Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/5670--19-9889

Acoustic Calibration of a Fiber Optic, Air-Backed, Mandrel Hydrophone with an Interrogation Approach Designed for Low Cost Arrays

Anthony Dandridge
Alan Tveten
S.T. Vohra

Optical Techniques Branch
Optical Sciences Division

June 5, 2019

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
05-06-2019

2. REPORT TYPE
NRL Memorandum Report

3. DATES COVERED *(From - To)*
Sept 1996 - July 1997

4. TITLE AND SUBTITLE

Acoustic Calibration of a Fiber Optic, Air-Backed, Mandrel Hydrophone with an Interrogation Approach Designed for Low Cost Arrays

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
56-6A94-09

5e. TASK NUMBER

5f. WORK UNIT NUMBER
6A94

6. AUTHOR(S)

Anthony Dandridge, Alan B. Tveten, and S.T. Vohra

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/5670--19-9889

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

10. SPONSOR / MONITOR'S ACRONYM(S)

NRL

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report describes some of NRL's earliest work performed on a Rayleigh backscatter interrogation system used to calibrate a fiber optic air-backed mandrel hydrophone. It provides insight into this unique form of interrogation and may be relevant to current day research into Rayleigh-based interrogation systems. The work was written up in the 1996/1997 time-frame, and submitted for publication as an NRL Memorandum Report, but for unknown reasons was not published.

Original Abstract: Using a novel fiber optic interrogation approach tailored for low cost arrays, a calibration of an air-backed mandrel has been successfully performed. The measurements were performed in June 1996. This interrogation approach has the potential to lower "wet-end" cost of acoustic arrays by an order of magnitude.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Anthony Dandridge
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	Unclassified Unlimited	17	**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited			(202) 767-9340

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

This page intentionally left blank.

Acoustic Calibration of a Fiber Optic, Air-Backed, Mandrel Hydrophone With an Interrogation Approach Designed for Low Cost Arrays

Introduction

Over the past decade there have been a number of impressive demonstrations of fiber-optic tactical- and surveillance-grade acoustic arrays. These at-sea demonstrations include the 48-channel All Optical Towed Array (AOTA)[1], the 49-channel LightWeight Planar Array (LWPA),[2] the Magellan 16-channel Vertical Line Array (VLA)[3], a 8-channel Arctic array,[4] and in May 1996, a 64-channel, bottom mounted surveillance array (All Optical Deployable System)[5]. These arrays have demonstrated performance equal to or better than conventional piezo-ceramic arrays. Each array offers advantages over conventional piezo-ceramic arrays such as performance, size, weight, power consumption, immunity to EMI and projected increased reliability. Although there have been a number of cost projections of fiber optic hydrophone systems indicating reduced acquisition and life cycle costs, with the reduced number of acoustic arrays the Navy is purchasing (since the "end" of the Cold War) the cost benefit was not sufficient for the Navy to abandon the familiar piezo-ceramic technology for this all optical approach. Although low cost methods to wrap fiber coils for transducers have been developed, the cost of the components such as the fiber couplers and the labor associated with interferometer fabrication (specifically fiber fusing) have limited the cost saving potential of this technology. Consequently, there is considerable interest in developing new approaches to fiber optic sensing which retain the performance of current approaches while lowering further the system cost, in particular that of the wet-end. Such an approach is the Ultra Thinline Array approach, which combines intrinsic Rayleigh scattering in the optical fiber with using pulse code modulation (PCM) interrogation. In this report we present the first successful acoustic calibration of an air-backed transducer with this type of interrogation.

Background

The majority of fiber optic acoustic sensor arrays are formed by discrete fiber interferometers, such as the Mach-Zehnder or Michelson interferometer. An array of these sensors are powered by one or more optical sources. Several signals are then multiplexed on fibers from the array using either frequency-division, time-division or wavelength-division multiplexing techniques or combinations of these techniques. Typically these techniques require two fiber optic couplers per sensor for this passive telemetry approach. If the hydrophone interferometer is a Mach-Zehnder then two

---

Manuscript approved May 17, 2019.

couplers are also required to form the interferometer such that a total of 4 couplers are required per acoustic channel. Current prices of these devices are $100 each with a projected cost of ~$30. For a hydrophone system using 40 meters of TA-20 coated payout fiber (~$0.19 per meter) for the sensing arm of the interferometer, the projected low cost couplers dominate the material cost by an order of magnitude. Also associated with this approach are ~8 to 10 fusion splices per acoustic channel which adds to the touch labor time cost of the device. Even one of the most optically efficient approaches (from the optical component standpoint) the in-line Michelson approach, has approximately one coupler and two splices per sensor. Consequently, during the development of fiber optic acoustic sensors which has often concentrated on meeting performance goals, there has also been a concurrent effort to reduce the system cost specifically that of the wet-end.

In 1984, the most promising sensor approach for towed arrays under development at NRL, was a coated optical fiber design incorporating ~30 meters of helixed fiber distributed over an approximate 1-m aperture. The fiber was nylon jacketed to an outer diameter of 1-mm which in the 5 to 1000 Hz region gave a flat acoustic response[6]. This sensing element was configured as a discrete Mach-Zehnder interferometer with a short path imbalance (~4-cm) to meet the noise specification when interrogated with a semiconductor diode laser. At this time NRL considered the possibility of using a combination of pulsed interrogation and Rayleigh scattering in the optical fiber to form sensing elements. This concept eliminates much of the componentry in the array since the sensing element is simply a continuous, helixed length of coated optical fiber. Initial work on this approach was not promising due to many factors including the relatively low phase responsivity of the coated fiber hydrophone, poor optical throughput in the acousto-optic modulator and low power of the optical sources. It was concluded that a better approach was to localize the reflections in specific regions to increase the optical signals. This approach was similar to that being pursued by Plessey in the UK, where a reflectometric array was being developed in the mid 1980s[7]. A similar approach was also being investigated at NUWC (then NUSC) in this time frame[8]. Neither of these systems produced the performance in terms of self-noise achieved by the discrete fiber interferometers, this low self-noise was a requirement for surveillance grade acoustic sensor systems.

In the late 1980s and early 1990s NRL demonstrated a number of interrogation/multiplexing approaches to both decrease the number of fibers between the source/receiver and the fiber optic array. Again the emphasis was to achieve wet-end simplicity while maintaining usable array self-noise performance. In December 1990, during the last AOTA program sea test, NRL demonstrated a small time division which used an in-line Michelson approach which had acceptable self-noise performance[9]. NRL also demonstrated an in-line Michelson TDM approach for the LightWeight Planar Array program that met the stringent self-noise specification[10]. As mentioned earlier this approach requires only one fiber optic coupler and potentially two optical splices per acoustic channel. At the same time NUWC also demonstrated a number of sensors using in-line Bragg gratings to form the sensors in a reflectometric array[11]. Due to a number of reasons including the basic hydrophone design as well as problems with the interrogation system, this approach had high self-noise in the towed environment[12,13]. Developments at both NRL and NUWC (Thin-line Optical Towed Array program) have reduced both the hydrophone self-noise and the noise of the Bragg grating interferometer interrogation approach, such that the system is now capable of supporting high performance acoustic towed arrays. This approach has the advantage of eliminating the labor associated with the fiber splices, so the cost driver is now the cost of the fiber optic Bragg gratings, which optically define the sensors.

In the late summer of 1995 NRL was asked to evaluate a NUWC proposal for an Ultra Thin Array (UTA), including a detailed review of the work to date. This effort, which had been pursued over the last few years under internal NUWC funding proposed a coated fiber hydrophone with a Rayleigh backscatter interrogation approach using pulse code modulation PCM of the optical source. In terms of the use of coated fiber the approach has similar limitations to those described above for the early coated fiber sensor work. Although a pseudo-calibration had been performed at Dodge Pond, the coated fiber response appeared to be dominated by vibration and acceleration effects rather than the scalar portion of the pressure field. However, if the noise of the interrogation approach was such that surveillance grade performance could be achieved with air-backed mandrels, the wet end could be extremely low cost using COTS components. Although some system noise data from NUWC indicated a degree of feasibility, from the information provided it was not clear what hydrophone responsivity and optical noise was achieved. As NRL had previously worked with a PCM multiplexed fiber optic array[14,15] it was relatively simple to perform a basic characterization of the approach with existing NRL hardware. This work, indicated that, in the fiber length regions where laser noise did not dominate, relatively low noise interrogation could be performed[16]. In the summer of 1996 NRL bread-boarded a version of the interrogation scheme and calibrated an air-backed, mandrel based fiber optic hydrophone in System K at the Underwater Sound Reference Detachment (now closed) in Orlando FL. The results of this calibration (performed in June 1996) are the subject of this report.

Sensing Concept

Figure 1 illustrates the sensing concept. A long fiber is used as a distributed acoustic sensor element. Light injected from the source produces Rayleigh scattering as it passes along the fiber. This weak Rayleigh light is subjected to phase modulation due to acoustic perturbation of the fiber as illustrated. Light components scattered in the initial sections of fiber experiences low level phase modulation, whereas optical scattering components obtained from more distal sections of the fiber undergo larger amplitude phase shifts due to the accumulated perturbation effects along the fiber. By utilizing a pseudo-random code modulation of the input light, the scattering from different sections of the fiber can be resolved. This allows the phase modulation at a section in the fiber to be monitored. By monitoring the phase modulation experienced by two sections in the fiber, the differential signal provides a measure of the acoustically-induced phase over the length of fiber separating the two sensing sections. This capability allows a localized sensor aperture to be formed with any desired length and position along the fiber.

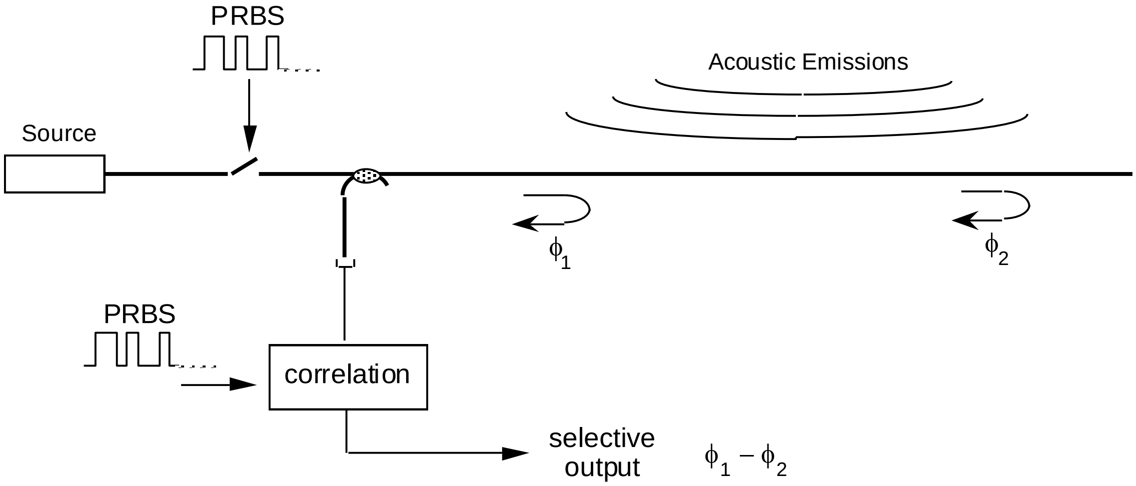

Figure 1. Sensing concept.

Experimental Configuration

The experimental system is shown schematically in Figure 2. The source was a Lightwave 123 Nd:YAG laser operating at 1.319 µm with 10 mW output power and a linewidth < 25 kHz. The laser light was passed through an isolator, into an 85% splitter (C1) and fed into an integrated optic chip (IOC) intensity modulator. The IOC was driven by a pseudo-random bit sequence (PRBS) which modulates the incoming light with the PRBS sequence before it passes through another isolator, a 3 dB coupler (C2) and into the sensing fiber. Rayleigh backscattered light from the sensing fiber was directed by way of C2 into a final coupler where it was coherently mixed with a strong local oscillator signal obtained from the other port of C1 as shown. A differential detection scheme was used with the two outputs on the final coupler before the signal was fed into a correlation circuit comprising of an electronic gate fed by the delayed PRBS signal. A piezoelectric transducer (PZT) was used to induce a signal phase modulation carrier in the received interferometer signal. The transducer (PZT1) was located in the local oscillator path. The mandrel based fiber optic hydrophone was placed in the sensing arm of the interferometer. A 15 bit PRBS signal was created using a linear shift register generator which was driven by a 10 MHz clock, to give a 100 nsec bit length. The electronic gate was driven with a variable m-bit delayed signal permitting the sensing fiber to be interrogated in increasing lengths of 10 meters. In this experiment the length of the sensing fiber length being interrogated was given by m*10 meters where m is the integer number of delayed bits on PRBS signal fed to the correlator circuit. However, by correlating the detected signal with another appropriately delayed PRBS and taking the difference between the two, any 10 meter or multiple of 10 meter sections of fiber in the sensing arm could be interrogated.

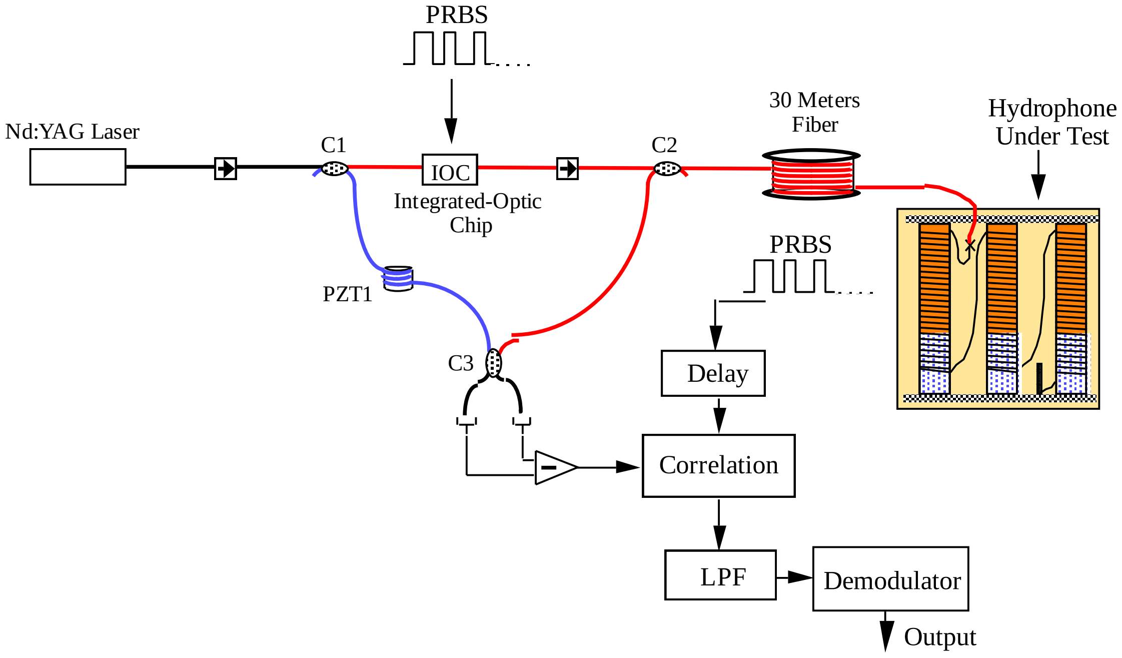

Figure 2. Experimental setup for Rayleigh backscatter interrogation technique.

Fiber Optic Hydrophone

Two fiber hydrophones were constructed for this calibration. Each one was a three element mandrel design configured as a planar hydrophone device. This was a convenient method of packaging the three mandrels. The total length of fiber on each mandrel was approximately that used for towed array hydrophones (the targeted application for this interrogation approach). The serial number PA (indicated Planar Array) served to describe the form factor of the hydrophone. The configuration of this device is shown in Figure 3.

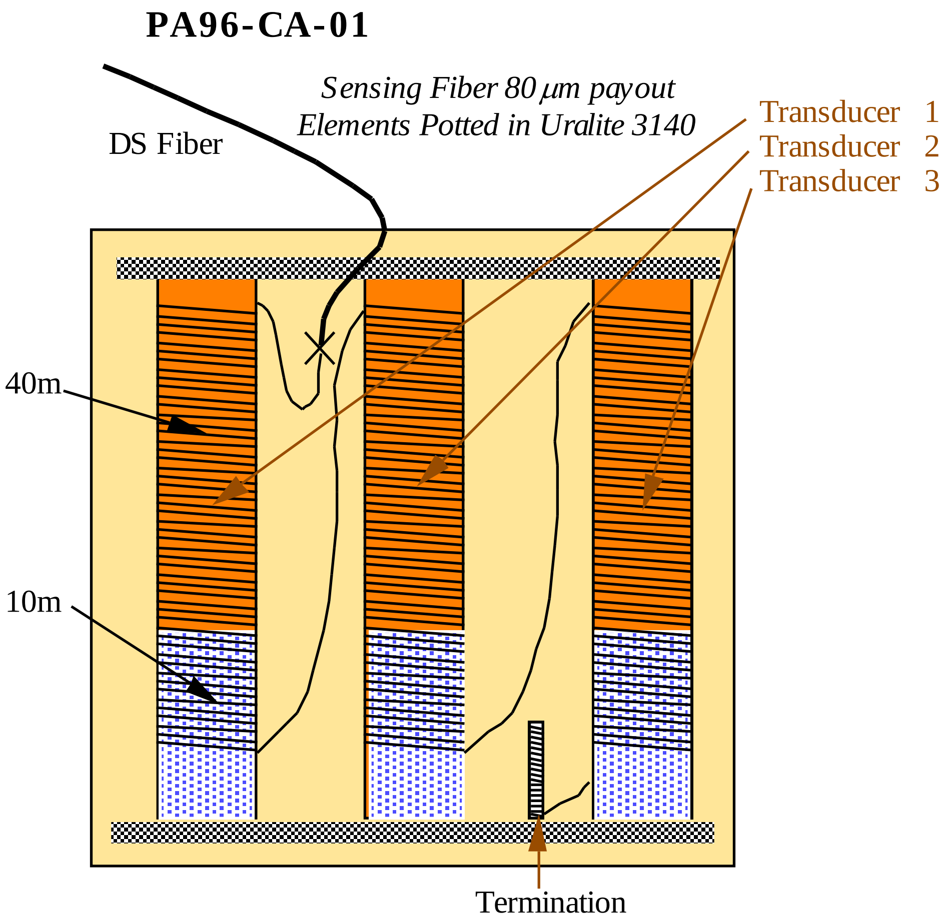

Figure 3. Details of hydrophone PA96-CA-01.

The first transducer, PA96-CA-01, had 50 meters of 80-µm diameter Corning Payout fiber wrapped on each mandrel. The first 40 meters was wrapped over the air-backed portion of the mandrel, while the last 10 meters was wrapped on a solid plastic section, this portion of the transducer was relatively acoustically insensitive. The mandrels were ~4-inches long and the diameter was 0.5-inch, the wall thickness was 0.0625-inch and material was polycarbonate. The input lead was Dispersion Shifted (DS) fiber which had a thick nylon jacket, this input lead was fused to the Payout fiber on the first sensing mandrel. The 150 meters of Payout fiber in the transducer was continuous. To terminate the sensing fiber, the Payout fiber exiting the third 10 meter insensitive region was fused to SMF-28 fiber which was wrapped around a small diameter mandrel. The end of this fiber was also crushed to further reduce any reflected light. These precautions were taken to ensure that the reflected light did not overwhelm the low intensity Rayleigh scattered light that the electro-optic system was designed to detect. The mandrels were held in place by a simple frame, the unit was potted in Uralite 3140.

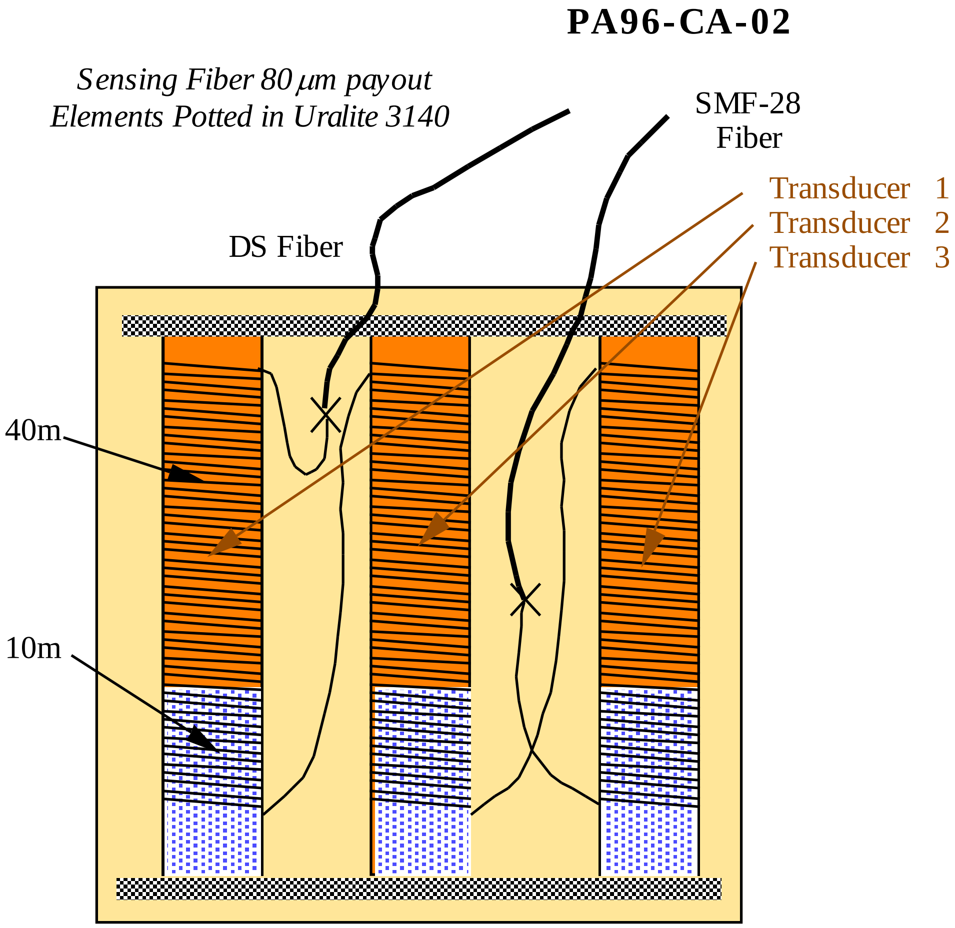

Figure 4. Details of hydrophone PA96-CA-02.

The construction of PA96-CA-02 was similar to PA96-CA-01 except the lead from the third insensitive region instead of going directly to the termination was fused to a 3-meter length of thick jacketed SMF 28 fiber. This approach had the advantage that by allowing the strong reflection at the end of the SMF 28 fiber to be seen the timing of the electronics could be performed with relative ease. When the timing was correctly set, the end of the SMF 28 fiber was tightly coiled to eliminate the reflection from the fiber end.

The expected responsivity along the length of the fiber in the transducer is shown in Figure 5. This Figure shows the reduction in responsivity from the maximum value (the full fiber length, the three flat regions correspond to the acoustically insensitive regions in the transducer. A nominal responsivity of the nylon coated DS fiber has been assumed (labeled "Fiber Lead" in the Figure).

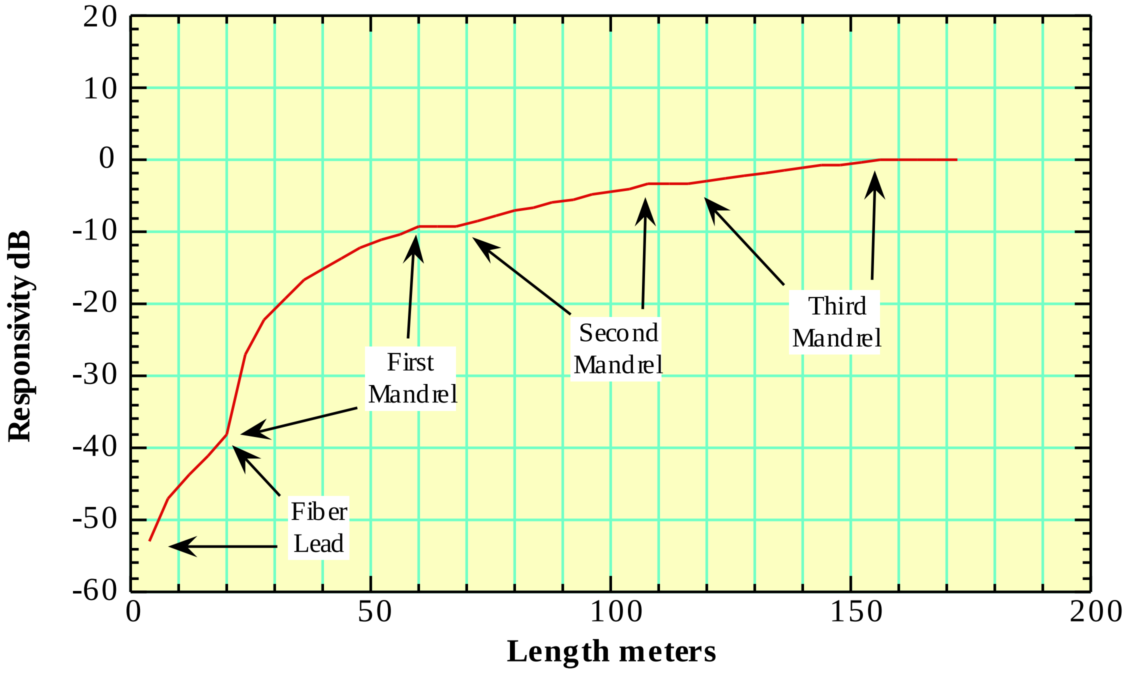

Figure 5. Calculated variation of transducer responsivity with fiber length.

An Optical Time Domain Reflectometer (OTDR) trace for PA96-CA-02 is shown in Figure 6. For convenience the light was sent through the transducer "backwards" (i.e., launching the light through the SMF 28 lead from the transducer. The transducer appears to be low loss, the step at the splice (152-meters) is associated with the different Numerical Aperture of the DS fiber compared to the Payout fiber rather than splice loss.

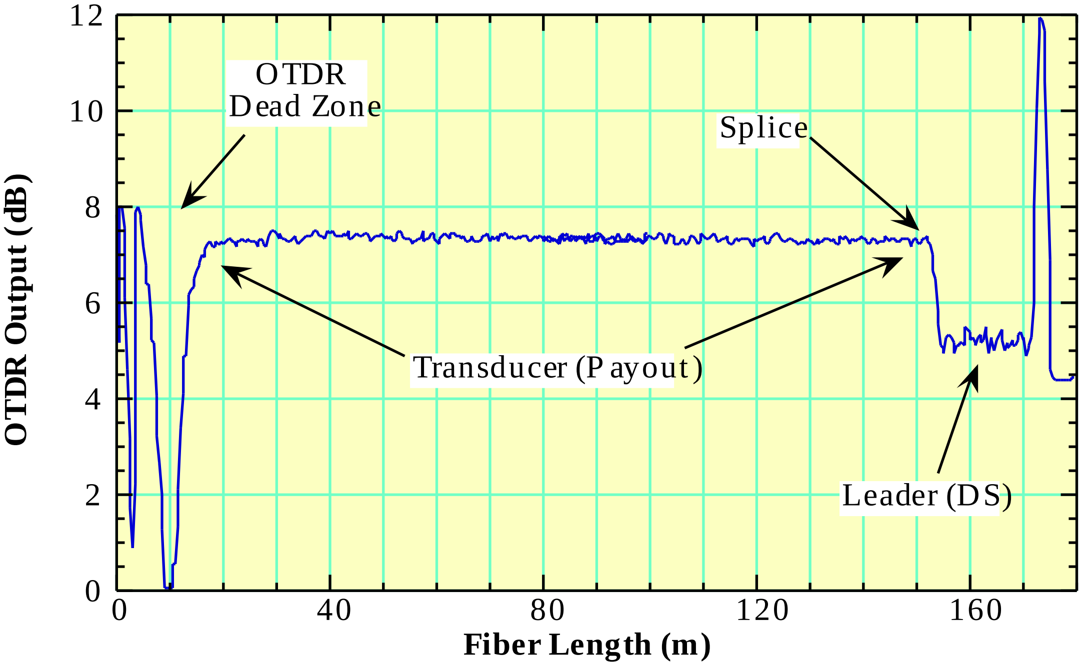

Figure 6. OTDR trace of PA96-CA-02.

The acoustic calibration was performed at the Underwater Sound Reference Detachment in Orlando FL. The measurements were performed in System K, a low frequency pressure tank calibrator as this provided the most benign environment for the fiber leads going to and from the transducers. Both transducers were mounted in the pressure tank, with three leads being passed though the pressure seal (one for PA96-CA-01 and two for PA96-CA-02). Although many calibrations have been performed on air-backed transducers, as this particular configuration had not been calibrated previously, it was necessary to perform a calibration of the transducer using a “conventional” interrogation technique (i.e., not using the Rayleigh backscatter as the source of optical power returned from the transducer). This conventional calibration could only be performed on PA96-CA-02, by allowing a strong reflection from the SMF 28 fiber end, which overwhelmed the Rayleigh scattered light. This allowed an interferometer to be formed incorporating the entire length of fiber in the transducer. The timing of the delayed code sequence was adjusted to correspond to this end reflection. With this timing a strong carrier signal was observed, this signal was demodulated with a conventional NRL differentiate cross-multiply demodulator. The resultant acoustic responsivity is shown in Figure 7. The demodulator constant of -30 dBV/rad has been removed from the measured data. As can be seen from the Figure the response is independent of frequency (over the test range of 5 to 1000 Hz) and has a mean value of -125 dB re rad/µPa. The observed) responsivity is approximately that expected from ~110 meters of sensing fiber (the active sensing length) on this type of air-backed mandrel. This is probably the first controlled calibration of a fiber optic transducer using a PCM interrogation approach.

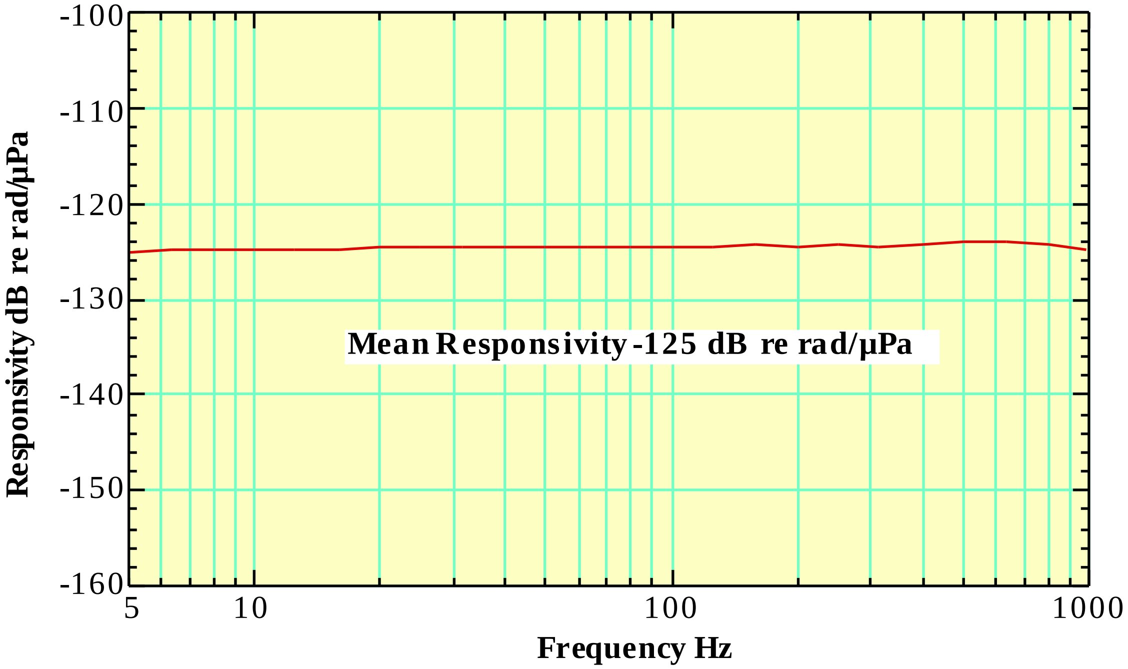

Figure 7. Calibration of PA96-CA-02 using strong SMF 28 end reflection and PCM interrogation.

Although the measurements with the PCM system with the strong end reflection were achieved relatively rapidly, considerable difficulty was encountered when trying to obtain signals using the Rayleigh scattering. The problems ranged from the low light levels from the scattering, continuous fading of the carrier signal over the period of the frequency scan and other signals not directly related to the acoustically induced phase shift being generated in the transducer. Much of these difficulties were traced to problems associated with the timing of the delayed PRN code. Although the initial timing (with the strong reflection) was relatively easy to set, the correct time delay for the configuration of the circuit in the condition where the end reflection was eliminated was difficult to set (the circuit timing had to be adjusted to the acoustically insensitive portion of the third mandrel). Due to ambiguities with this circuit it was difficult to determine on which portion of the fiber the delay had been set. In fact, post-test analysis indicated that after the initial measurement with the strong reflection, the timing had been adjusted in the wrong direction (i.e. the time slot after the reflection not the intended slot before the reflection). This led to much time being spent trying to recover a signal which was basically non-existent. This problem with the timing was only resolved, when a constant amplitude, constant frequency acoustic signal was generated in the tank and the length of the arc on the sine/cosine Lissajous figure from the demodulator was visually monitored. This technique allowed qualitative confirmation that the interrogation approach was working. By adjusting the delay, the arc of the sine/cosine was seen to increase as the interrogated scattering region was moved further into the transducer. This approach allowed approximate setting of the timing, such that three frequency sweeps using the Rayleigh scattering return could be obtained (plus another reference sweep with the strong reflection) in the last remaining minutes available in the calibration facility. The timing of these runs was not perfect, but they served to prove the viability of the interrogation approach for acoustic sensing, the results are shown in Figure 8.

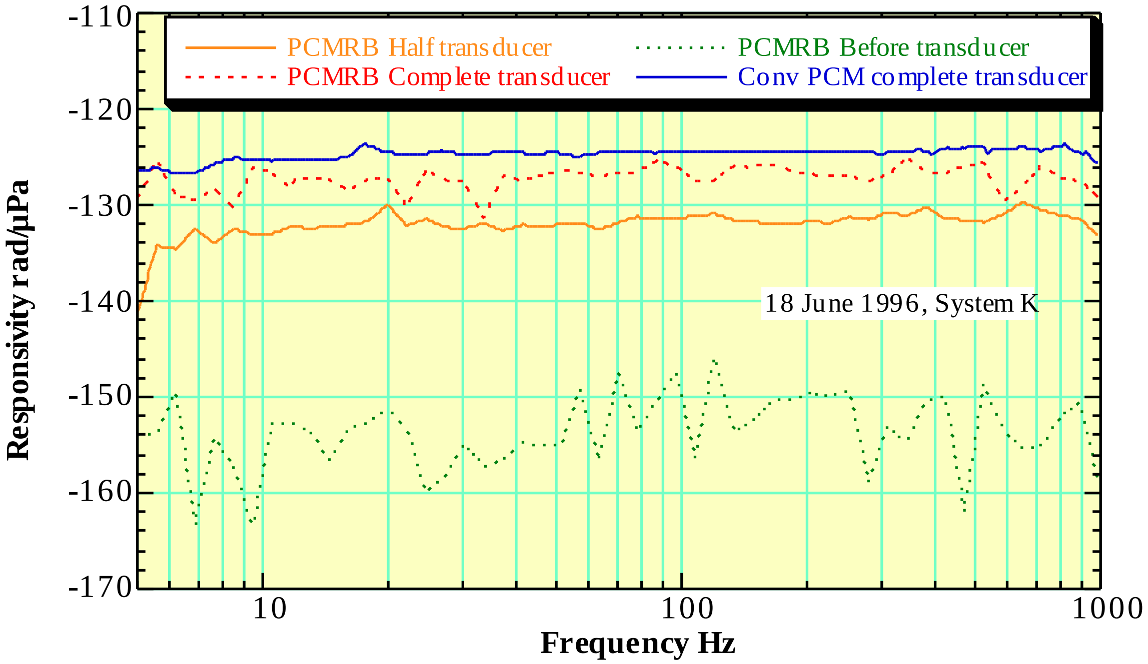

Figure 8. Calibration using the Rayleigh scattering return to form the interferometer. The timing was adjusted to different portions of the transducer.

The top trace shows the repeat of the conventional PCM calibration (the mean value is similar to Figure 7), the next (lower) trace was intended to be the complete transducer, but using the Rayleigh scattering return. The mean value of this result is approximately 2 to 3 dB below the strong reflection responsivity, this discrepancy is probably due to the fact that the timing was such we may have been looking at scattering from the middle of the acoustically sensitive region of the third mandrel, rather than the acoustically insensitive region at the end of the third mandrel. The next lower trace correspond to the responsivity obtained from scattering from approximately the middle of the transducer (the result is approximately 7 dB below the conventional PCM result). The final run (lowest trace) shows the result when the delay was set to use the scattering from before the transducer. The mean level is approximately 30 dB below the conventional PCM result and the level corresponds to acoustic pick-up from the thick jacketed fiber and the relatively high optical noise in the system. Although the signal to noise obtained using the Rayleigh scattering signal was not as good as the strong reflection signal (resulting in more scatter in the calibration curve, this result serves to verify the potential of this technique for interrogation of fiber optic acoustic sensors.

Summary

An acoustic calibration of an air-backed, mandrel based acoustic sensor has been performed using the intrinsic Rayleigh backscatter to form the interferometer. By adjusting the delay of the PRN code sequence different lengths of fiber within the transducer could be interrogated. Other than the fiber there were no optical components in the hydrophone. The calibration showed that the transducer had a flat frequency response, the magnitude of the responsivity appeared to scale with the acoustically active length of fiber being interrogated. This interrogation approach has the potential to lower "wet-end" cost of acoustic arrays by an order of magnitude.

Acknowledgments

The authors would like to thank Dr. Aileen Sansone of NUWC-Newport and Mr. Scott Littlefield of ONR for their interest and support of this effort.

References

---

[1] B. A. Blakely, M. J. Berliner, P. B. Davis, A. L. Deus, R. C. Elswick, R. I. Ochsenknecht, A. Dandridge and A. Yurek, “An Optical Towed Array Sea Test Results” (U), U. S. Navy Journal of Underwater Acoustics, **43**, 551, 1993.

[2] A. Dandridge, "Development of Fiber Optic Sensor Systems", Invited Talk, Optical Fiber Sensor Conference (OFS-10), Glasgow Scotland, October 1994.

[3] A. Dandridge, A. B. Tveten, M. Opsasnick and A. M. Yurek, "At sea performance of a 16-channel vertical line acoustic array", DoD Photonics Conference, McLean VA, March 1996 and A. M. Yurek, A. B. Tveten, D. N. Phillips, Y. Y. Chao and A. Dandridge, “16-Channel Lightweight All-Optical Vertical Line Array”, Proceedings of Optical Fiber Sensor Conference (OFS-9), Florence Italy, May 1993.

[4] A. M. Yurek, A. B. Tveten and A. Dandridge, “Acoustic Noise Measurements Utilizing a Fiber Optic Hydrophone in the Arctic (U)”, U. S. Navy Journal of Underwater Acoustics, **41**, 139, 1991. Also: A. M. Yurek, A. B. Tveten, Y. Chao and A. Dandridge, “Arctic Test of a High Performance Fiber Optic Hydrophone Array (U)”, U. S. Navy Journal of Underwater Acoustics, **43**, 387, 1993.

[5] A. D. Kersey, A. M. Yurek, A. Dandridge, C. A. Villaruel and G. B. Cogdell, "All-Optical Deployable System: Architecture and Performance Study (U)", Confidential NRL Formal Report, #9718, 1995.

[6] N. Lagakos, A. Dandridge and J. A. Bucaro, "Optimizing Fiber Coatings for Interferometric Acoustic Sensing (U)”, U. S. Navy Journal of Underwater Acoustics, **37**, 233, 1987.

[7] Thornton et al, "Experimental performance of optical hydrophone with downlead insensitivity", Optical Fiber Sensor Conference OFS'84, Stuttgart, September 1984.

[8] E. L. Green, G. E. Holmberg, J. C. Gremillion and F. C. Allard, "Remote passive phase sensor", Optical Fiber Sensor Conference, OFC/OFS'85, San Diego CA, Feb. 1985.

[9] A. M. Yurek, A. Dandridge and A. B. Tveten, “Self noise performance of a TDM fiber optic array for towed array applications (U)”, NRL Confidential Memorandum Report #7445, 1994.

[10] M. J. Marrone, A. D. Kersey, and A. Dandridge, “Noise performance of a multiplexed array of fiber optic Michelson sensors”, NRL Memorandum Report #7418, 1993.

[11] G. H. Ames and A. L. Deus, "TDM/WDM Architecture for an optical acoustic array (U)", U. S. Navy Journal of Underwater Acoustics, **43**, 505, 1993.

---

[12] A. Dandridge, A. B. Tveten and A. M. Yurek, “At sea self noise performance of continuous, extended fiber optic hydrophones for towed arrays (U)”, Confidential NRL Memorandum Report #7476, 1994.

[13] A. Dandridge, M. Opsasnick, A. B. Tveten and A. M. Yurek, "Noise performance of path matched differential interferometer systems for fiber optic towed arrays (U)", Confidential NRL Memorandum Report #7625, 1996.

[14] A. D. Kersey, A. Dandridge and M. A. Davis, “Code-division multiplexed interferometric array with phase noise reduction and low crosstalk”, Proceedings of Optical Fiber Sensor Conference (OFS-8), Monterey CA, 1992.

[15] A. D. Kersey, A. Dandridge and M. A. Davis, “Low crosstalk code-division multiplexed interferometric array”, Electron. Lett., **28**, 351, 1992.

[16] M. A. Davis, A. D. Kersey and A. Dandridge, “Interrogation Approach for Low-Cost Fiber Optic Hydrophone Arrays: Noise Performance (U)”, Secret NRL Memorandum Report 5670/97-7848, 1997.