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APPLICATIONS OF THE PARAMETRIC ACOUSTIC SOURCE

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ABSTRACT

This paper describes some of the more important applications of the parametric acoustic source and discusses most of them in terms of full-scale at-sea or facility testing. Parametric source applications for high resolution bottom and subbottom profiling are presented for environments ranging from very shallow to deep ocean. The projectors used were from 10 cm in diameter to a high-power source having an 80 kW input. Detection and echo ranging systems that employ compact, battery powered sources for diver-carried sonars are described. Communications applications are also considered. Data rate improvements made possible by the parametric source are verified by comparing conventional and nonlinear sources and by medium-range acoustic television transmission.

I. INTRODUCTION

Ninety-five years ago Lord Rayleigh put his hand into the baths here at Bath, drew it quickly through the water and noticed his fingers were "thrown into transverse vibration and strike one another."[1] Rayleigh, noting that the effect "seems like the aeolian string" probably was the first to consciously produce a nonlinear effect in water. Exploitation of the phenomenon had to await Peter Westervelt's benchmark paper "Scattering of Sound by Sound"[2] in 1957 and, more particularly, his "Parametric Acoustic Array"[3] in 1963. Bellin and Beyer[4] quickly verified Westervelt's predictions by a well designed experiment that, for the first time, produced measurable difference frequency levels and beam patterns. Other early contributors, notably Berktay,[5,6,7] Tucker,[8] and Muir and Blue[9] played major roles in launching the new technology.

Some parametric sources have been used commercially and it has been shown that, in many applications, they have advantages over conventional direct radiation sources. This paper will present some of the applications and illustrate them through a description of the hardware and the results of tests conducted at sea.

One of the earliest uses of the parametric source was for subbottom profiling in 1970 at Narragansett Bay. The results, for a parametric source using a 0.4-m square projector having a mean primary frequency of 170 kHz and a difference frequency glide from 2 to 4 kHz, produced the right hand profile shown in Figure 1. The water depth was 50 m and approximately 45 m of bottom penetration was achieved using the 5° beam. A conventional source, using the same size projector and working frequencies, produced the profile at the left. The advantage of the parametric source is obvious.

II. SOME DESIGN AND MEASUREMENT CONSIDERATIONS

Before discussing applications, it might be helpful to briefly describe some of the problems the parametric source designer may encounter.

Source Nonlinearities

Figure 2 illustrates the effect on the beam pattern when an excessive level of difference frequency energy is directly radiated. This condition is usually avoided by including a high-pass filter between the amplifier and transducer (all elements in parallel) or through the use of separate drivers and transducer elements for each primary frequency (*checkerboarding*). The checkerboarding technique has the disadvantages of requiring almost twice as much primary power as the parallel connection

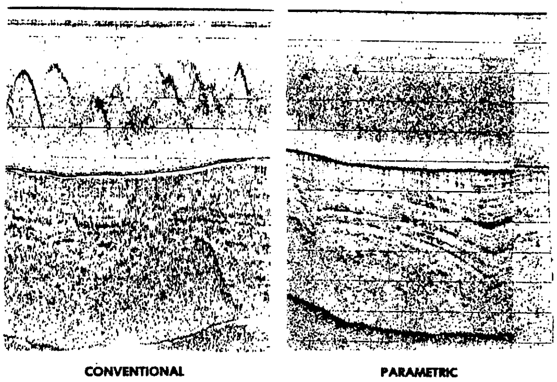

Figure 1. Comparison of Conventional and Parametric Bottom Profiling

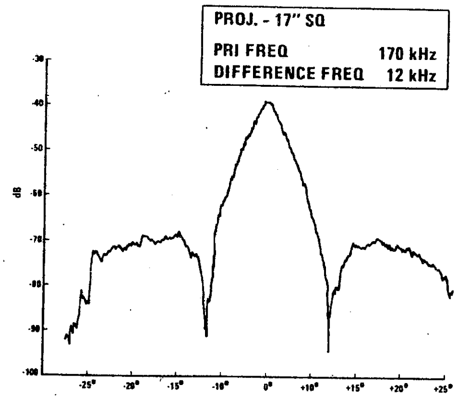

Figure 2. Effect of Direct Radiation from a Parametric Source

(because the array is 50% thinned) and of sometimes producing excessive sidelobes at the difference frequency (the result of large element spacings). For the parallel connection, maintaining the difference frequency to the projector at 50 dB, or more, below the primary level will usually preclude beam pattern problems.

Transducer nonlinearity has recently become a problem. Figure 3 is a comparison of the difference frequency beam patterns from 0.75 m diameter projector made of tonpliz elements and filled with different fluids. The projector was operated at a mean frequency of 37 kHz with the primary pressure a few decibles below the cavitation threshold in water. The difference frequency was 2.5 kHz. The poor patterns for the polyalkylene glycol[10,11,12] are the result of the internal cavitation having a relatively low threshold. Also, the difference frequency source level is 2.5 dB lower and the back lobe (reflected from surface) is about 5 dB higher using the glycol. The glycol exhibits a *soft* cavitation that results in a smooth pattern near threshold instead of the jagged one exhibited by cavitation occurring in the water outside the transducer. Tests[13] conducted in a resonant cylinder showed that while polyalkylene glycol had an initial cavitation threshold above that of castor oil, it dropped once cavitation was initiated. In some cases, the glycol threshold was below that of water.

A similar but less pronounced beam broadening effect was observed on one section of the NUSC TOPS transducer, in which tonpliz elements are also used. Subsequent disassembly and examination revealed that eight element mounting rings where broken in the section that exhibited the broad pattern. Re-testing must be completed before the cause of the broad beam can be established. No nonlinear effects have been observed in any of the NUSC transducers constructed of half-wave long bars or half-wave thick plates using air or Corprene (Trademark) for pressure release. However, nonlinear effects have been observed in individual rings that are operated in air.[14] Research in the area of transducer nonlinearity is continuing.

Another cause of nonlinearity is cavitation in the medium. When the primary pressure is just slightly above cavitation, the main lobe of the difference frequency may be unaffected but the pattern will exhibit a jagged response at lower levels around the main lobe. At levels well above the cavitation threshold the pattern can become almost omnidirectional.

Receiver Nonlinearities

The receiving system can distort difference frequency beam patterns because of nonlinearity in the hydrophone or the electronics. Hydrophones vary widely in response to the high level primary pressure; many will generate difference frequencies at pressure levels just above 1 atmosphere. In a typical case, the difference frequency contribution of the hydrophone has the shape of the primary pattern squared, overlaying the normal broad difference frequency pattern. (An overload of the receiving electronics produces a similar pattern.) Hydrophone nonlinearity can be avoided by increasing the range or using a different hydrophone. Electronics problems can be eliminated by preventing primary frequency overload by using a low pass filter before the active components.

III. APPLICATIONS

High Resolution Sounding

Two of the most successful applications of the parametric source are those of bottom and subbottom profiling. The advantages of the parametric source for bathymetry or bottom profiling are the narrow *sidelobeless* beams that can be radiated at relatively low frequencies where absorption remains reasonably low. The parametric source is therefore applicable to high resolution profiling in deep water, e.g., when surveying for pipe and power lines and locating bottom characteristics suitable for deep sea mining. High resolution in range is achieved by using the wide bandwidth inherent in the source. High resolution can be obtained by transmitting very short pulses or large time bandwidth pulses, such as FM slides or pseudorandom noise.

Early in 1976, the Ocean Systems Center of the Raytheon Company delivered a finite amplitude depth sounder (FADS) to Deep Sea Ventures, Inc., for use in deep water mining operations. This sounder uses FM glide and replica correlation. It achieves 1 m range resolution and a 3° beam from a projector approximately one-quarter the size required in a conventional system. Excellent records were obtained at depths of 4600 m.

A deep water Doppler navigation sonar using a parametric source has been designed and tested by Sperry Marine Systems[15] with good results. The high spatial resolution of the narrow beam at a suitable frequency is needed to achieve the desired accuracy for this system.

The Naval Ocean Research and Development Activity (NORDA) recently investigated the parametric source for side-scan mapping of in-shore waters. The results of a portion of a test conducted at NUSC's Seneca Lake Facility are shown in Figure 4. A transducer 0.9 m in diameter was used; it transmitted a 10 ms CW pulse at a 19 kHz difference frequency with a source level of 224 dB//1 μPam. The transducer was rotated through 360°, starting at the North, along the length of the lake. Note the contour of the shore and the returns from the anchor cable depressors of another barge at a 4 km range.

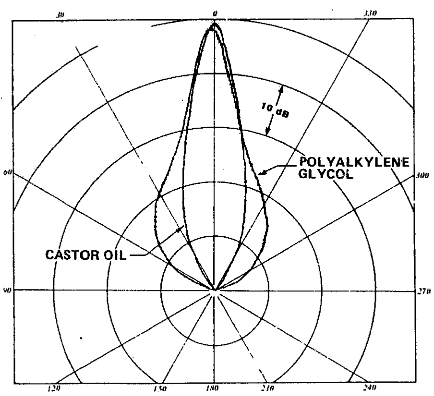

Figure 3. Difference Frequency Patterns with Two Transducer Fluids

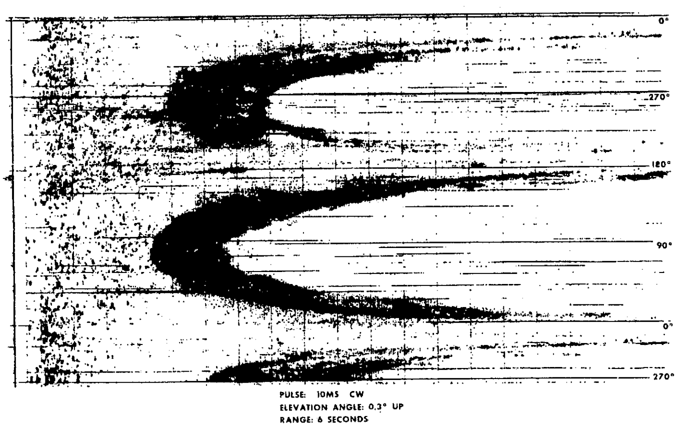

Figure 4. Seneca Lake Side Scan

The parametric source can be advantageous even for shallow water bathymetry because it permits a beam having very low sidelobes to be radiated from less expensive single element projectors. Although the primary pattern of many projectors constructed of a single disc or slab of ceramic exhibits high sidelobe levels, the difference frequency pattern can be nearly free of sidelobes. An example of this application is shown in Figure 5, where the results for a 10 cm ceramic disc transducer operating at a mean primary frequency of 650 kHz are shown. The transducer produced a source level of 180 dB//1 μPam at a difference frequency of 24 kHz with a beamwidth of 7°. A number of rocks ranging from 0.3 to 1 m high near the 5 m depth line are shown. A unique feature of this sounder is that the difference frequency is near the radial resonance of the ceramic disc. Because the same transducer is used for receiving, improved hydrophone sensitivity is realized.

It may be that one of the first applications, i.e., subbottom profiling, will emerge as the paramount one. Many researchers[16,17,18] have considered or used the parametric source to determine bottom composition or to detect objects buried in the bottom. The need for good penetration (which requires low frequencies) and high resolution (which requires narrow beamwidths) makes the parametric source uniquely qualified in these areas.

Figure 6 illustrates the use of the parametric source to measure the depth and shape of a dredging spoils pile. The 0.9 m, 65 kHz transducer having a 14 kHz 2.5° beamwidth difference frequency was again used. Rough seas caused the periodic ripple that detracts somewhat from the good vertical resolution characteristic of the narrow beam. However, very steep slopes have been recorded. The original bottom is about 25 m deep; above that depth several layers of dumping can be seen.

A bottom and subbottom profile in the somewhat deeper water of Seneca Lake is illustrated in Figure 7. Here a 4° beam having a 4 ms pulse length at 3.5 kHz difference frequency shows bottom penetration up to 50 m in water 150 m deep. Note (at the right of the figure) the resolution obtained on the bottom formations in shallower water.

The NUSC TOwed Parametric Source (TOPS), shown in Figure 8, was used to obtain subbottom data in deep water. This transducer consists of four sections, each having an aperture of 0.53 × 0.45 m. Overall dimensions are 2 × 0.59 m with a transducer mass of 500 kg. A deep-water subbottom profile, using a mean primary frequency of 24 kHz and a difference frequency of 2 kHz, is shown in Figure 9. The difference frequency source level was 215 dB//1 μPam and the beamwidth was 2.2 × 5.0°. The primary acoustic power was 10 kW per frequency (40 kW peak envelope power).

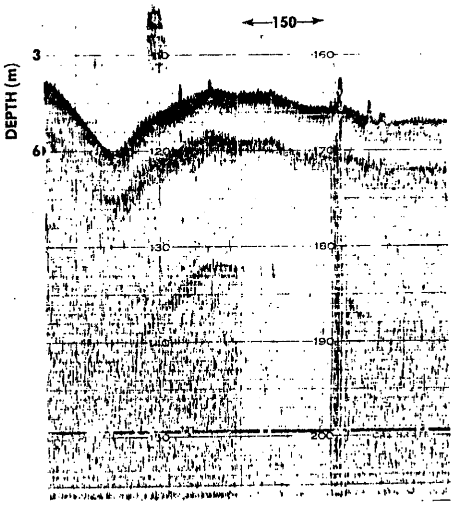

Figure 5. High Resolution Parametric Depth Sounder

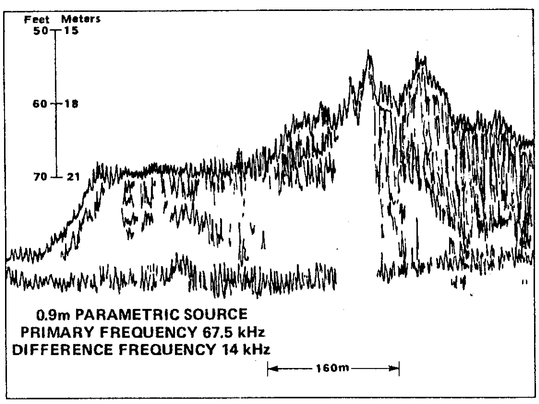

Figure 6. Dredging Spoils: Long Island Sound

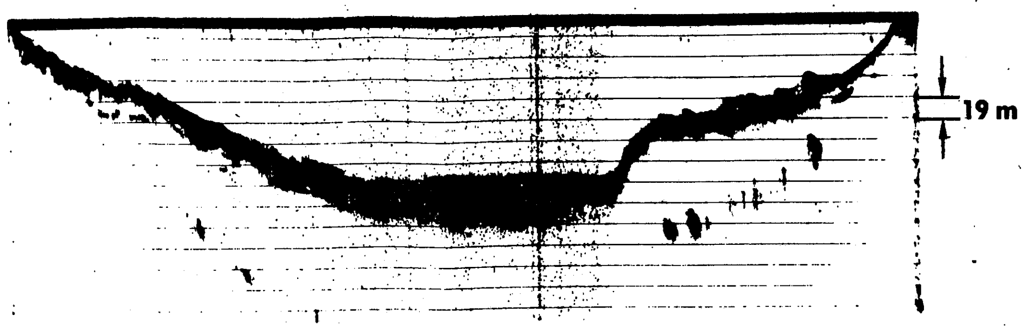

Figure 7.Sub-Bottom Profile: Seneca Lake (2 km Track)

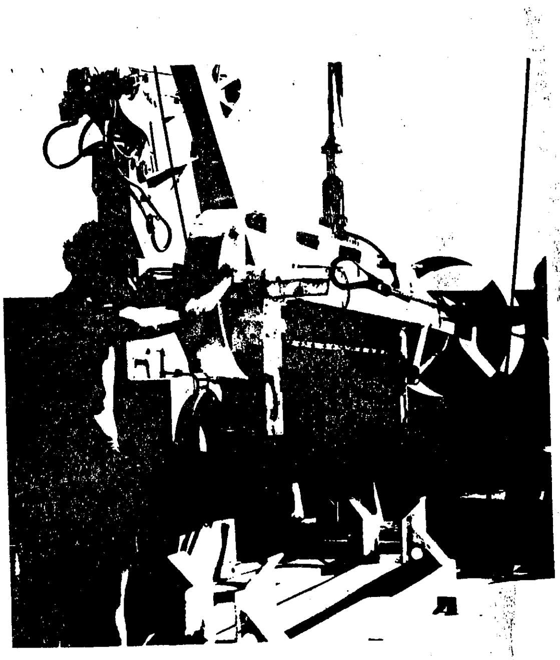

Figure 8.The NUSC Towed Parametric Source

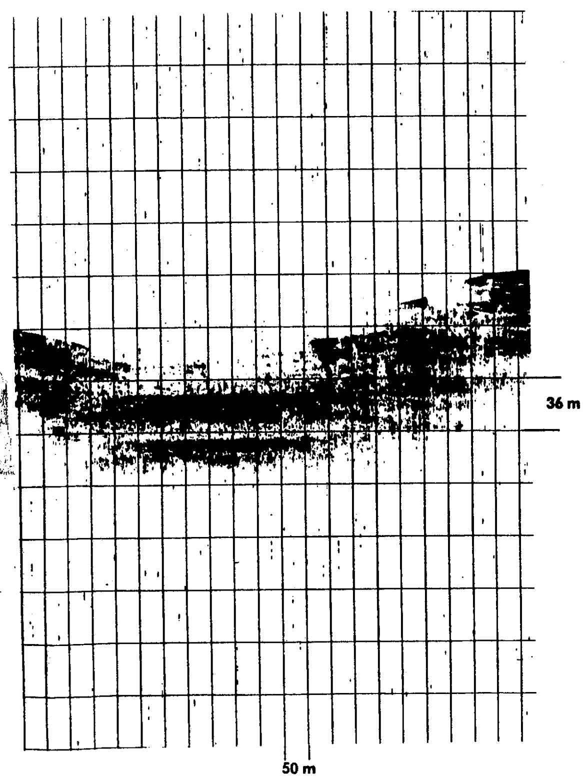

Figure 9. Deep Water Sub-Bottom Profile

APPLICATIONS OF THE PARAMETRIC ACOUSTIC SOURCE

A very large parametric source capable of average bottom penetrations of 1000 m has been proposed. Such a source would be used for detailed surveys of areas where the existence of oil or gas is suspected and, possibly, to determine suitable locations for deep ocean dumping. The projector has an area of 75 m^2 and operates at a mean primary frequency of 3.5 kHz with a primary acoustic power of 550 kW per frequency, or 2.2 MW PEP. The difference frequency for maximum bottom penetration is near 70 Hz and the source level is 208 dB//1 μPam. A 3 dB beamwidth of 4.5° is predicted. The predicted performance of this source assumes a towed line array and replica correlation for receiving. Such a source may never be built, but the design illustrates what could be achieved by a large optimized parametric source.

The parametric source has also been employed in the study of volume scattering in the deep scattering layer. The advantages to this application are the (1) wide band of frequencies that can be covered by a single transducer, (2) good vertical resolution, and (3) very short *ringing time* of the source following the transmitted pulse. The short, clean transmit pulse makes it possible to receive scattering from shallow layers when the transducer is positioned just below the surface. A view of an ascending scattering layer is shown in Figure 10. Here, the layer is illuminated and the backscatter is received by the 0.9 m diameter transducer operating at a mean primary frequency of 65 kHz. The 14 kHz difference frequency was generated with a source level of 220 dB//1 μPam and a 2.5° beamwidth. A second, deeper layer is also visible.

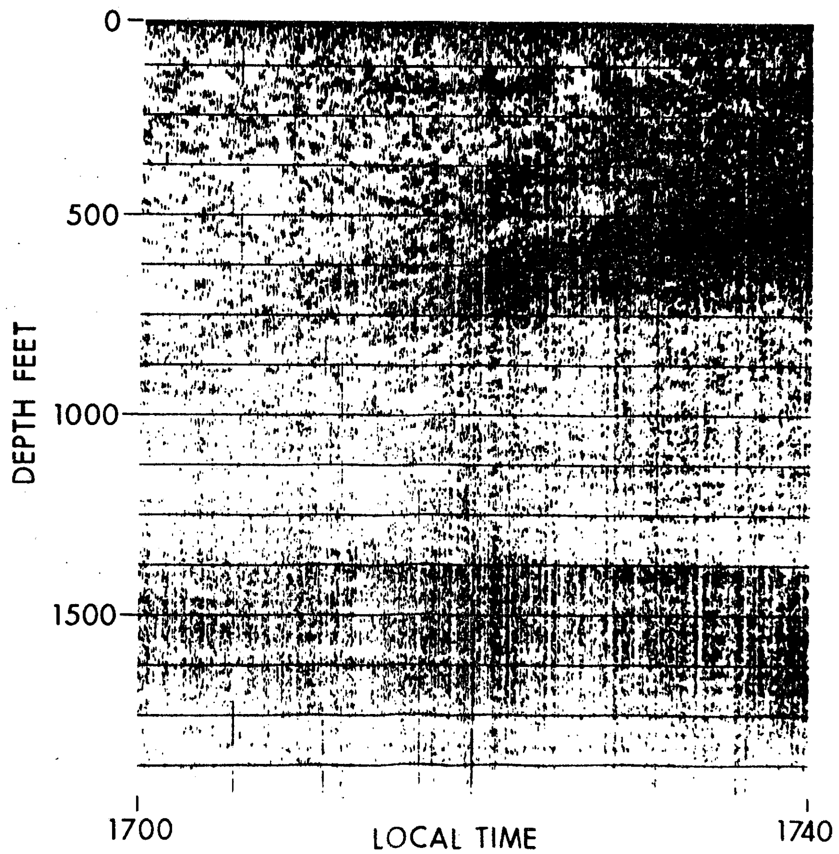

Figure 10. Deep Scattering Layer Using a Parametric Source

APPLICATIONS OF THE PARAMETRIC ACOUSTIC SOURCE

Echo Ranging

The unique beam pattern of the parametric source provides a distinct improvement in the performance of active sonar under reverberation limited conditions. Such conditions are usually encountered in the shallow water areas of the oceans. Figure 11 illustrates, for a small-scale situation, the potential advantages of the parametric source for echo ranging. A comparison was made of conventional and parametric systems in an experiment at NUSC's Millstone Quarry Facility in 1971; each system used the same projector. The transducer depth was 4.5 m and the range to the target was 36 m; the source level was the same in each case. The target in each case was an LC-10 hydrophone (7.8 cm long by 1.3 cm diameter); target strength was -35 dB. Note that the narrow parametric beam eliminates surface reverberation and the target is unobscured.

On a larger scale, Figure 12 displays a return from a 5 dB target at a range of 8.7 kyd in Seneca Lake. The difference frequency was 12 kHz with a source level of 221 dB//1 μPam and a conical 3° beam. Reverberation is just above the noise level for the parametric source. The much higher reverberation completely obscures the target for the conventional source.

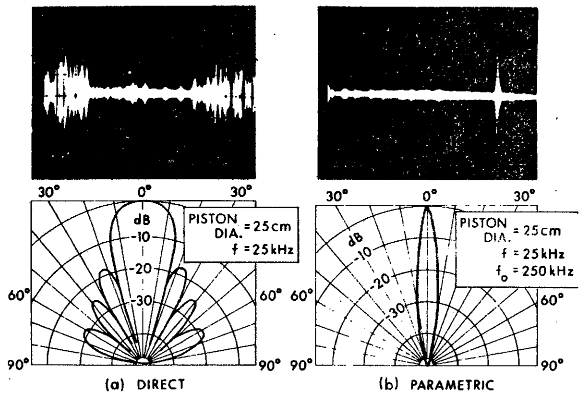

Figure 11. Echo Ranging Performance

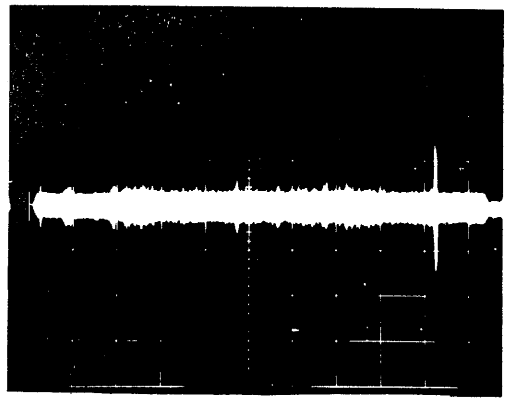

Figure 12. Parametric Return 5 dB Target

In 1977, NUSC designed and tested a small battery powered parametric source for diver-carried sonars and other compact, remote sonar applications. The components of the source are shown in Figure 13. The signal generator (at the left) drives the 400 W power amplifier (center). The 8 cm diameter transducer (lower left) uses a half-wave-thick, air-backed ceramic disc resonant at 460 kHz. The power supply, consisting of eight 9 V alkaline batteries and an energy storage capacitor delivers the 400 W pulse power. The signal generator and amplifier employ switching, instead of linear circuitry, to maximize efficiency and eliminate the power drain between transmitted pulses.

The primary source level of 224 dB//1 μPa rms per frequency produces 172 to 175 dB//1 μPam at difference frequencies from 15 to 20 kHz. The 0.5% duty cycle results in a battery life of 3 hr. The beam pattern at the 15 kHz difference frequency is shown in Figure 14. This source demonstrates that, despite their low efficiency, battery powered parametric sources can be practical.

Communications

The narrowbeam, broadband features of the parametric source are particularly advantageous in underwater acoustic communication systems. Narrow beams markedly reduce multipath distortion, and broadband capabilities permit high data rates to be transmitted.

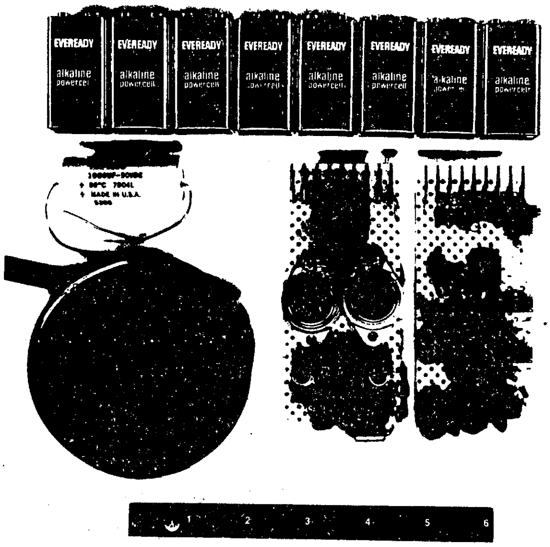

Figure 13. Components of the Battery Powered Parametric Source

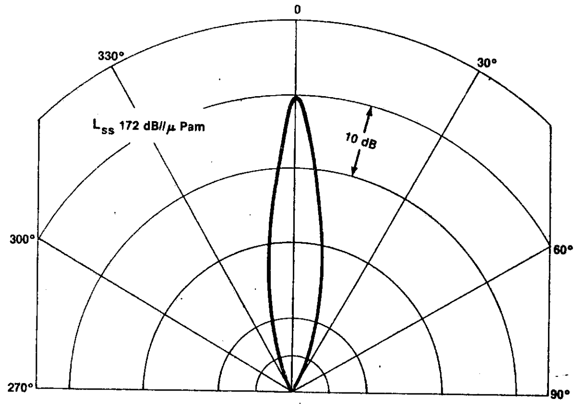

Figure 14. Battery Powered Parametric Source Beam Pattern

The first parametric voice system, deployed by NUSC in 1972 to transmit speech between points in Long Island Sound, had a

- Projector diameter of 25 cm
- Primary center frequency of 250 kHz
- Primary 3 dB beamwidth of 2°
- Primary source level for each frequency of 237 dB//1 μPam
- Power input for each frequency of 2 kW
- Difference frequency of 8 to 11 kHz
- Difference frequency source level of 190 dB//1 μPam
- Difference frequency (3 dB beamwidth) of 4°

More recently a larger source has been used at NUSC for the transmission of voice and wideband, high data rate multi-tone communication signals. Data rates for multi-tone transmission have reached over 6000 bits/sec using a difference frequency band from 8 to 15 kHz. These tests have demonstrated that such rates are achievable in both deep and shallow water.

An example of a situation in which a very narrow beam is required to avoid multipath is shown in Figure 15. The velocity profile is such that rays 3° above and below the optimum travel via the bottom. A parametric source having a 3° beamwidth proved capable of reaching the receiver with a communication signal essentially free of multipath.

Two tests were made at Seneca Lake under the above propagation conditions. The first test transmitted high-fidelity music having a bandwidth from 30 Hz to 15 kHz to a distance of 3.9 km. A phasing single-sideband generator, combined with a 60 kHz carrier to the 0.9 m projector, was used to shift the baseband music to a lower sideband between 65 and 79.97 kHz. The difference frequency in the 5 to 19.97 kHz band was received and the music recovered. The quality was essentially the same as that of an FM broadcast.

The second test transmitted a slow-scan television signal over the same 3.9 km path. A scan converter generated a 256 line, 34 sec/frame format from the standard 525 line, 1/30 sec/frame input from the camera. Two band shifting operations, one to place the 1.2 to 2.3 kHz FM video band on a 10 kHz carrier and the other to place the resultant 11.2 to 12.3 band on a 60 kHz carrier, were performed. The 60 kHz carrier was reinserted and transmitted along with the 71.2 to 72.3 video information. The resulting difference frequency energy in the 11.2 to 12.3 kHz band was received on the second barge. The receiver then amplified, filtered, and shifted the hydrophone signal back to the original slow-scan band of 1.2 to 2.3 kHz.

Figure 16 shows the results of the test with the picture transmitted at the top and received below. The SNR was better than 20 dB and no picture quality degradation was observed. Notice, particularly, the absence of the *ghosts* that would exist if multipaths were present. Picture resolution and frame rate were limited in this test by the 1100 Hz bandwidth of the scan converter. The parametric source is capable of a much wider bandwidth (up to at least 15 kHz). In conjunction with an optimized converter, it could have transmitted picture information at a resolution-frame rate product approximately 10 times that discussed here.

From the foregoing experiments, it is evident that the parametric source offers important advantages over conventional communication sources. Aiming the narrow beam can present a problem in a mobile situation but, under some conditions, initial steering can be achieved by direction finding on a broadbeam transmission from one of the terminals.

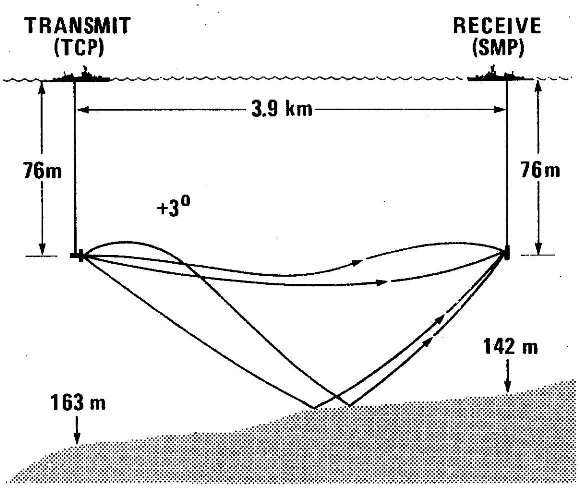

Figure 15. Seneca Lake Test Geometry

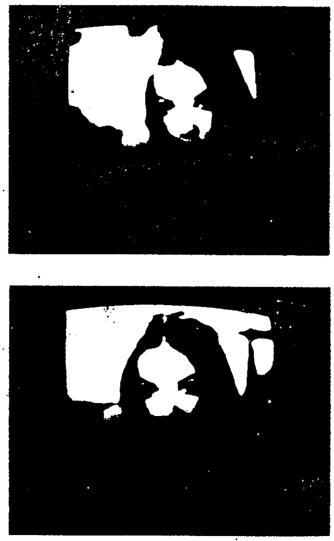

Figure 16. Parametric Underwater Television Transmission

IV. CONCLUSIONS

There is little doubt that the parametric underwater acoustic source can outperform conventional sources in some traditional applications. In a few cases, recognition of this fact has resulted in the development of equipment that exploits the technique. It seems, however, much more could have been made available, in the two decades since Westervelt's first paper. The cost of the parametric source for most potential applications is greater than for the conventional source but not significantly so, especially with the advent of economical transistor power amplifiers. Apparently, the good news concerning parametric source development has been, for the most part, confined to the scientific community. The scarcity of literature in application oriented publications supports this impression. Papers published in trade journals describing the performance of compact, well designed, operational equipment are needed to *spread the word.*

APPLICATIONS OF THE PARAMETRIC ACOUSTIC SOURCE

REFERENCES

1. Fourth Baron Rayleigh, *The Life of the Third Baron Rayleigh*, London, 1924, p. 136.

2. P. J. Westervelt, "Scattering of Sound by Sound," *J. Acoust. Soc. Am.*, 25, 199-203 (1957).

3. P. J. Westervelt, "Parametric Acoustic Array," *J. Acoust. Soc. Am.*, 35, 535-537 (1963).

4. J. L. S. Bellin and R. T. Beyer, "Experimental Investigation of an End-Fire Array," *J. Acoust. Soc. Am.*, 34, 1051-1054 (1962).

5. H.O. Berktay, "Possible Exploitation of Non-Linear Acoustics in Underwater Transmitting Applications," *J. Sound Vib.*, 2(4), 435-461 (1965).

6. H.O. Berktay, "Nonlinear Interaction of Two Sound Beams," J. Acoust. Soc. Am., 38, 480-481, (1965).

7. H.O. Berktay, "Some Proposals for Underwater Transmitting Applications of Non-Linear Acoustics," *J. Sound Vib.*, 6(2), 244-254 (1967).

8. D. G. Tucker, "The Exploitation of Non-Linearity in Underwater Acoustics," *J. Sound Vib.*, 2(4) 429-434 (1965).

9. T.G. Muir and J.E. Blue, "Experiments on the Acoustic Modulation of Large-Amplitude Waves," *J. Acoust. Soc. Am.*, 46, 227-232 (1969).

10. C. E. Green, "Polyalkylene Glycol as a Transducer Fluid." NUC TP 390, Naval Undersea Center, San Diego, CA 92132, May 1974.

11. C. E. Green, "An All Purpose Fluid for Filling Sonar Transducers," *Presented at the 93rd Meeting of the Acoust. Soc. Am.*, 6-10 June 1977.

12. C. M. Thompson, *The Use of Polyalkylene Glycol in Sonar Transducers*, Naval Research Laboratory Report 8283, 15 February 1979.

13. M. B. Moffett, "Cavitation Thresholds of Polyalkylene Glycol and of Castor Oil," NUSC Technical Memorandum No. 781148, 14 July 1978.

14. C. L. LeBlanc, R. W. Dunham, and T. D. Sullivan, *Dynamic Nonlinearities in Piezoelectric Sonar Ceramics*, NUSC Technical Report 5263, 27 December 1976.

15. J. Kritz, "Parametric Array Doppler Sonar," *IEEE J. Ocean Eng.*, OE-2(2), 190-200 (1977).

16. J. Jarzynski and L. Flax, "Penetration into a Sand Sediment of Difference Frequency Sound Generated by a Parametric Array," *J. Acoust. Soc. Am*, 63(5) 1365, May 1978.

17. C. W. Horton, *The Penetration of Highly Directional Acoustic Beams into a Sedimentary Bottom*, Applied Research Lab/U. of Texas. Austin Report ARL-TR-74-28, 16 July 1974.

18. W.L. Konrad, "Application of the Parametric Source to Bottom and Subbottom Profiling," Proceedings of the 1973 Symposium, Finite-Amplitude Wave Effects in Fluids, Copenhagen (1973).