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TECHNOLOGY EVOLUTION AND ADVANCES IN FISHERIES ACOUSTICS

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Key words: sonar, fisheries acoustics, echosounders, technology.

ABSTRACT

Application of sonar technology to fisheries acoustics has made significant advances over recent decades. The echosounder systems evolved from the simple analog single-beam and single-frequency systems to more sophisticated digital multi-beam and multi-frequency systems. In this paper, a brief review of major technological advances in fisheries acoustics is given, as well as examples of their applications.

I. INTRODUCTION

Use of active sonar (*so*und *na*vigation and *r*anging) as a primary tool to explore oceans has many advantages compared to conventional biological sampling, such as trawls and nets. First, underwater sound propagates at about 1500 m/s and can travel a much larger distance, making it possible to sample a much larger volume in a relatively shorter period of time. Secondly, acoustic measurements are remote, less invasive, and non-extractive. Thirdly, it can provide higher spatial resolution in both horizontal and vertical (or range for down-looking echosounders) directions. In this paper, a review of several major technical advances in fisheries and zooplankton acoustics is given. In Section II, the significant advances in sonar technology are described and the corresponding capability of acoustic characterization and classification is provided. Other technologies, including those currently used and expected to be used in the future, are also described briefly in Section III. Finally, summaries are given in Section IV.

II. TECHNOLOGICAL EVOLUTION

A timeline involving major technology milestones in fisheries acoustics is illustrated in Fig. 1, where the years corresponding to the milestone events are approximate. These events will be described accordingly in this section. More detailed information regarding some of these events have been provided elsewhere [15, 67].

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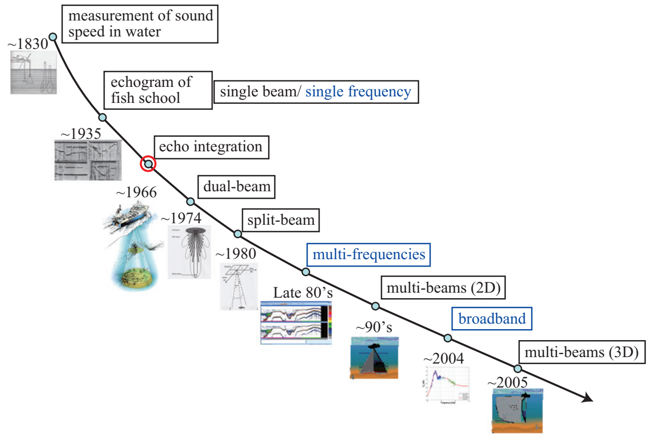

Fig. 1. Chronological events that mark the milestones of acoustic technology advances in fisheries acoustics.

1. Application in Early Days (before WWII)

The earliest measurement of sound speed in water was performed almost two hundred years ago in Lake Geneva, Switzerland and reported by Colladon and Strum [18]. The sound speed in water was estimated to be about 1435 m/s. About a hundred years later, use of echo as a sounding technology to measure the bottom depth was reported in 1920's [1]. As early as in the late 20's to early 30's of the 20th century, many publications reported the applications of active sonar technology in fisheries research for the detection of fish and zooplankton aggregations [44, 49, 63, 76]. After WWII, rapid advances in techniques helped the application of sonar to fisheries acoustics significantly. The discovery of the deep scattering layer (DSL.) resulting from echoes from various marine organisms provided a fresh vision of the oceans [6, 10, 38, 45]. Acoustic surveys in fishery applications became realistic starting in the early 1940's [77], and were conducted more frequently and routinely afterwards [3, 7, 20]. During this period, the sonar systems were simple and primitive, and primarily consisted of a single beam (channel) with a single narrow band frequency, a simple pulse-echo system. The outputs were analog and the standard outputs were graphs plotted on paper [2, 76]. All of the efforts during this period of time that involved using acoustic instruments for fisheries survey were not quantitative. However, echo counting ability of the system enabled some degree of quantitative measurements when the fish school is shallow and dispersed [7].

2. Echo-Integration Technology

In the late 1960's, as the revolution in computer science started to impact almost every branch of science, technology and our daily life, digital technology began to be applied to oceanographic instruments [46, 65]. The digital technology allowed scientists to apply more sophisticated signal processing techniques to post-process the recorded raw echo data. One of the most important milestones in terms of data processing was the introduction of the echo-integration technique [66], which takes advantages of randomness of the scattering targets. It was used successfully in many survey cruises in the late 60's and in 70's to count fish [58], to estimate fish abundance [4, 37], or to estimate the variance of the echo-integration technology [9]. Echo-integration is essentially an integration of echo intensity over a specified range (time) window. The received intensity can be expressed as:

$$\bar{I}_r(r) = \frac{1}{V_{ins}\rho_w c_w}\left\langle \int_{V_{ins}} \sum_k \sum_{k'} p_r(\vec{r}_k) p_r^*(\vec{r}_{k'}) dV \right\rangle$$

$$= \frac{1}{V_{ins}\rho_w c_w} \iiint_{V_{ins}} \sum_k \sum_{k'} \left\langle p_r(\vec{r}_k) p_r^*(\vec{r}_{k'}) \right\rangle r^2 \sin\theta \, d\theta \, d\phi \, dr$$

$$= \frac{1}{V_{ins}\rho_w c_w} \iiint_{V_{ins}} \left(\underbrace{\sum_k \left\langle |p_r(\vec{r}_k)|^2 \right\rangle}_{incoherent} + \underbrace{\sum_k \sum_{k' \neq k} \left\langle p_r(\vec{r}_k) p_r^*(\vec{r}_{k'}) \right\rangle}_{coherent} \right) r^2 \sin\theta \, d\theta \, d\phi \, dr \quad (1)$$

where $p_r(\vec{r}_k)$ is the received acoustic pressure (complex value) of the k^{th} target at range $\vec{r}_k$ within the insonified sample volume V_{ins}, ρ_w and c_w are density of and sound speed in seawater, respectively, and (r, θ, ϕ) are the position variables in spherical coordinates. If we assume the targets are randomly distributed in the sample volume (assume a stochastic process), the *coherent component* (the second term in the parenthesis) is considerably smaller than the *incoherent component* (the first term in the parenthesis), hence can be ignored. This is especially true for high frequency echosounder systems ($kd >> 1$, where k is the acoustic wave length and d is the average separation between adjacent fish within the fish aggregation). This is the essence of *echo-integration*. The incoherent component is a linear combination of the backscattering energy from individual targets, manifesting the well known *linearity principle* in echo-integration [29]:

$$\bar{I}_r(r) \propto n(r)\bar{\sigma}_{bs}(r), \quad (2)$$

where $\bar{\sigma}_{bs}$ is the average differential backscattering cross section at range r and $n(r)$ is the number of scatterers within the specified sample range [$r - \Delta/2$ $r + \Delta/2$], where Δ is the distance spanned by the transmit pulse duration. Since $\bar{\sigma}_{bs}$ can be determined either *ex situ*, where the animals were either tethered or caged [61, 70, 71], or *in situ*, where we need to know the precise information on target position, which requires better technologies to locate the targets, we can estimate the abundance of the targets, $n(r)$, at different ranges.

A quantity that is used extensively in fisheries acoustics, as well as in other sonar applications, is the target strength, defined as the equivalence of the differential backscattering cross section compared with 1 m^2 [16, 83]:

$$TS = 10\log_{10}\sigma_{bs} \quad \text{re } 1 \text{ m}^2 \quad (3)$$

The echo-integration technology was a major milestone in transforming the qualitative acoustic fisheries application in early days to the modern quantitative fisheries acoustic surveys as indicated in Fig. 1 (red circle), i.e. from observing fish or zooplankton aggregations to estimating abundance/biomass of fish or zooplankton acoustically. It allows scientists to infer the biological quantities, such as abundance or biomass, from the acoustically measured quantities. To perform such a conversion correctly, we need to know the average differential backscattering cross section (σ_{bs}), or target strength (TS) of fish species of interest. This requirement motivated scientists and engineers to develop new technologies for fish target strength measurements.

3. Acoustic Systems with Multiple Beams

To obtain accurate target strength measurements, either for acoustic system calibration or for directly estimating the target strength of animals of interest, we need to know the exact location of the animal within the beam since the echo amplitude of any target within the acoustically insonified volume is a function of the target position in the beam. A number of acoustic sensing technologies, such as dual-, split-, and multi-beam, have been developed to measure target strength from individual targets and some other acoustic quantities (volume backscattering strength, nautical area scattering coefficient, etc.). These technologies differ from those using echo statistics to infer the target strength indirectly [19, 28, 35].

1) Dual-Beam Systems

The dual-beam technique was one of the techniques introduced to fisheries acoustics in the early 1970's to estimate the polar-angle measured from the beam axis of an individual target within the acoustic beam [25], facilitating the measurement of target strength either *in situ* or *ex situ*. It takes advantage of the beampattern differences between two independent transducers, one with a wide beamwidth and the other with a narrow beamwidth [24, 25] (Fig. 2(a)). The ratio of the backscattering intensities of the echoes from the wide and narrow beam transducers is used to determine the polar-angle of a single target [67]. The dual-beam technology uses only

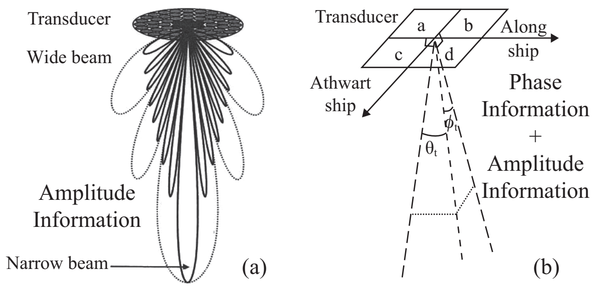

Fig. 2. Conceptual illustrations of (a) dual-beam and (b) split-beam acoustic systems. The drawings are taken from Simmonds and MacLennan [67] with permission.

the information of amplitude or intensity with no phase information, and it can determine only two of three parameters in the spherical coordinates, i.e. (r, θ) out of (r, θ, ϕ) (Fig. 2). For a circular transducer, the beampattern is independent of the azimuth angle, and hence two parameters (r, θ) are adequate for target strength measurement of any scattering object or target in the acoustic beam [78, 86].

2) Split-Beam Systems

A different technique, the split-beam technique was introduced to ocean acoustics soon after the dual-beam technology became reality [8], although its application to fisheries acoustics started somewhat later [26, 27, 32, 56]. In contrast to a dual-beam system, a split-beam system uses not only the amplitude information, but also the phase information. It uses a so called "interferometry" technique in which it takes advantage of the phase differences between adjacent transducer quadrants [56] (Fig. 2(b)). The phase difference is the function of the acoustic wavenumber (k), the distance between the "acoustic center of mass" of adjacent quadrants, and the angle of target relative to the acoustic beam axis of the transducer. All four quadrants function as transmitters and transmit simultaneously, while they receive the backscattered signals independently, forming four beams with two beams perpendicular to the other two. The target location can be uniquely and accurately (after careful calibration) determined [15, 67, 75, 84]. Through analysis of system performance as a function of signal-to-noise ratio and angular location of the target, Ehrenberg [26] found that the split-beam systems have a superior performance compared to the dual-beam systems. Currently, the split-beam technology is still a standard technique used in many commercial and scientific fisheries acoustic surveys worldwide, and this technology marks a major advance in acoustic technology (Fig. 1).

3) Multi-Beam Systems

Both dual-beam and split-beam systems can resolve only one target at each range increment. If there is more than one target present in the acoustic beam at the same range (time), echoes from different targets will add coherently. In such a case, neither a dual-beam nor a split-beam system can determine the angular locations of the targets correctly. Since echoes from different targets interfere with each other and produce a combined complex quantity (phase and amplitude), the estimated target location is similar to the geometric center of the insonified targets (i.e. the mean phase reflects the "center of mass"). However, in some cases, the inferred location could be outside of the region that bounds the involved targets. This phenomenon results from the so called "baseline decorrelation" [43, 55] or "coincidence echo" [30] when the phase is close to π (rad) or 180°. Multi-beam sonars, on the other hand, consist of multi-transducer elements and can resolve multiple targets at the same range simultaneously. Multi-beam sonars are based on the concept of applying coherent summation over all or a subset of array elements [15, 67, 83], and has been used widely in radar phase-array applications [47, 48, 64]. An N-element linear-array multi-beam can form N-1 independent beams in 2D, hence capable of resolving maximum of N-1 targets at the same range.

Although the application of multi-beam technology to fisheries acoustics began as early as in the late 70's [60], the technology became widely accepted in the 1990's when significant improvements occurred in both hardware and software technology [17, 31, 33, 34, 57, 59]. The number of applications of multi-beam sonars in fisheries acoustics have increased significantly since the Simrad ME70 echosounder and MS70 multi-beam sonar became commercially available [21, 22, 51, 52, 62, 79, 80]. There are two types of multi-beam systems: pseudo 3D and true 3D.

A pseudo 3D multi-beam system collects a true 2D image in the athwartship plane for each ping and then forms a 3D volumetric image by combining a series of pings along the ship track (Fig. 3). This type of echogram is not a true 3D image but if fish schools move at a much slower speed than that of the ship (~11 knots), as they usually do, the derived 3D images of fish school or aggregation will be reasonably representative and informative. Currently, most commercially available multi-beam systems are of this type, such as Simrad SM20 (formerly SM2000), Simrad ME70, and Reson SeaBat 7000 and 8000 series.

A true 3D multi-beam system is one that images a 3D volume with one ping, such as Simrad MS70, which has a total of 500 beams (25 × 20) as illustrated in Fig. 4 [52, 62]. A true 3D multi-beam sonar system like MS70 enables scientists to image the instantaneous shape of a fish school and track its change as a function of time, which can provide more accurate morphological information on the shape and size dynamics of fish schools or aggregations. Although this system is currently used, its application to actual acoustic survey still requires further research. However, the potential of such a system is enormous and we expect its full survey operation to become reality in the near future (Fig. 1).

4. Acoustic Systems with Multiple Frequencies

Concurrent with the advances in number of beams for sonar or echosounder systems, there has been a parallel development in terms of number of frequencies.

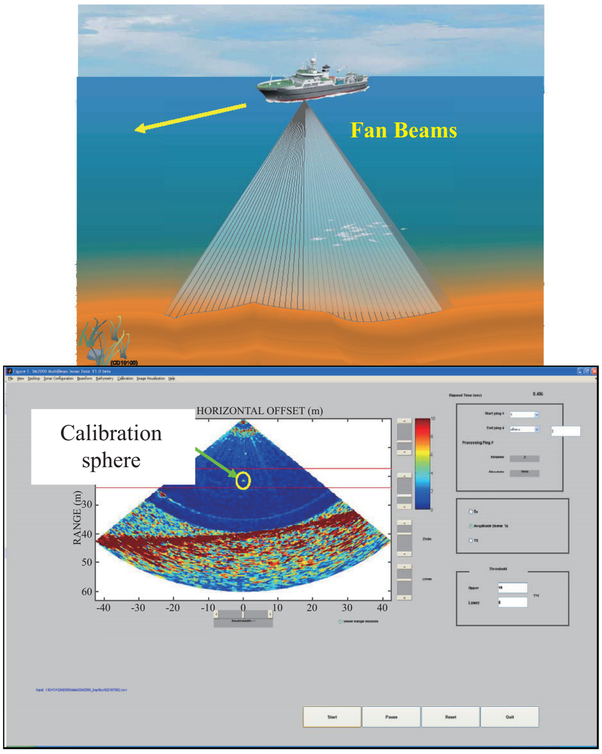

Fig. 3. Illustration of a 2D multi-beam echosunder, Simrad ME70 (top), and a Simrad SM20 image display of one ping during a calibration (bottom), where the calibration sphere is an aluminum sphere with a diameter of 38 mm.

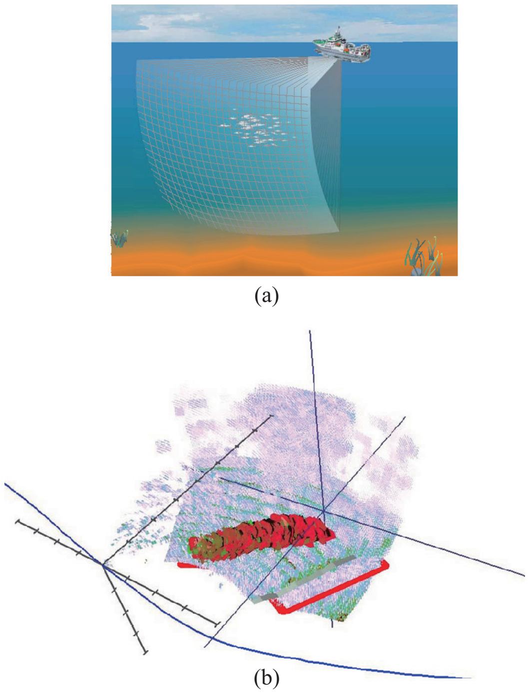

Fig. 4. (a) Illustration of a 3D multi-beam echosunder (Simrad MS70), (b) a herring school mapped by a single ping of the MS70 multi-beam sonar system (courtesy of Dr. Korneliussen).

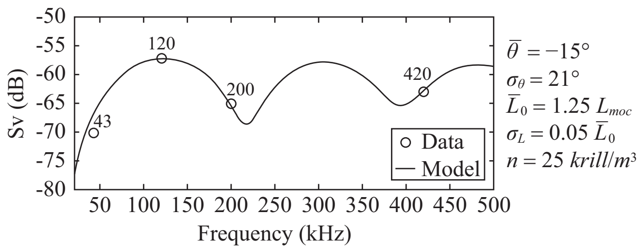

Fig. 5. Comparison of the acoustic backscattering data from Antarctic krill (*Euphausia superba*) recorded by BIOMAPER II [5] at 43-, 120-, 200-, and 420 kHz on a Southern Ocean GLOBEC cruise in Margerate Bay in 2002. The inverted parameters shown in the legend on the right are obtained with a nonlinear least-square inversion algorithm, where $\bar{\theta}$ and σ_θ are the mean and standard deviation of angle of orientation, L_{moc} is the mean body length of the krill in the aggregation from the MOCNESS sampling [87], $\bar{L}$ and σ_L are the inverted mean and standard deviation of krill body length, and n is the inverted abundance of the krill aggregation.

1) Multiple Discrete Frequency Systems

The strong frequency dependence of signals backscattered by marine animals has been a known phenomenon for many decades. Technology evolution from single frequency to (narrow band) multiple frequency systems (Fig. 1) provided scientists with additional capability to characterize or classify the scattering targets [12, 14, 39, 40, 41, 42].

Since both multi-frequency and multi-beam technologies have developed concurrently, the combination of two types of technologies is natural. For example, the BIOacoustic Sensing Platform And Relay (BIOSPAR) is a dual beam and dual frequency system constructed by the Woods Hole Oceanographic Institution (WHOI) with the acoustic components provided by BioSonics, Inc. [85]. This system has the shape of a spar buoy and carries two down-looking dual-beam transducers, operated at 120 kHz and 420 kHz, respectively. It can be deployed as either a moored or a drifting data acquisition system. This system was used successfully to measure the target strengths of more than 40 live individual zooplankton and microneckton [86].

Despite the success of the dual-beam/multi-frequency systems such as BIOSPAR, most hybrid multi-frequency and multi-beam echosounders currently used worldwide are those that integrate the split-beam and multi-frequency technologies. Acoustic survey ships, such as G. O. Sars, (IMR, Norway), NOAA ships Oscar Dyson, Miller Freeman, and Delaware II, are equipped with a number of split-beam echosounders at different frequencies, including all or a subset of 18-, 38-, 70-, 120-, 200-, and 333 kHz. Multi-frequency backscattering data can provide more information than a single frequency system [12, 41]), especially when the transition from Rayleigh scattering to geometric scattering is involved [16]. Fig. 5 shows a comparison between the data and the scattering model inferred from a four-frequency acoustic data set recorded with the BIOMAPER II [5]. The data are from Antarctic krill

(*Euphausia superba*) collected during a Southern Ocean GLOBEC cruise in 2002. The theoretical prediction (solid curve) is obtained using the parameters resulting from a nonlinear least-square inversion algorithm [53, 54]. The inverted parameters are given in the figure legend.

2) Broadband or Wideband Systems

If the multi-frequency systems described in the previous section cover a wide frequency band with a number of discrete frequencies, they can be regarded as broadband or wideband acoustic systems. However, in this paper, we refer to a broadband or wideband system as a system that contains a single transducer that can provide a frequency response of the acoustic scattering over a continuous broad frequency band [50, 73]. A continuous broadband system allows the study of the impulse response of the acoustic scattering by marine organisms directly [88], the spectral characterization of the scattering by marine animals from different anatomic groups [73, 74], and/or the temporal characterization of these groups using a pulse compression technique [13]. The pulse compression technology not only increases the time domain resolution, which is inversely proportional to the system bandwidth (Figs. 6(a) and 6(b)), but also improves the signal-to-noise ratio (SNR) by a factor of approximately $2BT$, where B is the bandwidth of the system and T is the pulse duration [82]. The results shown in Fig. 6 are from theoretical simulations. The transmit signal (Fig. 6(a)) is a chirp signal with frequency swept from 0 to 4000 kHz in 100 ms.

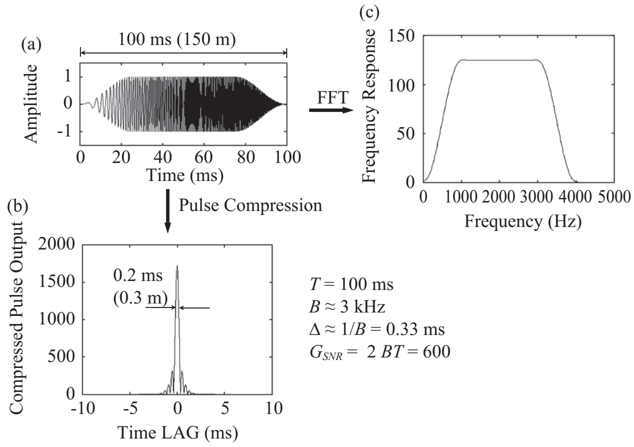

Fig. 6. An example of the acoustic characteristics of a broadband system. (a) a transmit chirp signal, sweeping from 0 to 4 kHz over a time window of 100 ms; (b) compressed pulse output; (c) corresponding frequency response of the time series in (a). The bandwidth (*B*) of the transmit signal is approximately 3 kHz, resulting in a compressed pulse output resolution of 0.33 ms resolution in the time domain and 0.5 m in the spatial domain, assuming a 1500 m/s sound speed. The gain in signal-to-noise can be determined by $G_{snr} \approx 2\,BT = 600$, or about 28 dB, where *T* is the pulse duration (100 ms). Units on the vertical axes of all three plots are linear quantities in arbitrary scale.

III. OTHER TECHNIQUES

In addition to the acoustic technologies described in Section II, there are others that have been used for different applications in fisheries acoustics

1. Sidescan Sonars

The side-scan sonar is a single-beam acoustic system normally mounted on a towed body with its beam axis perpendicular to the cruise track. The beamwidth is narrow in fore-aft direction (alongship), typically 1°, but much wide in the vertical plane (athwartship), typically 40° [67]. Unlike down-looking echosounders, sidescan sonars form a fan-beam for each ping and, by combining the successive ping, can provide 3D acoustic images of the water column on both sides of the vessel or towfish [68, 69]. There are two types of side-scan sonars: one uses amplitude information only, i.e., the backscattering as a function of time or range, and the other uses both phase and amplitude information, i.e., the interferometry technique that is also used for split-beam. It provides not only the backscattering as a function of time or range, but also the direction of arrival (DOA) of fish schools for water column imaging or bathymetry for seafloor mapping [75].

2. Scanning Sonars

Scanning sonars allow the sonar head to rotate mechanically in either 1D or 2D, providing either 2D or 3D images [67]. This type of acoustic instrument is normally a single-beam device and often used for fish school searching. Such systems have a highly directional pencil beam, capable of resolving small features such as small aggregations of fish and zooplankton, as well as individual targets depending on the range and the size of target. Since mechanical rotation requires more time, scanning sonars work best when targeted fish or zooplankton aggregations are “static”.

3. Acoustic Doppler Current Profiler (ADCP)

ADCPs are commonly used for mapping the currents in the oceans but can also be used for mapping fish or zooplankton schools, as long as the size of the fish school is much larger than the boundary of the four ADCP beams [23, 89]. This type of instruments consists of four down-looking beams, each having a tilt angle relative to the vertical direction. The phase differences between beams reflect the moving speed of the target of interest (fish, zooplankton, or current), an acoustic Doppler effect [23].

4. Acoustic Lens

Acoustic camera or acoustic lens refers to an acoustic system that utilizes a technique similar to that of optical cameras. It can be operated in dark or turbid water where optical cameras are unable to provide images with satisfactory quality. There are two important features for such systems. First, it has to be in the geometric scattering region, i.e. the physical size of the acoustic lens must be much greater than the acoustic wave length, so the ray theory can be applied. Second, it is a multi-beam system but its beamforming operation is performed automatically when the backscattered acoustic "rays" enter the acoustic lens. The acoustic lens uses a special fluid in which the sound speed is different from that in the surrounding water. The acoustic rays are refracted due to sound speed difference between two fluids and focused to an acoustic array, forming an acoustic "video" image for each ping. An "acoustic movie" can be obtained with a series of pings recorded continuously [67]. An example of this type of instrument is the Dual frequency IDentification SONars (DIDSON) system.

5. Parametric Sonars

Parametric sonars utilize the nonlinearity of the sonar system to extract the energy leaked from the quadratic component [36]. Although the efficiency of parametric sonars is low (could be less than 1%), they can provide very directional acoustic insonification at much lower frequencies compared to the physical dimension or aperture of the sonar head. Such a characteristic could be very useful for studying fish with swimbladders since swimbladders resonate acoustically at very low frequencies (1 kHz or lower). The advantage of measuring fish scattering at or near resonance frequencies is that the acoustic backscattering is almost independent of fish orientation, making estimates of abundance easier and more accurate.

IV. SUMAARY

In this paper, a summary of the evolution of sonar technologies used in fisheries acoustic is presented. Fig. 1 provides a chronological depiction of the advances in technology advances. The echo-integration technology played a key role for transforming qualitative acoustic measurements to quantitative measurements. At the same time, other technologies have resulted in significantly improving data quality in terms of resolution and information content and extraction.

It should be pointed out that there are many important scientific and engineering issues associated with the application of sonar techniques to the fisheries acoustics field that are not discussed in this paper, such as system calibration, error analysis, and operation engineering, but the major milestones in acoustic technologies have been addressed here.

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