Ceramic and Fibre Optic Hydrophone as Sensors for Lightweight Arrays - a Comparative Study

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***Abstract*—Design and development of lightweight arrays has been a subject of intense study in recent years. This is largely owing to the successful deployment of autonomous vehicles as operational platforms for many underwater applications. The acoustic sensing capabilities of these platforms can be greatly improved by adding a hydrophone array and towing it behind them. Apart from the conventional ceramic based acoustic sensing technology, distributed feedback fibre laser hydrophones has opened up another possibility for the design of thin line towed arrays. However, either not enough information is available (or they are scattered) in the literature to compare the performance envelop of these two technologies from a thin line towed array application perspective. The purpose of this paper is to do a literature survey and compare the status of lightweight and thin line towed hydrophone arrays based on the two technologies for use from small autonomous platforms. The different performance parameters of the array such as its sensitivity, channel count, frequency and bandwidth of operation, power budget, vibration isolation requirements and flow induced noise effect have been addressed. The comparisons are based on both the studies conducted at our laboratory and also results reported on similar systems developed elsewhere. It is believed that this study would help researchers and users in the field of underwater acoustics to understand the areas of performance improvement required under both technologies and make an informed decision on the selection of a technology for a particular application. It is concluded, based on the study conducted and results presented here, that ceramic based acoustic sensor arrays are still a better choice for operation as a thin line towed array compared to the distributed feedback fibre laser hydrophones.**

***Keywords*—Lightweight arrays, towed arrays, AUV sensor arrays**

1. Introduction

Towed hydrophone arrays have been in use for many underwater applications for years [1]. The realm of application include Navy, Seismic industry, oceanography, geoscience etc. Traditionally towed arrays have been operated from ships and submarines. They are long, heavy and requires immense resources for their deployment and recovery resulting in high operational costs. The advent of autonomous platforms such as autonomous underwater vehicles (AUVs), underwater gliders, unmanned surface vehicles as well as wave gliders have opened up new possibilities in underwater acoustic sensing applications. According to Navy's UUV Master Plan, first published in 2000 and updated in 2004, the envisaged uses for UUV platforms in underwater operations can be listed as below [2].

- Intelligence, surveillance and reconnaissance (ISR)
- Mine counter measures (MCM)
- Oceanography
- Anti-submarine warfare (ASW)
- Inspection/identification
- Time critical strike (TCS)
- Communication/navigation network node (CN3)
- Payload delivery
- Information operation

The current AUV platforms have been equipped with side scan and multi-beam sonars for generating seabed imagery and bathymetry information. They are also being used in MCM applications. By equipping AUVs with a hydrophone array, their capability to detect and localise underwater objects can be improved. Such a system might offer a cost effective solution for some of the underwater applications like harbour protection and surveillance, underwater noise monitoring, vessel noise characterisation and also useful for marine marine mammal monitoring. By having a dedicated or opportunistic acoustic source on the platform, it could be used for applications such as seabed characterisation and bi-static sonar related applications. Some of the advantages of an AUV equipped with an acoustic source and a thin line towed array for seabed characterisation (and possibly for seismic survey) are listed below.

- As an AUV can operate away from the surface and close to the seabed, the system do not suffer from the sound speed variations in the medium and

also scattering due to biologics and other suspended particles in the water column.
- The acoustic power transmission requirement is less compared to a surface operated system as losses due to spreading and attenuation can be reduced. Thus the impact on marine flora and fauna is of less concern
- As the system can operate closer to the seabed, measurements at very low grazing angles could be performed using a much shorter array
- The system does not suffer from surface fluctuations due to wind and waves and hence more accurate measurements are possible
- Finally, the mobility and autonomy of the system helps to reduce the operational costs freeing up time and resources

Easy and rapid deployment as well as wide area coverage due to its high mobility are other advantageous of an AUV towed array configuration.

The objective of this paper is to compare the capabilities of thin line arrays based two sensor technologies with regard to its application as a towed hydrophone sensor array for operations from autonomous platforms. The comparisons are based on the information available in open literature and also based on the experience of the authors in working with such systems. Apart from the main operational requirements (such as noise floor, sensitivity, bandwidth etc.), the other parameters of interests for comparisons are the size, cost and complexity, reliability, power consumption, ease of manufacturing and maintenance. Many of these aspects have been included in this study.

2. Sensor Technologies and Arrays

In this section we briefly look at the two sensor technologies, their status and some of the arrays built using them. These systems will form the basis for our comparisons later and draw conclusions thereof.

2.1. Piezo-ceramic based hydrophone array

Piezo-ceramic (PZT) based hydrophone sensor is a well matured technology and hence is the first natural choice for building thin line hydrophone arrays. The availability of low profile ceramic sensors and miniature electronic components have made it possible to build lightweight and small diameter hydrophone arrays that could be easily integrated with current autonomous marine platforms. Potter et.al in 2000 [3] built a small diameter hydrophone array and this is considered as the forerunner to many of the subsequent thin line array development at ARL. The array, which was 8 mm in diameter and contained 6 acoustic channels, was built as a technology demonstrator and was not intended for use from autonomous marine vehicles. In 2005, ARL took up a project on lightweight array technology development for use from AUVs and built a 12-channel array encapsulated in a 10.5mm diameter polyurethane tube. In 2006 the array was converted into a digital version and an additional non-acoustic sensor was added to it [4]. This non-acoustic sensor provided information on the depth of the array and its heading using an electronic compass. The array was further improved by adding more channels and at present we have two versions of the ARL developed digital thin line arrays (DTLA), a 15 mm diameter version with 12 channels and a 20 mm diameter version with 24 channels. The array aperture is decided by the spacing between the channels which is decided prior to the assembly of the array. The following Table 1 shows summary of the specifications of DTLA and its associated receiver system.

Thin line arrays have also been built by other research institutions and companies. For example, Centre for Marine Research and Experimentation (CMRE), Italy has built a Slim Line Towed Array (SLITA) and tested using their AUV Ocean Explorer (OEx) [5]. Jason D Holmes et. al [6] from Boston University has built a towed hydrophone array for ocean acoustic measurements and inversions in collaboration with Woods Hole Oceanographic Institute (WHOI) and tested using REMUS 100 AUV. A couple of commercial companies also claim to have built and tested thin line hydrophone arrays from marine autonomous platforms such as a wave glider [7], [8]. A table showing key information regarding some of these arrays and as available in open literature is given in Table 2.

2.2. Fibre laser sensor based hydrophone array

The optical hydrophone development date backs to late 1970s and driven by the requirement to have a simple, lightweight robust sensor that could be multiplexed and remotely interrogated without any need for electronics or electrical power within the array [9], [10]. Fibre optic hydrophones offer immunity from electromagnetic interference noise, which the conventional ceramic hydrophones could not offer, and there is no dense cabling involved. The initial versions of fibre optic hydrophones were constructed by coiling hundreds of meters of fibre on a complaint mandrel (for obtaining sufficient sensitivity) and were based on interferometric phase detection which offered the highest sensitivity [11], [12]. Ultra thin fibre optic hydrophones were built using fibre Bragg grating based sensor elements for improved sensitivity [13], [14]. These systems still required a sensing arm and a reference arm in an interferometric configuration for their implementation and so practical systems did not offer much size and weight reductions as compared to the ceramic based sensor systems. Most fibre optic hydrophone arrays were used either as seabed arrays or as a hull array on submarines. as they were less flexible and compact for towed array applications. The development of DFB-FL sensors in the 1990s offered an alternative approach to building compact and high sensitivity fibre optic hydrophones without the need for winding them on a air-backed complaint mandrel or having to provide extra coating to improve their sensitivity [15], [16]. In terms of sensitivity per unit length, a 5cm fibre laser sensor is approximately equivalent to a 10m fibre optic sensor coil.

TABLE 1. BRIEF SPECIFICATIONS OF ARL DESIGNED DTLA

Array Parameter	Specification	Remarks
Mechanical specifications		
Array diameter	15mm and 20mm	12 channels and 24 channels respectively
Array aperture and length		This is decided by the number of channels and their spacing
Tow cable	8.2mm diameter	6 twisted pairs and 6 single conductors. Can be detached from the array
Array connector	MIN K-16 (Seacon)	16-pin underwater connector
Buoyancy	Negatively buoyant under 1kg	Can be made neutrally buoyant by adding flotation collars
Acoustic sensor and array electronics		
Sensitivity	-208dB ref 1V/μPa	Three sensors with –217dB ref 1V/μPa connected in series
Sensor type	Navy type II ceramic sensor originally manufactured by EDO Acoustics Corp., USA	
Frequency band	250Hz to 10kHz	The sensor has much wider bandwidth. This is the array bandwidth limited by sampling frequency
Anti-aliasing filter	8th order low pass filter with 4-bit programmable gain amplifier	Both cut off frequency and the gain are programmable in the field
Signal conditioning amplifier	Low noise amplifier with 60dB gain over two stages	First stage 20dB and second stage 40dB
Data interface	SPI, 32-bit serial	Array can be configured either as analog or digital
Sampling frequency	24kHz/channel	Multiplexed
Pressure sensor	Rated for 150m $\pm$ 0.5m accuracy	MEMS sensor Digital output, I^2C interface
Electronic compass	$\pm$ 3 deg accuracy	Honeywell, HMC 5843
Array power	1W/channel	Including digitisation
Receiver system		
Receiver	PC104 Plus embedded processor with BlackFin DSP	
Receiver power	15W	
Operating system	TinyCore Linux	A lightweight Linux OS

TABLE 2. SUMMARY OF OTHER PIEZO-CERAMIC BASED THIN LINE ARRAY DEVELOPMENT

Array	Organisation	Brief specification	Remarks
SLIm Towed Array (SLITA)	CMRE, Italy	31mm diameter, 48 channels, 24-bit ADC	Extensive field tests conducted using Ocean Explorer AUV
AUV towed hydrophone array	Boston university and WHOI	28mm diameter, 6-channels	Integrated and field tested with REMUS 100 AUV
Digital Thin Line Array	Seiche Marine Acoustic Solutions UK	20mm diameter, 32 channels, 20-bit, Pressure,temperature and heading sensors	Analog or digital version. Claims to have tested with their wave gliders
Thin Line Array	SEA Ltd., UK JSK Naval Support Inc., Canada	16mm diameter, 32-channels, 8 non-acoustic channels (pressure, temp and heading)	Claims to have tested with Liquid Robotics wave gliders and able to detect and track submarines

Plenty of research has been carried out on the development of fibre laser hydrophones and its implementation as an array. Reviewing all of them is beyond the scope of this manuscript and we focus on some of the successful design and implementation of DFB-FL based hydrophone arrays.

3. Characterisation of thin line arrays

The array needs to be characterised for various performance deciding parameters before one can use them in the field. These performance parameters include, but not limited to, noise floor, sensitivity, bandwidth, impact of flow noise and vibration while under tow etc. The tow platform noise (or its coupling to the array) is also a factor that would impact the array performance and this is platform specific. A good description of origins of AUV noise from different sources, characterisation and its coupling paths to the array has been discussed in [17], [18], [19]. In this discussion much attention has not been paid to the platform noise and its impact other than making a statement that it needs to be taken care of in the application and could potentially impede the detection performance of the array if not addressed. The primary operational platform for thin line arrays considered in this discussion is the AUV. Most AUVs swim at a maximum speed of approximately 5 knots (2.5 m/s) and hence the impact of flow noise and vibration on DTLA has been evaluated in this regime. The ensuing paragraphs give an account of some of the parameters that have been studied with respect to DTLA. Wherever possible, results available in open literature for other thin line arrays have been provided or cited. There is limited literature available on the characterisation of thin line array based on DFB fibre laser sensor technology. This is largely due to the fact that the technology itself is not fully matured and or not widely available to many. Apart from a couple of field deployments, most studies conducted are primarily in the lab environment and the systems developed are mostly lab prototypes. Nevertheless, to make this study more meaningful, results from relevant studies have been given and their references are also provided in this study.

3.1. Flow and vibration induced noise

Flow noise is considered to be one of the important parameters that would restrict the use of thin line array for towed applications [20], [21]. Figure 1 shows the many different mechanisms that would contribute to the flow noise [22]. The blocks on the right indicate the sources of noise due to vibration and can be reduced by having a VIM if it is very significant. The blocks on the left relates to noise due to turbulent flow, which is more difficult to deal with.

As the array diameter become smaller, the flow becomes more turbulent and hence induced flow noise also increases [3], [23]. Further, the separation of the sensor from the turbulent boundary layer (TBL) or the tube walls becomes smaller as the array diameter becomes smaller and hence the coupling of flow noise from tube walls to the sensors increases. There are theoretical frameworks which would

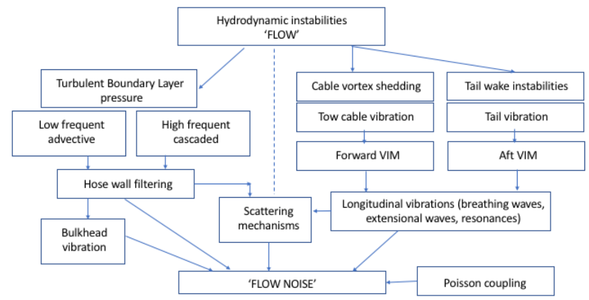

Figure 1. Various mechanisms that contribute to the flow noise on a towed array system. The blocks on the right represents noise due to vibration and those on the left due to turbulent flow

help to compute the flow induced noise on a towed array [20], [24]. Thomas Elboth et.al has investigated the flow and flow noise around a seismic streamer cable and also explored the use of hydrophobic coatings to reduce the flow noise [25], [26]. However, measurement and separation of flow induced noise is difficult in a field environment due to the presence of other environmental noises. The platform generated noise and the vibration induced noise could contaminate the flow noise measurements. In the following paragraphs noise floor and flow induced noise and their impact on the performance on the thin line arrays built using the two sensor technologies are discussed.

3.1.1. Piezo-ceramic based thin line arrays. The DTLA has been tested in a reasonably quiet lake for measuring and quantifying the noise floor and also the flow induced noise at different tow speeds. The details of the experimental setup used, procedures employed and the results obtained have been reported in a previous conference publication [**?**]. The results are reproduced here and summarised in figure 2 for the purpose of discussions.

Major conclusions from this study has been the following

- The stationary noise floor measured using the array matches well with that measured using a reference hydrophone.
- The noise floor goes up by about 10 dB when the array starts to move and stabilises at a tow speed of 2 to 3 knots. Thereafter the noise floor increases approximately by 2 dB per knot. Nevertheless, as for most tropical waters the ambient and the platform generated noises would be higher for frequencies above 400 Hz, the flow-induced noise not likely to be a performance limiting parameter.
- The vibration induced noise, as measured by the accelerometers inside the array, was not significant for tow speeds up to 4 knots. For speeds above 4 knots (and up to 10 knots) the vibration levels showed significant levels for frequencies below 100 Hz and rapidly decreasing before it died down at the tail of

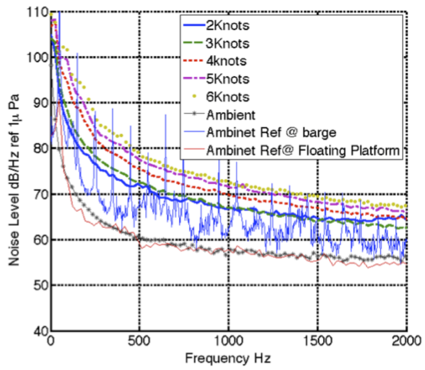

Figure 2. Flow noise levels due to DTLA towed at different speeds in a lake. The blue curve with spiky signal is the ambient signal when contaminated with generator noise at the platform

the array. Hence for tow speeds up to 4 knots, the array may not require a vibration isolator.

- The array appeared to be moving along a straight line for tow speeds of approximately 2 knots and above and under no current condition.

The SLITA system from CMRE also has been studied for its performance under various flow conditions and the results of their observations have been reported in [5]. They had towed the array initially using a surface vessel (R/V Leonardo) and found that the platform noise is very high and hence could not quantify the impact of flow noise on the array. Later the array was towed using their AUV, Ocean Explorer, where they were able to isolate the flow induced noise using frequency-wavenumber analysis. Though specific flow-induced noise levels against different tow speeds are not available, the experiments concluded that for the waters of their interest ambient noise would be the limiting factor rather than the flow induced noise.

Jason D Holmes et.al has used a thin line array on REMUS 100 AUV and found that though the flow induced noise on the array was of primary concern, for frequencies in the region 500 Hz to 10 kHz and for tow speeds not exceeding 3 knots the system is ambient noise limited [27]. They also found that by adding a drogue of sufficient length to the tail of the array, it can be towed in a straight line for speeds above 2 knots though this would add extra drag on to the system. These observations are consistent with our measurements on DTLA mentioned earlier.

There are at least a couple of commercial thin line array systems which their manufacturers claims to have been sold worldwide and used in ASW or other marine applications. One such system is the KraitArray system from a UK company called Systems Engineering & Assessment (SEA) Ltd., (www.sea.co.uk) which has since been acquired by Cohort plc (w.cohortplc.com) in 2007. JSK Naval Support Inc., Canada also has advertised the KraitArray as their product and it is not clear whether the two companies or their products are related. Seiche Marine Acoustic Solutions, another UK company also has developed a digital thin line array (see w.seiche.com) which is commercially available. However, neither of these systems have been benchmarked for flow-induced noise levels and its impact on the array performance when towed at different speeds. In a recent article that appeared in Janes International Defence Review [28], the company SEA mentions that they plan to carry out a test in an internal tank facility to measure the flow induced noise on the array, even though they are confident that it will not be a major factor that would affect the array performance.

In short, many tests on ceramic based thin line arrays indicate that though there is a significant increase in the noise floor due to flow induced noise, in the real operational environment it is less likely to be a limiting factor compared to the vehicle noise and the ambient noise, especially for frequencies above 400 Hz and tow speeds not exceeding 4 knots. It is also evident from studies conducted that when used from an AUV platform the vibration induced noise is negligible for tow speeds up to 4 knots and no vibration isolation is required at those speeds. At higher speeds the vibration induced noise levels increases, but only significant for frequencies below approximately 200 Hz. Tests also indicated that, when there is no current, the array with a drogue attached to its tail does not suffer from snaking for tow speeds of 2 knots and above.

3.1.2. DFB-FL sensor hydrophone towed arrays. There is limited study conducted on the impact of flow noise on towed array based on fibre laser hydrophones. Theoretical frame work developed for axial flow over a cylinder can be extended to apply to many towed array configurations [24]. However, in the case of DFB-FL hydrophone array, the specific construction of the array does not always satisfy the axial flow conditions. For example, to improve the sensitivity of fibre laser hydrophones often diaphragms are used at the end of the laser section and these diaphragms are subjected to a transverse flow instead of axial flow. Unni et. al [29] addressed this issue and did a theoretical study on a diaphragm based fibre laser hydrophone and the predicted flow induced noise levels are provided in figure **??**.

In this study it was seen that noise generated due to pressure fluctuations at the turbulent boundary layer is not significant for speeds up to 2m/s (4 knots) and for frequencies greater than 200Hz in comparison with the ambient noise levels for sea state 2. It is also found that there is only marginal noise reduction due to increased separation of the sensor from the turbulent wall for array dimensions used in thin line arrays. W. Zhang et. al in [31] reported that their 8-element DFB-FL array when towed at 3 knots speed in a quiet lake showed an increase of approximately 40 dB in the noise floor for frequencies from 200 to 2000 Hz as compared to when the array was static. However, the paper does not describe how the increased noise compares with the ambient noise level. The experimental quantification and validation of flow noise due to DFB-FL towed array is still an open problem and more research work needs to be

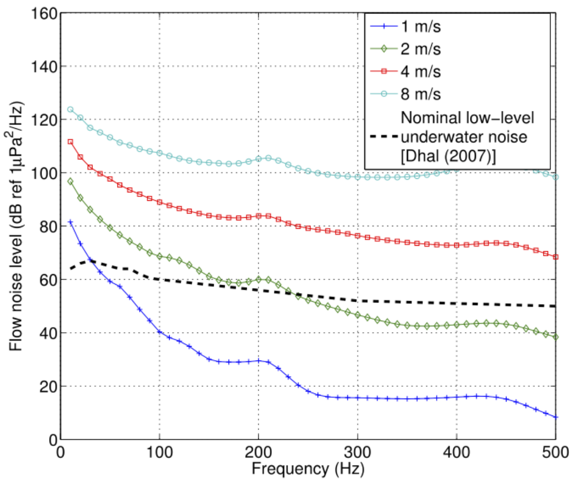

Figure 3. Theoretically estimated flow noise levels for fibre laser sensor with 16 mm diaphragm diameter and encapsulated in a 20 diameter tube. [29]. The plot also shows typical ambient noise level as given in [30]

done to understand whether it is likely to be a performance limiting component and if so under what conditions.

3.2. Sensitivity and impact of environmental parameters

The fibre laser hydrophones are more sensitive than its previous counterparts, the mandrel wound fibre optic hydrophones. Even so, to get the sensitivity comparable to the conventional ceramic based hydrophones additional sensitivity enhancement techniques will have to be incorporated. The techniques include using more complaint materials for coating the fibre or using diaphragms at the ends of the sensor to amplify the effect of pressure variations [**?**], [32], [33], [34]. Unlike PZT-based hydrophones, the fibre laser sensor based hydrophone are sensitive to other environmental parameters. The requirements of both high sensitivity and high dynamic range cannot be met simultaneously by the DFB-FL hydrophones. This is because the huge increase in hydrostatic pressure with depth would drive the shift in wavelength beyond the dynamic range of the system and this is of serious consideration when designing arrays where different element operates at different centre wavelengths. This calls for pressure compensation techniques to facilitate operation of the array over the dynamic range of interest [35], [36], [37], [38] and within the operating band of the demultiplexer. This requirement in turn makes the overall diameter of the array much larger than the sensor itself and often comparable to the diameter of their piezo-ceramic counterpart.

Another factor that needs to be considered when designing with the fibre laser hydrophone is its sensitivity to temperature (approximately 15 pico meter/°C) [38]. If not compensated, this could also shift the wavelength fibre laser beyond the passband of the demultiplexer used for detection and thus could lead to reduction in the dynamic range of the array.

3.3. Noise floor and acoustic bandwidth

Realising a low noise-floor for the ceramic based hydrophones is not difficult. There are many very low noise preamplifiers which can be used to amplify the signals from high impedance sensors. Both low voltage and current noise for the signal conditioning amplifiers are desirable and the emphasis should be on the low current noise as the ceramic sensors are high impedance devices and hence voltage resulting from quiescent current flow through such an high impedance (100 MΩ) device could add to the noise voltage. For most applications, especially in shallow and tropical waters, the low noise-floor levels requirement is not a constraint as the ambient noise levels are pretty high.

The DFB fibre laser hydrophones are comparable to PZT based hydrophones in terms of achievable noise floor. Noise floor close to sea state zero has been achieved by many for the fibre laser sensors in the lab environment and it is not until very recently this has been demonstrated in the field [39]. Though a deep sea state zero (DSS0) noise floor is desirable for application in very low noise environmental conditions, for most shallow water applications a sea state 2 noise floor would suffice as the ambient noise levels are relatively high.

The conventional ceramic based hydrophones are very broadband and bandwidths of tens of kHz are common. However the fibre laser hydrophones are very limited in their bandwidth. Though the maximum bandwidth that has been achieved is about 7 kHz, in most cases the tested and verified bandwidth is only about 5 kHz or below [37].

3.4. Channel count

The number of channels for a ceramic based array technology is only limited by the availability of space and power budget. For example, traditional towed arrays based on piezo-ceramic technology have been using channels in excess of hundreds. As the diameter of the array gets smaller, the number of channels that can be packed inside the tube also get smaller. The DTLA can comfortably encapsulate up to 12 channels into a 15mm diameter tube and up to 24 channels into a 20mm diameter array. The array also include an non-acoustic sensor module close to its tail which can provide depth, heading and temperature information. The channels could be multiplexed and digitised inside the array or at the array receiver. The manufacturer of KraitArray claims that they were able to pack up to 32 acoustic channels and 8 non-acoustic channels into a 16mm diameter array. Seiche Marine Acoustic Solutions were successful in packing 32 channels in a 20mm array as per their company product brochure. CMRE, Italy were successful in building a 48-channel, 31mm diameter digital array with 24-bit capability as mentioned elsewhere in this document.

The number of sensors or channels that can be realised using DFB fibre laser hydrophone technology is limited by both physical and practical constraints. The array is formed by serially connecting multiple sensors operating at different centre wavelength. Schematic of a typical fibre laser array configuration is shown in figure 4.

The number of sensors that could be multiplexed is decided by the available optical bandwidth, sensor spacing and optical pump power. Each laser sensor has to be fabricated with low side-lobe levels so that adjacent sensors will not interfere and would provide stable operation. As the lasers are connected serially and each laser section would consume a fraction of the available energy, the pump source energy will be depleted as more and more sensors are added. In addition, there will be losses at each splicing joint and the combined loss at each sensor could be up to 0.5dB with the current technology. The highest number of multiplexed sensor array realised on a single fibre and using a single source is a 16-channel DFB-FL array lab prototype reported by S. Foster et.al. [40]. He used 500mW pump source and each packaged sensor was giving a sensitivity of 120 dB re Hz/Pa. Fabio Souto from Maritime and Aerospace, Thales, Australia reported a thin lightweight fibre optic towed array (FOTA) demonstrator system comprising of 32 channels in a 25 mm diameter, 50 m aperture array and operated from a surface vessel [41]. However, the report did not provide a complete description of the array architecture and construction. In a latest publication Junbin Huang et.al. [42] claims to have developed a 64-element fibre laser sensing system with four optical pumps, 8 wavelength and 8 space division multiplexing systems. The system has been tested for its acoustic sensing and currently the team is working on addressing 'many problems' including the noise problem.

3.5. Cost, complexity and reliability

The technology for fabricating and characterising ceramic based hydrophones are well established. The sensors are commercially available and making an array out of them is not difficult. Similarly the receiving electronics for processing signals can be built easily using low cost and low power embedded processor systems. There are even real-time processing systems that has been tested out in the field from an AUV based platform. On the other hand, even though fibre laser sensors can be sourced commercially, the technology for building arrays out of them is not easy and well established. As brought out in the earlier section, the DFB-FL sensors for array application require to be built with great care so as to ensure enough channels can be accommodated without compromising its performance. This requires specific knowledge and skill. There are only couple of instances of successful implementation of 16-channel or more DFB-FLS arrays and none has been integrated and tested on an AUV or other autonomous platforms, yet. Even though the cost of fabricating fibre laser sensors by itself may not be costly, the overall cost associated with building an array and relevant processing electronics could turn out to be costlier than their ceramic counter parts. By the same arguments above, the cost of maintaining the fibre laser array could also be more than a ceramic array. Reliability is another important issue that needs to be considered. The ceramic based arrays have been traditionally built to withstand harsh environments and tow conditions. Failure of a single sensor will impact only marginally as data from other sensors are still available. However, in a fibre laser sensor based hydrophone array, failure of as single sensor could cause problems for data from other sensors as they are all serially connected and multiplexed. So, from a reliability perspective also the ceramic based sensor array appears to be a better choice.

4. Results from field applications

The operational capabilities of the thin line arrays based on the two technologies are required to be evaluated through field tests before its usefulness for a specific application can be determined. Hence, in this section we look at the successful deployment of thin line towed array systems at sea using different platforms and their measured performances as reported in open literature.

4.1. Ceramic based thin line arrays

The thin line arrays, both analog and digital versions, developed using the piezo-ceramic sensors have been subjected to extensive field tests by their developers. For example, the DTLA has been integrated and tested with many AUV platforms as well as an ROV platform as shown in figure 5

All the AUV integration and field evaluation works have been performed through research collaborations. In 2009, the DTLA was tested for its functionality towards underwater object detection and tracking for the first time using the Ocean Explorer AUV platform in collaboration with CMRE . Some of the major conclusions from these tests were the following

- The array has performed well in demonstrating its beamforming capabilities and it was able to detect and locate a pinger within the designed accuracy limits
- Frequency wavenumber analysis indicated that there is an increase of 3dB in noise level for tow speeds up to 2.4knots and a further increase of 3dB for tow speeds up to 2.8knots. The major contributor to this noise increase is believed to be flow noise
- The ambient noise measured at the site by the array was comparable to that measured by a reference hydrophone. The ambient noise was found to be dominant compared to the flow noise indicating that flow induced noise may not limit the array performance
- The acoustic communication signals from the modem was interfering with the array due to poor design of anti-aliasing filter. These signals were later used for estimating the seabed type through computation of reflection coefficient [43]

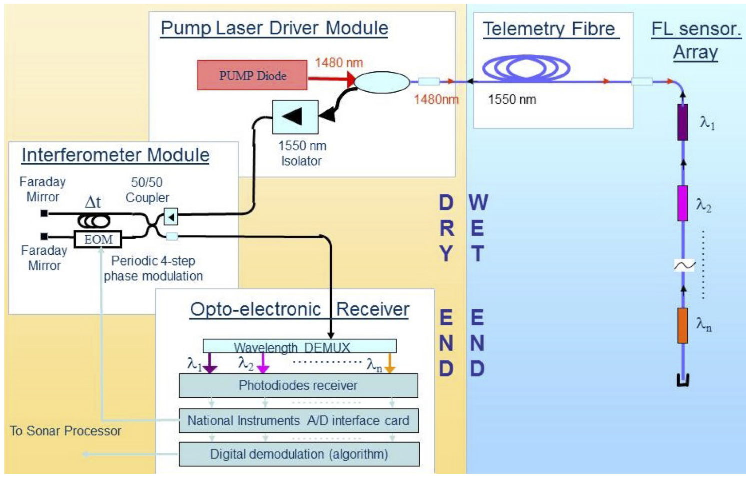

Figure 4. Block diagram of fibre laser hydrophone array with de-multiplexer
[37]

Figure 5. DTLA integrated with different AUV platforms and an ROV platform

The data from the above experiment were also used to demonstrate the capability of the system for seabed characterisation using an opportunistic source, the acoustic modem, on the AUV. The details are covered in a research publication by Chotiros and Pallayil [43] in the Journal of Oceanic Engineering. In 2014, the DTLA was integrated with SEACAT AUV manufactured by ATLAS Electronik, Germany and successfully tested for its capability for detecting a source (with a source level of 140 dB ref 1 μPa) about 3km away from the AUV. DTLA has also been extensively tested using ARL designed AUV, STARFISH, for its target detection and tracking capability as well as seabed classification. In 2017, the 24-channel DTLA with an aperture of 18 m and 40 m long was successfully integrated with REMUS 100 AUV in collaboration with Woods Hole Oceanographic Institute. The system was tested in the field during the seabed characterisation experiment 2017 at New England Sea. The data from this experiment is under processing.

CMRE has carried out many field tests using their slim line array, SLITA, using the Ocean Explorer AUV platform and also the SLOCUM gliders [44]. The main objectives of these tests were to evaluate the usefulness of the SLITA system in ASW operations and also in persistent autonomous surveillance. In ref [45] Stephanie Kemna et.al discusses the potential use of AUVs with BENS array (a modified version of SLITA array) for littoral surveillance application in a multi-static sonar environment. Charles W Holland et.al has used this system in a study for resolving meso-scale seabed variability through reflection measurements [46]. Stan Dosso et.al reported automated estimation of seabed properties from acoustic recordings of a 32-element array towed by the AUV Ocean Explorer [47].

J.D Holmes et. al used a 6-channel array on REMUS 100 system for ocean acoustic measurement and inversions. In this paper he also describes the ability of such a system to characterise the ocean acoustic waveguide though the synthetic aperture Hankel transform technique. In summary the results from many field tests conducted by various researchers has established the usefulness of ceramic based thin line arrays for many underwater applications such as ASW operations, seabed characterisation and marine mammal monitoring.

Systems Engineering & Assessment (SEA) Ltd. in an article claims that they were able to detect and track a submarine using KraitArray on a Wave Glider built by Liquid Robotics [28]. The article does not provide details of how the beamforming was performed and how the sensor positions were estimated as from the video it appeared the array was snaking while being towed by the glider.

From the above discussions it is clear that the thin line arrays built using piezo-ceramic sensors and married to AUV and USV platforms have become operational systems in many underwater applications such as surveillance, ASW and oceanography.

TABLE 3. COMPARISON OF TWO SENSOR TECHNOLOGIES - A QUICK SUMMARY

Parameter	**Sensor Technologies** *Piezo-Ceramic*	*DFB-FL*
Technology	Well developed, field proven and easy to manufacture and maintain	Relatively new and still under development. Technology not widely available
Application	Widely tested and proven on many autonomous platforms	Mostly used as seabed arrays on deployed from ships/submarines. Yet to see integrated with AUVs
No. of channels	Limited only by power budget, cost and space availability. Not limited by technology	Limited by technology. 8 to 16 channels may be feasible for thin line array. 32 channels may use bigger diameter arrays
Frequency and bandwidth	Very high bandwidth. A couple of tens of kHz are common	Limited bandwidth. Mostly under 5kHz. Maximum reported 7kHz
Sensitivity	Reasonable sensitivity for most applications. Not sensitive to non-acoustic parameters	Good sensitivity. Sensitive to pressure and temperature needing to compensate for them to obtain desired dynamic range
Noise floor	Sea-state-zero achievable	Sea-state-zero achievable
Flow noise	Relatively well studied. For most waters system is ambient noise limited	Not well tested in the field Theoretical study indicates flow noise effect may not be detrimental
Vibration	No vibration isolation may be required for operational speeds up to 4knots	No studies conducted in the field. Vibration isolation would be required as the array could be very sensitive to vibrations
Array diameter	10 to 30mm diameter for 12 to 48 channels	20 to 30mm diameter for 8 to 32 channels
Weight	About 2.5kg in air for 24 channel DTLA with 15m tow cable.	Approximately 5kg/km
Receiver system	Simple, mostly PC104 and DSP based embedded platform. Weighs under 5kg including power source	Complex and sophisticated. May require special vibration free mounting. May weigh under 30kg
Power consumpiton	1W/channel by the array. About 40W/24 channel for DTLA, including receiver	Array does not consume power. Receiving electronics $\sim$24W/16 channels
Cost	Relatively low cost due to well established technology	At present the overall system cost may be more than ceramic based array due to immature technology and special manufacturing requirements.
Robustness and maitainability	Robust for harsh environment Easy to maintain	May require special design for robustness in harsh environment. May not be easy to maintain

4.2. DFB-FL sensor arrays

The DFB-FL sensor arrays are yet to be integrated and tested on an AUV or USV platform. Scott Foster et. al has reported testing of an 8-channel fibre laser sensor array in the filed, but as a seabed array [39]. This array was interrogated over a 4 km fibre optic link and was found to have a flat acoustic sensitivity response up to 5 kHz with noise floor corresponding to sea-state-zero. The technology is still not well developed and most experiments have been performed in the lab environment. The first field demonstration of DFB-FL towed array sensor has been reported by Fabio Souto [41] where the system was able to detect and track a diver support vessel. However this 32-channel array measuring 25mm in diameter was operated from a surface vessel and was only an engineering test. There are only limited fibre laser sensor hydrophone related works reported in open literature since 2013. Moreover, only Thales Australia seems to have the only company which has matured this technology and built an field operational system.

5. Summary and conclusions

In this paper we have compared two acoustic sensor technologies towards development of lightweight arrays for use with autonomous platforms such as AUVs and USVs. These are the traditional piezo-ceramic based sensor and a very recent technology based on distributed feedback fibre laser sensor. The piezo-ceramic sensor based lightweight arrays is a well matured technology and has been used with AUV and USV platforms for many underwater applications. However, the fibre laser sensor technology, though very promising, is still not matured enough for field applications. Based on the studies conducted it is believed that most of the underwater application demands can be met by piezo-ceramic based sensor arrays at reasonable costs. The following Table 3 summarises our observations on some of the key parameters and how do they compare with the two sensor technologies.

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