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A tracking transducer for following fish movement in shallow water and at close range

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Abstract − Shallow water studies of fish behavior have used various methods for tracking fish. A new technique is shown to be promising because it can combine acoustic sizing with fish behavior studies. The principle of radar tracking, aligning the antenna beam with a target, was applied with an acoustic splitbeam transducer and dual-axis rotators for tracking individual fish over long periods of time. Deviation of the target from the beam axis produces a correction to point the axis toward the target. Initial studies with active acoustics have also evolved an acoustic tag tracking method. The system has successfully tracked several different types of fish, from juvenile salmon to sharks. The high speed of the rotators allows observations to be made at very short ranges. Much of the development of the tracking transducer targeted fish movement through dams on the Columbia and Snake Rivers. In a recent experiment, adult salmon, returning to the Fraser River, Canada were tracked to measure avoidance to surveying vessels. The feasibility for tracking sharks was shown at the Tacoma WA Point Defiance Aquarium. A proposed method for tracking salmon, sharks or other species with echoes and/or using acoustic tags will allow the determination of behavior, acoustic size, abundance, and associated pelagic assemblages. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

fish behavior / splitbeam / sonar / acoustic size

Résumé − Un transducteur acoustique permettant de suivre les déplacements des poissons en petits fonds et à petite échelle. Les études du comportement des poissons en petits fonds utilisent diverses méthodes pour effectuer le suivi des poissons. Une nouvelle technique semble prometteuse car elle combine les mesures acoustiques avec des études comportementales du poisson. Le principe du radar, alignant l'antenne avec la cible a été appliqué avec un transducteur et une platine orientable à deux axes pour effectuer le suivi du poisson sur de longues périodes. Les mouvements de la cible par rapport à l'axe du faisceau sont mesurés en temps réel et permettent de réorienter l'axe vers la cible. Les études initiales ont aussi mis en jeu une méthode de marquage acoustique. Le système a fonctionné avec succès avec divers types de poissons, des saumons juvéniles aux requins. La grande vitesse de rotation de la platine permet de faire des observations à très petites échelles. La plupart des développements des transducteurs ont eu pour objectif de suivre les mouvements des poissons au niveau des barrages des fleuves Columbia et Snake. Dans une expérience récente, des saumons adultes, retournant vers le fleuve Fraser, au Canada, ont été pistés pour mesurer l'évitement face aux bateaux effectuant le suivi. La faisabilité du suivi des requins a été montrée à l'Aquarium de Tacoma. Une méthode proposée pour pister les saumons, requins et autres espèces à partir des échos et /ou en utilisant des marques acoustiques permettra de déterminer les comportements, les mesures acoustiques, l'abondance et le comportement collectif des poissons pélagiques. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

comportement du poisson / sonar multifaisceau / mesures acoustiques

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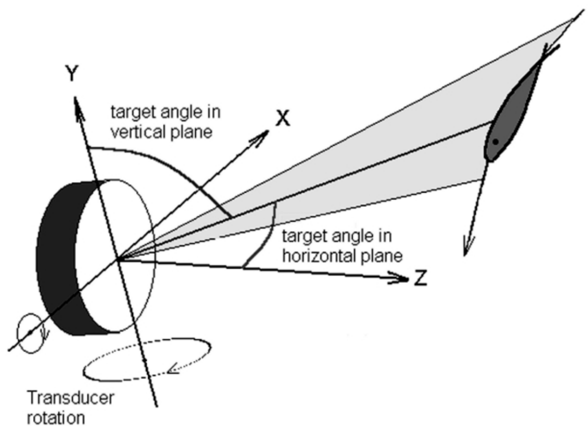

Figure 1. Fish tracking with a rotating splitbeam transducer. The vertical (γ) and horizontal (ψ) angles of the fish target are determined by a splitbeam transducer. Fish movement is monitored and transducer is rotated in order to follow fish movement.

1. INTRODUCTION

We first applied the principle of tracking radar in 1994, using a Simrad EY500 splitbeam echosounder aligning the transducer beam axis with a target by using dual-axis rotators to track individual fish over longer periods of time (*figure 1*). The present system uses a BioSonics DT6000 splitbeam sonar to identify an individual fish echo and to determine the three-dimensional position of a fish target with a transducer mounted on a high-speed dual-axis rotator. The split-beam sonar detects the deviation of the target from the transducer's beam axis and sends this information to a tracking computer. The tracking computer uses a predictive tracking algorithm to align the transducer axis to the target using high-speed motors of the dual-axis rotator. At the same time data regarding the fish position and movement, and Target Strength (TS, acoustic size of the fish) are recorded on hard disk. Individual fish tracks can be visualized using computer programs (e.g. AutoCAD or TecPlot). Fish tracks over 50 m have been obtained with this tracking system.

The tracking splitbeam transducer offered the possibility of providing intermediate track lengths and detailed behavioral information of individual fish in the near-dam forebay hydraulic environment. Tracking systems were first deployed at dams in Snake and Columbia Rivers in 1995, 1996, and 1997 (Hedgepeth et al., 1999). The objective of study at the dams was to monitor fish behavior and trajectories while they are approaching the dam and turbine intakes in order to gather data for designing a fish bypass system.

Tracks at Ice Harbor Dam, Snake River in 1995 showed that fish were drawn into the bypass sluiceway when it operated, and that the depth of fish, as they approached the dam, determined turbine entrainment. In 1996, at The Dalles Dam, Columbia River, the tracking transducer showed that fish trajectories were steeper into turbine intakes when occlusion plates were installed in front of the intakes. The study of fish behavior around spillway overflow weirs at John Day Dam, Columbia River in 1997, showed that as near-surface fish approached the weirs they sounded and attempted to move away from the spillway. In general, however, most fish tended to follow streamlines of flow, except later in the season when non-salmonid species were present.

Later tracking studies showed promise in other riverine applications. At Lower Granite Dam two systems were used in the receive mode to track acoustic tags (Johnson et al., 1998). A 1998 study on the Fraser River had the objective to determine if fish actively avoided a standard acoustic survey boat. The feasibility for tracking sharks was shown at the Tacoma WA Point Defiance Aquarium.

This paper documents the present state of the tracking methodology and suggests methods to track salmon, sharks, or other species both with echoes and by using acoustic tags. This methodology may help in the simultaneous assessment of fish sizing (and perhaps species identification), behavior, abundance, and associated pelagic assemblages.

2. METHODS

The tracking transducer was designed to follow fish at angular speeds of more than 90 degrees per second using ping rates of 10 pings per second. That ping rate in the active mode limits the range of data to about 75 m. The system description (*figures 1* and *2*) follows below.

The splitbeam transducer contains additional elements that are electrically divided into two orthogonal pairs. An acoustic wave front propagating towards the transducer arrives at different times at the pairs causing the phase angle of the electrical output signal from the pairs to differ. The vertical angle γ (relative to the transducer and orientation in *figure 1*) is determined from the electrical phase difference between the vertical transducer pair, and the horizontal angle ψ from the horizontal pair. These calculated angles are computer output, transferred via a serial port in the form of a telegram to a second computer. The telegram contains single-echo detections for one ping: range, time, signal strength, vertical angle γ (degrees), and horizontal angle ψ (degrees). The stepper motor control computer receives vertical and horizontal angle measurements and then programs the stepper motors to keep the main axis of the transducer beam aimed on the target, thereby tracking the target. *Figure 2* shows a slightly different architecture in motor angles in that one axis θ is contained inside the other ϕ. Thus the new stepper motor angles θ' and ϕ' required to follow

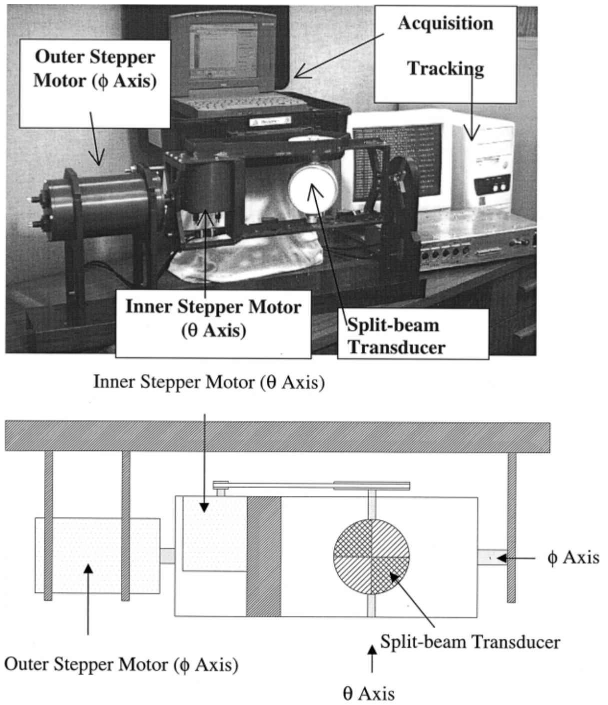

Figure 2. Photo and diagram of the implementation of a rotating splitbeam transducer for tracking fish. The angles of the fish position from a splitbeam transducer are used to determine new transducer angles towards the target. Motors turn the transducer to follow the fish movement.

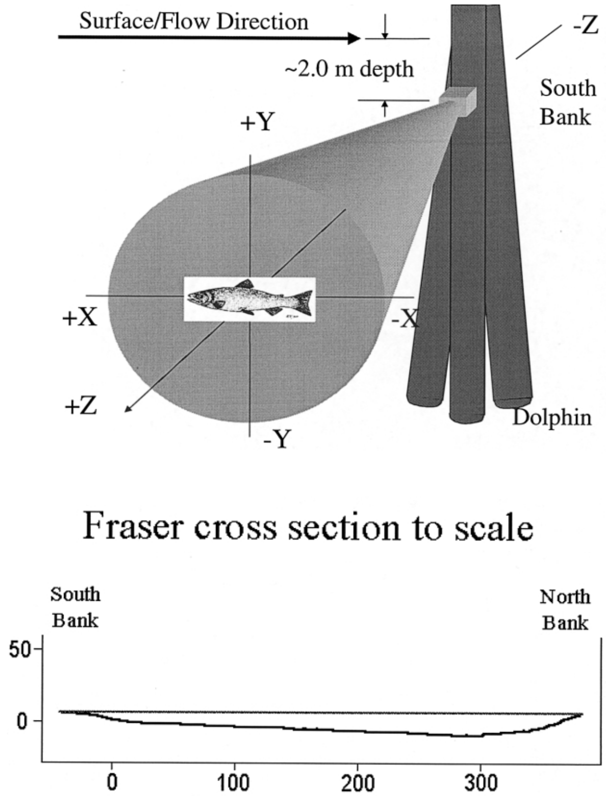

Figure 3. Cross section of the Fraser River near Mission, BC, Canada. Scales are indicated in meters. At the top is the deployment of the active tracking transducer (at position 0, South Bank).

the fish using the present stepper motor angles θ and ϕ are somewhat complicated by this architecture:

$$\theta' = \sin^{-1}\left(\cos\theta\sin\psi + \sin\theta\sqrt{1-\sin^2\gamma-\sin^2\psi}\right) \quad (1)$$

$$\phi' = \tan^{-1}\left(\frac{-\sin\theta\sin\phi\sin\psi + \cos\phi\sin\gamma + \cos\theta\sin\phi\sqrt{1-\sin^2\gamma-\sin^2\psi}}{-\sin\theta\cos\phi\sin\psi - \sin\phi\sin\gamma + \cos\theta\cos\phi\sqrt{1-\sin^2\gamma-\sin^2\psi}}\right)$$

Cartesian coordinates of the fish (x, y and z) are estimated using range and angles. A predictive algorithm is added to the rotator control program. The algorithm predicts incremental movement of Δx, Δy and Δz using a weighted history of the last five positions which weights the recent increments more (1, 0.5, 0.25, 0.125). If echoes were used to track fish, only a single transducer is required to estimate range. Tracking tags for positions required two systems, and one system for direction finding.

3. RESULTS

An example of fish tracked by the tracking transducer system was from a study conducted on the Fraser River in summer 1998, near Mission, British Columbia. A mud/silt bottom characterized the site, which was somewhat sound absorbent. There was mild tidal influence, up to one meter at lower water levels near season's end. Flows had stronger currents on the north bank. *Figure 3* shows a cross-sectional and three-dimensional view of the study site. A stationary barge was tied to the shore side of a dolphin, at the south bank, and the active splitbeam was attached outside, 2 m below surface.

Figure 4 shows an example of echoes from active tracking of three upstream-migrating salmon. The ping rate was about 8 pings·s^{-1} over 4 min (1 900 pings) of data shown. Fish were tracked for about 1 min each moving upstream at about 0.75 m·s^{-1}. *Figure 5* shows projections of another fish tracked late in the season, exhibiting the largest target strength nearly perpendicular to the beam, and with a speed of 0.8 m·s^{-1}.

A second nearby stationary splitbeam system showed possible positional biases that had the effect of rotating the fish trajectory away from the shore, and reduced the apparent fish velocities. The active track-

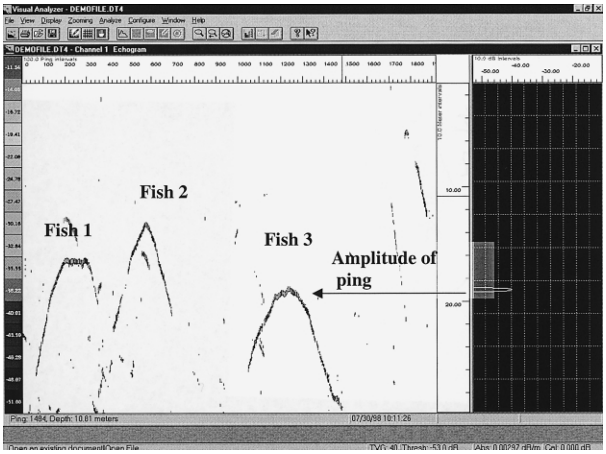

Figure 4. Example of echoes from the active tracking of three upstream migrating salmon in the Fraser River near Mission, BC, Canada, 30 July 1998. The ping rate is about 8 pings·s^{-1} over the 4 min (1 900 pings) of data shown above. Fish 3 was tracked for nearly 1 min moving at about 0.75 m·s^{-1}. The color scale represents the echo intensity (red strongest).

ing system should measure the angle and fish speed with reduced bias because the fish target is mainly on the beam's axis.

In 1997, at John Day Dam on the Columbia River, overflow weirs were placed into spillways 18 and 19 as an experiment to attract fish to the surface flows at the spillways and to hopefully guide them against entering turbines. Two BioSonics 430 kHz DT6000 six-degree beam (full beamwidth at half power) split-beam systems were used for the tracking systems to determine travel routes and velocities of the fish within roughly 15 m of the spillway weirs. The tracking systems were lowered about 18 m below the surface, resting on the spillway ogee below anticipated fish passage routes.

Figure 6 shows fish vectors tracked during the spring study in front of spillbay 18. The velocity vectors, $\bar{V}_{apparent}$, were estimated as the change in position divided by the change in time, shown in *figure 6a*. $\bar{V}_{apparent}$ is the sum of the water velocity, $\bar{V}_{water}$, and the 'real' fish vector (i.e. fish effort vector), $\bar{V}_{effort}$. The fish effort vector can be estimated as:

$$\bar{V}_{effort} = \bar{V}_{apparent} - \bar{V}_{water} \quad (2)$$

The water velocity was measured at various stations in a physical model the John Day Dam. These measurements were extrapolated to estimate the water velocity vector at a particular fish position in a three-dimensional space. *Figure 6b* shows fish effort vectors at spillbay 18, away from the dam and downward in response to the surface flow generated by the placement of overflow weirs. Fish, in deeper water with weirs installed, made little effort to avoid the spillbay. However, fish at all depths appeared to make an effort to move upstream from the dam when the weirs were absent.

During 1997, BioSonics provided the tracking component of the Behavior Acoustic Tracking System (BATS) project to look at pinging acoustic tags attached to rainbow trout in the forebay of Lower Granite Dam on the Snake River (Johnson et al. 1998).

The tracking equipment consisted of two BioSonics 201-kHz six-degree (half power full beam) tracking

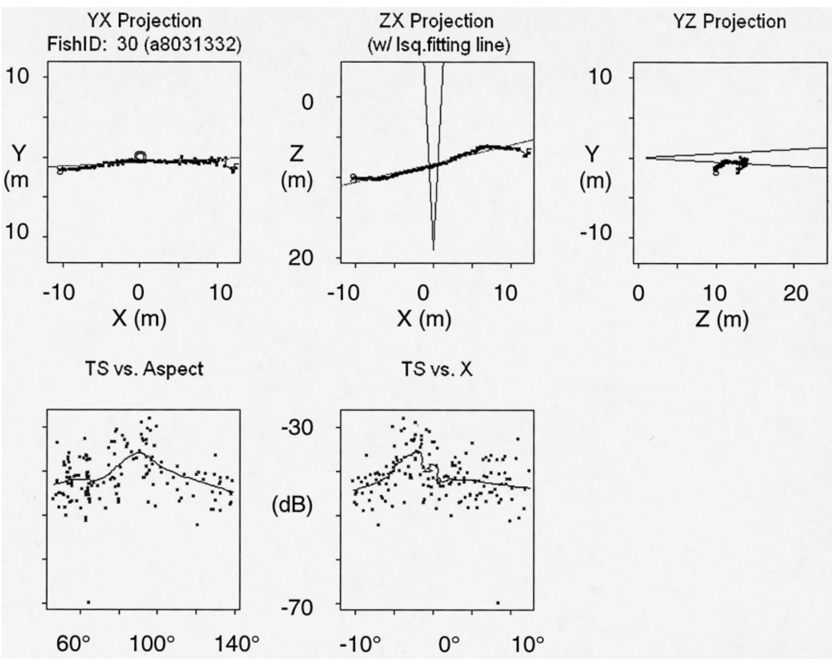

Figure 5. Projections from fish in the Fraser River tracked by the active tracking transducer. Refer to *figure 3* for the coordinate system (X: along river, Y: up/down, and Z: across river). The fish was tracked traveling upstream at 0.82 m·s^{-1} for 25 m. The target strength (TS) is highest at right angles to the fish. Statistics: X–speed = 0.82 m·s^{-1}; mean TS = –40.9 dB; Y/X, Z/X slopes = 2.4°, 13.3; total pings = 191; total X = 22.79 m; total Y = 0.26 m; total Z = 3.25 m.

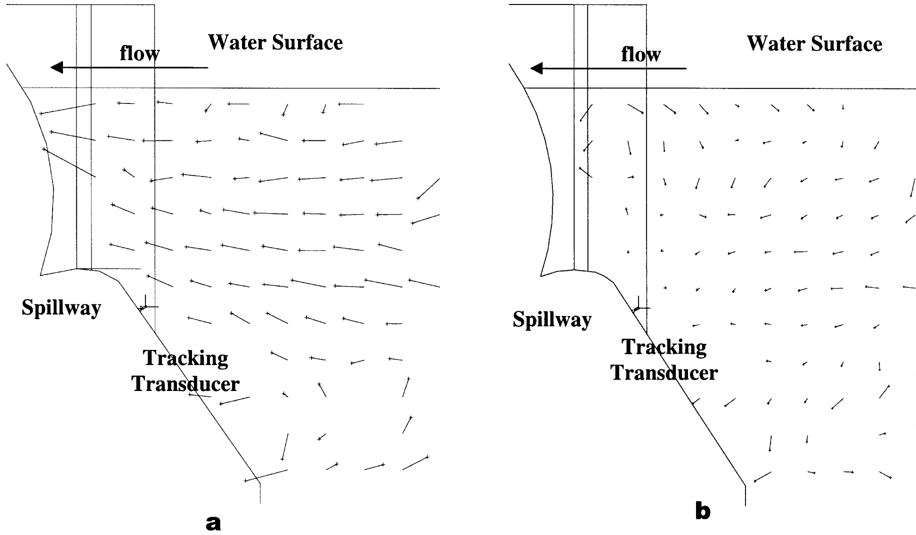

Figure 6. Side view of average fish velocities in 3 m × 3 m blocks at Spillbays 18 and 19 for the 1997 spring period at John Dam spillway. Fish effort was estimated as the difference between the tracked apparent fish velocity and water velocity. Apparent fish velocities are shown in (a) and estimated fish effort velocities in (b), overflow weir installed. The angle shows the position of the tracking transducer with 1-m lines. Velocities are indicated in m·s^{-1} with one fourth the same reference dimension.

transducer systems placed 12.2 m apart and 3.0 m below the water surface. A 6-mm diameter 125-dB re µPa 200-kHz tag emitted a 1 ms-long pulse every 100 ms, or ten times each second. A primary system acquired the acoustic tag, and a secondary system scanned along the primary bearing until it located and centered on the tag (*figure 7*). The tag was followed by both systems using equation (1). The tag positions were then estimated by interpolated triangulation. Serial communications ports, in order to synchronize movements and to pass information about the tag position, linked the primary and secondary motor control computers. Typical *x, y* and *z* temporal positions from the tracked tag appear in *figure 8*.

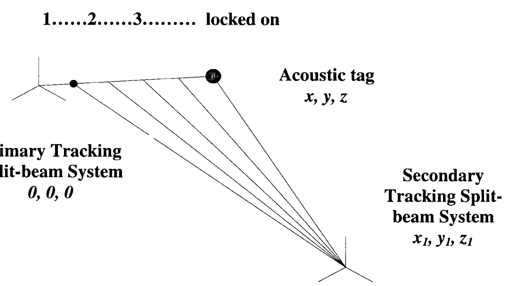

Figure 7. Once the acoustic tag is acquired by the primary system, the secondary system scans along the primary bearing until it locates and centers on the tag. The tag position is then estimated by interpolated triangulation.

4. DISCUSSION

The tracking system combines the advances made in active and passive radar-type tracking in an instrumentation package which has primarily been used in a fixed (as opposed to mobile) deployment. The high-speed of the rotators allows observations to be made at very short ranges. The inspiration for the initial tracking-transducer system arose after acoustic transect studies made in the shallow water of the Gulf of Nicoya, Costa Rica, whose initial goal was to assess larger commercially important fish (Hedgepeth 1994; Hedgepeth et al. 1996). That study was restricted by the fixed deployment of the transducer on the boat and by the single-beam nature of the transducer. If a system could scan more of the water, especially near optimal and essential fish habitat, a better assessment could be made. By locking onto targets and tracking them for relatively long time periods, large fish could be discriminated from the overwhelming amount of engraulids and clupeids in the shallow water embayment.

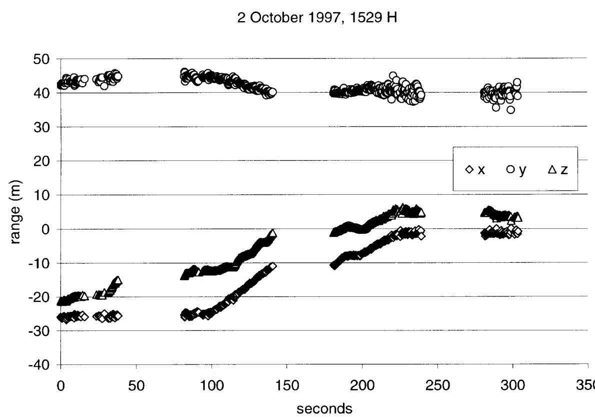

Figure 8. Example of positional estimates of a 200-kHz acoustic tag tracked by primary and secondary tracking transducers.

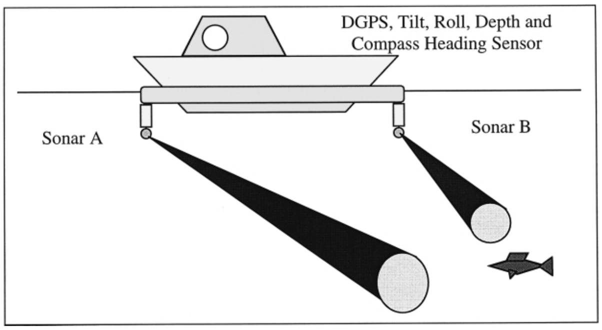

Figure 9. A proposed method for the simultaneous tracking of salmon, sharks, or other species using echoes and acoustic tags will allow the determination of behavior, acoustic sizing, abundance, and associated pelagic assemblages.

The Columbia and Snake Rivers studies showed that the same system used for echo tracking could be used to track active tags. The BATS study demonstrated the feasibility of coordinating tracking systems by implementing triangulation for position estimation. Such a system can be deployed from a moving platform for shallow water research. We have successfully deployed the system from a small boat pinging in the active mode and following salmon fish feed.

One possible future system deployment may consist of two main parts, each in its own housing: scanning sonar A and scanning sonar B (*figure 9*). These housings are mounted on an aluminum frame that is attached to the side of a moving vessel. This underwater package is pulled through the water with electrical cables running to either end, providing a connection between the underwater units and the shipboard computer.

Both sonars were mounted on a common chassis to provide a rigid frame of reference. The chassis also contains a sensor package that includes a compass, high precision tilt and roll sensor, and pressure transducer to measure depth below the surface. Absolute coordinates for individuals are obtained using a differential global positioning system (DGPS) combined with relative tracked positions, tilt and roll, elevation with respect to the water surface, and compass heading.

The transducer rotator assembly is modified to allow 360 degrees rotation in the outer stepper motor and 200 degrees rotation in the inner axis. This is accomplished by removing the distal to motor bearing and 'beefing up' the proximal one, and by transferring the mounting bracket from a lateral design to one attached to the outer stepper motor case's end plate.

The predictive tracking algorithm is adjusted to include inputs from the mounting frame's motion. Inclusion of DGPS, compass heading, tilt, and heave allow the transducer aiming to anticipate the next fish position. Other sensors can be included in the data stream; for example a profiling acoustic current meter can help estimate fish effort vectors.

The radar-type tracking system has been useful in determining fish behavior using echoes to center and follow fish. It can also be used to track acoustic tags. Today there is a need for automated tag tracking due to the demands placed upon human observers in small boats with manually pointed hydrophones (M. Gregor, Sonotronics, personnal communication).

Other technologies than radar-type tracking (besides manual steering) are also being used today for examining fish and plankton behavior, especially those using multi-element arrays. Two such systems are the Department of Energy's Pacific Northwest National Laboratory's (PNNL) multibeam-sonar tool, called Dual-Head Multibeam Sonar, and Scripp's Institution of Oceanography's FishTV (Jaffe 1995; McGehee and Jaffe, 1996). PNNL has developed software, called MTrack, that tracks individual fish and allows the creation of a three-dimensional animation of what took place underwater. The Dual-Head Multibeam may be an example of a Mills Cross array (a type first used in radio astronomy). Recently it tracked about 15 000 juvenile salmons as they approached the bypass at Bonneville Dam, finding the fish work harder as they approach a prototype bypass by swimming against the current, toward the bottom of the bypass and parallel to the bypass structure. These behaviors were similar to John Day dam's spillway-study findings (BioSonics, 1998).

Urick (1983) stated that the Mills Cross has the advantages of light weight and reduced transducer elements at the expense of lower array gain and a lower sensitivity than a rectangular array. Where the signal-to-noise is low a rectangular array or a highly directional radar-type transducer may be preferable. FishTV is a rectangular array that has been useful in determining plankton behavior. In addition, Jaffe (1996) discussed the tracking limitations of the rectangular array as a function of temporal ping rate. FishTV uses a set of 16 rectangular transducers arranged in two groups of eight in order to resolve an image. Eight of these transducers are used as transmitters and the other eight transducers are used as receivers. All receivers are operated simultaneously, but each of the transmitters is operated sequentially. The field of view (FOV) is approximately 16 degrees by 20 degrees as compared to a FOV of the motorized tracking transducer of about 14 degrees by 14 degrees prior to movement.

The disadvantages of having to move or scan a volume are lessened in shallow water. As an example using the motorized transducer, a 100-m radius hemisphere can be scanned by a six-degree transducer (assuming square 10-degree coverage per ping) in 43 s, assuming the operation is limited by the sound speed. In shallow water a 10-m radius hemisphere would be scanned in 4.3 s. Thus the tracking transducer is well suited for shallow water surveys, assessing individual organisms. In deep water, the system will be useful, especially for tracking acoustic tags or organisms with large acoustic reflectivity. In both shallow and deep water there is potential of combining acoustic sizing and perhaps species classification with behavior measurements using the tracking transducer. We are hopeful of improving the present state of the system with faster pingrates and stepper motors and are currently in the process of investigating more sophisticated tracking algorithms (e.g. Brookner, 1998).

References

BioSonics, 1998. Hydroacoustic evaluation and studies at the John Day Dam, 1997. Final Report Contract no. DACW57-96-D-005. Task Order no. 03. Prepared for: Department of the Army, Portland District COE.

Brookner, E., 1998. Tracking and Kalman Filtering Made Easy. John Wiley & Sons, New York.

Hedgepeth J.B., 1994. Stock assessment with hydroacoustic estimates of abundance via tuning and smoothed EM Estimation. PhD. Dissertation, University of Washington, Seattle, WA.

Hedgepeth, J.B., Gallucci, V.F., Thorne, R.E., Campos, J., 1996. The application of some acoustic methods for stock assessment for small scale fisheries. In: Gallucci, V.F., Saila, S.B., Gustafson, D.J., Rothschild, B.J. (Eds.), Stock Assessment. Lewis Publishing, Boca Raton, pp. 271–353.

Hedgepeth, J., Fuhriman, D., Acker, W., 1999. Fish behavior measured by a tracking radar-type acoustic transducer near hydroelectric dams. In: Odeh, M. (Ed.), Innovations in fish passage technology. American Fisheries Society, Bethesda, Maryland, pp. 155–171.

Jaffe, J.S., 1995. FTV, a sonar for tracking macrozooplankton in three-dimensions. Deep-Sea Res. 42, 1495–1512.

Jaffe, J.S., 1996. Temporal sampling of backscattered sonar signals. ICES J. Mar. Sci. 53, 359–361.

Johnson, R.L., Geist, D.R., Mueller, R.P., Moursund, R.A., Hedgepeth, J., Fuhriman, D., Wirtz, A.R., 1998. Behavioral Acoustic Tracking System (BATS). Report prepared for U.S. Army Corps of Engineers Walla Walla District, Walla Walla, WA 99362, Battelle Pacific Northwest Division P.O. Box 999 Richland, WA 99352.

McGehee, D., Jaffe, J.S., 1996. Three-dimensional swimming behavior of individual zooplankters: Observations using the acoustical imaging system FishTV. ICES J. Mar. Sci. 53, 363–369.

Urick, R.J., 1983. Principles of underwater sound. McGraw Hill, Inc. New York.