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Technical Article

Survey of Acoustic Frequency Use for Underwater Acoustic Cognitive Technology

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ABSTRACT: *The available underwater acoustic spectrum is limited. Therefore, it is imperative to avoid frequency interference from overlapping frequencies of underwater acoustic equipment (UAE) for the co-existence of the UAE. Cognitive technology that senses idle spectrum and actively avoids frequency interference is an efficient method to facilitate the collision-free operation of multiple UAE with overlapping frequencies. Cognitive technology is adopted to identify the frequency usage of UAE to apply cognitive technology. To this end, we investigated two principle underwater acoustic sources: UAE and marine animals. The UAE is classified into five types: underwater acoustic modem, acoustic positioning system, multi-beam echo-sounder, side-scan sonar, and sub-bottom profiler. We analyzed the parameters of the frequency band, directivity, range, and depth, which play a critical role in the design of underwater acoustic cognitive technology. Moreover, the frequency band of several marine species was also examined. The mid-frequency band from 10 - 40 kHz was found to be the busiest. Lastly, this study provides useful insights into the design of underwater acoustic cognitive technologies, where it is essential to avoid interference among the UAE in this mid-frequency band.*

1. Introduction

The growing interest in marine space has highlighted the significance of marine resource development, maritime exploration, and maritime defense. Consequently, underwater exploratory missions are becoming more complex and diverse. Accordingly, various mission-specific underwater acoustic equipment (UAE) has been developed, including underwater navigation, underwater mapping exploration, underwater image acquisition, marine physical quantity measurement, and data exchange. Depending on the operating characteristics and required functions, the frequency band used by such UAE vary. However, because there is no permit or restriction on frequency use in open frequency bands, such as those underwater, a variety of acoustic equipment is mixed, causing the issue of frequency overlaps between artificial interferences. Acoustic communication systems and acoustic positioning systems are integral acoustic equipment, particularly in systems equipped with sonar equipment for seabed mapping or image acquisition, such as unmanned surface vehicles (USVs), autonomous surface vehicles (ASVs), autonomous underwater vehicle (AUVs), and remotely operated vehicles (ROVs). When such acoustic equipment operates simultaneously, signal interferences occur between communication, navigation, and sonar devices. In addition to man-made acoustic interferences, underwater marine animals cause natural acoustic interferences. For example, some marine mammals use sound waves to communicate between themselves and analyze reflected sound waves to avoid obstacles and determine the proceeding direction (echolocation), and when these signals interfere with artificial signals, it can cause severe damage. There have been reports of cases where interferences between artificial signals produced from equipment and naturally occurring signals have led to dolphins colliding with ships and getting beached after losing their heading, leading to the destruction of marine life.

Numerous cases and studies are underway to solve the aforementioned problems caused by acoustic signal interferences. Kongsberg's K-Sync equipment (Kongsberg, 2020) allows the user to set signal generating time, cycles, and intervals for each piece of equipment when operating different acoustic equipment. It prevents different pieces of equipment from generating signals simultaneously to avoid signal interferences. Studies have been conducted to investigate the frequency bands of marine mammals to avoid natural

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acoustic interferences (Ferguson and Cleary, 2001; Richardson et al., 2013) and predict the frequencies used by marine animals to prevent signal interference (Moore et al., 2012; Cheng 2017). The communication and network fields are leading the research on underwater signal interference avoidance techniques, and studies have been actively conducted to avoid interferences by applying multiple media access control methods and using orthogonal times, frequencies, codes, and phases between signals, or avoid signal interferences using a directional antenna-applied transceiving method and an idle listening method before transmission (Ali et al., 2020; Chitre et al., 2008; Goyal et al., 2019; Murad et al., 2015; Jiang 2008; Zolich et al., 2019).

As the use of UAE increases, their frequencies also increase, making underwater frequency bands increasingly chaotic. Therefore, network technology for frequency interference avoidance also becomes increasingly significant. Network technology is adopted to avoid signal interferences while using the limited underwater frequency bands more efficiently. The process of avoiding signal interferences requires the application of underwater cognitive acoustic network technology to actively avoid the occupied frequency bands by detecting idle underwater frequency bands and dynamically allocating frequency bands (Li et al., 2016; Luo et al., 2014; Luo et al., 2016a; Luo et al., 2016b; Cheng et al., 2017). To apply the cognitive network technology, The application of the cognitive network technology requires recognizing which underwater frequency bands are available temporally and spatially, which prerequisites the investigation of underwater acoustic frequency usage status.

In this study, we investigate and analyze UAE that uses sound waves and marine animals that communicate using sound waves. Moreover, we summarize and describe the main frequency bands used by marine animals and the frequency usages of commercial products for distinct UAE to use them as basic data for underwater wireless cognitive network technology. The investigated and analyzed acoustic equipment is classified according to the model of each manufacturer based on the purpose of use, and devices used primarily for marine exploration and investigation are chosen. The chosen equipment types include an underwater acoustic modem, acoustic positioning system, multi-beam echo-sounder (MBES), side-scan sonar (SSS), and sub-bottom profiler (SBP). We describe the equipment operating characteristics according to the equipment type to determine the temporal and spatial availability of frequency bands and introduce the required specifications based on the described equipment characteristics. In this study, the frequency bands of the marine equipment and marine animals are investigated and illustrated in graphs, and the major frequency bands of each piece of equipment and marine animals are combined and illustrated in graphs for comparison and analysis.

This study is organized as follows: In Section 2, status of underwater acoustic equipment frequencies is summarized and plotted. In Section 3, the frequencies used by marine animals are analyzed and summarized. Lastly, Section 4 provides the conclusion of this study.

2. Status of Underwater Acoustic Equipment Frequencies

2.1 Underwater Acoustic Modems

Table 1 lists the specifications of product models for each manufacturer of commercial underwater acoustic telemetry modems. The commercial underwater acoustic telemetry modems use a frequency band from 2.5–180 kHz; however, depending on the transmission distance, the frequency range varies. A frequency band of 20–180 kHz is used in a communication range of 1 km or less, 7.5–78 kHz in a communication range of 1–5 km, 7–31 kHz in a communication range of 5–10 km, and 2.5–31 kHz in a communication range of over 10 km. As shown in Fig. 1, the primary frequency bands

Table 1 Specifications of underwater acoustic telemetry modems (Zia et al., 2021)

Manufacturer	Model	Freq. band (kHz)	Comm. range (m)	Operating depth (m)	Baud rate (bps)
AquaSeNT. (AquaSeNT, 2020)	AM-OFDM-13A	21–27	5000	200	1500, 3000, 4500, 6000, 9000
	AM-D2000	9–15	5000	2000	375–1500
	AM-AUV	21–27	5000	-	375, 750, 1,500
Aquatec (Aquatec, 2020)	AQUAmodem 500	27–31	250	200	25–100
	AQUAmodem 1000	7.5–12	5000	1000	300–2000
Blueprint Subsea (Blueprint Subsea, 2020)	Sea Trac X150	24–32	1000	100–2000	100
	Sea Trac X110	24–32	1000	100–2000	100
	Sea Trac X110	24–32	1000	300	100
Desert Star Systems (Desert Star Systems, 2020).	SAM-1	33.8–42, 65–75	1000	300	5–150
DiveNET (DiveNET, 2020)	Microlink	10–30	1000	300	78
	Sealink C	0–20	8000	300–400	88
	Sealink R	10–45	2500	300	560, 1200
	Sealink S	0–20	8000	300–400	80

Table 1 Specifications of underwater acoustic telemetry modems (Zia et al., 2021) (Continuation)

Manufacturer	Model	Freq. band (kHz)	Comm. range (m)	Operating depth (m)	Baud rate (bps)
DSPComm (DSPComm, 2020)	AquaComm	16–30	3000–5000	-	100, 240, 480
	AquaComm Gen2	16–30	8000	-	100–1000
	AquaNetwork	16–30	3000	-	100, 480
EvoLogics (Evologics, 2020)	S2CR 48/78	48–78	1000	200–2000	31200
	S2CR 42/65	42–65	1000	200–2000	31200
	S2CR 18/34	18–34	3500	200–2000 / 6000	13900
	S2CR 15/27	15–27	6000	200–6000	9.2
	S2CR 12/24	13–24	6000	200–6000	9.2
	S2CR 7/17	7–17	6000 / 10000	200–6000 / 10000	6900
	S2CM 48/78	48–78	1000	200, 2000	31200
	S2CM 42/65	42–65	1000	200–2000	3,200
	S2CM 18/34	18–34	3500	200, 2000	13900
	S2CM 15/27	15–27	6000	200, 2000	9.2
	S2CM HS	120–180	300	200, 2000	62500
	S2CT 42/65	42–65	100	200	31200
	S2CT 18/34	18–34	3500	200	13900
Kongsberg (Kongsberg, 2020)	cNODE Modem MiniS 34-180	21–31	1000	4000	6000
	cNODE Modem MiniS 34-40V	21–31	4000	4000	6000
Linkquest (LinkQuest, 2020)	UWM1000	26.77–44.62	350	200	17800
	UWM2000	26.77–44.62	1200 / 1500	2000 / 4000	17800
	UWM2000H	26.77–44.62	1200 / 1500	2000	17800
	UWM2200	53.55–89.25	1000	1000 / 2000	35700
	UWM3000	7.5–12.5	3000 / 5000	7000	5000
	UWM3000H	7.5–12.5	3000 / 6000	2000 / 4000 / 7000	5000
	UWM4000	12.75–21.25	4000	3000 / 7000	8500
	UWM10000	7.5–12.5	7000 / 10000	2000 / 4000 / 7000	5000
Sercel (Sercel, 2020)	MATS 3G 12kHz	10–15	15000	6000	850 / 2100 / 3600 / 5500 / 7400
	MATS 3G 34kHz	30–39	15000	6000	1000 / 3000 / 6400 / 9200 / 13000 / 16500 / 24600
Sonardyne (Sonardyne, 2020)	MODEM6 Transceiver (Surface)	21–32.5	7000	-	200–9000
	MODEM6 Transceiver (Surface)_1	14–19	12000	-	200–9000
	MODEM6 Standard	21–32.5	5000	3000 / 5000	200–9000
Teledyne Marine (Teledyne Marine, 2020)	ATM-903(OEM)	9–14 16–21 22–27	2000–6000	500 / 2000 / 6000	80 for frequency hopped 140–2400 for MFSK 2560–15360 for PSK
	ATM-915/916	9–14 16–21 22–27	2000–6000	500	140–15360
	ATM-925/926	9–14 16–21 22–27	2000–6000	2000	140–15360
	ATM-965/966	9–14 16–21 22–27	2000–6000	6000	140–15360

Table 1 Specifications of underwater acoustic telemetry modems (Zia et al., 2021) (Continuation)

Manufacturer	Model	Freq. band (kHz)	Comm. range (m)	Operating depth (m)	Baud rate (bps)
TriTech (Tritech, 2020)	Micron Modem	20–28	500	150	40
Subnero Pte Ltd (Subnero Pte Ltd, 2020)	M25M	20–32	3000–5000	-	15000
Thales (Thales, 2020)	TUUM-5	8–11	15000		
		25–40	15000		
	TUUM-6	1–60	37000		200
Wärtsilä ELAC Nautik (Wärtsilä) (Wartsila, 2020)	UT2200	8.087–42	-	-	-
	UT3000	1–60	-	-	-

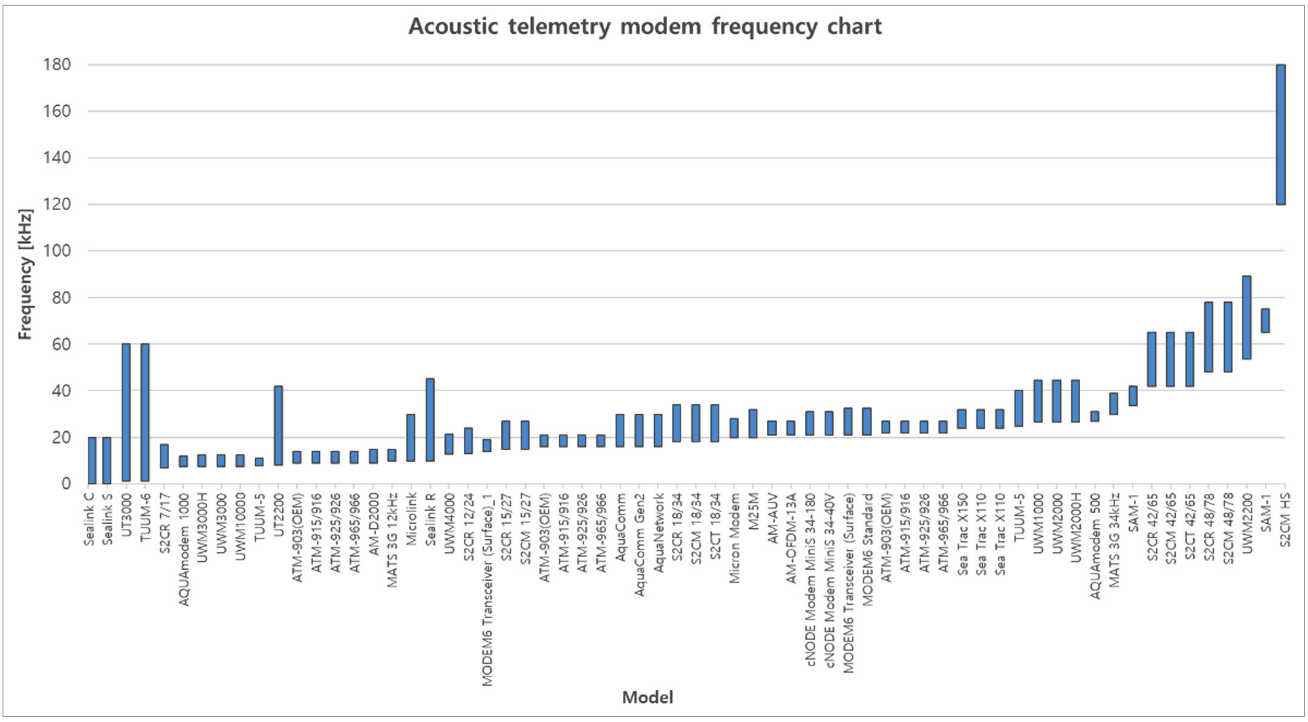

Fig. 1 Acoustic telemetry modem frequency chart

of commercial acoustic telemetry modems are concentrated in the 10–30 kHz band because underwater acoustic signals propagate most smoothly in this band. As shown in Fig. 2, the communication range of the commercial acoustic telemetry modems is mostly around 5 km, and a small number of long-range acoustic telemetry models of 10 km or longer exists. Remarkably, Thales TUMM-6 has a communication range of 37 km. Fig. 3 illustrates a graph for the operating depths of the commercial underwater acoustic telemetry modems distributed randomly according to the product characteristics and purpose, and it can be seen that a maximum operating depth of 10 km is achievable.

2.2 Acoustic Positioning Systems

An acoustic positioning system tracks the relative position of a vehicle being tracked. Generally, an underwater acoustic sensor, which becomes a baseline, is installed on the ship or seabed, and after installing underwater acoustic sensors for response (transponders) on the tracking-target vehicle, the acoustic signals are transmitted and received between the underwater acoustic sensors at both ends. The system can be linked to a satellite navigation system to track the absolute position of an object.

Acoustic positioning systems are essential for tracking the position of underwater vehicles, such as underwater robots, and, based on the tracking method, acoustic positioning systems are classified as long baseline (LBL), short baseline (SBL), and ultrashort baseline (USBL). LBL refers to estimating the position by installing the baseline at a fixed position on the seabed and measuring the slant range from the widely spaced transponder. SBL refers to estimating the position by installing the baseline at a fixed position on the seabed and measuring the relative arrival time from three or more transponders installed on a ship (Vickery, 1998). USBL involves estimating the position by installing the baseline on a ship or an underwater vehicle that performs the role of the mother ship and measuring the relative phase of the

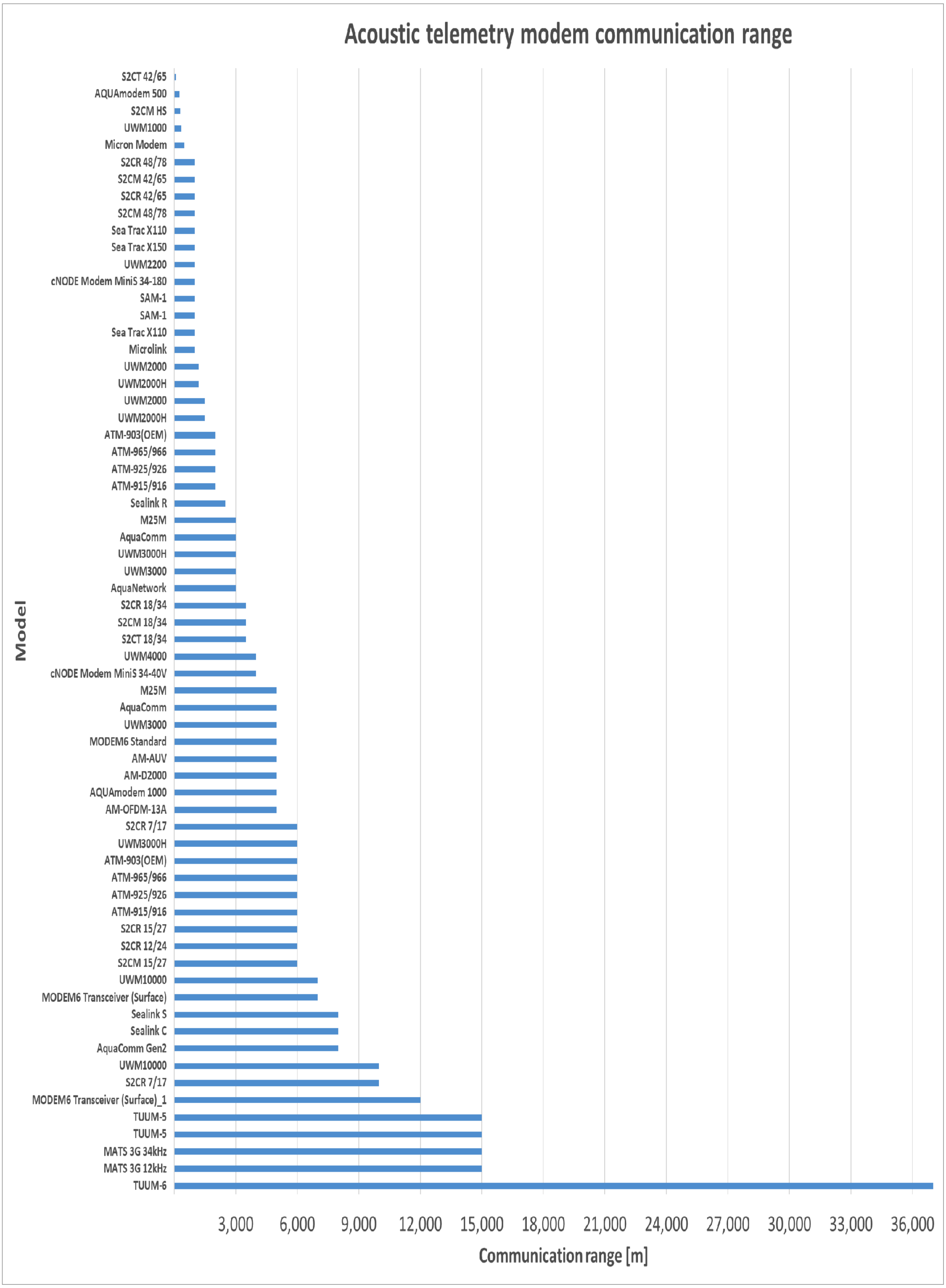

Fig. 2 Acoustic telemetry modem communication range

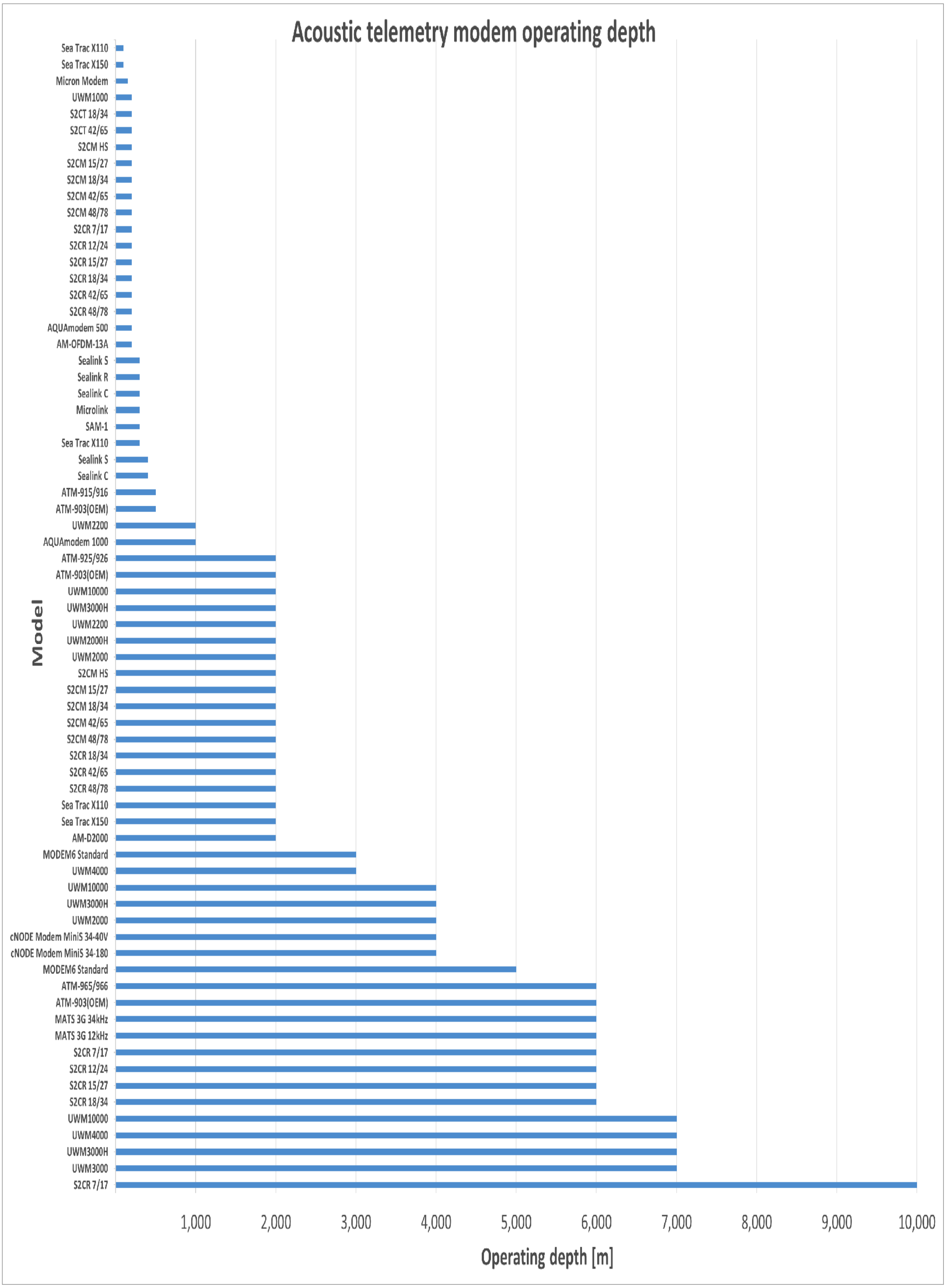

Fig. 3 Acoustic telemetry modem operating depth

acoustic signals received using the array sensors embedded in the single transponder (Soppet, 2011).

Table 2 lists the specifications of product models for different acoustic positioning system manufacturers. Numerous acoustic positioning system models use SSBL, USBL, and LBL simultaneously, and many models also use USBL and acoustic telemetry functions simultaneously. In Table 2, the field of view indicates the angle for the zone where the acoustic positioning system

Table 2 Specifications of acoustic positioning systems

Manufacturer	Model	Freq. band (kHz)	Field of view (degree)	Operating range (m)
Evologics (Evologics, 2020)	S2C R 7/17W	7–17	hemispherical	8000
	S2C R 7/17D	7–17	80	10000
	S2C R 7/17	7–17	hemispherical	8000
	S2C R 12/24	13–24	70	6000
	S2C R 15/27	15–27	120	6000
	S2C R 18/34H	18–34	hemispherical	3000
	S2C R 18/34	18–34	Horizontally Omni	3500
	S2C R 42/65	42–65	100	1000
	S2C R 48/78	48–78	Horizontally Omni	1000
	S2C M HS	12–180	Omni	300
Kongsberg (Kongsberg, 2020)	HiPAP 502	21–31	200	5000
	HiPAP 452	21–31	120	5000
	HiPAP 352	21–31	120	5000
	HiPAP 352P	21–31	120	4000
	HiPAP 102	10–15	120	10000
	MicroPAP 200	0.005–0.1	160	4000
	MicroPAP 200-NEL	21–31	160	995
	MicroPAP 201-2	21–31	160	4000
	MicroPAP 201-3	21–31	160	4000
	MicroPAP 201-3-NEL	21–31	160	995
	MicroPAP 201-H	21–31	160	4000
Sonardyne (Sonardyne, 2020)	AVTRAK 6 Type8220-3111	19–34	Omni	3000
	AVTRAK 6 Type8220-7212	19–34	Directional	7000
	Dunker 6 Type8309.1351	21–32.5	Omni	1000
	Dunker 6 Type8309.1353	21–32.5	Directional	1000
	Dunker 6 Type8309.1355	14–19	Omni	1000
	Dunker 6 Type8309.1356	14–19	Directional	1000
	HPT 5000/7000 Type8142-001	19–34	180	7000
	HPT 5000/7000 Type8142-002	19–34	180	7000
	GYRO IUSBL	19–34	180	7000
	Marker 6	19–34	Omni, 260	4000
iXBlue (iXBlue, 2020).	Posidonia	8–18	70, 100	10000
	Posidonia2	8–14	70, 100	10000
	Gaps M5	20–30	200	995
	Gaps M7	20–30	200	4000
	Ramses	18–36	Omni	4000

Table 2 Specifications of acoustic positioning systems (Continuation)

Manufacturer	Model	Freq. band (kHz)	Field of view (degree)	Operating range (m)
Applied Acoustic Engineering (Applied Acoustic Engineering, 2020).	Easytrak Nexus2 EZT-2886-N	18–32	180	995
	Easytrak Nexus2 EZT-2886-C	18–32	180	2000
	Easytrak Nexus2 EZT-2780-N	18–32	150	995
	Easytrak Nexus2 EZT-2780-C	18–32	150	3000
LinkQuest (LinkQuest, 2020)	TrackLink 1500	31–43.2	120–150	1000
	TrackLink 5000	14.2–19.8	120	5000
	TrackLink 1000	7.5–12.5	90–120	11000
Teledyne Marine (Teledyne Marine, 2020)	USBL DAT	9–14	Omni (toroidal)	6000
	USBL DAT	16–21	Omni (toroidal)	4000
	USBL DAT	22–27	Omni (toroidal)	2000
	LBL SM-975	9–14	hemispherical	10000
	LBL SM-975	16–21	hemispherical	10000
	LBL SM-975	22–27	hemispherical	
Advanced Navigation (Advanced Navigation, 2020)	Subsonus	30	300 (hemispherical)	1000
Blueprint Subsea (Blueprint Subsea, 2020)	SeaTrac X150	24–32	-	1000

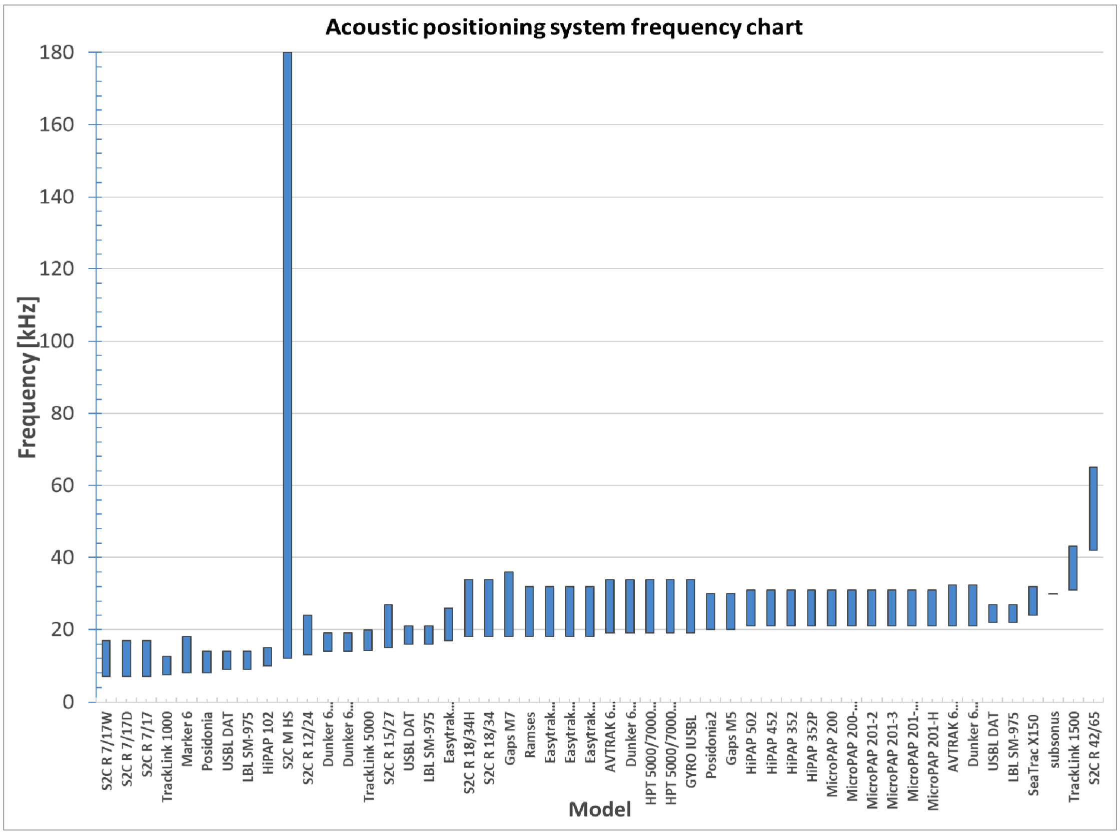

Fig. 4 Acoustic positioning system frequency chart

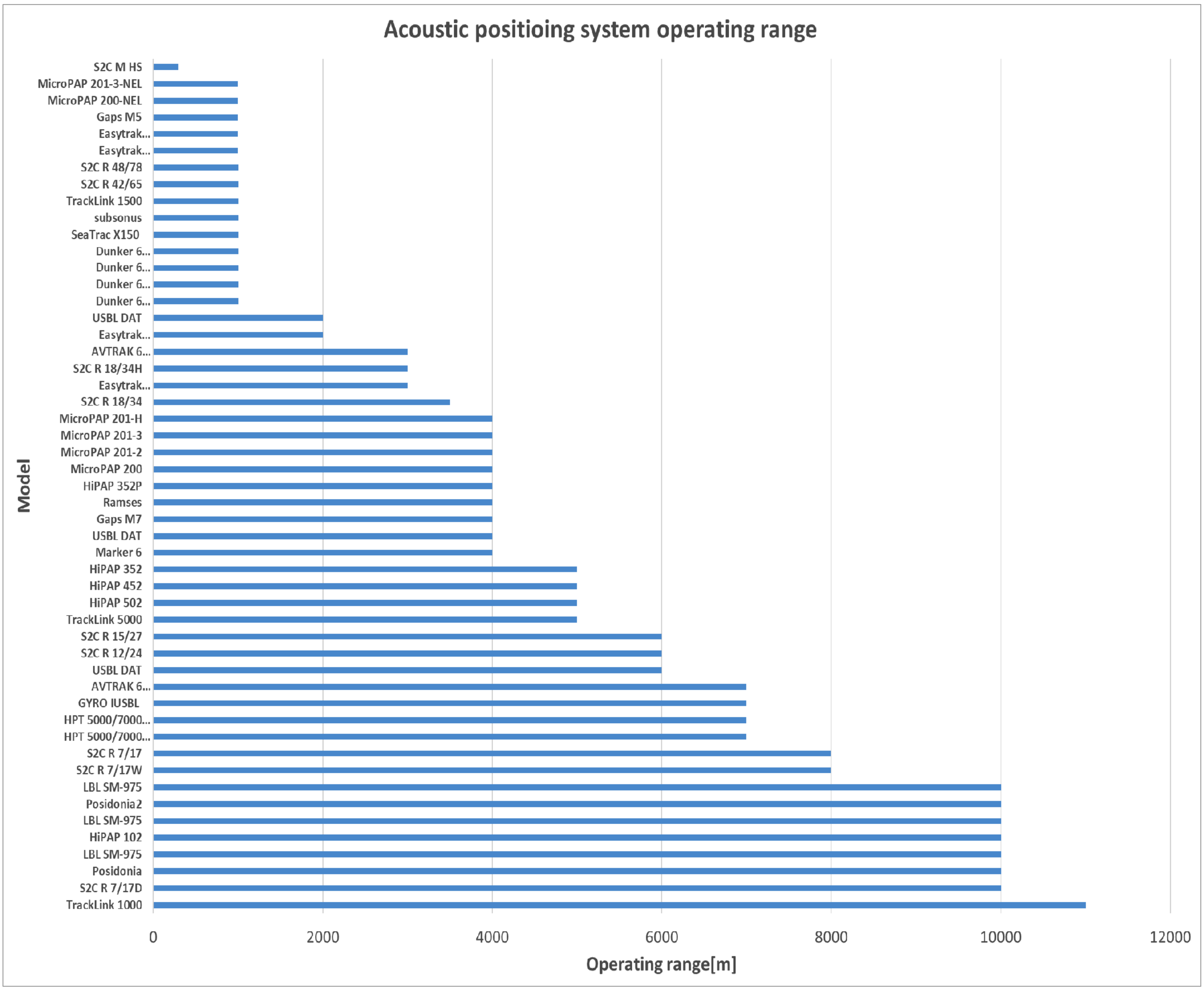

Fig. 5 Acoustic positioning system operating depth

can operate. In an acoustic positioning system, multiple transducers are structured in an array, producing acoustic signals, and the combination of the beam pattern of each transducer signal determines the system's operating range. The field of view value—the beamwidth of the combined acoustic signals—is the half-power beamwidth of the acoustic signals in general and indicates the beamwidth from the maximum acoustic strength to an acoustic signal strength of -3 dB lower. Fig. 4 illustrates the frequency band distribution of the acoustic positioning systems, and similar to the underwater acoustic telemetry modems, the primary frequency bands are concentrated between 10–30 kHz. As depicted in Fig. 5, the acoustic systems have various operating ranges from 300–11000 m.

2.3 Multi Beam Echo-Sounders (MBES)

MBES is a system that emits hundreds of sound waves simultaneously and receives the reflected waves from the seabed to create an automated topographical map on a computer. It measures the distance of an obstacle at each angle. MBES is used in exploring seabed topography, searching for sunken ships, identifying submarine geological characteristics, installing and repairing submarine pipes and cables, securing views of underwater vehicles, and other underwater operations.

Table 3 lists the specifications of product models for each commercial MBES manufacturer. In the beamwidth of the sound wave generated by MBES, "x" indicates the horizontal x vertical beamwidth, which ranges from 0.5°–5°. In the beamwidth column in Table 3, the listed beamwidth values, such as 1°, 2°, and 3°, can be selectively used according to the resolution required in the corresponding frequency band, and, as the beamwidth becomes narrower, the resolution increases. However, the number of sound waves generated by the MBES also increases. Therefore, the beamwidth increases in the low-frequency band and decreases in the high-frequency band. As shown in Fig. 6, 10–1000 kHz is used as the frequency band of MBES, and the primary frequency bands used are between 200–500 kHz, which are high-frequency bands compared to those of the communication or navigation systems. Fig. 7 illustrates the operating depths of MBES, which are distributed variously from 100–11000 m.

Table 3 Specifications of MBESs

Manufacturer	Model	Freq. band (kHz)	Beam width (degree)	Immersion depth (m)
R2onic (R2onic, 2020)	Sonic 2020	700 200–450	2°x 2° at 450 kHz 4°x4°at 20 0kHz,	100 / 4000 (Opt.)
	Sonic 2022	700 170–450	0.9°x 0.9° at 450 kHz 2°x2°at 200 kHz,	100 / 4000 & 6000 (Opt.)
	Sonic 2024	700 170–450	0.45°x 0.9° at 450 kHz 1°x2°at 200 kHz,	-
	Sonic 2026	100 90	-	-
	Sonic 2026	170–450	0.45°x 0.9° at 450 kHz 1°x1°at 200 kHz, 2°x2°a t90 kHz,	100 / 4000 (Opt.)
Kongsberg (Kongsberg, 2020)	EM 2040 single RX	200–400	0.4°, 0.7°	600
	EM 2040 dual RX	200–400	0.4°, 0.7°	600
	EM 2040c single head	200–400	1°	490
	EM 2040C dual head	200–400	1°	490
	EM 2040P	200–400	1°	510
	EM 712	40–100	0.25°, 0.5°,1°, 2°	3600
	EM 302	30	0.5°,1°, 2°, 4°	7000
	EM 122	12	0.5°, 1°, 2°	11000
	M3	500	3°	50
Wärtsilä ELAC Nautik (Wärtsilä) (Wartsila, 2020)	Seabeam 3050	50	1°, 1.5°, 3°	3500
	Seabeam 3030	26	1°, 1.5°, 3°	7500
	Seabeam 3012	12	1°, 2°	11000
	Seabeam 3020	20	1°, 2°	9000
Imagenex (Imagenex, 2020)	837BXi Delta T1000	260	3°, 1.5°, 0.75°	1000
	837BXi Delta T300	260	3°, 1.5°, 0.75°	300
	837AXi	165	3°, 1.5°, 0.75°	6000
	DT102Xi	675	3°, 1.5°, 0.75°	300
	DT101Xi	240	3°, 1.5°, 0.75°	300
	DT360	675	3°, 1.5°, 0.75°	1000
	965A 1100	1100	1.5°	2000
	965A	675	1.5°	2000
	965	260	1.5°	300
	965	675	1.5°	300
Teledyne Marine (Teledyne Marine, 2020)	MB1	170–220	4°x 3°	240
	MB2	200–460	1.8°x 1.8°	240
	SeaBat T20-P	200–400	1°, 2°	575
	SeaBat T20-R	200–400	1°, 2°	575
	SeaBat T20-R IDH	200–400	1°, 2°	575
	SeaBat T50-P	200–400	0.5°, 1°	575
	SeaBat T50-R	200–400	0.5°, 1°	575
	SeaBat T50-R IDH	200–400	0.5°, 1°	575
	SeaBat T50 Extended Range	150/200/400	0.5°, 1°, 1.5°	900
	SeaBat 7111	100	1.9°x 1.5°	1000
	SeaBat 7160	44	2.0°x 1.5°	3000
	HydroSweep MD50	52–62	0.5°, 0.75°, 1°, 1.5°	2500
	HydroSweep MD30	24–30	1°, 1.5°, 3°	7000
	HydroSweep DS	14–16	0.5°, 1°, 2°	11000
	Parasound M D, P35, P70	18–24	4.5°x 5.0°	11000

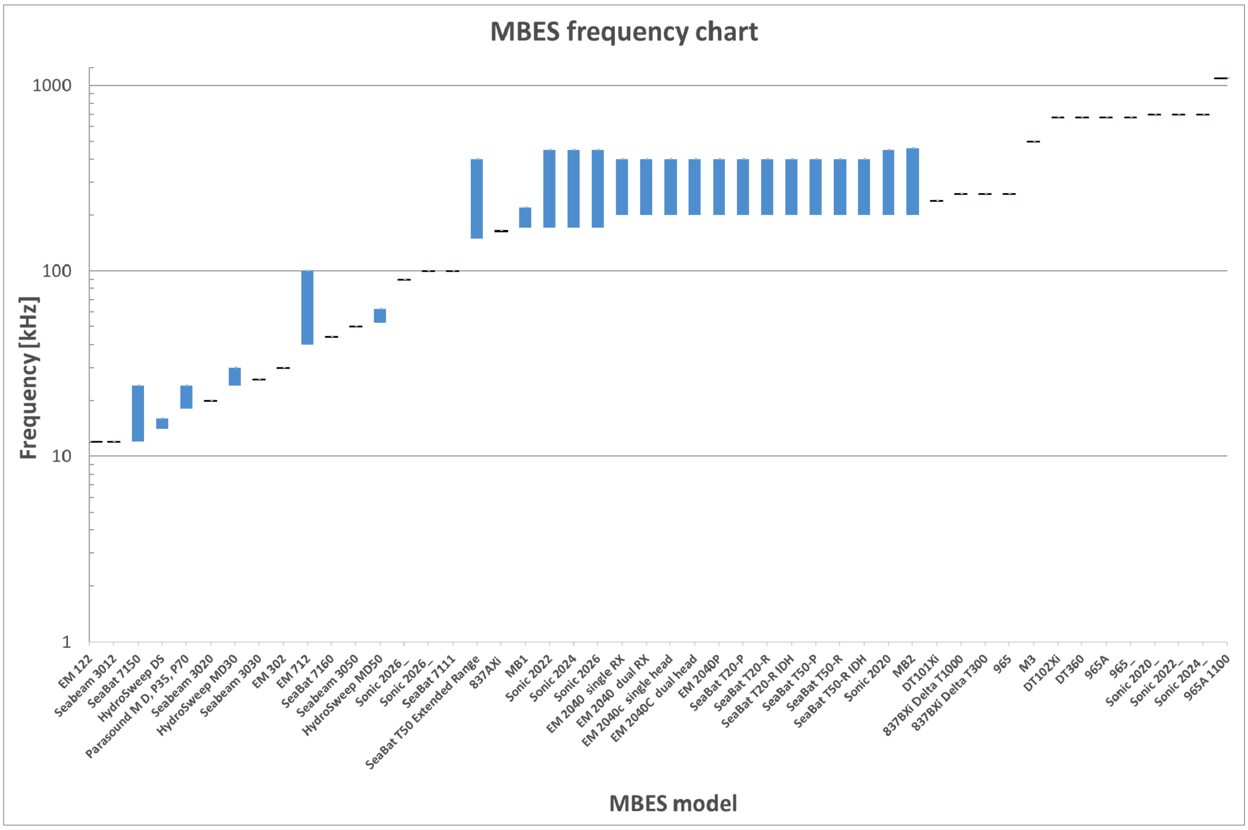

Fig. 6 MBES frequency chart

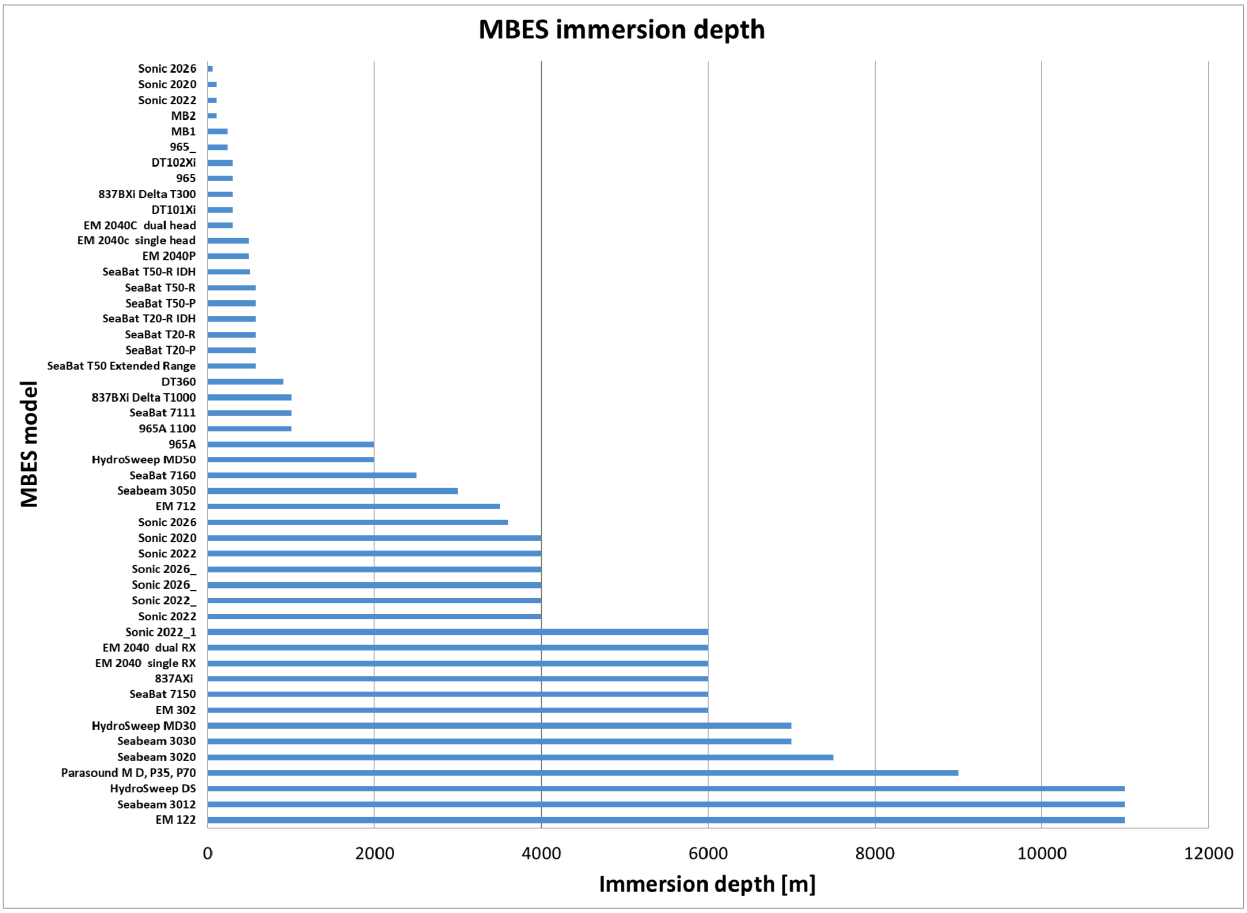

Fig. 7 MBES immersion depth

2.4 Side-Scan Sonars (SSS)

SSS systems use a towing fish to generate sound waves in the left and right directions underwater and receive the reflected waves to create an automated topographic map on a computer. It measures the distance of an obstacle at each angle. Occasionally, SSS systems simultaneously perform the bathymetry function of measuring the underwater depth in the sea; examples include EdgeTech's 6205 bath model and Sonardyne's SOLSTICE model. Table 4 lists the specifications of

Table 4 Specifications of SSSs

Manufacturer	Model	Freq. band (kHz)	Depth rating (m)	Operating range (m)	Beam width (horizontal) degree	Beam width (vertical) degree	dual/tri simultaneous Freq.(kHz)
EdgeTech (EdgeTech, 2020)	2000 series	100	300, 2000, 3000 depending on tow fish	500	1.08	-	100 / 400
	2001 series	300	-	230	0.6	-	300 / 600
	2002 series	400	-	150	0.56	-	100 / 400
	2003 series	600	-	120	0.26	-	300 / 600
	2205 sonars	75	options to 6000 m	-	-	-	75 / 120 75 / 410
		100		-	-	-	100 / 400
		120		500	-	-	75 / 120
		300		300	-	-	300 / 600
		400		-	-	-	100 / 400
		410		200	-	-	75 / 410
		230		-	-	-	230 / 850
		540		150	-	-	230 / 540 / 1600
		600		-	-	-	300 / 600 600 / 1600
		850		75	-	-	230 / 850
		1600		35	-	-	600 / 1600
	2300 combined	120	2000 (3000 m optional)	500	0.68	50	120 / 410 / 850
		230		300	0.5	50	230 / 540 / 850
		410		200	0.3	50	120 / 410 / 850
		540		150	0.26	50	230 / 540 / 850
		850		75	0.2	50	120 / 410 / 850 230 / 540 / 850
	2400 specials	75	options to 6000 m	1250	1.3	75	75 / 410
		120		500	1.1	75	120 / 410
		410		150	0.75	75	75 / 410 120 / 410
	4125 High Res.	400	200	150	0.46	50	400 / 900
		600	-	120	0.33	50	600 / 1600
		900	-	75	0.28	50	400 / 900
		1600	-	35	0.2	50	600 / 1600
	4205 multi	120	2000	600	0.7	50	120 / 410 / 850 120 / 410
		230	2000	350	0.44	50	230 / 540 / 850 230 / 850
		410	2000	200	0.28	50	120 / 410 / 850 120 / 410
		540	2000	150	0.26	50	230 / 540 / 850 230 / 540
		850	2000	90	0.23	50	230 / 540 / 850 230 / 850

Table 4 Specifications of SSSs (Continuation)

Manufacturer	Model	Freq. band (kHz)	Depth rating (m)	Operating range (m)	Beam width (horizontal) degree	Beam width (vertical) degree	dual/tri simultaneous Freq.(kHz)
	6205 bath	230	100	250	0.54	-	230/540 with 540kHz Bath 230/540 with 230kHzBath
		550	100	150	0.36	-	540/1600 with 540kHz Bath 540/850 with 540 kHz Bath
		850	100	75	0.29	-	540/850 with 540kHz Bath
		1600	100	35	0.2	-	540/1600 with 540kHz Bath
Imagenex (Imagenex, 2020)	BlackFin 1100	1100	1000	-	0.25	60	-
	878 RGB	120	1000	500	1	60	120/260/540 Tri. Freq. simultaneous
		260	1000	300	1	60	
		540	1000	120	1	60	
	878	260	1000	300	1	60	260/540 dual or single
		540	1000	120	0.5	60	
	SportScan	330	30	120	1.8	60	single
		800	30		0.7	30	330/800 dual
	YellowFin	260	300	200	2.2	75	260/330/800 Tri. Freq.
		330	300	200	1.8	60	
		800	300	200	0.7	30	
Kongsberg (Kongsberg, 2020)	PulSAR	550–1000	100	100 @550 kHz	0.5	50	-
Sonardyne (Sonardyne, 2020)	SOLSTICE	725–775	300	200	0.15		with bathymetry
C-MAX (C-MAX, 2020)	CM2	100	2000	500	1	90	100/325 dual
		325	2000	150	0.3	90	325/780 dual 100/325 dual
		780	2000	50	0.2	90	325/780 dual
Tritech (Tritech, 2020)	SeaKing AUV/ROV	325	4000	200	1	30	-
		675	4000	100	0.5	30	-
	SeaKing Towfish	325	40	200	1.7	30	-
		675	40	100	1	30	-
	SeaKing Towfish SK150	150	120	350	1.4	60	-
	StarFish 450F	450	50	100	1.7	60	-
	StarFish 450H	450	50	100	1.7	60	-
	StarFish 452F	450	50	100	0.8	60	-
	StarFish AUV	450	300	100	0.5	60	-
	StarFish 990F	1000	50	35	0.3	60	-
Innomar (Innomar, 2020)	SES-2000 sss	100	50		0.9	35	-

product models for each SSS system manufacturer. SSS systems use dual or triple frequency bands simultaneously. In Table 4, “230/540 with 540 kHz Bath” shown for the 6205 bath model means that SSS and bathymetry functions are performed simultaneously by using dual-frequency bands of 230 and 540 kHz for SSS and a frequency band of 540 kHz for bathymetry. As illustrated in Fig. 8, the frequency bands of SSS are distributed between 75–1600 kHz, and the primary frequency bands are concentrated between 100–1000 kHz. The horizontal beamwidth of SSS is distributed between 0.26°–1.8°, and the vertical beamwidth is distributed between 30°–90°. Fig. 9 illustrates the operating ranges of SSS, and SSS systems operate in various ranges from 35–1250 m.

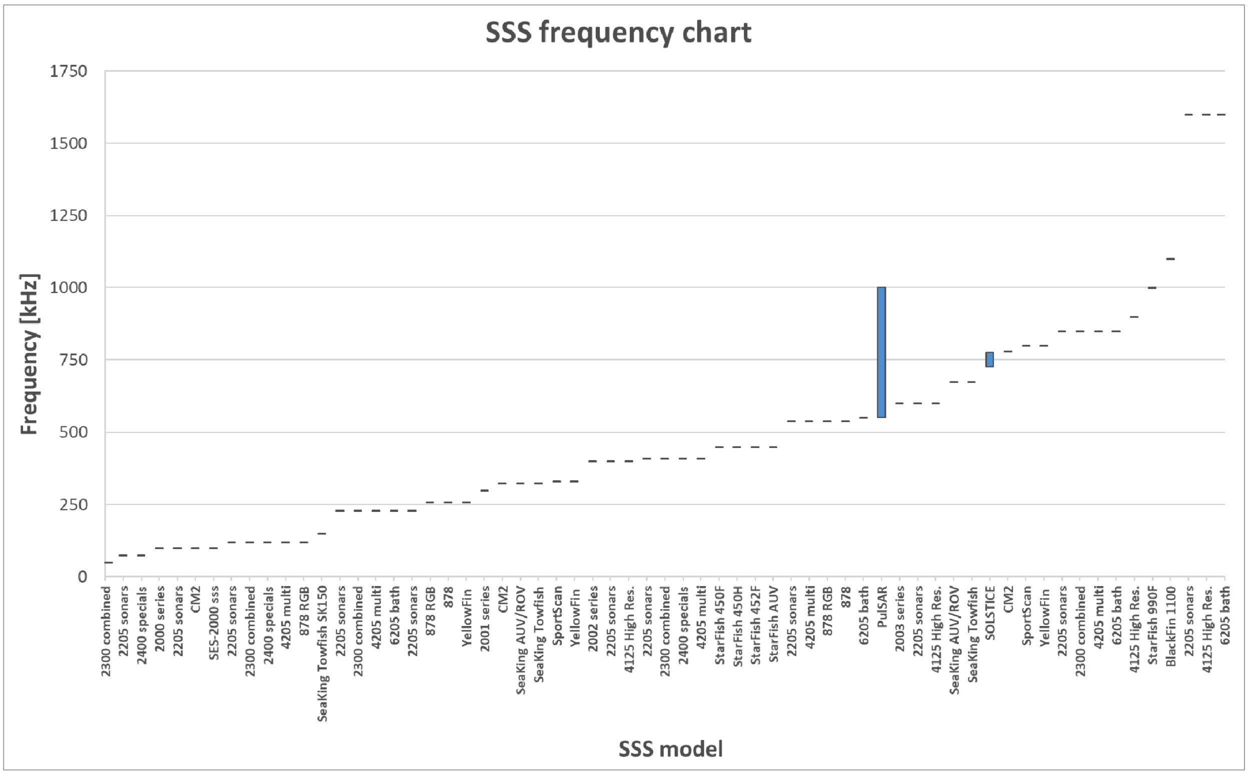

Fig. 8 SSS frequency chart

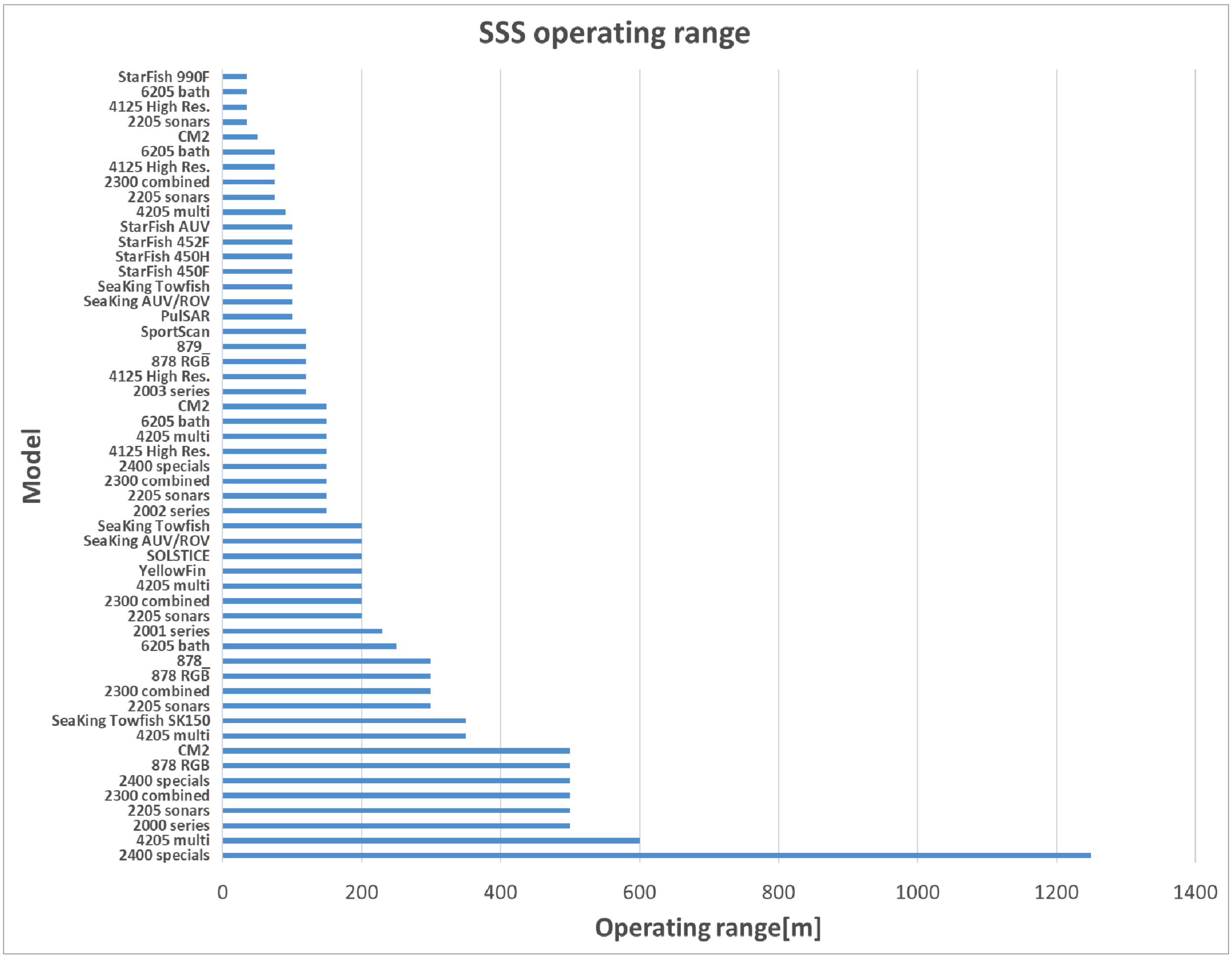

Fig. 9 SSS operating range

2.5 Sub-Bottom Profilers (SBP)

SBP systems generate low-frequency sound waves to a submerged-body underwater and receive the reflected waves from the seabed to create a topographic map and sub-bottom profiles on a computer. It is used to investigate submerged artifacts, explore buried naval mines, and investigate marine and inland water geology, the conditions of buried submarine pipelines and cables, and marine and inland water sub-bottom profiles.

Table 5 lists the specifications of product models for each SBP manufacturer. As shown in Fig. 10, SBP uses the primary frequency band (generally 90–110 kHz) and the secondary frequency band (≤ 30 kHz) simultaneously. The frequency bands are lower than 120 kHz, which is comparatively lower than those of MBES or SSS. Moreover, SBP produces the loudest noise among the acoustic equipment, which may interfere with other acoustic equipment. Fig. 11 illustrates the operating depths of SBP, which are distributed variously between 30–11000 m.

Table 5 Specifications of SBPs

Manufacturer	Model	Freq. band (kHz)	Operating depth (m)
EdgeTech (EdgeTech, 2020)	2000-ccs	0.5–12	3000
	2000-dss	2–16	3000
	2000-tvd	1–10	3000
	2205 DW-424	4–24	6000
	2205 DW-216	2–16	6000
	2205 DW-106	1–10	6000
	2300 4xDW-106	1–10	6000
	2400 DW-106	1–10	6000
	2400 DW-216	2–16	6000
	2400 DW-424	4–24	6000
	3300 (2x2 array)	2–16	300
	3300 (3x3 array)	2–16	1500
	330 0(4x4 array)	2–16	3000
	3300 (5x5 array)	2–16	5000
	3300 (triangle)	1–10	1500
	3300 (“dice 5”)	1–10	3000
	3300 (hexagonal)	1–10	5000
Innomar (Innomar, 2020)	SES-2000 smart	90–110	100
		5–15	
	SES-2000 compact	85–115	400
		2–22	
	SES-2000 light	85–115	400
		2–22	
	SES-2000 standard	85–115	500
		2–22	
	SES-2000 quattro (4array)	85–115	30
		2–22	
	SES-2000 quattro (single)	85–115	500
		2–22	
	SES-2000 sixpack (6array)	85–115	30
		2–22	
	SES-2000 sixpack (single)	85–115	1000
		2–22	
	SES-2000 medium-100	85–115	2000
		2–22	
	SES-2000 medium-70	60–80	2500
		0.5–15	
	SES-2000 deep-36	30–42	6000
		1–10	

Table 5 Specifications of SBPs (Continuation)

Manufacturer	Model	Freq. band (kHz)	Operating depth (m)
Innomar (Innomar, 2020)	SES-2000 deep-15	10–20	11000
		0.5–5.5	
	SES-2000 ROV	85–115	1000/2000
		4–22	
	SES-2000 AUV	85–115	2000
		4–18	
iXBlue (iXBlue, 2020)	Echoes 1500	0.5–2.5	400
	Echoes 3500 T1	1.7–5.5	shallow
	Echoes 3500 T3	1.7–5.5	Continental
	Echoes 3500 T7	1.7–5.5	deep
	Echoes 5000	2–6	6000
	Echoes 10000	5–15	shallow
Kongsberg (Kongsberg, 2020)	TOPAS PS 18	15–21	11000
		0.5–6	
	TOPAS PS 40	35–45	
		1–10	2000
	TOPAS PS 120	70–100	2–500
		2–30	400
	SBP 27	2–9	11000
	SBP120	2.5–6.5	11000
	SBP300	2.5–6.5	11000
	GeoPulse	2–12	3000
	GeoPulse Plus	1.5–18	2000–4000

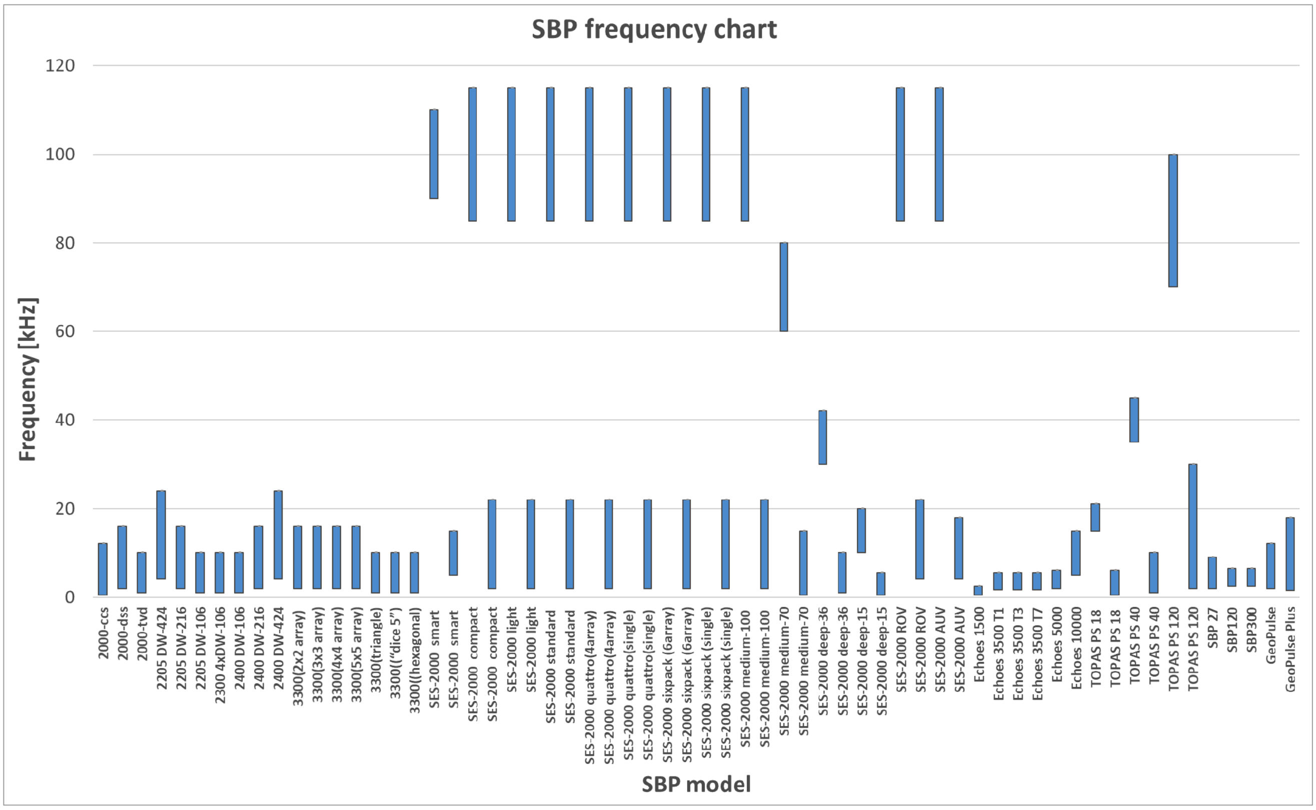

Fig. 10 SBP frequency chart

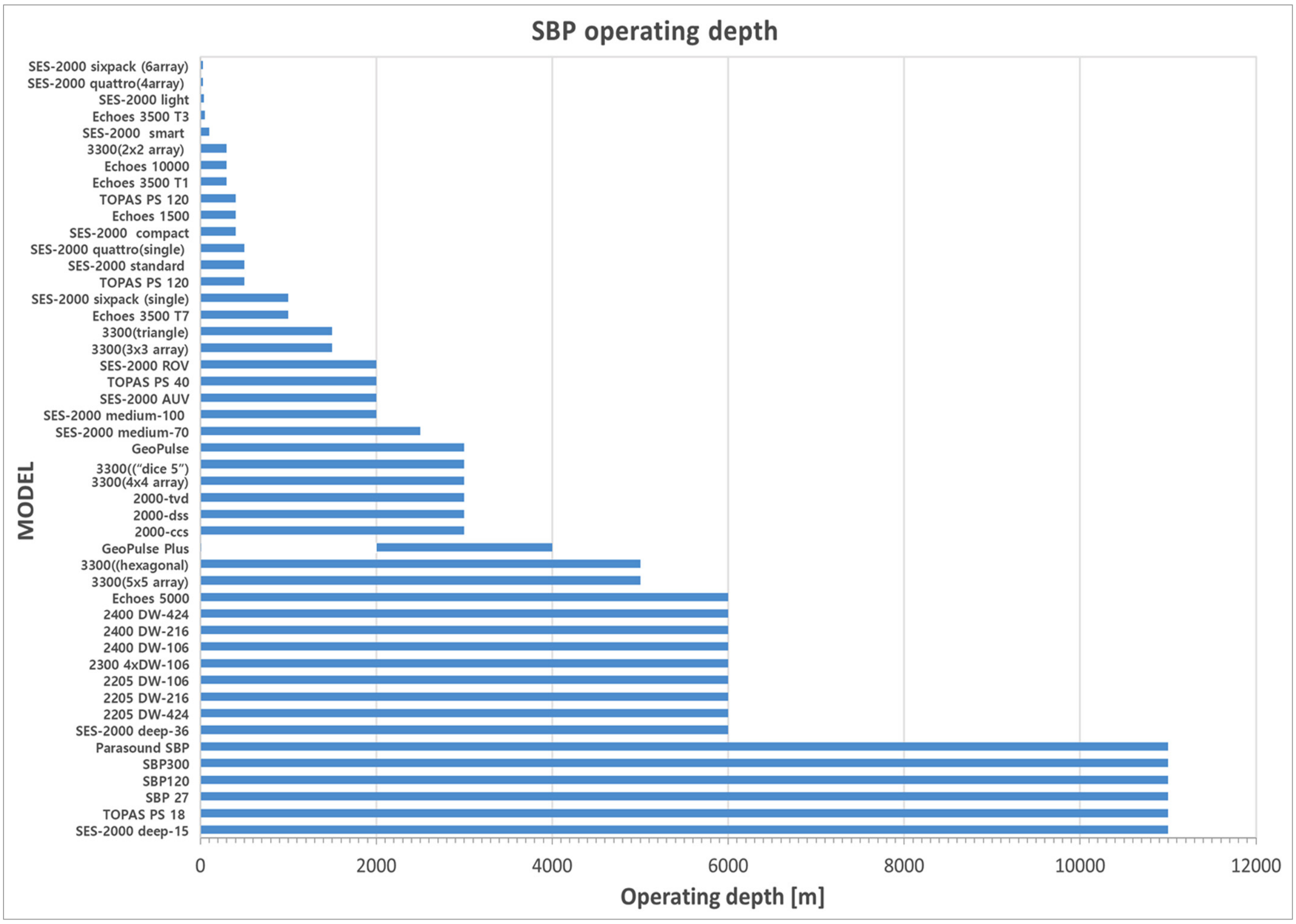

Fig. 11 SBP operating depth

3. Frequencies Used by Marine Animals

The spatial characteristics of major habits or ecological characteristics of marine animals should be considered to determine whether the frequency bands of marine animals using sound waves are available spatiotemporally. However, it is skipped in this study because it is outside the research scope, and we will only deal with the status of the frequency bands used by marine animals. Table 6 summarizes the frequency ranges and the dominant frequency ranges used by marine animals that communicate using sound waves. As shown in Fig. 12, underwater marine animals generate frequencies in the 0.01–170 kHz band, and the dominant frequencies are below 20 kHz. These frequencies match the primary frequency bands generated by UAE, such as underwater acoustic modems and acoustic positioning systems, which may cause communication collisions between acoustic equipment and marine animals.

Table 6 Frequencies used by marine animals (National Research Council, 2000)

Species	Frequency range (kHz)	Dominant frequencies (kHz)
Gray Whale (adults)	0.02–2	0.02–1.2
Gray Whale (calf clicks)	0.1–20	3.4–4
Humpback Whale	0.03–8	0.12–4
Finback Whale	0.014–0.75	0.02–0.04
Mink Whale	0.04–2	0.06–0.14
Southern Right Whale	0.03–2.2	0.05–0.5
Bowhead Whale	0.02–3.5	0.1–0.4
Blue Whale Pacific	0.01–0.39	0.016–0.024
Blue Whale Atlantic	-	0.01–0.02
Sperm Whale (clicks)	0.1–30	2–16
White Whale (whistles)	0.26–20	2–5.9

Table 6 Frequencies used by marine animals (National Research Council, 2000) (Continuation)

Species	Frequency range (kHz)	Dominant frequencies (kHz)
White Whale (clicks)	40–120	
Killer Whale (whistles)	1.5–18	6–12
Killer Whale (clicks)	1.2–25	-
Long-finned pilot whale (whistle)	1–8	-
Bottlenose dolphin (whistles)	0.8–24	3.5–14.5
Bottlenose dolphin (clicks)	1–150	30–130
Atlantic white-sided dolphin (whistle)	3–20	-
Common dolphin (whistle)	3–20	-
Harbor porpoise (clicks)	110–170	-
Gray seal	0.1–40	0.1–10
Cusk eel (chatter)	1.098–1.886	-
Cusk eel (drumming)	0.1–0.5	-
Cusk eel (knocks, clicks)	0.038–5	-

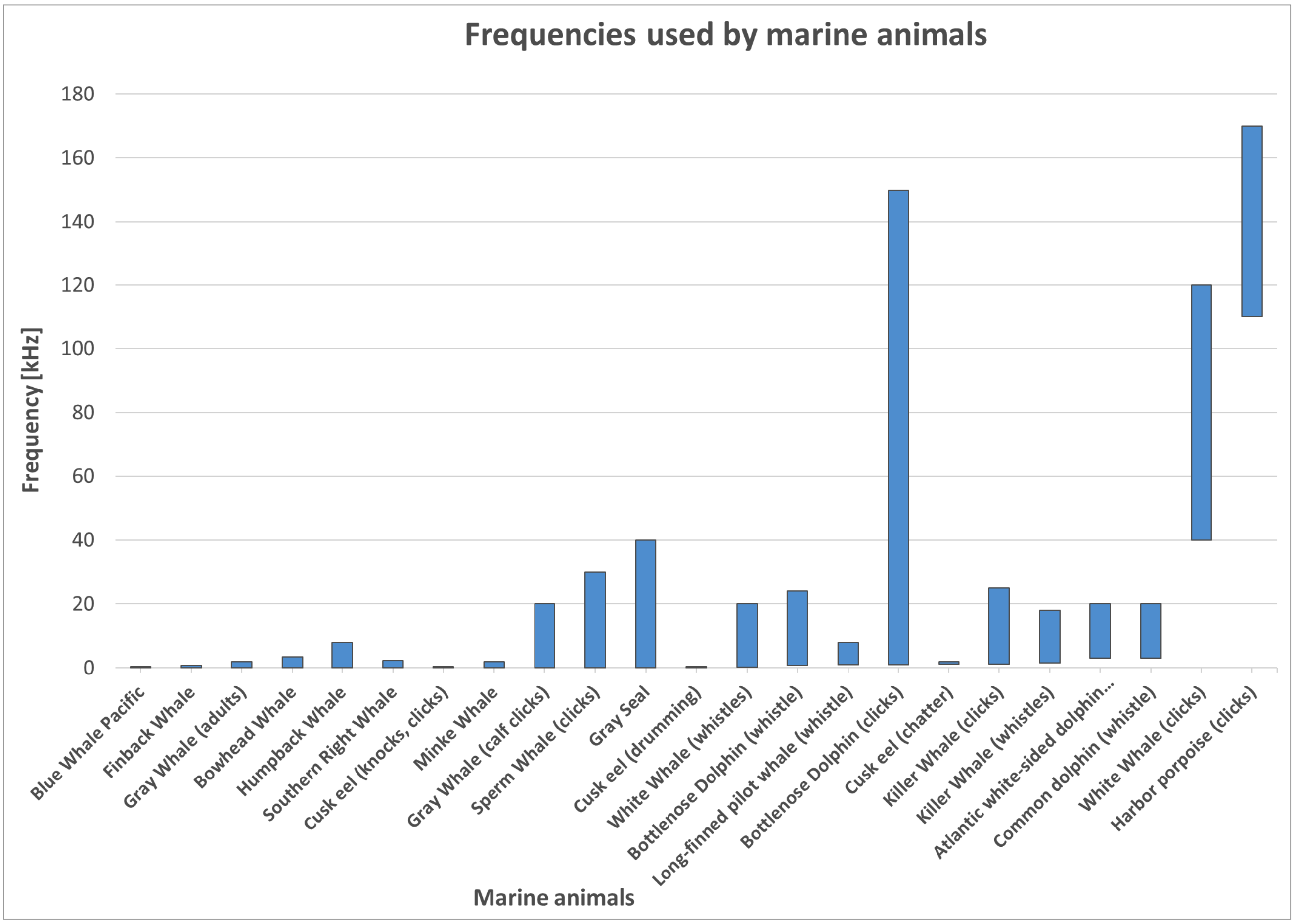

Fig. 12 Marine animal sound frequency chart

4. Conclusion

In this study, we investigated and analyzed the frequency bands used by commercial products for each manufacturer of UAE according to the purpose of use. Moreover, we also investigated the frequency bands used by marine animals that communicate using sound waves. Fig. 13 illustrates a graph that summarizes and illustrates the primary frequency bands used by each piece of equipment and the dominant frequency bands of marine animals. The frequency bands illustrated in Fig. 13 are the frequency bands of equipment and marine animals that are within 80% of the minimum and maximum frequency range for each marine animal and acoustic equipment type investigated. As

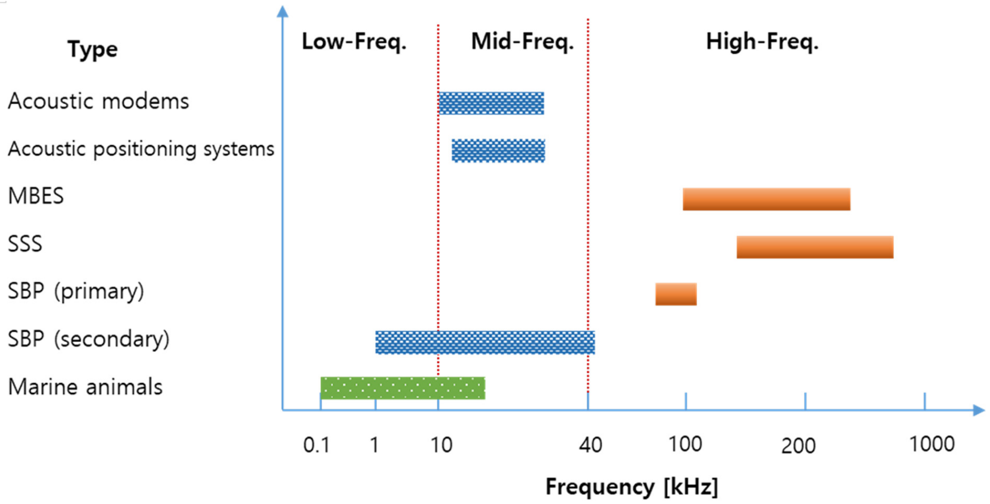

Fig. 13 The frequency bands for the acoustic equipment and marineanimals

shown in Fig. 13, the frequencies overlap most in the mid-frequency range (10–40 kHz) because both acoustic equipment and marine animals use these frequencies. In the case of acoustic telemetry modems and acoustic positioning systems, the primary frequency bands are almost identical and overlap in a range of 10–30 kHz, meaning that a collision avoidance method is required to prevent signal interference. The frequency band of MBES is a high-frequency band compared to that of the above equipment and is concentrated between 50–500 kHz. The frequency band of SSS is primarily distributed between 150–850 kHz, and the same model can use dual or triple frequency bands simultaneously. SBP uses the primary frequency band (60–110 kHz) and the secondary frequency band (45 kHz or lower) simultaneously and produces the largest noise among acoustic equipment, which increases the likelihood of causing interferences in other acoustic equipment. Meanwhile, marine animals primarily generate acoustic signals in the range of 0.1–20 kHz, and measures should be in place to avoid frequency overlaps with the secondary frequency bands of acoustic modems, acoustic positioning systems, and SBP. Moreover, the frequency bands of the analyzed acoustic equipment and marine animals can be used as reference data to avoid signal interferences when operating multiple pieces of UAE simultaneously. Finally, the frequency bands of UAE and marine animals can be used to develop technology for underwater spectral sensing, sharing, and frequency band determination in underwater acoustic cognitive technology, where it is crucial to avoid underwater signal interferences.

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