Sidescan Sonar

Ingo Klaucke

Abstract Sidescan sonar allows obtaining an acoustic image of the seafloor at high resolution, wide swath and relatively low cost. For that purpose the backscattered signal of an acoustic pulse sent out sideways from an instrument carrier is registered. At low incident angles small-scale relief is well imaged and the length of shadows allows calculation of the height of seafloor features but sidescan sonar is particularly useful in mapping compositional differences of the seafloor. Sidescan sonar images are, however, mostly uncalibrated and need some form of ground-truthing for meaningful geological interpretation. Interferometric sidescan sonar systems now also provide bathymetric information together with backscatter strength.

1 History of Sonar

The acronym Sonar stands for SOund NAvigation and Ranging and was coined during WW II in analogy to Radar or Radio detection and ranging. The use of sound for the detection of obstacles such as icebergs or submarines, however, dates back to developments made in the aftermath of the sinking of RMS Titanic and WW I (Hackmann 1985). The Canadian engineer Reginald Fessenden and independently Alexander Behm in Germany developed the first working echosounders (Wille 2005). In an echosounder piezoelectric elements transform an electrical pulse into an acoustic signal and vice versa. Behm in particular intended his sonar for the detection of icebergs, which did not work out because of too many reflections from surface waves. His invention, however, quickly turned out to be useful for measuring the depth of the seafloor.

The first experiences with side-scan sonar were carried out by Hagemann (1958) but his work for the US Navy was kept secret and only published in 1980. Based on Hagemann's work, a first side-looking sonar (called the Shadow Graph) was built

I. Klaucke (✉)
GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
e-mail: iklaucke@geomar.de

A. Micallef et al. (eds.), *Submarine Geomorphology*, Springer Geology,
DOI 10.1007/978-3-319-57852-1_2

by a company specialised in military equipment (Westinghouse) in the early 1960s (MIT Museum 2016). At the same period in Great Britain sound was also used for imaging the seafloor (Chesterman et al. 1958) and soon later a first sidescan sonar was built for the National Institute of Oceanography (Tucker and Stubbs 1961), which is now part of the National Oceanography Centre Southampton. Additional experiments with side-looking sonar were carried out by Harold Edgerton, an electrical engineer at MIT who had become famous for using stroboscope flash lighting in photography in order to make fast moving processes visible. Building on this experience, he used sound to "image" the seafloor with repeating acoustic pulses and via his company EG&G worked on several projects for the US Navy (MIT Museum 2016). Very quickly, sidescan sonar proved to be a valuable tool for the systematic investigation of the seafloor and the generation of seafloor image mosaics (Clay et al. 1964) showing much hitherto unknown details (Belderson et al. 1972). The earliest commercial sidescan sonar systems were used for marine archaeological purposes, in particular the search for sunken ships (Bass 1968; Rosencrantz et al. 1972). At the end of the 1960s the evolution of sidescan sonar to that point culminated in the construction of the Geological Long-Range Inclined Asdic GLORIA (Rusby 1970; Somers et al. 1978), which was capable of achieving up to 60 km wide swaths by using a 6.5 kHz signal. From 1984 onwards the US Geological Survey started mapping the entire Economic Exclusive Zone of the continental United States. The resulting mosaics were the first systematic inventory of major areas of the seafloor (EEZ-Scan 84 Scientific Staff 1986; EEZ-Scan 85 Scientific Staff 1987; EEZ-Scan 87 Scientific Staff 1991) and spawned a wealth of scientific discoveries (Garder et al. 1996 and references therein). Further information can also be found at the USGS web page http://coastalmap.marine.usgs.gov/gloria/. Similar long-range, 6.5–12 kHz systems (SeaMARC-II, Hawaii MR-1) and mid-range, 30–35 kHz (SeaMARC-I, TOBI) sidescan sonar systems were developed in the late 1970s and early 1980s for different research institutes, but the instruments were also used commercially (Kosalos and Chayes 1983; Huggett and Millard 1992).

Sidescan sonar then underwent a phase of quiet evolution and constant improvements rather than evolutionary steps. This evolution was driven by commercial manufacturers and included the use of digital rather than analogue recording of the data, the use of increasingly higher frequencies for shallow water applications, and the use of frequency-modulated (chirp) signals that allow a better signal-to-noise ratio and less power consumption than the traditional pulse. The next major step in the development of sidescan sonar was the more widespread use of interferometric sonar systems that use two or more parallel receiver arrays that allow calculating bathymetry from phase differences of the signal received by the different receivers (Blackinton et al. 1983). These interferometric sidescan sonars originally achieved swath widths of up to 7 times the towing altitude and less resolution than multibeam systems (de Moustier 1988), but advances in signal processing now allow modern systems calculating interferometric bathymetry over the entire swath, i.e. up to 15 times the towing altitude.

To obtain high-resolution imagery along-track either the pulse repetition rate is high or the speed of the system travelling through the water must be decreased. In addition the along-track beam angle must be low. A high pulse repetition rate will restrict the distance the pulse can travel, therefore be usually used with higher sonar frequencies. The high sonar frequencies however have strong signal attenuation and consequently a limited range. The beam angle, on the other hand, is a function of the length of the transducer, as long transducer arrays produce a narrower beam. The length of transducers, however, is limited by the length of the towfish. More recently the development of synthetic aperture sonar allowed major improvements in the along-track resolution of sidescan sonar systems. These new systems have a high pulse repetition rate and allow calculation of a large synthetic transducer length. This technique requires very high precision in towfish position and altitude. The synthetic aperture sonar has been recently combined with a parametric signal that has been used for quite some time in sediment echosounding (see Chapter "Reflection and Refraction Seismic Methods" for more information) in order to derive sidescan sonar imagery from both parametric and the primary signals (Zakharina and Dybedal 2007).

2 Principles of Sidescan Sonar

In sidescan sonar systems an acoustic pulse with a narrow opening angle in the along-track and wide opening angle in the across-track direction is emitted sideways from either a vessel, a towed body or an autonomous vehicle (Fig. 1). Upon reaching an interface with sufficient acoustic impedance contrast, such as the seafloor, most of the acoustic energy will be reflected away from the instrument. At the same time multi-directional scattering will occur at the interface and some of the scattered energy will be scattered back to the instrument. This backscattered energy carries the information that is used in sidescan sonar imaging. As for all sonar systems this can be described by the active sonar formula:

$$\mathrm{BS} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{TS}$$

where BS is the backscatter strength, SL the source level, TL the transmission loss and TS the target strength.

The backscatter strength depends on a number of factors including the angle of incidence, the roughness of the seafloor and the scattering behaviour of the material at the seafloor. However, depending on the frequency of the acoustic signal, not all acoustic energy will be reflected and scattered but some portion will also be refracted into the sediments and scattered at deeper interfaces (Fig. 1) resulting in volume backscatter to be registered. This effect increases with decreasing sonar frequency.

The resolution of the sonar system is determined by the pulse length and sampling frequency for the across-track resolution (Fig. 2), and by the beam angle and

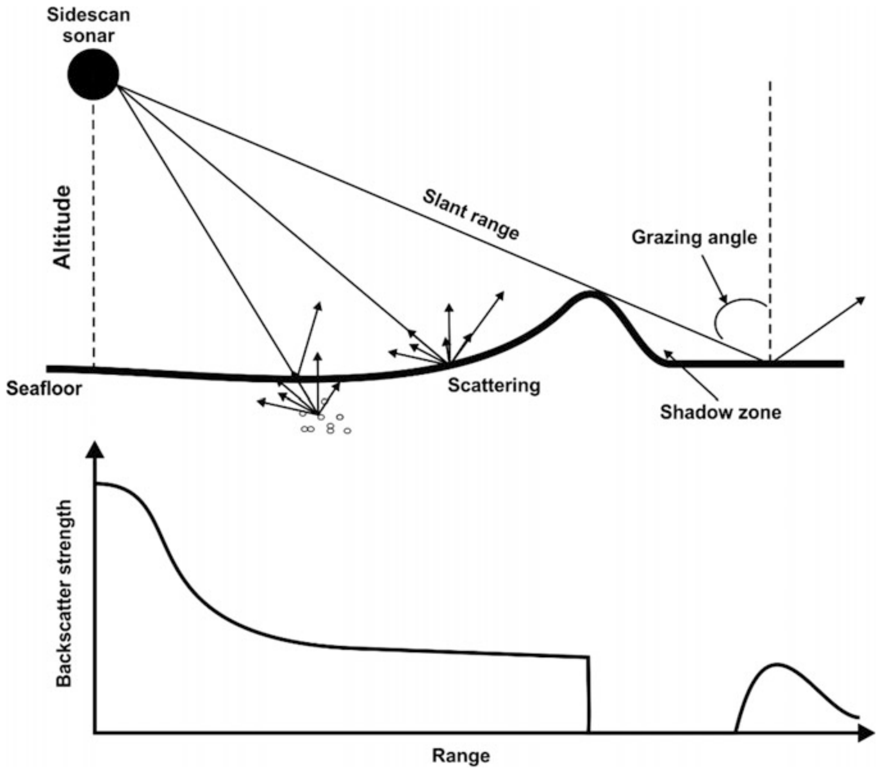

Fig. 1 Principles of sidescan sonar and definition of terms used in the text. Backscatter strength is high with near vertical incidence and produces no return in the shadow zone

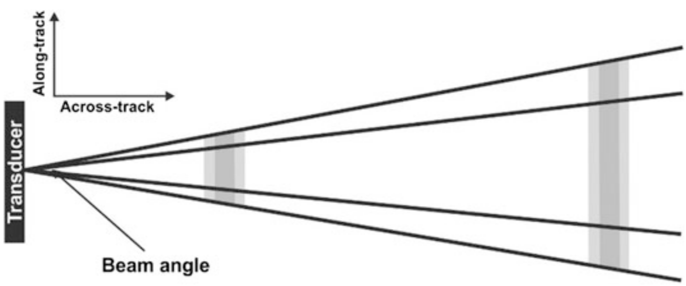

Fig. 2 Across-track and along-track resolution in digital sidescan sonar. Higher frequency or wider bandwidth result in better across-track resolution (*dark grey* vs. *light grey*). A smaller beam angle improves along-track resolution. In conventional, non-digital systems, the far range across-track resolution would be worse than the near-range resolution because of the increasing footprint size of the acoustic signal

survey speed for the along-track resolution. The across-track resolution of analogue systems is given by:

$$X = \frac{cL}{2 \cos \theta} = \frac{c}{2B}$$

where L is the pulse length of the transmitted pulse, θ is the grazing angle, c is the speed of sound in water, and B is the bandwidth. The resolution of digital systems, on the other hand, is determined by the sampling frequency of the A/D converter. The along-track resolution is the width of the beam on the ground or the distance travelled by the transducer during the reception interval, whichever is less. The width of the beam on the ground is given by:

$$Y = R\varphi$$

where R is the range and φ is the beam angle in radians. The along-track resolution consequently decreases with increasing range and the along-track resolution is generally much lower than the across-track resolution.

3 State of the Art

Long-range sidescan sonar systems such as GLORIA or the Hawaii MR-1 system have become obsolete by the continuous development of full ocean depth multi-beam bathymetry systems (see Chapter "Multibeam Echosounders"). Mid-range, deep-towed systems such as SeaMarc-I, TOBI or the Russian MAK-I system have been retired as well, leaving just a few deep-towed systems working in the 75–120 kHz range on the market. Such systems provide up to 1500 m wide swaths and depending on survey speed allow processing the data with roughly 1 m pixel size. In the past, they were commonly installed on a neutrally-buoyant towfish but increasingly more systems are now used on autonomous underwater vehicles (AUV). The majority of sidescan sonar systems on the market, however, are small, portable, high-frequency systems for use in relatively shallow water, i.e. on the continental shelves and upper slope areas. These systems operate with signal frequencies in excess of 200 kHz with some systems now exceeding 1 MHz. This choice of frequencies and depth ratings closely reflects the main usage of sidescan sonar, which includes marine archaeology, submarine cable and pipeline inspection, obstacle recognition and search and rescue operations, mine detection, marine habitat mapping, and marine geological and fisheries applications.

Raw sidescan sonar data are commonly displayed as a water-fall image during data acquisition. However, a certain number of data processing steps have to be applied in order to derive georeferenced sidescan sonar mosaics of the seafloor. The effects of these processing steps should be known by the interpreter, as they may induce or enhance artefacts and distortions. Sidescan sonar instruments record the acoustic amplitude at the receiver versus time. Historically the received signals were recorded on electro-static paper and high backscatter intensities corresponding to high electrical currents would burn the paper dark. Nowadays, with digital processing of the data, both positive (high backscatter is white and shadows are black) and negative representation of the backscatter data are possible. Verifying the display convention is therefore required before interpretation.

Typical waterfall displays show no signal returns as the acoustic energy travels through the water column, followed by a strong signal including specular reflection from the seafloor beneath the instrument, being the closest reflecting object. As time increases, signals returning from further and further away give a complete swath of backscatter returns for the single ping. The received signal decreases in amplitude for increasing range due to the transmission losses in the water (Fig. 3). A time-varying gain (TVG) function is generally applied in order to highlight backscatter changes at far range. The raw sidescan sonar data are displayed as backscatter intensity versus time or sample number, which is the slant range and

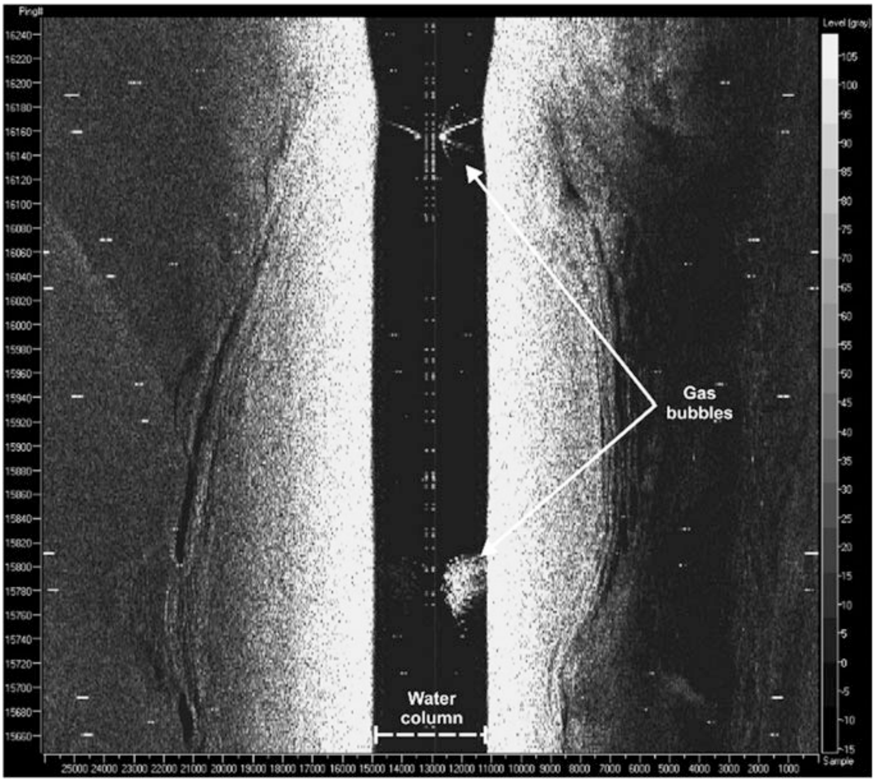

Fig. 3 Unprocessed sidescan sonar record during acquisition. Weak or no backscatter is displayed as *dark grey* or *black* whereas strong backscatter is shown as *white*. The *central black stripe* corresponds to lack of returns from the water column

corresponds to the distance between the transducer and the seafloor (Fig. 1). Knowing the altitude of the receiver over the seafloor, the ground range D can be calculated using:

$$D = \sqrt{R^2 - h^2}$$

where R is the slant-range distance and h the altitude of the instrument above the seafloor. This equation assumes a flat seafloor, but can induce distortion if this assumption is significantly invalid. Many sidescan sonar acquisition packages allow online display of the slant-to-ground-range correction, but this also cuts out the water column data that can contain valuable information such as fish schools, gas bubbles (Fig. 3), or nepheloid layers. Once the slant-to-ground-range correction has been applied, navigation, heading and attitude information are combined with the backscatter intensity values in order to correctly position the latter on a geographic map (Fig. 4). For this purpose, precise positioning is crucial, but the resolution of

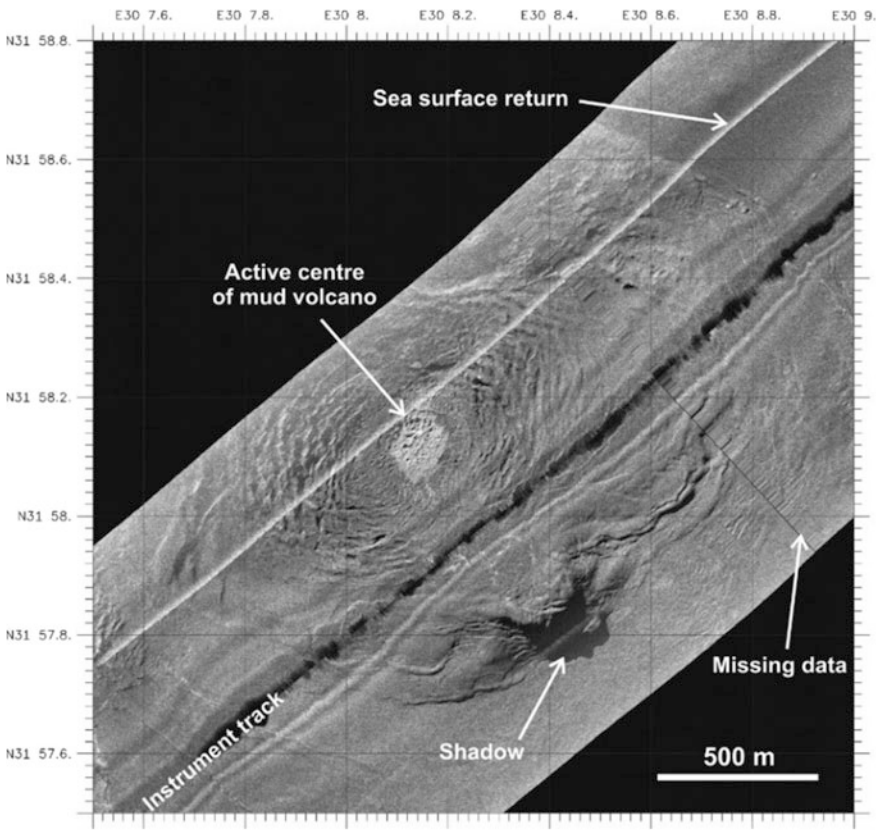

Fig. 4 Geo-referenced sidescan sonar image of a submarine mud volcano showing different backscatter intensities on the seafloor and relief in form of shadows. High backscatter is *white*

sidescan sonar images, which can be smaller than 10 cm, frequently exceeds the navigational precision. In addition, physically correct positioning of each sidescan sonar pixel on the ground generally leads to blurred images that are difficult to interpret. For this reason, sidescan sonar images are based on smoothed track, heading and attitude values that induce a certain degree of distortion and inaccurate positioning. Precise positioning, however, becomes crucial for synthetic aperture sonars. Most sidescan sonar systems are positioned using a layback method, where the length and azimuth of the towing cable is combined with the ship's position. More precise positioning requires the use of a range finder, transponders on the seafloor (long baseline system), an inertial navigation system, an ultra-short baseline system (for deep-towed sonars), or a combination of these systems.

The interpretation of sidescan sonar images still relies on the experience of the user, as calibrated sidescan sonar images relating specific backscatter intensities to well-defined lithologies are generally not available. Although standard sidescan sonar systems do not provide bathymetry, relief can be deduced from sidescan sonar images using the length of shadows and the altitude of the instrument above the seafloor (Fig. 4). In addition, lateral incidence at the far range highlights even small scale relief. The real benefit of sidescan sonar, however, is the distinction of areas of different seafloor roughness that is directly related to lithological differences. In that way sandy deposits, for instance, can be distinguished from muddy environments even if no difference in relief is involved. Different software packages are available to aid the user in establishing different backscatter classes that ultimately require "ground-truthing" in order to derive a meaningful geological interpretation.

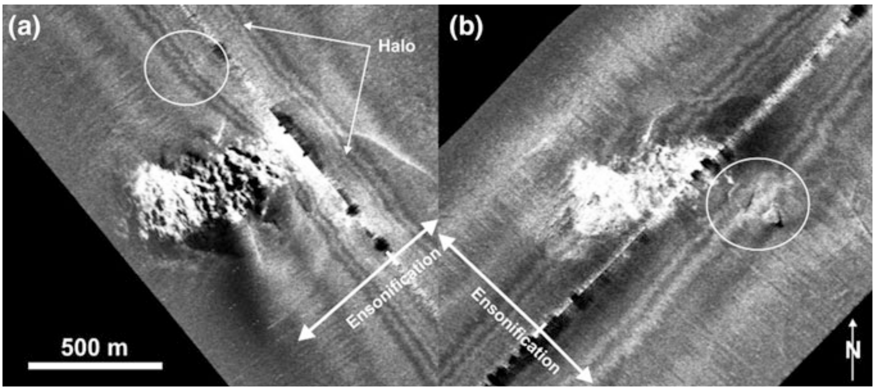

Fig. 5 Sidescan sonar image of Mound 12 offshore Costa Rica (modified after Klaucke et al. 2008) showing the effect of ensonification direction on the imaging of NW-SE trending structures. **a** Survey track parallel to the structures. **b** Survey track perpendicular to the structures. *Note* Alternating bands of high and low backscatter intensity (*the halo*) parallel to the nadir are the effect of side lobes during the beamforming of the sonar signal. Wiggly returns (*white circle* in picture **a**) indicate roll of the tow-fish that was not corrected for. Also note that features in the nadir region are poorly imaged (*white circle* in picture **b** and invisible in picture **a**)

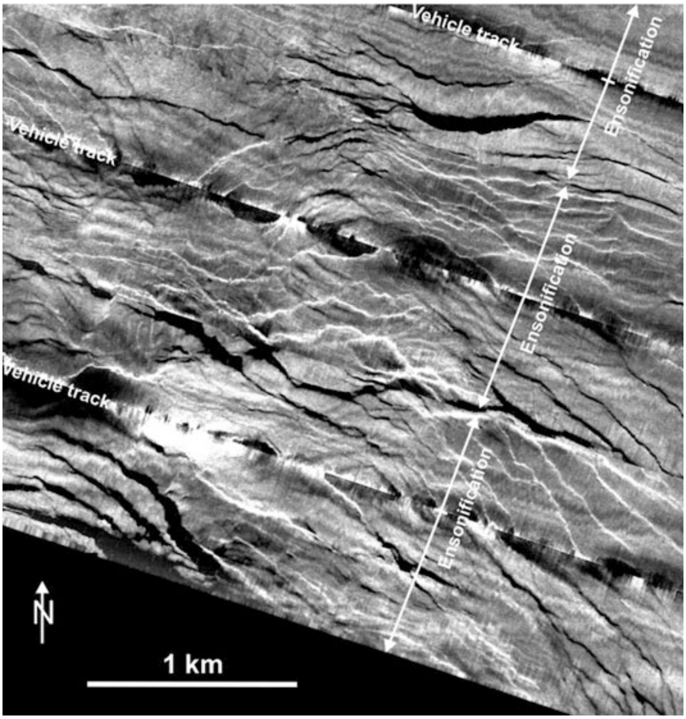

Fig. 6 Mosaic of sidescan sonar images showing fault scarps. Note that depending on ensonification direction the fault scarp changes from high backscatter (*white*) to shadows (*black*). Most fault scarps are dipping to the SW

Guidelines for the interpretation of sidescan sonar images have been published previously (Belderson et al. 1972; Johnson and Helferty 1990). For geomorphological interpretations, particular attention must be paid to the direction of ensonification. Linear structures are generally well imaged along tracks that are parallel to the alignment orientation (i.e. ensonification is perpendicular to the alignments), but may be subdued or invisible on tracks that are perpendicular to the structures (Fig. 5). In addition, features that are close to the nadir (vehicle track) are only poorly imaged. Sidescan sonar survey lines are consequently best planned at a 45° angle to elongated structures and at some distance to smaller targets in order to ensure lateral ensonification. Finally, attention must be paid to adjacent sonar images composing a mosaic. Features showing high backscatter intensity on one track (or one channel) may show low backscatter intensity on the adjacent track (channel) due to different directions of ensonification (Fig. 6).

4 Strengths and Weaknesses

Compared to other acoustic systems used for mapping the seafloor such as multibeam bathymetry systems (see Chapter "Multibeam Echosounders"), sidescan sonar systems are relatively cheap and simple to use. Time-consuming calibration procedures are not necessary nor are expensive additional sensors such as high-precision motion and heading sensors, although basic motion information can help in data processing. In addition, sidescan sonar provides high-resolution seafloor images over comparably large swath widths. Finally, sidescan sonar allows imaging very small-scale relief (in particular at high grazing angles) and provides important indications for the nature and composition of the seafloor. Among the drawbacks of sidescan sonar systems is the fact that the vast majority is used on towed or autonomous underwater vehicles resulting in difficulties to provide accurate navigational data. Some users find it difficult to interpret backscatter data that are generally uncalibrated and frequently show alternating angles of ensonification across the swath (Fig. 6). The latter can be overcome by a survey design using more than 50% overlap between adjoining swaths. This survey design has the advantage of producing two images with different "illumination" but almost doubles survey time. The biggest drawback, however, for many users is the absence of bathymetric information from standard sidescan sonar systems. Interferometric sidescan sonar overcomes this problem and provides a cost-effective tool for quick bathymetric and seafloor backscatter imagery surveys of the seafloor, as these systems are still cheaper than multibeam systems and cover wider swaths. Survey parameters such as towing altitude and choice of pulse length are well-tuned for either bathymetry or seafloor backscatter imagery.

5 Future Developments

Sidescan sonar systems are still widely used in mine detection, submarine pipeline inspection and marine archaeology. It is easy to predict that current developments such as synthetic aperture sonar and parametric synthetic aperture sonar will become more widely available even though these systems are significantly more expensive than traditional systems and require improvement in the navigation accuracy of the towfish and/or AUV. In terms of frequencies used for sidescan sonar, the end of the range appears to be reached. Physics effectively limits the use of even higher frequencies, because attenuation becomes too strong and in consequence the range becomes too small. Additional progress will likely come from improvements in signal processing and a better use of multi-frequency sonar capabilities. The use of colour to represent the different sonar frequencies allows representing more of the information content of the data and appears to be promising (Tamsett et al. 2016). At present, this is limited to multi-frequency instruments, but in the future it might be possible to use the chirp signal for such an approach. Another field that is likely to develop in the future is the use of multi-platform sonars that are installed on an entire swarm of AUVs that communicate with each other. In this way, specific targets on the seafloor are illuminated from several different grazing angles and even different frequencies, which may significantly improve our capacities to characterise the seafloor at any given location.

Acknowledgements Tim Le Bas is thanked for the critical reading of an earlier version of this chapter.

References

Bass GF (1968) New tool for undersea archaeology. Nat Geogr 134:403–423

Belderson RH, Kenyon NH, Stride AH, Stubbs AR (1972) Sonographs of the sea floor. A picture atlas. Elsevier, Amsterdam

Blackinton JG, Hussong DM, Kosalos JG (1983) First results from a combination of side-scan and seafloor mapping system (SeaMARC II). Proc Offshore Technol Conf OTC 4478:307–314

Chesterman WD, Clynick PR, Stride AH (1958) An acoustic aid to sea bed survey. Acustica 8:185–290

Clay CS, Ess J, Weisman I (1964) Lateral echo sounding of the ocean bottom on the continental rise. J Geophys Res 69:3823–3835

De Moustier C (1988) State of the art in swath bathymetry survey systems. Int Hydro Rev LXV: 25–54

EEZ-Scan 84 Scientific Staff (1986) Atlas of the U.S. Exclusive Economic Zone, Western Conterminous United States: U.S. Geological Survey Miscellaneous Investigations Series I-1792, scale 1:500,000, 152 pp

EEZ-Scan 85 Scientific Staff (1987) Atlas of the U. S. Exclusive Economic Zone, Gulf of Mexico and Eastern Caribbean Areas: U. S. Geological Survey Miscellaneous Investigations I-1864-A, scale 1:500,00, 104 pp

EEZ-Scan 87 Scientific Staff (1991) Atlas of the U. S. exclusive economic zone Atlantic continental margin: U. S. Geological Survey Miscellaneous Investigations Series I-2054, 174 pp

Gardner JV, Field ME, Twichell DC (eds) (1996) Geology of the United States Seafloor: the view from GLORIA. Cambridge University Press, Cambridge, p 371

Hackmann WD (1985) Seek and strike: sonar, anti-submarine warfare and the Royal Navy, 1914–54. Stationary Office Books, London, p 522

Hagemann J (1958) Facsimile recording of sonic values of the ocean bottom. US Patent 4197591A. http://www.google.com/patents/US4197591. Accessed on 28 Apr 2016

Huggett QJ, Millard NW (1992) Towed ocean bottom instrument TOBI: a new deep-towed platform for side-scan sonar and other geophysical surveys. Offshore Technol Conf. doi:10.4043/6849-MS

Johnson HP, Helferty M (1990) The geological interpretation of sidescan sonar. Rev Geophys 28:357–380

Klaucke I, Masson DG, Petersen CJ, Weinrebe W, Ranero CR (2008) Multifrequency geoacoustic imaging of fluid escape structures offshore Costa Rica: implications for the quantification of seep processes. G-cubed 9:Q04010. doi:10.1029/2007gc001708

Kosalos JG, Chayes D (1983) A portable system for ocean bottom imaging and charting. OCEANS'83 proceedings, pp 619–656

MIT museum. http://web.mit.edu/museum/exhibitions/klein-side-scan-sonar.html. Accessed 26 Jul 2016

Rosencrantz DM, Klein M, Edgerton HE (1972) The use of sonar. In: Underwater archeology: a nascent discipline, Paris, pp 257–270
Rusby S (1970) A long-range sidescan sonar for use in the deep sea (G.L.O.R.I.A. project). Int Hydrogr Rev 47:25–39
Somers ML, Carson RM, Revie JA, Edge RH, Barrows BJ, Andrews AG (1978) GLORIA II—an improved long range sidescan sonar. In: Proceedings of the Institute of Electrical Engineering on Offshore Instrumentation and Communications, Oceanology International Technical Session J BPS Publications, London pp 16–24
Tamsett D, McIlveny J, Watts A (2016) Colour sonar: multi-frequency sidescan sonar images of the seabed in the inner sound of the Pentland Firth, Scotland. J Mar Sci Eng 4:26. doi:10.3390/jmse4010026
Tucker MJ, Stubbs AR (1961) A narrow-beam echo-ranger for fishery and geological investigations. Brit J Appl Phys 12:103–110
Wille PC (2005) Sound images of the ocean in research and monitoring. Springer, Heidelberg, p 471
Zakharina M, Dybedal J (2007) The parametric sidescan sonar instrument and synthetic aperture sonar processing. In: Blondel P, Caiti A (eds) Buried waste in the seabed: acoustic imaging and biotoxicity (results from the European SITAR project). Springer, Heidelberg, pp 13–18

http://www.springer.com/978-3-319-57851-4

Submarine Geomorphology
Micallef, A.; Krastel, S.; Savini, A. (Eds.)
2018, XV, 556 p. 195 illus., 55 illus. in color., Hardcover
ISBN: 978-3-319-57851-4