SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549 / https://doi.org/10.14445/23488549/IJECE-V9I7P102

Volume 9 Issue 7, 7-12, July 2022

Original Article

Triplet Sensors in Towed Array Sonar Systems

Sasmita Mohapatra[1], Krithika T[2], Sukrutha K[3], Aditya Raj[4]

[1,2,3,4]*Electronics and Communication Engineering, Sir M Visvesvaraya Institute of Technology, Karnataka, India.*

Received: 07 May 2022 Revised: 01 July 2022 Accepted: 16 July 2022 Published: 30 July 2022

Abstract - *Cardioid or triplet towed arrays are used in sonar applications to resolve left/right ambiguity by placing a null in the ambiguous direction. It leaves an uncalibrated residual signal in the opposite direction from which the desired signal arrives. In the sonar signal processing, the weighted delayed sum beam forming is used to discriminate between signal arrival from different bearings; however, in the towed linear array, there will be a symmetry in signal arrival delays produced from acoustic signal arriving from two distinct directions one being on the left side and other beings on right side of the array resulting in left /right ambiguity. Here Cardioid or triplet arrays consisting of a line of triplets instead of a line of single hydrophones are used. Each triplet consists of three closely-spaced omnidirectional hydrophones evenly mounted on a circle perpendicular to the array axis.*

Keywords - *Cardioid, Hydrophones, Omnidirectional, Sensor, Triplet array.*

1. Introduction

The Towed array of sonars consists of a Wet end subsystem. Onboard electronics subsystems have sonar signal processing modules, post-signal processing modules, Sonar HMI modules and a launch and recovery system (Winch) for deploying/retrieving the towed subsystem. The advantages of Towed Array-based sonar over the Hull mounted array sonar are variable depth operation capability to mitigate layer problems and exploit SOFAR channels in the sea. Another advantage is the larger aperture for the sensor system allowing low-frequency operation and long-range capability.

The beam forming followed by energy detection is the signal processing technic is used to obtain the direction of arrival of the signal. Beamforming in the time domain is generally done by applying the weighted delayed sum of the array of hydrophone (sensors) outputs placed in the towed array sensor system. However, due to symmetry in the linear nature of Towed array toward signals arriving from the left side and right side, every angle on the left side will have a corresponding angle on the right side which has a similar set of delays at hydrophone points.

The Towed array systems should have the arrangement of sensor systems which allows us to form unidirectional beams, this formation of unidirectional beams will logically produce the effect of having two directional sensors, one looking towards the left side and the other looking towards the right side of the array.

2. Materials and Methods

2.1. Triplet Array

The Cardioid beam forming can be used to solve the inherent L/R ambiguity resolution problem in towed array sonar systems. The Cardioid beam forming uses the Triplet array sensor instead of one single-line array. The triplet array system consists of closely spaced hydrophone elements spaced 120˚ apart. The signal processing technique can be employed to convert the triplet array into logically two directional hydrophone systems, one looking towards the left and the other towards the right is understanding the Design, Manufacturing and Use of the products and build robustness into the product so that the product continues to function satisfactorily under the encountered stresses. Each triplet element consists of closely spaced omnidirectional hydrophone sensors placed in a single housing, evenly mounted on a circle perpendicular to the array axis. Referenced on the right-handed Cartesian system (X, Y, Z), Y is the array axis pointing at the towing direction; the X axis points at the starboard broadside and the Zaxis points at the sea surface, as shown in Fig. 1. Let K be the number of triplets in the array and let k = 1, 2, . . K be the triplet index.

Similarly, let j = 1, 2, 3 be the index of the hydrophones within each triplet. The angular separation between the equally-spaced triplet sensors is denoted as γ, where $\gamma = 2/3\pi$ (120˚). Due to forces applied to the array during the tow, the array is often twisted concerning its original deployment position. The twist angle of the k-th triplet is denoted as βk and is defined clockwise concerning the Z axis. Then the angles of each sensor concerning Z can be defined as follows:

$$\begin{aligned} \varphi 1k &= \beta k \\ \varphi 2k &= \beta k + \gamma \\ \varphi 3k &= \beta k - \gamma \end{aligned} \qquad (1)$$

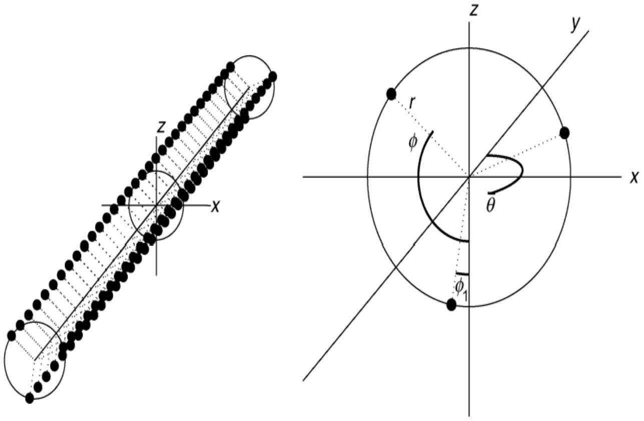

Fig. 1 Geometry of hydrophone triplet

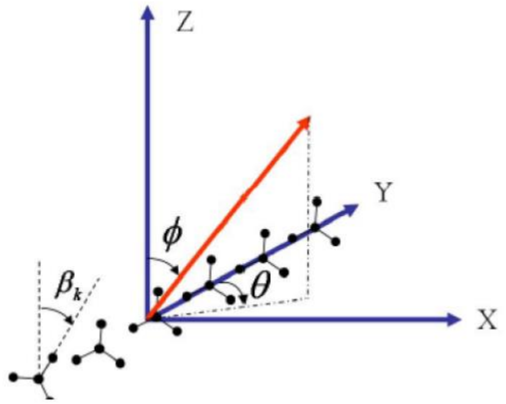

Fig. 2 Triplet Array in Cartesian Co-ordinates

As per this notation, the vector vjk is defined to locate the jth hydrophone in the kth triplet element.

$$v_{jk} = \begin{bmatrix} r\sin\emptyset_{jk} \\ y_k \\ r\cos\emptyset_{jk} \end{bmatrix} \tag{2}$$

Here r is the circle's radius in the triplet housing system in which three hydrophones are mounted at 120˚ apart, and yk is the Y coordinate of the kth triplet element. Rolling sensors are used across the towed array to measure the twist in the array, and necessary shape correction can be employed for the triplet array before signal processing.

2.2. Cardioid Beamforming

Cardioid beam forming resolves the port/ starboard ambiguity problem in towed arrays. The Cardioid beam pattern is obtained from the normal single line array beam pattern by weighing the beam pattern of the line array with the help of the cardioid-shaped function, which places the null at the ambiguous side. The time domain method of cardioid beam forming is explained below. Let us consider (θ, Ø) is steering direction, where θ is the azimuth angle (clockwise) on the X-Y plane, and Ø is the elevation angle (from vertical) in the X-Z plane. The unit vector u(θ , Ø) is defined below.

$$u(\theta,\emptyset) = \begin{bmatrix} \sin\emptyset\sin\theta \\ \sin\emptyset\cos\theta \\ \cos\emptyset \end{bmatrix} \tag{3}$$

The signal received on the triplet hydrophone element is related in the following way.

$$s_{jk} = s_k\left(t - d_{jk}\right) \tag{4}$$

Where,

$$d_{jk} = \frac{\{u(\theta,\emptyset)\cdot v_{jk}\}}{c} \tag{5}$$

The time delay between the triplet phones is defined by the ratio of the projection of vjk on u(θ, φ) to the sound speed where the scalar operator is, i.e. the inner product of the two vectors given by the following equation.

$$\{\, u(\theta,\emptyset)\cdot v_{jk}\} = r(\sin\emptyset_{jk}\, sin\emptyset sin\theta + y_k sin\emptyset cos\theta + \cos\emptyset_{jk}\, cos\emptyset) \tag{6}$$

By considering the triplet element at the origin, it becomes that yk = 0, so the inner product gets simplified to

$$\{\, u(\theta,\emptyset)\cdot v_{jk}\} = r(\sin\emptyset_{jk}\, sin\emptyset sin\theta + \cos\emptyset_{jk}\, cos\emptyset) \tag{7}$$

The main idea behind the cardioid beam forming is to suppress the signal from an ambiguous direction. The former beam output in cardioid beam forming is given by

$$b_{jk}(\theta,\emptyset) = \sum_{j=1}^{3} s_{jk}\left(t - d_{jk}\right)\{u(\theta,\emptyset)\cdot v_{j,k}\} \tag{8}$$

Using Sjk given by (4), output due to the signal coming from the desired direction becomes,

$$b_{jk}(\theta,\emptyset) = \sum_{j=1}^{3} s_{jk}\left(t - 2d_{jk}\right)\{u(\theta,\emptyset)\cdot v_{j,k}\} \tag{9}$$

The signal arriving from an ambiguous direction will have the following relation,

$$s_{jk} = s_k(t + d_{jk}) \tag{10}$$

Using Sjk given by (10), output due to the signal coming from an ambiguous direction becomes

$$b_k(\theta,\emptyset) = \sum_{j=1}^{3} s_{jk}(t)\,\{u(\theta,\emptyset)\cdot v_{j,k}\} \qquad (11)$$

Or equivalently

$$b_k(\theta,\emptyset) = s_{jk}(t)\,\sum_{j=1}^{3}\{u(\theta,\emptyset)\cdot v_{j,k}\} = 0 \qquad (12)$$

3. Results and Discussion

3.1. Array Element Simulation

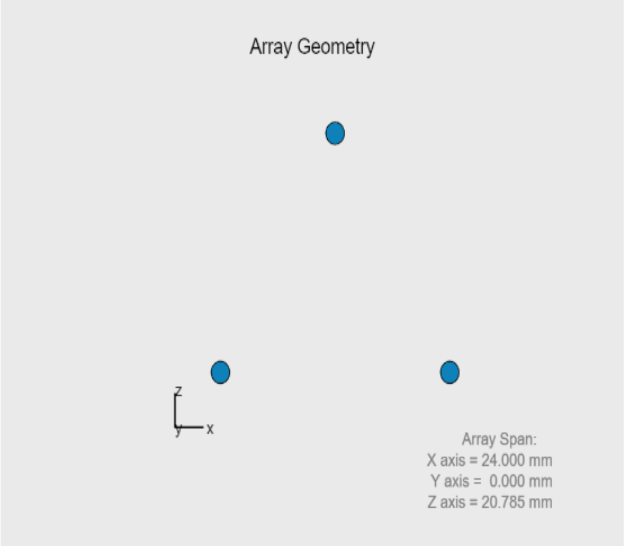

Fig. 3 Array element geometry in Phased Array MATLAB Tool Box

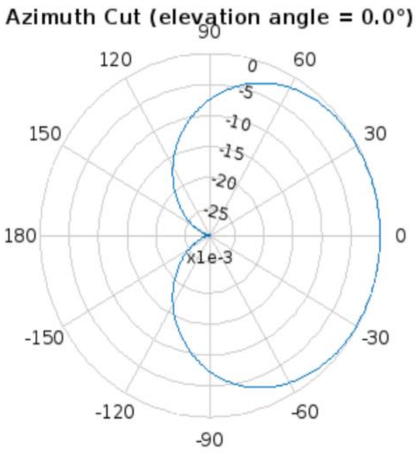

Fig. 4 Cardioid Beam former output from single Triplet element at the broad side

3.2. Single Line Array Simulation

Initially, a study case of 32 hydrophone elements single line array is simulated using an omnidirectional sensor system.

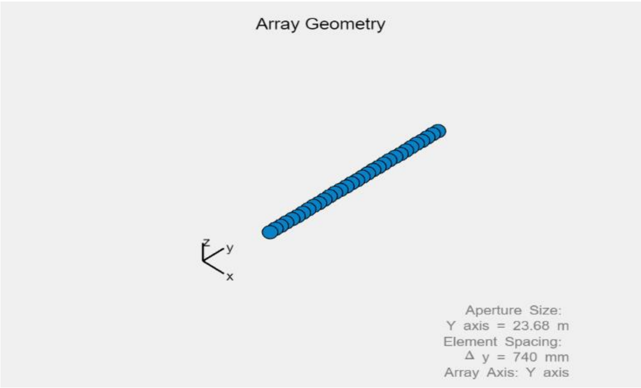

Fig. 5 Single Line Array in Phased Array Matlab Tool Box

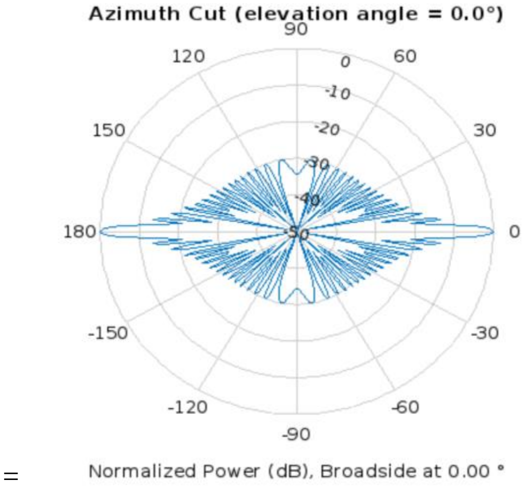

Fig. 6 Beam former output for broadside, having left/Right ambiguity

3.3. Triplet Array

The array of triplet elements is constructed in Matlab phased array toolbox. Cardioid beam forming is carried out to obtain the directional response with a better 3dB response. The cardioid beam forming is carried out at each triplet element level to convert each element into a single directional hydrophone. Then, delayed sum beamforming is applied over the array of these logically directional hydrophones to obtain the steered response with better 3dB performance.

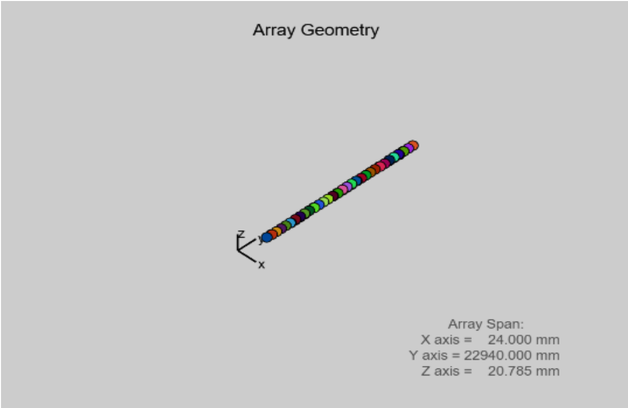

Fig. 7 Array of Triplet Elements in Phased Array Tool Box

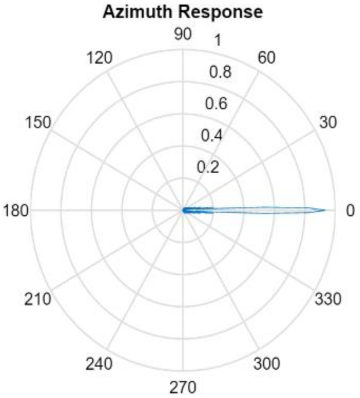

Fig. 8 Cardioid Beam former output from Array Triplet elements

The array of triplet elements is constructed in Matlab phased array toolbox, and Cardioid beam forming is carried out to obtain the directional response with a better 3dB response. Here, the cardioid beam forming is carried out at each triplet element level to convert each element into a single directional hydrophone. Then, delayed sum beamforming is applied over an array of these logically directional hydrophones to obtain the steered response with better 3dB performance.

The output from the cardioid beamformer that is displayed on the display cabinet of the towed array sonar is shown. It can be observed that the port/starboard ambiguity, which downgrades active sonar performance, is rectified. The Port Starboard discrimination is very good.

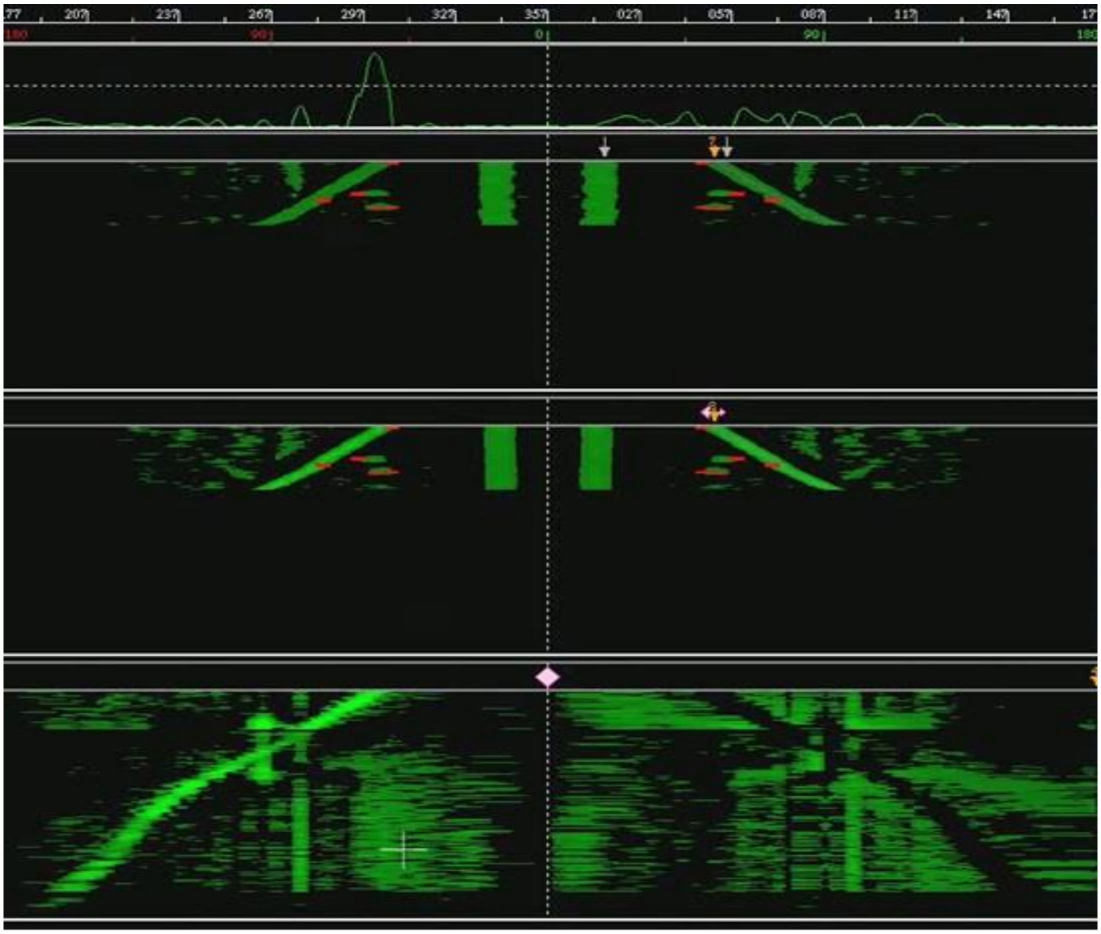

Fig. 9 Cardioid beamformer output on the display cabinet of the towed array sonar

4. Conclusion

Single Line arrays have inherent Left / Right Ambiguity in Towed Array Sonar systems. Triplet Array in Towed Sonar systems can effectively solve the Left / Right Ambiguity problem in single-line Towed Array sonars. The output from the cardioid beamformer that is displayed on the display cabinet of the towed array sonar is shown above. It can be observed that the port/starboard ambiguity, which downgrades active sonar performance, is rectified. The Port Starboard discrimination is very good. In future, the effective use of Cardioid beam forming along with a Quad array can be exploited to obtain Left /Right ambiguity resolution with high bearing accuracy and better 3dB performance

Acknowledgements

The content of this document pertains to work performed by Bharat Electronics Limited (BEL). We sincerely thank Mr. Nitin Anand (Manager, Design & Engineering/Sonar Systems/Naval Systems1, BEL) for his kind support and guidance.

References

[1] Ruiping Song et al., "Multi-Submarines Detection using Multistatic Sonar System," *2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC)*, pp. 1671-1675, 2020. *Crossref*, https://doi.org/10.1109/ITOEC49072.2020.9141581

[2] Huiqing Zhang et al., "A Dual-Path Deep Neural Network for Sonar Image Quality Evaluation," *IEEE International Conference on Networking, Sensing and Control (ICNSC)*, pp. 1-5, 2020. *Crossref*, https://doi.org/10.1109/ICNSC48988.2020.9238081

[3] Jiamin Zhang, "Sonar Target Recognition Research Based on AUV," *37th Chinese Control Conference (CCC)*, pp. 9603-9607, 2018. *Crossref*, https://doi.org/10.23919/ChiCC.2018.8483330

[4] José E. Almanza-Medina, B. Henson, and Y. V. Zakharov, "Deep Learning Architectures for Navigation using Forward Looking Sonar Images," *IEEE Access*, vol. 9, pp. 33880-33896, 2021. *Crossref*, https://doi.org/10.1109/ACCESS.2021.3061440

[5] Warren P. Du Plessis, “Audio Sonar for Gaining Hands-on Experience of Radar Principles,” *IEEE Radar Conference*, 2020. *Crossref*, https://doi.org/10.1109/RadarConf2043947.2020.9266593

[6] Xiaoguang Wang et al., "Automatic Target Recognition using Multiple-Aspect Sonar Images," *IEEE Congress on Evolutionary Computation(CEC)*, pp. 2330-2337, 2014. *Crossref*, https://doi.org/10.1109/CEC.2014.6900261

[7] Jojish Joseph V et al., "Dynamic Reliability Estimation for Towed Array Sonars," *OCEANS 2022 - Chennai*, pp. 1-7, 2022. *Crossref*, https://doi.org/10.1109/OCEANSChennai45887.2022.9775314

[8] S. Wei, and W. Fangyong, "Estimation of Towed-Array Heading using Reverberation Data," *IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC)*, pp. 1-4, 2021. *Crossref*, https://doi.org/10.1109/ICSPCC52875.2021.9564642

[9] Jiutao Wu et al., "Tow Ship Interference Suppression for Towed Array Sonar via Subspace Reconstruction," *10th International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1-7, 2018. *Crossref*, https://doi.org/10.1109/WCSP.2018.8555587

[10] Jun Wang, and Junsheng Jiao, "Track Before Detect for Low Frequency Active Towed Array Sonar," *IEEE International Conference on Signal, Information and Data Processing (ICSIDP)*, pp. 1-5, 2019. *Crossref*, https://doi.org/10.1109/ICSIDP47821.2019.9173085

[11] Jingyi Wang et al., "Research on Detection Range Prediction for Oversea Wide-Aperture Towed Sonar," *OES China Ocean Acoustics (COA)*, pp. 57-61, 2021. *Crossref*, https://doi.org/10.1109/COA50123.2021.9519971

[12] R. J. Urick, “*Radiated Noise of Ships, Submarines and Torpedoes: Radiated-Noise Levels,*” In Principles of Underwater Sound, 3rd Ed., Westport, CT: Peninsula Publishing, pp. 332–342, 1983.

[13] A. D. Waite, “*SONAR for Practising Engineers,*” Wiley, UK, 2002.

[14] Sudarshan M Hattaraki, “Left/Right Ambiguity Resolution in Towed Array.”

[15] G. Haralabus, and A. Baldacci, “Unambiguous Triplet Array Beam Forming and Calibration Algorithms to Facilitate an Environmentally Adaptive Active Sonar Concept,” *OCEANS 2006*, 2006. *Crossref*, https://doi.org/10.1109/OCEANS.2006.307115

[16] S. G. Lemon, “Towed-Array History, 1917–2003,” *IEEE Journal of Oceanic Engineering*, pp. 365–373, 2004. *Crossref*, https://doi.org/10.1109/JOE.2004.829791

[17] Alessandro Barbagelata, Piero Guerrini, and Luigi Troiano, “Thirty Years of Towed Arrays at NURC,” *Oceanography*, vol. 21, no. 2, pp. 24–33, 2008. *Crossref*, https://doi.org/10.5670/oceanog.2008.49

[18] M. Lasky et al., “Recent Progress in Towed Hydrophone Array Research,” *IEEE Journal of Oceanic Engineering*, vol. 29, no. 2, pp. 374–387, 2004.

[19] A. Baldacci, and G. Haralabus, “Signal Processing for an Active Sonar System Suitable for Advanced Sensor Technology Applications and Environmental Adaptation Schemes,” *In Signal Processing Conference*, 14th European, 2006.

[20] K. M. Becker, and J. R. Preston, “The ONR Five Octave Research Array (FORA) At Penn State,” *In OCEANS 2003, Proceedings, San Diego*, vol. 5, 2003. *Crossref*, https://doi.org/10.1109/OCEANS.2003.178321

[21] Georgios Haralabus, and Alberto Baldacci, “Unambiguous Triplet Array Beamforming and Calibration Algorithms to Facilitate an Environmentally Adaptive Active Sonar Concept,” *In OCEANS Boston*, 2006. *Crossref*, https://doi.org/10.1109/OCEANS.2006.307115

[22] J. Groen et al., “Adaptive Port– Starboard Beamforming of Triplet Sonar Arrays,” *IEEE Journal of Oceanic Engineering*, vol. 30, no. 2, pp. 348–359, 2005. *Crossref*, https://doi.org/10.1109/JOE.2005.850880

[23] Lawrence J. Ziomek, “*An Introduction to Sonar Systems Engineering*,” Boca Raton, FL: CRC Press, Inpublication.

[24] Lawrence E. Kinsler et al., “*Fundamentals of Acoustics,*” 4th Edition, New York: John Wiley & Sons, p. 175, 2000.

[25] D. Kapolka, “*Underwater Acoustics for Naval Applications*,” Course Notes for PH3452-Underwater Acoustics, Naval Postgraduate School, Monterey, CA, Winter, p. 90, 2015.

[26] X. Lurton, “Transducers and Array Processing,in an Introduction to Underwater Acoustics, Principles and Applications,” Chichester, UK: *Springer/Praxis Publishing*, p. 149, 2002.

[27] Cetacean Research Technology, 2016. [Online]. Available: http://www.cetaceanresearch.com/hydrophones/C55-hydrophone/index.html