it. Systems incorporating a mixture of the above techniques are also available (Vickery, 1998a).

An entirely different approach is taken in terrain aided navigation systems, where an autonomous underwater vehicle (AUV) uses its onboard sensors to estimate its position, and also to create a map of the surroundings, e.g. a scanning sonar for imaging as in Williams et al. (2001) or an altimeter for terrain mapping (Karlsson, 2002). It is obvious, that the lack of dependence upon external equipment, such as the beacons necessary in LBL systems, is a significant advantage in many applications.

### 2.2.6 Communication

An important use for underwater acoustics is communication. In the oceans, there exists an acoustic waveguide (the SOFAR channel), created by the combined effects of temperature and pressure on sound velocity. It has been suggested that cetaceans (e.g. sperm- and humpback whales) use this sound channel to communicate over long distances; as they can be heard at great distances (Abileah et al., 1996).

Over more modest distances, voice communication, using sound as the carrier wave, has been implemented in diver and submarines applications since the 1940s.

Another important use is found in acoustic releases, where bottom-moored (buoyant) equipment can be released and retrieved with the help of (coded) acoustic signals which trigger the release of the equipment.

Acoustic data communication with a data rate as high as 500 kbit/s over a short (60 m) range has been reported (Kaya and Yauchi, 1989). Commercial high-performance long range systems, (e.g., from LinkQuest, 2008 or Tritech, 2008), can transmit at around 15 kbit/s over 1–2 km, provided the water is deep. A more typical modem has a data rate around 500–2000 bit/s. In shallow water, the range and/or bitrate is decreased substantially due to multipath and noise problems, on moving platforms the doppler effect is an additional factor which must also to be considered. A brief introduction to the subject is found in Quazi and Konrad (1982), and a more detailed description is found in Kilfoyle and Baggeroer (2000).

Considerable interest has been shown in the field of underwater communication ad-hoc networks, where a number of communication devices relay information between each other. The communication devices are typically self-organizing, in that they able to they attach to the network and automatically exchange configuration data such as location, time and status. Thus the network can adapt to changes in the configuration, and take advantage of new devices employed to optimize data transfer rates. In addition, mobile units can also taken part in the network. A starting point for this subject is Heidemann et al. (2006).



### 2.2.7 Underwater acoustic sensor networks

Underwater acoustic sensor networks (UCAN) have the potential to radically improve the reliability and time response of present day oceanographic monitoring applications. However, the characteristics of the underwater acoustic communication channel and the proposed function of the networks, create research challenges which are distinct from those encountered in land based sensor networks (Akyildiz et al., 2005), and hence many of the lessons learned from land-based sensor networks can not be transferred to UCANs. In particular, the protocol strategies of land based sensor networks often rely upon the presence of a large number of nodes, however, the cost of an underwater node is likely to enforce sparse networks. Land networks typically also presume a homogeneous network, whereas the nodes within proposed UCAN contain a variety of platforms (i.e., AUVs, mooring etc) and therefore UCANs are likely to be heterogeneous in nature.

However, perhaps the greatest distinction arises from the propagation characteristics of the channel. The acoustic channel has limited and often asymmetric bandwidth, has long and variable delays with high delay variance, and has high error rates, owing to multi-path propagation and doppler spread (Acar and Adams, 2006). The effect of these characteristics, upon the channel, also varies with whether the communication is horizontal or vertical. Hence, those modulation techniques which have been proposed and implemented, have typically required some form of additional on-line channel estimation, and multi-access strategies have focused upon forms of code division and time division multiple-access (Akyildiz et al., 2005).

Examples of some of the practical problems encountered in implementation of UCANs can be found in Acar and Adams (2006) and Codiga et al. (2005) which describe alternative UCAN implementations, each employing commercial acoustic modems.

### 2.2.8 Current and water speed

The first self-recording current meters were based on a mechanical propeller system. The main disadvantages of such instruments is that there must exist an initial threshold current sufficient to overcome the mechanical friction within the rotor and to orientate the instrument with the ocean currents. These instruments are also vulnerable to marine fouling, which increases the affects of friction further.

The speed of a current can also be determined by measuring the difference in transit time between two ultrasonic pulses that are simultaneously transmitted in opposite directions, over the same distance. The time-of-flight along one path is dependent upon the fluid velocity component along the same path. The difference in transit time for the two pulses will therefore be directly proportional to the water current speed along the same axis and at that point. This also allows the speed of sound to be measured. To make a velocity profile (i.e., for both current and speed of sound), the instrument is hoisted up and down in the water column.

This principle, the use of acoustic travel time (ATT), has been abandoned for more versatile instruments, based on the well-known principle of doppler shift, which relates the change in frequency of a source to the relative velocities of the source and the observer. If high-frequency sound is transmitted into a volume of water, there will be a diffuse backscattered sound from the volume, due to particles and bubbles in the water. These diffuse echoes can be received and detected; if the water has a velocity relative the transducer, the received signal will be frequency shifted due to the doppler effect, and the water velocity can be determined. If three or more beams are used, the direction of the current can be found. If the return signal is gated in time, the doppler shift can be measured as a function of time (or, applying a known or assumed velocity profile, as a function of range).

Today, the preferred form of current meter are acoustic doppler instruments, which first appeared in the mid 1960s, and became wide spread in the 1980s, (Pettigrew and Irish, 1983). Reviews of the development of current meters can be found in e.g.



Williams (1996) and Woodward and Appell (1986).

Typically the profiler takes vertical profiles, and often sits on the seabed facing upwards, from where it is possible to also measure wave height and other wave data. Alternatively, if it faces downwards they can be mounted horizontally or on the hull of a ship. The range can be up to several hundreds of meters with high accuracy (Doisy, 2004).

There are basically two types of doppler current meters: Single-point current meters, which measure current speed and direction at one specific depth, and current profilers, which in most cases measure both vertical and horizontal current speed and direction. The achievable distance range of these measurements is based on the transmitted frequency, the acoustic source level (i.e. the transmitted power), the transducer efficiency, and the pulse length. There is also a zone close to the instrument and near the surface/bottom, where doppler instruments can not measure. This is owing to two effects. Firstly, that the same transducer is used for both reception and transmission, and therefore there must be settling time between reception and transmission. Secondly, there is a need to reject false readings due to the interaction of the side lobes with sea surface/bottom.

In any Doppler Current Profiler (DCP) a series of short sound pulses are transmitted into the water, along the axis of a narrow beam. Generally, there are numerous scatterers available within the insonified volume (also called the reverberation volume), such as microbubbles, debris, plankton, etc. The sound energy backscattered from these particles is received by the instrument and analyzed with respect to doppler shift. Particles with a relative movement away from the instrument will produce a lower returned frequency, a downshift. Particles moving towards the instrument will produce a higher returned frequency, an upshift. Since the reflections received are not from a single target, but from the scatterers in the reverberation volume together, the appropriate descriptor of the fluid motion is the mean shift of a doppler spectrum, rather than a doppler shift due to a single target. Methods for determining the doppler spectrum differ in approach and efficiency between instrument manufacturers, and affect the performance.

The signals received by each transducer are partitioned into time segments or range cells along the acoustic beams, and a water velocity profile along the beam axis can thus be calculated. By changing the acoustic pulse length, the range resolution with which the doppler shift and corresponding velocities are measured, can be varied.

The velocity profile from a single acoustic beam is a projection of the water current vector profile on the beam axis. In theory, the projected velocity profiles from two beams are sufficient for measurement of horizontal velocity profiles from a stationary instrument, provided the beams have a known orientation and there is no vertical velocity component. In practice, three or four beams are used, as all three velocity components can then be calculated without restrictions, and the profiler can then be used from a ship, given auxiliary data (i.e., orientation, speed over ground, course etc.) are available.

In addition to the transducers, modern doppler instruments contain a frequency generator, amplifier, analog-to-digital-converter, a processor using signal processing techniques and algorithms to estimate the doppler shift, a high precision real time clock, magnetic compass and a pitch and roll sensor to compensate for instrument movement. Some instruments also measure other oceanographic parameters such as conductivity and pressure, as these parameters give important information about position of the surface, and sound velocity, etc.

In general, the instruments first determine current velocity related to the transducer's heading by combining the observed values of frequency change along the axes of each of the acoustic beams. Absolute velocity components referred to east – west and north-south coordinates are then obtained using measurements from an internal compass.

The primary use of an acoustic doppler current profiler is the measurement of vertical profiles of the horizontal components of ocean current velocity. Over the past decade, interest has increased in secondary measurements, such as vertical component, backscatter and wave data.



Directional wave measurements seek to statistically describe basic wave parameters in terms of wave amplitude, period and direction. Some doppler profilers measure both current and waves using the same transducers. The wave energy only propagates to some finite depth, beneath which it can not be seen or measured. Because of this the installation depth is critical for these instruments.

A navigation instrument called doppler velocity log (DVL) is similar to the doppler velocity profiler. The DVL typically sits on a ship hull, and by measuring the doppler shift of the sound reflected from the seabed the platform velocity can be calculated, which in turn can be used for dead reckoning or precision navigation with resolutions down to fractions of cm/s at high data rates.

#### 2.2.9 Ocean acoustic tomography

The concept of acoustic tomography grew out of research on long-range acoustics that began during the Second World War. The use of long-range acoustics to measure oceanic variability (and using oceanography to determine acoustic variability) began in the 1960s, and tomography was formally introduced as a tool for ocean observation by Munk and Wunsch (1979).

Tomography relies on accurate measurement of the time-of-flight along specific acoustic ray paths, hence precision time keeping and instrument navigation are required. Since the speed of sound is a function of temperature, measured changes in travel time are also a measure of changes in temperature averaged along the ray path; the technique inherently provides an averaged measurement.

Reciprocal tomography uses simultaneous acoustic pulses transmitted in opposite directions along an acoustic path. The differences in reciprocal travel time are a measure of large-scale current. The original notion of tomography was to use ray multipaths, (i.e. with rays that turn at a variety of varying depths), to determine the variations of temperature and current as a function of depth. However, the resolution of the vertical structure of current and temperature depends upon the ray paths determined by the characteristics of the local sound speed profile.

In some regions (e.g., the Atlantic and polar regions), significant depth resolution is obtained, while in other regions (e.g., the Northeast Pacific where the sampling by ray paths is redundant), only the depth average is obtained. Surface-reflected rays are easily used, while bottom-interacting acoustics are to be avoided. In deep-water tomography, refracting rays typically have lower turning depths between 3–4 km.

Over the decade 1981–1991, tomography experiments (that is, experiments exploring the utility of tomography for ocean observation) were conducted at ever-increasing ranges, beginning with 10's of km and ending at antipodal distances with the Heard Island experiment (Munk and Baggeroer, 1994b) (Dushaw, 2008).

Experiments have been conducted at mesoscale ranges in the western North Atlantic and Pacific, while trans-basin acoustic measurements have been made across the Arctic Ocean, Mediterranean, and North Pacific basins. Experiments focused on regional oceanography have been conducted in the Greenland Sea, the Gulf Stream, the Sargasso Sea, the equatorial Pacific, the Kuroshio (Lebedev et al., 2003), and around Hawaii. Reviews of this work are to be found in Munk et al. (1994a), Dushaw et al. (2001), Worcester (2001), and Munk (2006) .

Tomography can be used to measure temperature across "choke points" in the ocean, such as the Fram Strait. The tomographic measurements made in the Arctic (Mikhalevsky and Gavrilov, 2001) were some of the first to suggest the warming that is occurring there.

The Acoustic Thermometry of Ocean Climate (ATOC) program was conducted over the decade 1996–2006 in the Northeast Pacific (Dushaw et al., 2009), showing little secular trends in ocean temperature during that decade, but large interannual variability, sometimes occurring on timescales of a few weeks.

As we move to the era of ocean observing systems, the role for tomography is as a natural complement to the measurements made by altimetry and profiling floats. Tomography is a subsurface measurement of temperature; the contribution of salinity is negligible. The measurement can be made without risk of calibration drift, and, since it is naturally integrating, it provides observations on large-scale oceanographic vari-



ability which are not sensitive to the noise from smaller-scale oceanographic structures (Munk et al., 1995). Tomography measurements are nearly instantaneous and can be made at any sampling rate; increased sampling adds essentially no additional cost. The number of acoustic paths increases quadratically as the number of sources and receivers increase. Because of the nature of the data, tomography is best employed in conjunction with numerical ocean models (e.g., through such programs as "Estimating the Circulation & Climate of the Ocean" (ECCO, 2009)), since data assimilation techniques treat all data and its uncertainty in a formally correct way.

#### 2.2.10 Passive acoustic monitoring

The ambient sound field is an element of the marine environment which has not yet been fully exploited in the monitoring and measurement of marine processes. The ambient sound field contains quantitative information about physical processes at the sea surface, including wind speed, rainfall rate and type, and bubble formation and presence. Lower frequencies can be used to detect seismic and volcanic activities. Marine animals, especially whales, use sound for communication and hunting which can be detected and censused using passive recorders. Whilst human-generated noise from shipping, harbors, seismic exploration, sonars and other marine activities can be monitored directly.

Relatively simple and robust acoustic recorders are already available today. The ability to "record everything" (i.e., every discrete sample made) is also steadily improving, but the quantity of data recorded using such a strategy can become overwhelming. Depending on the form of measurement required, low-duty cycle instruments that can report the data in near real time will be needed, and here smart onboard processing of the ambient sound facilitates only the transfer of pertinent information to users on shore.

This technology would be readily transferred to many different ocean instrumentation packages, including moorings, bottom-mounted cabled arrays, autonomous profilers and drifters. An example of such an instrument is the Passive Aquatic Listener (PAL), which has been developed and deployed by the Applied Physics Laboratory at the University of Washington. PALs have been successfully used to study for example oceanic rainfall (Ma and Nystuen, 2005) and to detect killer whales in coastal marine waters (Nystuen, 2006).

It should be noted that passive acoustic monitoring is a remote sensing technology that is best made well away from the often destructive (to the instrument) environments or processes where measurements are desired, i.e. the sea surface, ice-covered seas, volcanoes, etc. The instrument is protected from human vandalism, a surprisingly big problem, by its underwater location.

### 2.3 Acoustic daylight

The method known as acoustic daylight imaging uses the ambient acoustic noise field, in a similar way as daylight is employed in the creation of photographs. The basic idea relies upon the fact that objects in the ambient noise field will scatter the incident sound. The technique focuses the resulting sound field with an acoustic lens to form an "image" on an array of transducers. After suitable signal conditioning and digital processing, an image, depicting the acoustic field (an "acoustic image") can be displayed on a monitor. The method has been used in practice, and was implemented in the ADONIS system, at the Scripps Institution of Oceanography during the mid 1990s. The ADONIS system had a 3 m reflector, a 130 element hydrophone array and operated in the frequency band 8–80 kHz. It was capable of imaging object up to a distance of 40 meters with a framerate of 25 Hz (Buckingham, 1999).

#### 2.3.1 Bioacoustics

Bioacoustics is a cross-cutting field too large to go into in this context. However, an important application is worth mentioning – fish biomass estimation with sonar. In principle, the echo strength of a sound pulse that is reflected from schools of fish can provide information size and location of fish and fish schools (Misund et al., 1995).



This method is well established in fisheries research and is used to provide measures of abundance (population size). Of course, the method works well only when the fish type studied are located in midwater.

### 2.4 Challenges

When considering the challenges involved in the measurement of geometries and morphology via acoustic methods, there remains a need to increase the accuracy and resolution of multibeam and imaging sonars, so as to be able to assess and monitor small-scale (centimeter scale) bed morphology features in shallow, coastal, water. An additional challenge is to reduce the cost of multibeam sonar (and its auxiliary technology), to facilitate a wider application of the technique.

In the case of imaging sonars, the technical and practical problems inherent in the SAS technique are still significant. The main tasks to be addressed, in order to alleviate these problems, are to permit operation at increased tow-speeds and the construction of more stable platforms from which the measurements can be made. Possible solutions could include the use of coded acoustic signals and active tow-bodies.

An attempt to combine SAS technology with parametric sources, in order to accomplish a three-dimensional subbottom penetration instrument for the detection of buried waste was made by Zakharia et al. (2005). The outcome was promising, but technical problems stopped the project from reaching all of the goals. In the related field of radar technology, similar reasoning has earlier lead to the successful CARABAS radar (Hellsten, 1992).

An interesting development (Vardy et al., 2008) was reported recently, where shallow water sediment 3D voxel based images of the near surface sediments were produced acoustically by using the correlation between the source and the received signals, with frequency swept signals ("chirps") and methods derived from 3D exploration geophysics. However, the challenge is still to make the use of this and similar technologies more widespread and cost-effective.

The emerging field of AUVs has already triggered the further development of acoustic imaging methods, in particular terrain mapping and terrain based navigation. The development of imaging sonars with fast update rates (e.g., DIDSON, BlueView etc. above) will probably continue and will be merged with AUV navigation. Challenges here appear within areas such as robust feature extraction and the determination of an optimum feature set.

Further challenges within the field of acoustic current profilers concern the problems involved in measuring and characterizing turbulent flow and sediment fluxes (IEEE/OES, 2008).

## 3 Video based methods

Underwater video is a descendant to underwater photography and cinematography, which can be dated back to the mid 1800s and where underwater video has existed since the 1940s. Probably the first time underwater television was used was in conjunction with the Operation Crossroads tests of the atomic bombs at the Bikini atolls in 1948–1949 (Hanauer, 1994). In 1951, considerable public interest was directed towards the intense search for the lost submarine HMS Affray (Baker, 1998). To identify the large number of shipwrecks found in the search operations, the Royal Navy used a specially adapted television camera. Eventually, the submarine was identified in June that year, using the video camera. The first scientific results describing non-military use involved zooplankton studies and were reported in Nature (Barnes, 1952).

Since then, underwater video has been used for many purposes. Many examples are to be found in field of marine biology, such as abundance, behavioral studies, habitat and seabed mapping, studies of fishing and trawling, and the separation of living corals from dead. Underwater video is also used extensively in several industries, such as offshore exploration, drilling and pipeline work, fishery, as well as for search-and-rescue, security, and for military uses. Underwater movies attract public interest and has fascinated many; Jacques Cousteau's films alone have attracted 250 million viewers worldwide (Collins, 2007).



Any mapping method must perform a compromise between resolution, coverage, manpower and information content. When compared with other methods, video performs well in terms of resolution and information content, but requires significant effort in its deployment (Kautsky, 2006), this is particularly so if larger areas are to be mapped.

In a bibliography compiled in 2000 (Harvey and Mladenov, 2001) the number of academic papers concerning underwater video peaked during the mid 1990s. The probable reason for this was that prior to this time, video equipment was expensive and bulky, and thus not very apt for field use. The evolution of electronics had reduced the cost and size of video equipment sufficiently for widespread use in the 1990s, when many novel applications were reported. Today, papers about video technology per se are not as numerous, since video methodology is now well understood , and so is no longer mentioned specifically as a separate technique.

### 3.0.1 Visibility and illumination

One effect upon the optical properties of water, is that it becomes darker with depth. As the water depth increases, the light from the sun is absorbed and scattered. Even in the relatively non-turbid ocean water, the euphotic depth is 200 m or less. (The euphotic depth is where the light is too weak for photosynthesis; the light intensity at the euphotic depth is 1% of that at the surface.) In addition, the spectral composition of light also changes with depth. Absorption is greater for long wavelengths than for short, this is prominent effect even at shallow depths, say 10 m. Therefore most images taken in natural light will appear blue or green on video and thus for all but the most shallow-water applications, additional illumination is required.

The visibility of an object is related to the contrast, which is a function of the optical properties of the object, the background, the medium (water), and the illumination.

If the image contrast is high but the illumination is low, the visibility (i.e., contrast against background) will be low. This is the case for a bright (reflective) target in transparent, dark water. Partial remedies in such a case would be stronger illumination or a more sensitive camera. Alternatively it is also possible to use monochrome light with a wavelength corresponding to the minimum attenuation frequency of the water

On the other hand, there are common situations where the visibility is instead limited by a haze, created by backscattered light from particles in the water (i.e., turbidity) in between the light source and the observed object. These conditions are most prominent when an object is illuminated by artificial light emanating near the observer. In this situation, the amount of (image-creating) light reflected from the observed object will decrease as the distance from the observer increases. As a consequence, the contrast (the ratio between the light from the background + haze and the light from the object) will decrease with distance until it is below the detection threshold.

Increasing the illumination power will only worsen the situation as the background/haze intensity increases It can be compared to driving through fog with head lights on full, and where the droplets in the fog scatter the light back towards you and obstruct the view forward.

It is well known that this situation can be improved by separating the illumination source(s) and the observer/camera, so that the backscattered light is directed away from the observer as much as possible. The optimum distance between the light source and the observer is dependent upon the amount of backscatter, in coastal waters a practical distance is 2–3 m, and somewhat more in oceans. Moving the illumination towards the object will also improve the situation, but may be impractical.

Another concept which reduces the effect of backscatter is that of gated viewing, in which a short pulse of light (in the order of nanoseconds) is emitted, and the camera is opened only when the light pulse passes the desired viewing distance. Thus the backscatter from the turbidity is not registered on the image (Swartz, 1994).

A third way to increase visibility is to use polarized light filters, cross polarized between the illumination and the camera. Lately, successful results where polarized light is used in combination with an inversion algorithm have been reported. The method also yields a rough estimate of the 3D scene structure (Schechner and Karpel, 2005).



#### 3.0.2 Structured light imaging

Structured light sensing (SL) is an active sensing technique, in which a structured pattern of light is projected on to a scene and the resulting distortions in the pattern, in conjunction with geometry of the sensor and source, are used to construct a depth map of the scene using triangulation. The pattern can be either static (i.e., such as a grid), where only a single image is required to characterize the scene or a simpler pattern can be scanned across the scene, in which case a series of images are required.

However, whilst the signal to noise ratio of simple SL systems in air can be high, (through an appropriate choice of source level, pattern modulation and filtering), the effects of turbidity, absorption and forward and backscatter in marine applications require more elaborate and hybrid solutions. The effects of backscatter can be reduced by increasing the length of the base-line between source and receiver as can a choice of blue-green illumination. Such simple SL systems have been used to monitor bed profiles and sediment suspension using orthogonal laser-camera pairs (Crawford and Hay, 1998).

However, to enhance the signal to noise of the system further it has been found necessary to use a collimated point source in conjunction with receiver with a narrow field of view, which tracks the position of the spot as it scans the scene. Such synchronous scanning SL systems reduce the intersection of the beam and the receiver volume, further reducing the effects of forward and backscatter.

L-Bath (Moore et al., 2000) is a synchronous scanning system which removes the need for a single moving receiver by employing a linear charged coupled device (CCD) array as its receiver. It processes the distribution of radiance cross the sensor to provide the system with a measurement resolution which exceeds the target spot diameter. L-bath also employs a pulsed laser source, which allows short sensor integration times, to reduce the effects of ambient light. Model based estimates predict that 4 attenuation lengths at ranges of approaching 10 m with 10 cm spatial and depth resolutions could be achieved.

A commercial hybrid system, Spotmap (Evans et al., 1998), extends the range of the system by combining a two-axis optical scanner with lidar, to detect the time-of-flight and peak intensity of the reflected pulses. The system has a 90 degree field of view and is capable of processing 8000 points per second, which provides an imaging resolution comparable to that of ROV video.

### 3.0.3 Platforms

Underwater video systems are often classified by their platform, or camera carrier type. A selection of the typical forms of platform are given below.

- Tethered systems
  - Remotely operated vehicles (ROV)
  - Drop-frame cameras
  - Towed cameras
  - Fishing gear cameras (e.g. trawls)
- Untethered cameras
  - Autonomous underwater vehicles (AUV)
  - Diver operated cameras
  - Cameras attached to animals (“Crittercams”)
- Fixed cameras
  - Pole cameras
  - Underwater webcameras



## 3.1 Technology

There is an abundance of material on television engineering available, a fundamental textbook is for example Whitaker and Benson (2000). The subjects described here are a selection of those with a significant impact on underwater video.

### 3.1.1 Video image sensors

One way to categorize video systems is by the performance and/or type of the sensor. Not too long ago, the image sensors and the entire video system were analog, and high performance, light sensitive sensors were based upon the cathode ray tubes and had exotic names such as vidicon, newvicon, and plumbicon.

However, since 1990 or so, the majority of video imaging sensors have been of the solid-state type. The two major classes of sensors are Charge Coupled Devices (CCD) named after the mode of operation, and Complementary Metal Oxide Semiconductor (CMOS), named after the manufacturing process.

CCD and CMOS sensors are similar in that both convert light into electric signals. The light sensitive surface is divided into picture elements, pixels. The element can be one-dimensional (as in line-scan cameras) or a two-dimensional array (area-scan).

In a CCD, the pixels essentially are capacitors, which are charged from the photons in the incident light. Using a control circuit, the charge of each pixel is read out, sometimes one by one, and converted to a voltage at a single node (or tap), which is the (analog) output of the CCD. The CCD always needs supporting external electronics.

A CMOS sensor consists of an integrated circuit containing an array of photosensitive sensors that are in effect phototransistors. In contrast to the CCD, each array element has its own charge-to-voltage conversion, which reduces the image quality by introducing interpixel errors (noise). The additional components required at each pixel reduces the photosensitive area of the device. But due to the manufacturing process, it is possible to include most, if not all, of the auxiliary electronics onto the chip, essentially creating a “camera on a chip”, and even include image processing (Basset, 2007).

Until recently, CMOS sensors were used for less demanding applications, but the rate of development is rapid, and today it is safe to say that neither type is categorically better than the other. Instead, the demands of the application must determine which type is superior. If light sensitivity and image quality are major factors, the CCD sensor is still to be preferred, while CMOS type sensors excel in resolution and frame rate. These general observations are supported in a recent study (Hain et al., 2007), where a quantitative comparison was performed to evaluate and assess the characteristics of some contemporary CCD and CMOS sensors.

For a fixed size CCD/CMOS sensor, there is an inherent tradeoff between sensitivity and spatial resolution. Simply put, if the resolution increases, the area of each pixel decreases, and fewer photons hit a pixel, producing a weaker output signal. For a more in depth discussion and simulation results, see Farrell et al. (2006).

### 3.1.2 Low-light and high-speed

Until a few years ago, the best available low-light cameras were so-called Silicon Intensified Target (SIT) cameras, using a vacuum tube device and an image intensifier (II), to achieve very high sensitivities. The SIT receives a low light level image at its faceplate (photocathode), and by using the same principle as in electron multipliers, delivers an amplified electron flow at an anode, where it is scanned by an electron beam, creating a video signal just like a vidicon device.

In practice, a device called a MicroChannel Plate (MCP) is used (Wiza, 1979), today with up to millions of microscopic (dia. 10–40 $\mu$m) electron multipliers and one channel for each picture element.

The use of SIT cameras is rapidly being replaced by the intensified CCD (ICCD) type. It is designed in similar way to the SIT, but the anode on which the image is formed is fluorescent. The image created by the fluorescense is optically coupled to a solid state imager, and converted to a video signal. A slightly outdated, but still useful overview of this technology is found in Vigil (1995).



An example of a commercially available intensified (CMOS) camera reportedly has a sensitivity of 0.1 mlux at 1280×1024 pixels with single photon detection capabilities, and exposure times a low as 5 ns, and a frame rate of up to 100.000 frames/s (Lambert Instruments, 2008).

Another form of sensor, the electronically multiplied CCD (EMCCD), uses a technology in which the output tap from a cooled imaging CCD feeds a “gain register”, a type of electron multiplicator, before it is amplified in standard electronic amplifiers. For example, a Toshiba camera has a reported sensitivity of 0.25 mlux with standard definition resolution at a ~30 Hz framerate, and a remarkable dynamic range that makes it also usable in daylight conditions without modifications (Toshiba, 2008). The manufacturer Hamamatsu has other implementations of a similar technology.

Some commercial underwater packaged CCD cameras today have a reported sensitivity of approximately 15 mlux scene illumination at SD resolution, e.g. Tritech (2008) or ROSYS (2008).

### 3.1.3 Resolution

The resolution of a video image is characterized by spatial resolution (i.e. columns × rows for a digital image) and temporal resolution (frame rate and gating (or shutter) time).

The well-known standard definition video (SD) is rapidly being replaced by high definition (HD) formats from the consumer market. In a simplistic way, SD/PAL can be defined as 768×576 pixels at 25 Hz, while HD is 1920×1080 at 25 Hz.

An image sensor with 3840×2160 pixels at 30 Hz (four times HD) is commercially available as an improved-type CMOS (NHK, 2004), with an array size suitable for 35 mm optics. There exists at least one camera available using this sensor (ISG, 2008), with an internal bandwidth of 3.6 Gbit/s.

The Japanese broadcast company NHK has demonstrated a video system (Super-Hi Vision, SHV) with 7680×4320 pixels and frame rate of 30 Hz (Takayanagi et al., 2005), which is equivalent to 16 times the resolution of a standard HD system. The uncompressed bit rate is approximately 25 Gbit/s, however using compression NHK has reportedly managed to compress in real-time the video stream to between 180–600 Mbit/s (NHK, 2005).

A US based company (Red, 2008) has released a modular camera system aimed at the motion-picture industry and high-end professional applications. The product range includes sensors from HD to (in 2008) 24.4 mm×13.7 mm with a resolution of 4520×2540 pixels at up to 30 Hz. The company also promotes a 168×56 mm sensor scheduled for release during 2010, with a resolution of 28 000×1080 pixels at 25 fps.

Industrial video cameras are today (Reson, 2008) readily available with resolutions around 2000×1500 at 30 Hz, up to a resolution around 4500×3000 at 3–4 Hz.

#### 3.1.4 Compression

The limiting factor in video technology is not only the sensors, but also the corresponding data rate which results for high resolution and high frame rates. Using the example above, a 2000×1500 at 30 Hz camera with 12 bits conversion depth will yield around 1.1 Gbit/s uncompressed, or 128 Mbyte/s. Thus a 1 Tb disk would only be able to store two hours of such video footage.

For that reason digital video is normally compressed, (i.e., the number of bits necessary to convey the data – the bit rate – is decreased), where this is most often achieved at the cost of image quality, although lossless compression techniques also exist. The data compression (or encoding) is possible because consecutive images within a video stream contain spatial and temporal redundancies which can be are removed in the compression process. Generally speaking, the spatial redundancy is reduced by analysis of the changes within a frame (i.e., intraframe compression) while the temporal redundancy is reduced by isolating differences between frames (interframe compression).

There are a number of standards for video compression. Normally a compression algorithm attempts to form a compromise between the impact it has upon on different aspects of the video, where the aspects can include color, detail resolution, motion, file



size or low bitrate, ease of (de-)compression, etc. There are a plethora of alternative algorithms available, each with different qualities. For an introduction to the subject there are several modern textbooks available, for example Sadka (2002) or the very thorough Richardson (2002). The scheme for the encoding/decoding is often called codec, which is an algorithm (or device) that contains the method to go from uncompressed to compressed data (consisting of the "essence" and metadata), and back.

Unfortunately some underwater video does not compress well. Consider a typical underwater scene from a shallow water survey, where the camera is moving over a seabed; this generates a high bandwidth signal. However, since most of the picture elements shift between frames, interframe compression is not too effective, and the high spatial frequency content hampers intraframe compression. How the effect of "incompressibility" is seen in the resulting decompressed video depends on the actual codec used. It may be seen as larger files, a lower framerate, flattening of the colors, artifacts or loss of resolution, etc. On the other hand, other scenes taken from an almost stationary ROV depicting a structural element in low visibility, will have a low spatial bandwidth and little change between frames, and this video will compress well.

A class of efficient methods for image compression are discrete wavelet transform (DWT) compression algorithms. An implementation of DWT compression is the ISO standard JPEG-2000 (ISO, 2000), not to be confused with JPEG, which is another standard based on discrete cosine transforms (DCT). In particular, large images and images with low-contrast edges are good candidates for JPEG-2000 coding, and unlike the older JPEG standard, artifacts in the de-compressed image ("blocking") are not as visible. JPEG-2000 has, however, notably higher computational and memory demands than JPEG. For video purposes (MJPEG-2000) wavelet compression is used as intraframe compression only, but is still suitable for video sequences. A hybrid compression scheme, combining interframe compression with intraframe wavelet compression has been suggested in Hoag and Ingle (1995).

### 3.1.5 Video formats

The details which describe the timing and content of the output signal from the image sensor/camera are known as a video format. Most analog video formats come from the broadcast industry (PAL, NTSC, SECAM) and are still in use, and will be for some years, but the transition to digital video formats is already a fact.

The taxonomy for digital video formats is based on frame size (number of and arrangement of the digitized picture elements, the quality (dynamic range of each sampled pixel in number of bits, sampling scheme, pixel rate, frame rate) and the type of compression used. When stored on a computer, the file format needs to be specified. There are a large number of combinations of sizes, qualities and compressions, see for example Arnold et al. (2007).

### 3.1.6 Omnidirectional and compounded video

One way to create images with high resolution and with a large field of view is to create composite still images from video, using a technique known as mosaicking or "stitching". There are a large number of papers on this subject, and several implementations for underwater video, for example, MATISSE from IFREMER (Vincent et al., 2003) with a recent application described in Jerosch et al. (2007). Other approaches are for example Fleischer et al. (1995) and Rzhanov et al. (2000) and a comparison of several different methods is found in Negahdaripour and Firoozfam (2001). However, strictly, the result is not video since there is no temporal dimension.

However, if several cameras are arranged in an appropriate geometric configuration, a higher resolution video can be created by mosaicking together the individual video streams. Such panoramic mosaics are created from multiple overlapping sub-images from an array of video cameras, pieced together to form a high-resolution, wide field-of-view image. Using these techniques, such a camera array can provide positioning and motion vector estimation, as in the terrain aided navigation applications described earlier (Firoozfam and Negahdaripour, 2003). A study of the theoretical performance



of such multi-camera arrangements is found in Firoozfam and Negahdaripour (2004). An alternative approach to the generation of an omnidirectional view acquired from a single sensor using a spherical mirror is described in Ohte et al. (2006).

### 3.1.7 Stereo video

Another video technique which has drawn a lot of attention is underwater stereo video. These systems consist of at least two (calibrated) video cameras in a known geometric configuration. In addition to providing a depth dimension of the scene, the image data can be used to measure lengths, areas and speed in absolute terms using photogrammetric methods. Stereo video has been used for example in the offshore industry to facilitate the operations of ROV manipulators, and for the automatic inspection of ship hulls (Negahdaripour and Firoozfam, 2006). It has also been used for fisheries research in applications such as fish size estimation (Harvey et al., 2003). A relatively new application is in the study of centimeter-scale seabed morphology (Doucette et al., 2002).

### 3.1.8 Video transmission and recording

Digital video data can be transmitted as a stream (in appropriate formats) or stored in computer files, usually encapsulated in a container file format. The transmission of digital video data does not differ in any significant way from the transmission of any other form of digital data. Copper cable based standard 1 Gbit/s Ethernet is often used, when the signal has to be conveyed over relatively short distances (<100 m). Longer distances demand fiber optic technology. Low bandwidth video can be transmitted over acoustic links, at least over short distances (Pelekanakis et al., 2003).

It is of course important that a video signal can be recorded and archived. Until recently, tape recorders were used almost exclusively. A number of tape formats, physical as well as logical, today exist but most of them are rapidly being replaced by disk recording. The disks may be magnetic (hard disks) or optical (DVD, BluRay), and they have significant advantages compared to the tape. One of the most obvious is random access, making arbitrary temporal movements in the recording fast and precise. Hard disk drives are also, to an extent, more reliable than tape which is sensitive to heat, moisture, dust etc. Temporal synchronization between two or more video streams is also easier than with tape, (i.e. in stereo and compound video applications).

Recording to solid-state memory is an evolving and promising technique. There are already several solid-state video recorders on the market that use memory cards or solid-state disks. Currently, they are limited by price, capacity and sometimes speed, but they are a viable option in situations where factors as low power consumption or mechanical endurance are important.

#### 3.1.9 Image enhancement and restoration

Of course, many techniques from the ubiquitous field of image processing, (e.g. Gonzales and Woods (2008)), can be applied to underwater video. As the natural light changes its spectral composition with water depth, color correction sometimes is desirable. There are real time color correctors available, as well as contrast and gamma correctors. This can also be done during post-processing, using digital video editing software.

Since visibility can be defined as the contrast between object and background, the images can be optimized for contrast after capture, provided there is sufficient dynamic range in the signal, which in practice, is most often the case. A commercially available image enhancer device (LYYN, 2008) implements the optimization process in real time for SD resolution video, and a camera manufacturer (KAPPA, 2008) has integrated a contrast enhancement technique called DRE (Dynamic Range Enhancement) into certain models of their cameras.

There are a number of algorithms available for other forms of restoration, such as deblurring, and frame stabilization (Matsushita et al., 2005). As the computational power of microprocessors for embedded systems is rising, and the price is falling, the camera modules will likely contain more sophisticated image processing capabilities in



a relatively near future. Already post-processing computer programs for video editing, even for the consumer market, make image stabilization, color adjustments, de-blurring etc. available.

#### 3.1.10 Underwater holography

Holography is today a well-known concept, originally described by Nobel Prize winner Gabor (Gabor 1949), and pushed forward by the implementation of the laser by Maiman in 1960.

In a typical holographic imaging configuration, an object (or a set of objects) is illuminated by coherent (laser) light, scattered by the objects and projected onto a plane. A second light field, coherent with the first and called the reference beam, also illuminates the plane. Thereby an interference pattern is produced – this pattern is the hologram. The hologram can be recorded by for example, a photographic plate or a CCD.

If the recorded hologram is illuminated by the original reference beam, a reconstructed light field is created, identical to the light field which was scattered by the object or objects. To achieve this in practice, two main configurations are used – in-line (as used by Gabor) and off-axis holography, later developed by Leith and Upatnieks (1967), as a spin-off from advances in side-looking radar.

For transparent or nearly transparent objects the in-line holography method can be used. Here, a single beam of coherent light (Gabor actually used mercury arc light) passes through the imaged volume onto the recording plane. At the plane, the light diffracted by the (semi-) transparent objects in the beam path interferes with the original undiffracted beam to form a hologram. This method has an upper limit for the recordable particle size, a, determined by the Fraunhofer condition $a^2 \ll d\lambda$, where $d$ is distance from the object to the grating and $\lambda$ is the wavelength of the source. There is also a lower limit, around 3–10 $\mu$m or less, depending on wavelength, recording devices etc.

In off-axis holography, two angularly separate beams are used to record the image.

The imaged volume is illuminated with (diffused) laser light; a portion of which is reflected and projected on the recording plane. A reference beam also illuminates the plane, but it does so without passing the imaged volume. The reflected and the reference beams interfere, and form a hologram. This configuration can image arbitrarily large objects up to the instrumentation's field of view, and it is only limited by the performance characteristics of the laser and the optical system. The resolution is however lower than for a comparable in-line arrangement, and is limited by laser speckle and system optics, in practice to 30–40 $\mu$m.

A concept known as digital holography has been feasible since the introduction of suitable solid-state imaging sensors. Here, the holograms are recorded directly by the imaging sensor (e.g. a CCD), and stored digitally (see e.g. Kreuzer et al. (2001)). The reconstruction of the wavefield, previously done optically by the illumination of a hologram, is now performed by a numerical reconstruction algorithm. The digital holography makes it possible to rapidly record time consecutive holograms, which enables the creation of video sequences.

Holographic imaging of plankton (in a laboratory) was reported already by Knox (1966), and early work with in situ equipment was made by Stewart et al. (1970) for plankton research purposes. Later, Carder et al. (1982) at University of South Florida in St. Petersburg FL, USA, developed a submersible holographic particle velocimeter (HPV) for in situ measurement of sizes and settling rates of oceanic microparticles. It was deployed at depths down to 30 m, but limited by laser power output — the sample volume was a few cubic millimeters with a resolution of 15 $\mu$m. A review concerning optical holography for the recording of plankton is to be found in Hobson and Watson (2002).

Katz et al. (1984) developed an early version of a submersible, pulsed-laser-based holographic system, and again was used to measure the in situ distribution of microparticles, and bubbles (O'Hern et al., 1988).

This work, undertaken at John Hopkins University, Baltimore, MD USA, has continued since, and has resulted in a completely automated system for analyzing in-line



holograms recorded in the ocean. A recent paper describes a dual-view digital system, that simultaneously records two orthogonal in-line holograms at 15 frames/s, where each hologram records a volume of 40.5 $cm^3$ (Pfitsch et al., 2005). Within the volume (3.4 $cm^3$) where the two beams intersect the resolution is reported to be approximately 7.4 $\mu$m or optionally better. The group has undertaken work related to fluid and particle dynamics, (e.g. Holographic Particle Image Velocimetry – HPIV), where holography is used for measuring the characteristics of turbulence and addressing turbulence modeling issues (Katz et al., 1999), also biological studies have been performed, (e.g. as in Malkiel et al., 1999 and Sheng et al., 2007).

A Canadian group at Dalhousie University in Halifax, has designed a prototype of a remarkably uncomplex underwater holographic imaging instrument, and has performed Submersible Digital Inline Holographic Measurements (SDIHM) at depths of 12–18 m in fresh water and off the Canadian Atlantic coast. The resolution is reported to be less than 7 $\mu$m in a volume of 9 $mm^3$, with a field of view of 5 $mm^2$ (Jericho et al., 2006; Garcia-Sucerquia et al., 2006).

A collaboration between Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution has resulted in the development of yet another instrument (Loomis et al., 2007). Their Digital Holographic Imaging (DHI) recorder reportedly has sample volumes of up to 500 $cm^3$ with a resolution down to 9 microns, allowing objects ranging from 100 $\mu$m to 5 mm. The system is suitable for deployment on an AUV. The system has been tested in the laboratory and in the field for plankton studies.

Underwater holographic imaging instruments have been developed for decades by a group at the University of Aberdeen, Scotland UK. Their holographic camera HoloMar has been used for imaging of marine organisms (plankton) in their natural environment, and for studies of erosion processes. Developed in the 1990s and deployed in 2001, it is a somewhat bulky piece of equipment, measuring 2 m by 1 m, and weighing 2 tons (Watson, 2003).

However, the HoloMar camera can, uniquely, record simultaneously both in-line and off-axis holograms, and covers a range of object size from a few microns to tens of millimeters. Volumes up to 50 000 $cm^3$ (off-axis) and 9500 $cm^3$ (in-line) can be recorded. The recording of the holograms is made on photographic glass plates. Reproduction and analysis of the images is carried out in the laboratory, using a projection of the reconstructed image. By moving a computer-controlled video-camera through the reconstructed wavefield, individual objects can be imaged, and their size, shape and location determined.

Using digital holography, the second generation underwater holographic camera from Watson's group, the eHoloCam, is 1.4 m long, about 30 cm in diameter, and weighs 50 kg (Sun et al., 2007; Sun et al., 2008). The instrument is being commercialized and marketed by CDL Underwater Engineering of Aberdeen (CDL, 2008). The system at present is based on in-line recording, and has been deployed in the North Sea on four occasions to a depth of 450 m, although designed and tested for operation to 2000 m.

### 3.2 Challenges

Video observation methods are particularly advantageous for shallow water habitat studies . However, in such studies, there is a standing requirement for a greater spatial resolution and a larger field-of-view. The physical limitations of the environment which restrict visibility, currently make mosaicking the most viable alternative for large-scale super-resolution imagery.

No withstanding that image processing techniques for image stitching is a mature field, there still remains a need to find a methodology which can produce these images economically and preferably in an unsupervised manner. Future development in this field could lie with the combined use of AUVs and cameras.

Future challenges for both acoustic and video, are the development of robust methods for terrain mapping and terrain based navigation, where the major difficultly will lie in suitable methods of feature extraction and feature set selection . Another useful component in such system would be a method to automatically assess the utility of an



image sequence, to determine whether it can be used or should be rejected.

Video measurements produce very large amounts of data, and the evaluation is often labor intensive. Reliable and robust automatic methods to classify, or at least segment, video sequences would be very helpful to the interpreters.

A broader use of the holographic camera technique for plankton counting is probably imminent, especially if it can be coupled to automatic image recognition and in combination with AUVs. It is also well worth considering the technique for other uses, such as. near-shore or river-bed sediment load studies (bedload and suspended load), to provide a better understanding of beach erosion processes.

## 4 Conclusions

Tis paper has given a selected review of the use of acoustic and video techniques in underwater applications. The paper has demonstrated, by the number and the variety of the techniques, that sound and light are the most appropriate ways by which an understanding of the geometry and appearance of the underwater environment may be gained.

Both underwater acoustics and underwater video are mature and very active research fields. Thus given that it is not possible to exhaustively cover these fields in their entirely, it is inevitable that the selection of the techniques described, will be to some degree subjective, and therefore, a matter for dispute.

New technology quickly finds it way into the underwater observational methods. This is partly because the environment demands it; it is dark, cold, under high pressure, and hostile to measurement devices in general, and partly because the development in many cases is driven by industries at the technological forefront (offshore petroleum industry, research institutions, navies, etc.) that can not accept anything but the best available equipment.

On the other hand, most of the work in countries around the world is done by practitioners that use outdated or inferior equipment – not uncommmonly in the field of coastal monitoring and in environmental monitoring programs. To a degree this can be explained by a wish to adhere to well-known and accepted tools, but mostly it is simply a matter of resources.

A major challenge for the underwater instrument designers and engineers is therefore to be able to create and market modern equipment which is affordable not only to the specialists and high-tech companies, and that is easy to use and deploy, and that yields reliable results.

And still scientific challenges remain, not only to improve and extend existing techniques, but to find entirely new methods and phenomena that can be used for observation, and of course to understand better what we see.

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**Table 1.** A tentative classification of subbottom penetrating devices.

| Source | Frequency | Source type | Receiver config. | Penetration | Designation |
|---|---|---|---|---|---|
| Airgun (Airgun array) | 5–250 Hz | Broadband | Multichannel | −kilometers | Seismic |
| Sparker (Sparker array) | 200–1500 Hz | Broadband | Multichannel (single channel) | 1 km | High resolution seismic |
| Boomer | 400–4000 Hz | Broadband | Multichannel (single channel) | −100 m | High resolution seismic |
| Swept frequency source, "Chirp" | 2000–15 000 Hz (typical BW 3 kHz) | Broadband (Swept frequency) | Single channel | −100 m | High resolution subbottom profiler |
| Pinger | 2000–8000 Hz | Narrow band | Single channel | −25 m | Subbottom profiler |
| Echosounder | 10–500 kHz | Narrow band | Single or multiple channels | ≈0 m | Fathometer |