NURC: CELEBRATING 50 YEARS OF
INTERNATIONAL PARTNERSHIPS IN
OCEAN RESEARCH AND OPERATIONS

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Thirty Years of TOWED ARRAYS at NURC

The NATO Undersea Research Centre (NURC), from its earliest history, has studied a very broad range of underwater acoustic phenomena and their application to surveillance, detection, oceanography and, more recently, port protection. The principal measurement device used to probe acoustic signatures in the ocean is the hydrophone: a transducer that converts pressure fluctuations in the water, caused by the propagation of an acoustic wave, into an electrical signal. In its simplest and most common form, the hydrophone is designed to respond directly to the pressure in the incident sound wave, which, as a scalar quantity, tends to give the hydrophone a receiving directivity characteristic that is omnidirectional (see Box 1). Single hydrophones have been used at NURC since the early 1960s for measurements aimed at investigating acoustic propagation and ocean ambient noise characterization.

THE FIRST HYDROPHONE ARRAYS AT NURC

One of the first NURC systems to exploit the desirable characteristics gained by grouping several omnidirectional elements into arrays (see Box 2) was the MEDUSA system (Mediterranean Experimental Deep Underwater Sonar Apparatus, 1965–1973), which comprised a cylindrical array of 32 staves with six hydrophones per stave (Figure 1). The MEDUSA, which can also be credited as the first active sonar system at NURC, employed a centrally mounted array of ring transducers as the active component.

THE FIRST TOWED ARRAY AT NURC

Interest in scientific studies related to mobile acoustic surveillance systems led to the introduction of the first towed hydrophone line array at NURC in 1978. The Hughes Aircraft Corporation built the experimental array for the US Office of Naval Research (ONR), which loaned it to NURC to evaluate its performance in the relatively shallow continental shelf regions. Table 1 outlines array characteristics.

The array was calibrated (Figure 2) and tested in the autumn of 1978. For the calibration measurements, the array was coiled into a cylindrical shape, and test signals were transmitted from the centrally mounted acoustic source. The conclusions of the subsequent publication (Cheston et al., 1979) emphasized the principal problem—that tow-ship

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BOX 1. OMNIDIRECTIONAL AND DIRECTIONAL SENSORS

Omnidirectionality (i.e., sensor response does not depend on the angle of incidence of the stimulus) of a pressure-sensitive hydrophone is achieved when its dimensions are smaller than the wavelength of interest. However, a hydrophone can also be designed to respond to an attribute of particle motion, for example, displacement, velocity, or acceleration. In addition, hydrophones can be designed to respond to a pressure gradient or even to acoustic intensity. Because particle motions, pressure gradients, and intensity are all vector quantities, sensors that measure these quantities possess intrinsic directivity, regardless of the frequency.

BOX 2. HYDROPHONE ARRAYS

A transducer sensing a scalar quantity (pressure in the case of a hydrophone) whose dimensions are much smaller than the wavelength of the stimulus will exhibit a response that is independent of the angle of incidence of the stimulus (Box 1). However, directionality can be of great benefit when, for instance, a weak signal emanating from a single direction must be discriminated in the presence of high-level background noise. The sensor's dimensions must therefore be increased (with respect to a wavelength) so as to render the sensor directional. For practical reasons, it is more straightforward to construct a line or array of small sensors whose outputs are summed to form the directional "beam." The towed array consists essentially of a line of hydrophones mounted inside a flexible hose. The array is towed behind the ship via a cable that provides an electrical path for the signals. The depth of the array can be adjusted by varying the length of tow cable paid out.

Figure 1. The MEDUSA system being deployed off the NURC vessel *Maria Paolina G.* in 1969.

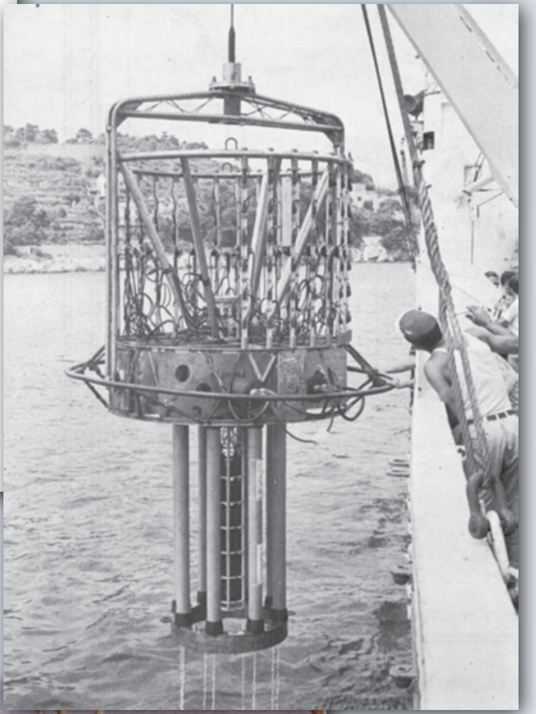

Table 1. Principal characteristics of the Office of Naval Research towed array

Number of channels	20
Hydrophones per channel	4
Channel spacing	1.1 m (λ/2 at 667 Hz)
Overall length (incl. VIMs)	40 m
Tow-cable length	1000 m
Tow-cable characteristics	16 twisted pairs
Sensors	1 depth sensor

Figure 2. Calibration of the US Office of Naval Research towed array in 1978.

noise is the ultimate limiting factor in detecting objects.

Some of the principal pros and cons of the towed-line array in comparison to a ship-hull-mounted array are:

Advantages

- Length (therefore directionality) independent of towing platform length (can be wound onto a drum)
- System (passive/active) can be positioned below surface layers/ thermocline, giving more favorable propagation conditions and hence higher probability of detection
- Array can be distanced from the towing platform by increasing the length of tow cable, thereby taking advantage of spherical spreading loss to reduce interference due to ship radiated noise
- Maintenance can be performed at the factory (no vessel down time)

Disadvantages

- Special handling equipment (large drum winches)
- Limited maneuverability of the towing vessel (speed, turn rate)
- Useful data only when the array is straight (data are lost during maneuvering)

Because acoustic surveillance studies (passive detection of submerged or surface vessels) require working with frequencies below 1 kHz (where most of a vessel's acoustic signature is concentrated), arrays providing fine angular resolutions for accurate bearing estimates will necessarily be too long to implement otherwise (see Box 3).

With towed-array research playing an ever-increasing role in NURC's scientific program, the idea of a quiet vessel equipped with the necessary handling equipment to deploy long towed arrays gradually took shape. This idea eventually led to the specifications for a new "acoustically quiet" research vessel to replace R/V *Maria Paolina G.* and, consequently, R/V *Alliance* came into service in 1988.

IMPORTANCE OF AMBIENT NOISE DIRECTIONALITY BECOMES APPARENT

The first sea trial in 1979 was done with an improved hydrophone array—the so-called "Prakla 128," named after the company that built it, Prakla-Seismos. The objective was to test a towed array's suitability as a mobile surveillance platform in the noisy shipping lanes of the Mediterranean. If the array behaved according to theory, low-noise regions between the interfering noise sources could be used to enhance detection capability.

To spatially discriminate and isolate sources of interference, the array should have both narrow major lobe (determined by the array length) and low sidelobe levels (determined by the array shading function, array stability, interchannel crosstalk, and other factors that deviate from ideal). Figure 3 shows a schematic diagram of the wet-end components of the Prakla 128 system, and Table 2 lists its principal characteristics.

The primary enhancements introduced by this array were:

- increased directivity index (see Box 4)
- light tow cable (allowing greater distances between towing vessel and array for a given depth of tow, thereby reducing ship-noise interference). The tow cable's behavior in uniform towing conditions is characterized by its "critical angle" (see Box 4).

BOX 3. HOW LONG SHOULD THE ARRAY BE?

Aperture half power beamwidth (for both electromagnetic and acoustic radiation) is given by:

$$\theta_{hp} = 51\frac{\lambda}{d} \text{ (degrees) and therefore: } \quad d = 51\frac{\lambda}{\theta_{hp}} \text{ (meters),}$$

where d is the length of the aperture or array, and λ is the wavelength. From this equation, assuming a desired angular resolution of 1°, the aperture or array must be 51 wavelengths long.

Example systems with a 1° beamwidth

System	Frequency	Wavelength (m)*	Array/Antenna Length (m)
X-band radar	10 GHz	0.030	1.53
Side-scan sonar	100 kHz	0.015	0.77
Towed array	1 kHz	1.500	76.50

* Note the velocity of propagation that governs λ is 3×10^8 m/s for electromagnetic waves in air and 1.5×10^3 m/s for acoustic waves in water.

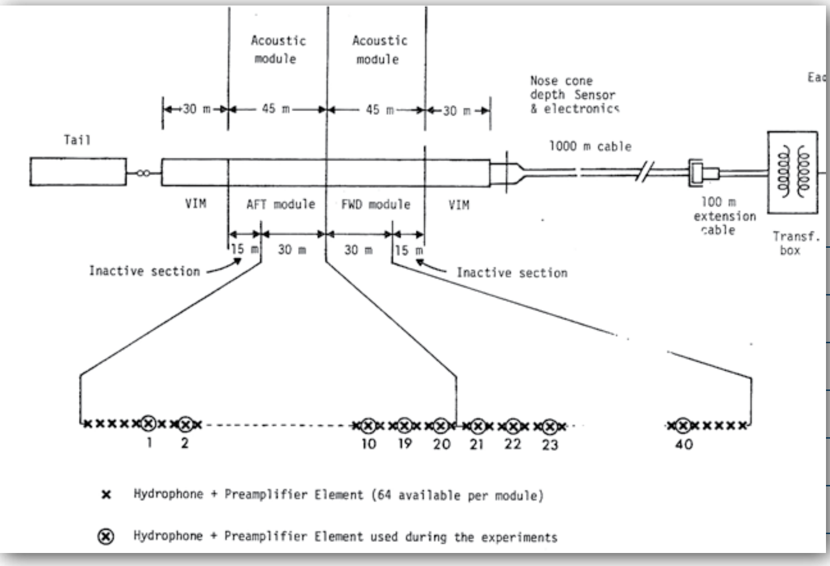

Figure 3. The Prakla 128 towed array.

Table 2. Principal characteristics of the Prakla 128 hydrophone array

Number of modules	2
Module length	45 m
Hose diameter	68 mm
Hydrophone channels/module	64
Hydrophone spacing	49 cm
Tow-cable length	1000 m
Tow-cable diameter	62 mm
Tow-cable in-water weight	0.3 kg/m
Tow-cable conductors	72 twisted pairs
Sensors	1 depth sensor

BOX 4: ARRAY ACRONYMS AND TERMS

Half power beamwidth (θ_{HP}): If the angular response of the array is normalized to unity at its peak value (the main response axis, or MRA), then θ_{HP} is the angular distance between the two points in the beam that has a value of half that of the MRA (in terms of intensity).

Beamforming: In the trivial case, the channels are summed together to form a beam that is perpendicular to the axis of the array. In the general case, the amplitudes and phases of individual channels are modified before summation to optimize the shape and steer the beam in any required direction.

Sidelobes of the beampattern: The local maxima that occur off the MRA but at lower amplitudes.

Directivity Index of an array: $DI = 10 \log_{10} \left[\frac{\text{power per unit solid angle received in the direction of the beam maximum}}{\text{average received power per unit solid angle}} \right]$

VIM (vibration isolation module): Acts as a shock absorber, attenuating effects of mechanical noise due to cable strum and ship motion.

Dehosing: The process of extracting the array from its protective hose.

Monostatic: A single ship is used for both transmission and detection.

Bistatic: Transmission and detection occur again on the same ship, but, in this case, a second receiver is towed by another ship. This configuration has (potentially) several advantages—most importantly, increased detection range from the source ship.

Critical angle of a tow cable: If a cable is towed with the wet end free, at a uniform speed, the resulting catenary is a straight line. The angle that the cable makes with the horizontal is its "critical angle" and is a function of towing speed, weight in water, and drag coefficient.

Unidirectional array: An array that does not suffer the left/right bearing ambiguity common to towed line arrays.

The measurements consisted of towing the array in a circular course. Suitable beamforming (see Box 4) of the hydrophone signals generated polar plots of the horizontal noise distribution and, as predicted, demonstrated significant directionality in the ocean ambient noise. One of the main problems encountered was the lack of a heading sensor in the array. Because the ship's course deviated significantly from the desired circle, array-bearing estimates were imprecise. A compass would have given a more consistent integration gain. The following year (1980), two depth gauges (fore and aft) plus a magnetic compass (fore) were added. The Prakla 128 array remained NURC's principal active/passive sonar receiver for the following decade, and was last deployed in 1989. Throughout that decade, it was used extensively on numerous sea trials.

NURC'S FIRST EXPERIMENTATION IN BISTATIC ACTIVE TOWED-ARRAY SONAR

The bistatic active sonar concept, in which another vessel with an auxiliary receiver is added to the principal source/receive ship, introduces several potential benefits, the most attractive being increased detection range. In parallel with the development and deployment of the Prakla 128 array, 1978 marked the beginning of the "BITOW" towed-array project. This towed array was built entirely at NURC and designed specifically to be used as an auxiliary receiver to investigate bistatic sonar techniques. The BITOW concept was significantly different from the Prakla 128 array in that the response was designed to be unidirectional (see Box 4). Standard line arrays are made up of a single line of omnidirectional hydrophone elements. Simply summing all the outputs forms a doughnut-shaped response pattern perpendicular to the axis of the array (a horizontal section shown by the red plot in Figure 12). Such an array generates the same output independent of whether the source is placed on the left or the right of the array; this configuration is the so-called "left/right bearing ambiguity." The BITOW array was designed to solve this issue by replacing the omnidirectional hydrophones with directional elements. In addition to the standard nonacoustic sensors (depth, heading), a unidirectional array must also have roll sensors to enable correct compensation of the single element directivity variation with roll angle. The BITOW array incorporated two roll sensors in its design.

Figure 4. The 93-m R/V *Alliance*, delivered to NURC in 1988, was designed to minimize ship noise in order to reduce interference with environmental measurements and acoustic experiments.

Figure 5. Detail of the two large-drum winches housing three separate towed arrays.

R/V ALLIANCE

In summer 1988, R/V *Alliance* (Figure 4) was brought into service, providing a significant enhancement to NURC's maritime capabilities. The most unusual aspect of R/V *Alliance* specifications was the stringent underwater radiated noise requirements. Extreme care was taken to decouple all sources of noise and vibration from the hull. For example, main propulsion and service generators were hard mounted to a sub base. The sub base was, in turn, resiliently mounted to a raft, which was resiliently mounted to the hull foundations. This mounting significantly reduced coupling of vibrations to the hull. Application of acoustic enclosures around all the generators reduced airborne noise coupling. Even this level of noise reduction was deemed insufficient for certain operations, and so a "quiet state" generator, supplying propulsion and service power, was integrated three decks above sea level to provide the optimal quiet towing platform. Towed-array handling equipment consisted of two large (2-m-diameter) drum winches, each with a pulling capacity of 20 tons (see Figure 5).

DEHOSING FACILITY

The ability to perform emergency maintenance on a towed array while at sea is an important asset and provides a major potential saving in ship time

Figure 6. Maintenance operation on a towed array after extraction from its protective hose using the onboard dehosing system (white steel pipe on deck).

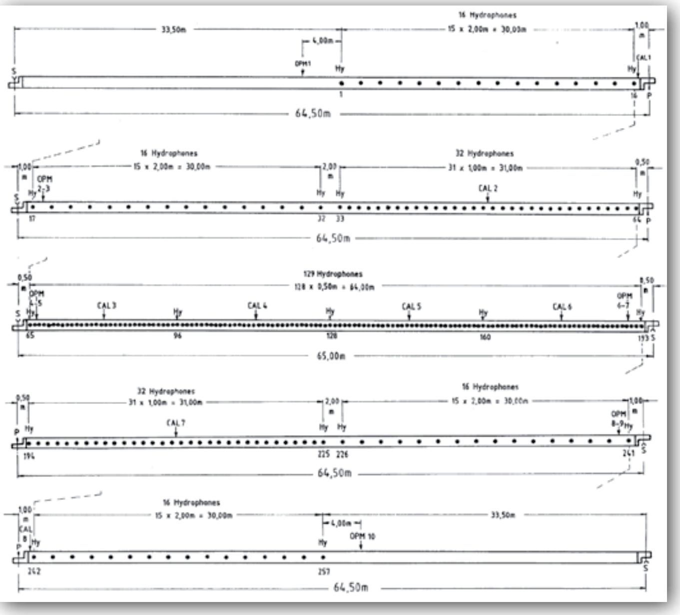

Figure 7. The hydrophone arrangement within the five modules making up the acoustic section of the Prakla 256 towed array.

in the event of an array malfunction. The need for such an at-sea capability is particularly true of NURC systems, which have always been experimental prototypes, with limited availability of spare sections. With the introduction of additional working spaces aboard R/V *Alliance*, it became feasible to install a fully functional array dehosing system on board. Extraction of the array from its protective polyurethane hose cannot be done under normal pressure because the friction on its internal walls is too high, and therefore a method of pressurizing is required. Figure 6 shows the 64-meter-length steel pipe implemented for this purpose on R/V *Alliance*.

MOVING BEYOND 64-ELEMENT ARRAYS—TOWED ARRAY WITH DIGITAL TELEMETRY

Although the Prakla 128 array consisted of 128 hydrophones, its tow cable contained only 72 pairs of conductors. Therefore, prior to deployment, the user would select 64 out of the 128 hydrophones available to transmit up the tow cable. The selection was implemented by using a small configuration module at the head of the array. Using a dedicated twisted pair of wires for each sensor in this way has a number of disadvantages:

- Interelement crosstalk: capacitive coupling of signals between wires increases with packing density and length of tow cable.
- Diameter of tow cable becomes impractical: increase in diameter increases the drag, therefore requiring a longer cable to achieve the same towing depth at a given speed.
- Connector complexity: cost increases with connector pin density. Reliability and ease of maintenance become compromised.

Because the bandwidth of hydrophone signals was typically of the order of a few kilohertz, and the bandwidth of the channel (tow cable) much greater, a towed array was clearly a prime candidate for the benefits afforded by a multiplexing scheme (multiple channels transmitted up a single cable pair). In 1986, the procurement of a 256-hydrophone towed array was initiated, via International Request for Quotation (RFQ) (Barbagelata, 1986). This RFQ marked the first steps toward NURC's implementation of a multiplexed towed array.

The system project was divided into the following tasks:

- RFQ for construction of the array modules, in which NURC supplied the hydrophones (bought from Seismic Engineering Company on a separate contract) and pre-amplifiers (designed and built at NURC)
- Initiation of an internal design/build of the digital multiplexer/telemetry module (named the High Speed Digital Link, or HSDL)
- RFQ for the procurement of the 1500-m-long tow cable
- Electromechanical termination of the tow cable

Figure 7 shows a schematic of the final configuration of this "Prakla 256" array (named after the contract was awarded to Prakla-Seismos of Germany). Table 3 lists the array's principal characteristics,

Table 3. Principal characteristics of the Prakla 256 hydrophone towed array

Number of hydrophones	256
Possible inter-element spacings	128 hydrophones at 0.5, 1, and 2 m
Overall length of acoustic section	254 m
Overall length of hosed section including telemetry and VIMs	423 m
Diameter of hose	90 mm
Nonacoustic sensors	2 depth, 2 heading
Tow-cable length, diameter	1500 m, 25.4 mm
Tow-cable electrical	Single co-ax
HSDL length/diameter	36 m/90 mm
HSDL analog signal conditioning	256 channels with programmable gain, bandpass filters
HSDL digital characteristics	Resolution:12 bit + gain Output serial data rate: 24.6 Mbit/s

Figure 8. Deployment of the Prakla 256 towed array from R/V *Alliance*.

and Figure 8 shows some images taken during deployment from R/V *Alliance*.

The complete Prakla 256 system made its cruise debut during an active-sonar trial in the Mediterranean Sea in June 1991 and was used extensively until its last deployment off the east coast of the United States in 2001. One of the outstanding collaborative achievements in which this array played a major role was the series of Shallow Water Active detection and Classification (SWAC) sea trials (Murdoch et al., 1995). These trials were conducted jointly with the Naval Undersea Warfare Centre (NUWC), New London, Connecticut. NUWC provided the low-frequency source, while NURC provided the towed arrays, source-handling equipment, and the ship R/V *Alliance*. Processing and display of array data were carried out in parallel by both teams. The SWAC sea trials commenced in 1994 and concluded in 1996 with participation in the NATO military exercise "Dynamic Mix." In addition to the NURC/NUWC partnership, the SWAC project relied heavily on the active participation of the Italian, Spanish, and Greek navies. Figure 9 is a schematic of the SWAC-trial towing configuration.

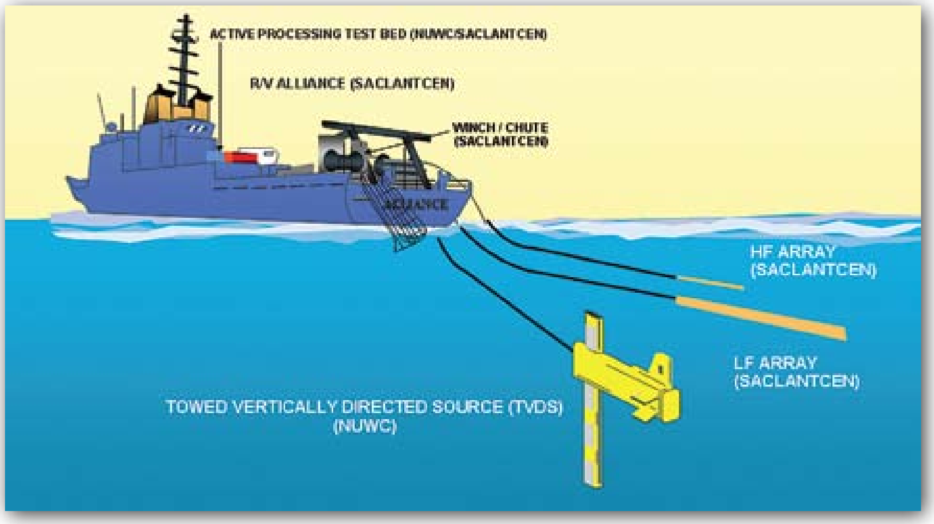

Figure 9. SWAC (Shallow Water Active detection and Classification) sea-trial systems configuration (from Murdoch et al., 1995). At the time, NURC was called SACLANTCEN.

TOWED ARRAY CALIBRATION IN THE LABORATORY ENVIRONMENT

The calibration technique shown in Figure 2 requires large expenditures and provides measurements of limited accuracy. To address this problem, in the mid

Figure 10. Laboratory line-array calibration system.

Table 4. Principal characteristics of the NURC Cardioid Array

Number of hydrophones	126 triplets (i.e., 378 hydrophones)
Possible intertriplet spacings	85 @ 21 cm, 84 @ 42 cm
Overall length of acoustic section	34.9 m
Overall length of hosed section, including VIMs	159 m
Diameter of hose	89 mm
Nonacoustic sensors	2 depth, 2 heading, 5 roll
Towable length, diameter	1200 m, 31 mm
Tow cable electrical	Copper pair (power), 2 multimode fibers (signals)
Analog signal conditioning	Fixed gain/filtering
Digitization	24-bit resolution
Telemetry	Data multiplexed onto a 12-node ATM network and converted to optical for transmission up tow cable

1980s, a laboratory-based towed array calibration system was set up at NURC, using a device (Zalesak and Trott, 1977) donated by the US Naval Research Laboratory. The system, shown in Figure 10, consists of a stainless steel pipe with three centrally mounted, flooded ring transducers. The two external transducers generate a standing acoustic wave inside the pipe, while the third (central) transducer measures acoustic pressure. By threading the array through the pipe and centering it on each hydrophone, the hydrophones' frequency responses can be measured. This system has been used to calibrate all NURC arrays (Troiano et al., 1995), and is still in use today.

UNIDIRECTIONAL ARRAYS REVISITED—THE NURC CARDIOID ARRAY

The shift in operational interest to littoral waters had already commenced in the 1990s. This shift provided new challenges to active sonar systems due to the highly reverberant nature of shallow-water environments. The greatly increased "clutter" experienced in these conditions is responsible for both an increase in false detections and a reduction in detection range. The strategy adopted at NURC in the new millennium to tackle these problems included:

- Broadband operation (requiring acquisition of a new sound source)
- Adaptive sub-band optimization (in which a broadband test pulse is transmitted and the results used to select a sub-band with optimal properties for the current environmental conditions)
- Multistatic operation (three or more platforms)
- Unidirectional towed array (to take advantage of the directional properties of the clutter, thereby allowing optimization of detection in a particular direction)

The last of the items in the bullets, and NURC's most recent major towed array system, is the Cardioid Array. An international RFQ (Barbagelata et al., 1997) for this array was issued in late 1997. The contract was awarded to J&S Marine (UK) in July of the following year. Table 4 lists the array's principal characteristics.

The Cardiod Array incorporated many technological advances that had taken place over the previous decade:

- Miniaturized and low-power analog and digital integrated circuits allowed the digitization and multiplexing of the hydrophone signal to take place close to the sensor itself. In this way, the telemetry system becomes distributed within the array itself, and thus no longer requires its own module. This approach greatly simplifies wiring and reduces connector pin-out requirements.
- Availability of large dynamic range (24-bit) ΔΣ analog-to-digital convert-

ers removed the requirement of variable gain/filtering and anti-alias filtering.

- Industry standard networking protocol (ATM) used in the telecommunications industry allowed use of standard off-the-shelf components for implementation and testing of the telemetry system.
- The high data rate produced by such a large number of sensors sampled at a relatively high bandwidth could easily be transmitted through the tow cable's optical fibers at an acceptable error rate, again using off-the-shelf components.

CLUSTERING OF HYDROPHONES INTO TRIPLETS

Figure 11a shows arrangement of the Cardioid Array hydrophones into triplets, while Figure 11b shows the actual physical arrangement. The unidirectional properties of the Cardioid Array are obtained by a two-stage process. First, the correct combination of a hydrophone triplet produces a steerable cardioid beam pattern (Figure 12a, blue line). Second, the sum of all the triplet cardioids forms the unidirectional beam (Figure 12b, green line). Figure 12 also shows how the ambiguous (left/right) beam from a classical line array (red line) becomes unambiguous when combined with the cardioid response.

The Cardioid Array has been a key component of sonar trials at NURC since 2001, having been used in approximately a dozen scientific experiments; Peter Nielsen and Christopher Harrison, both at NURC, have a paper on these data in progress. The majority of the trials are the result of joint projects with research institutes from other NATO nations, in particular, Defense Research and Development Canada, Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik (FWG) of Germany, the Netherlands Organization for Applied Scientific Research (TNO), and, in the United States, the Applied Research Laboratory at Pennsylvania State University, the Naval Research Laboratory, and NUWC.

WORK IN PROGRESS

Current interest in networked underwater sensors using autonomous underwater vehicles (AUVs) provided the incentive to develop special lightweight, small-diameter towed arrays for these vehicles. NURC is currently testing an internally designed and built slim-line towed array (SLITA) for its *Ocean Explorer* (OEX) AUV (see Figure 13). Table 5 lists specifications (from Biagini et al., 2007). The current tow-cable length is 42 m, but the actual length paid out can be less, depending on requirements by coiling any spare inside the payload section. Figure 14 is a photograph of the array taken during trials in January 2008.

CONCLUSIONS

Towed arrays have played an essential role in the scientific research conducted at NURC over the past 30 years. They have inspired innovation and the application of new technology, developing from simple analog arrays with a handful of sensors to digital systems

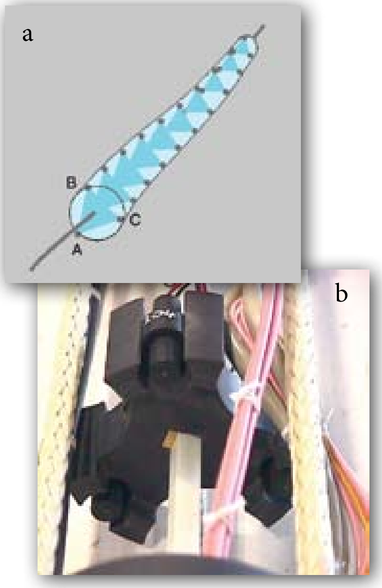

Figure 11. (a) Schematic of Cardioid Array hydrophone arrangement into triplets. (b) Hydrophones mounted on a triangular plastic spacer.

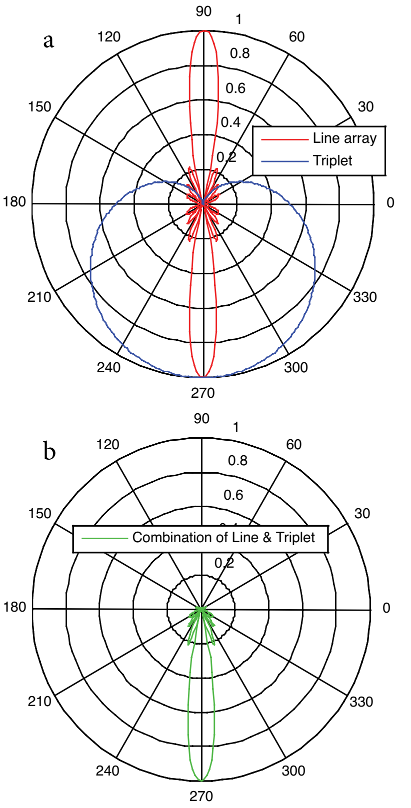

Figure 12. (a) Ambiguous beam of a classical line array (red) and a cardioid beam of a single triplet (blue). (b) Combination of classical line array and cardioid, resulting in a unidirectional beam.

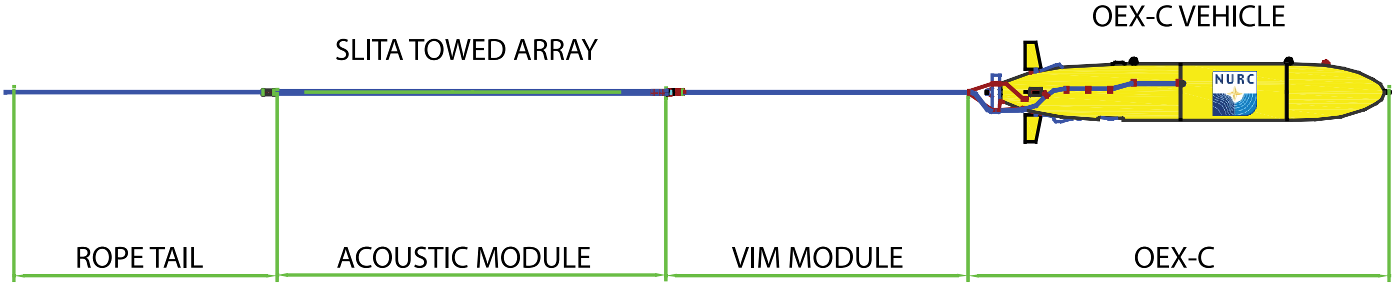

Figure 13. Schematic of the Slim Line Towed Array (SLITA) towed from the *Ocean Explorer* (OEX) AUV.

with may hundreds of hydrophones and broad dynamic range. The continual evolution of towed arrays to keep pace with changing operational requirements has required significant investment by NURC. This investment has benefited many NATO nations in the form of joint research projects, which provide cost-effective alternatives to internally funded research by providing access to NURC ships, equipment, engineering know-how, and scientific expertise that would otherwise be inaccessible.

Table 5. AUV Towed Array (SLITA) Specifications

PAYLOAD PROCESSOR	
Digitization	24-bit
Sample frequency	Up to 200 kHz/Channel
TOW CABLE	
Type	37 STP
Strain member	Kevlar
Outer diameter	16.6 mm
Cable length	42 m
VIM SECTION	
Outer diameter (OD)	30 mm
No-load length	7.5 m
Fully extended length	9.2 m
ACOUSTIC SECTION	
Acoustic module OD	30 mm
Acoustic module length	15 m
Weight in air	8.3 kg
Hydrophones per octave	32
Upper octave spacing	21 cm
Lower octave spacing	42 cm
Depth gauge type	Kulite ETM-345FE-375
Hydrophone	*Benthos* AQ4
Sensitivity	-201 dB re 1V/µPa
Pre-amplifier gain	+32.8 dB
Lower −3 dB roll off	70 Hz

Figure 14. SLITA array coiled on the R/V *Alliance* deck prior to deployment in January 2008.

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