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

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## Introduction

We first applied the principle of tracking radar in 1994, using a Simrad EY500 split-beam echosounder (Hedgepeth and Condiotty 1995), 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 split beam sonar to identify an individual fish echo and to determine 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 (acoustic size of fish) are recorded to hard disk. Individual fish tracks can be visualized in AutoCAD. Fish tracks over 50 meters have been obtained with this tracking system.

The tracking split-beam 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 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 proposes methods to track salmon, sharks or other species both with echoes and by using acoustic tags that will allow behavior, abundance, and associated pelagic assemblages to be determined.

## 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 (Figure 2) description follows.

The split-beam 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 fore-and-aft angle is determined from the electrical phase difference between the fore and the aft transducer pair, and the athwartships angle from the starboard and port signals. This difference is then calculated and output via serial port in the form of a telegram to a second PC. The telegram contains single-echo detections for one ping: header, time, signal strength, fore-and-aft angle $\gamma$ (degrees), and athwartships angle $\psi$ (degrees). The stepper motor control computer receives the fore-and-aft angle, and athwartships 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. The new stepper motor angles $\theta'$ and $\phi'$ required to follow the fish using the present stepper motor angles $\theta$ and $\phi$ are:

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

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, .5, .25, .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.

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

Figure 4 shows an example of echoes from active tracking of three upstream migrating salmon. The ping rate is about 8 pings per second over 4 minutes (1900 pings) of data shown. Fish were tracked for one about minute each moving upstream about 0.75 m/s. Figure 5 shows projections of another fish tracked late in the season, exhibiting largest TS nearly perpendicular to the beam, and with speed of .8 m/s.

A nearby second stationary split beam system showed possible positional biases that had the effect of rotating the fish trajectory away from shore, and reduced apparent fish velocities. The active tracking 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 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 fish within roughly 15 meters of the spillway weirs. The tracking systems were lowered about 18 meters 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, $\overline{V}_{apparent}$, are estimated as the change in position divided by the change in time, shown in Figure 6a. $\overline{V}_{apparent}$ is the sum of the water velocity, $\overline{V}_{water}$, and the "real" fish vector (i.e. fish effort vector), $\overline{V}_{effort}$. The fish effort vector can be estimated as

$$\overline{V}_{effort} = \overline{V}_{apparent} - \overline{V}_{water} . \tag{2}$$

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 three dimensional space. Figure 6b that shows fish effort vectors at spillbay 18, were away from the dam and downward in response to surface flow generated by the placement of overflow weirs. There was little effort to avoid the spillbay by fish in deeper water, with weirs installed. 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 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 movement 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.

## Results – A Proposed Mobile System

The proposed system combines the advances made in active and passive radar-type tracking in the same instrumentation package to be used in a 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 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 1) the fixed deployment of the transducer on the boat and 2) 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 long relatively long time periods, large fish could be discriminated from the overwhelming amount of engraulids and clupeids in the shallow water embayment.

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.

The system consists 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 which is attacked 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 ship board computer.

Both sonars are 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 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 1) removing the distal to motor bearing and “beefing up” the proximal one, and 2) 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 for ultimately estimating fish effort vectors.

The BATS approach used a primary and secondary tracking systems. The new design allows both systems to act as primary or secondary as the need arises. In addition to triangulation, time of arrival information is used. The time of arrival information will be especially important when the fish or tag is in line with the two transducers.

A system price is around $100 000. In the future, oil-filled sonar-type split beam transducers may be manufactured to halve costs and mass. A single board computer will be embedded in the echosounder to carry out the motor control and tracking functions. The ship board components will fit into two pelican cases, with one or two laptop personal computers for user interface, acquisition, coordination and data storage.

## Discussion

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, personal 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 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 for 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 salmon 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) states 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 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, Jaffee (1996) discussed 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. The proposed FOV of the motorized tracking transducer is a hemisphere.

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 seconds, assuming operation is limited by sound speed. In shallow water a 10 m radius hemisphere would be scanned in 4.3 seconds. Thus the tracking transducer is best suited for shallow water surveys, assessing individual organisms, in order to maximize detection probability. In deep water, the system will be useful, especially for tracking acoustic tags.

In conclusion, the tracking transducer system can be used either by itself or with additional systems for tracking fish using both echoes and acoustic tags. A versatile system is proposed to use two systems deployed on a rigid frame at either end of a small research vessel.

# 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.

Hedgepeth, J.B. 1994. Stock assessment with Hydroacoustic Estimates of Abundance Via Tuning and Smoothed EM Estimation. PhD. Dissertation, University of Washington.

Hedgepeth, J. and J. Condiotty, 1995. Radar tracking principles applied for acoustic fish detection. Poster presentation at ICES International Symposium on Fisheries and Plankton Acoustics, Aberdeen Scotland 12-16 July 1995.

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

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

Jaffe, J.S., 1995. FTV, a sonar for tracking macrozooplankton in three-dimensions. Deep-Sea Research 42(8):1495-1512.

Jaffe, J.S., 1996. Temporal sampling of backscattered sonar signals. ICES J. Mar. Sci., 53(2): 359-361.

Johnson, R.L., D.R. Geist, R.P. Mueller, R.A. Moursund, J. Hedgepeth, D. Fuhriman, A.R. Wirtz, 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. and J. S. Jaffe, 1996. Three-dimensional swimming behavior of individual zooplankters: Observations using the acoustical imaging system FishTV. ICES J. Mar. Sci., 53(2): 363-369.

Urick, R.J., 1983. Principles of underwater sound. McGraw Hill, Inc. New York. 423 pp.

List of Figures

Figure 1. Fish tracking with split beam transducer. The vertical and horizontal angle of the target is determined by a split beam digital echosounder. Fish movement is monitored and transducer is rotating following target movement.

Figure 2. Photo and diagram of the Tracking Transducer System. The angles of target position from a split beam transducer are used to determine new transducer angles towards the target. Motors turn the transducer to follow fish movement.

Figure 3. Cross section of the Fraser River near Mission, British Columbia, CA. The scale is m. At top is the deployment of the active tracking transducer (at position 0, south bank).

Figure 4. Example of echoes from active tracking of three upstream migrating salmon in the Fraser River near Mission, British Columbia, CA, 30 July 1998. The ping rate is about 8 pings per second over the 4 minutes (1900 pings) of data shown above. Fish 3 was tracked for nearly one minute moving about 0.75 m/s. Color scale is echo intensity (red strongest).

Figure 5. Projections and statistics 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). Fish was tracked traveling at 0.8 m/s for 25 m. Target Strength (TS) is highest at right angles to the fish.

Figure 6. Side view of average fish velocities in 3 m x 3 m blocks at Spillabays 18 and 19 for 1997 spring period at John Dam splillbay. The fish effort velocity vector can be estimated as the difference between the tracked apparent fish velocity and water velocity. Apparent fish velocities are shown in (a) and and estimated fish effort velocities in (b), overflow weir installed. Angle shows position of the tracking transducer with 1 m lines. Velocities are m/s with one fourth the same reference dimension.

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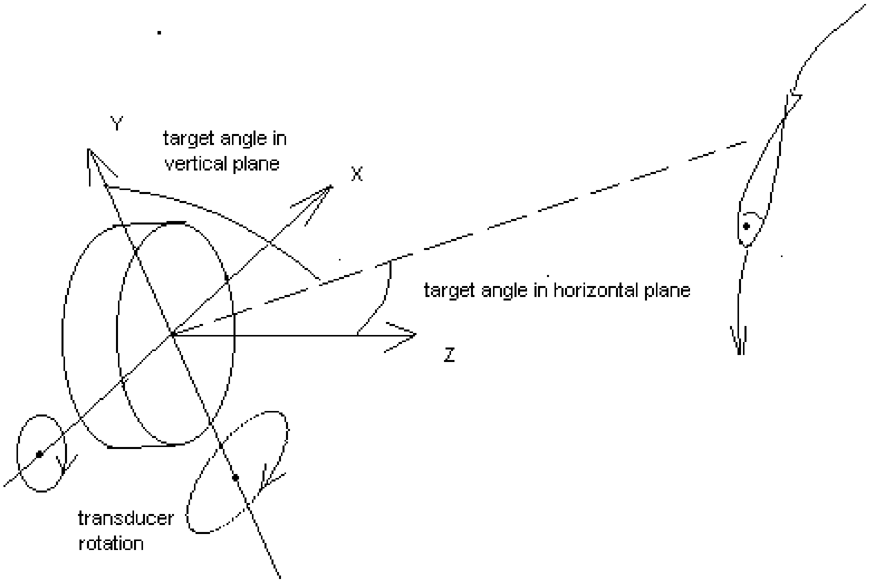
Figure 8. Example of positional estimates of a 200 kHz acoustic tag tracked by primary and secondary tracking transducers.

Figure 9. A proposed method of simultaneously tracking salmon, sharks or other species with echoes and using acoustic tags will allow behavior, abundance, and associated pelagic assemblages to be determined.



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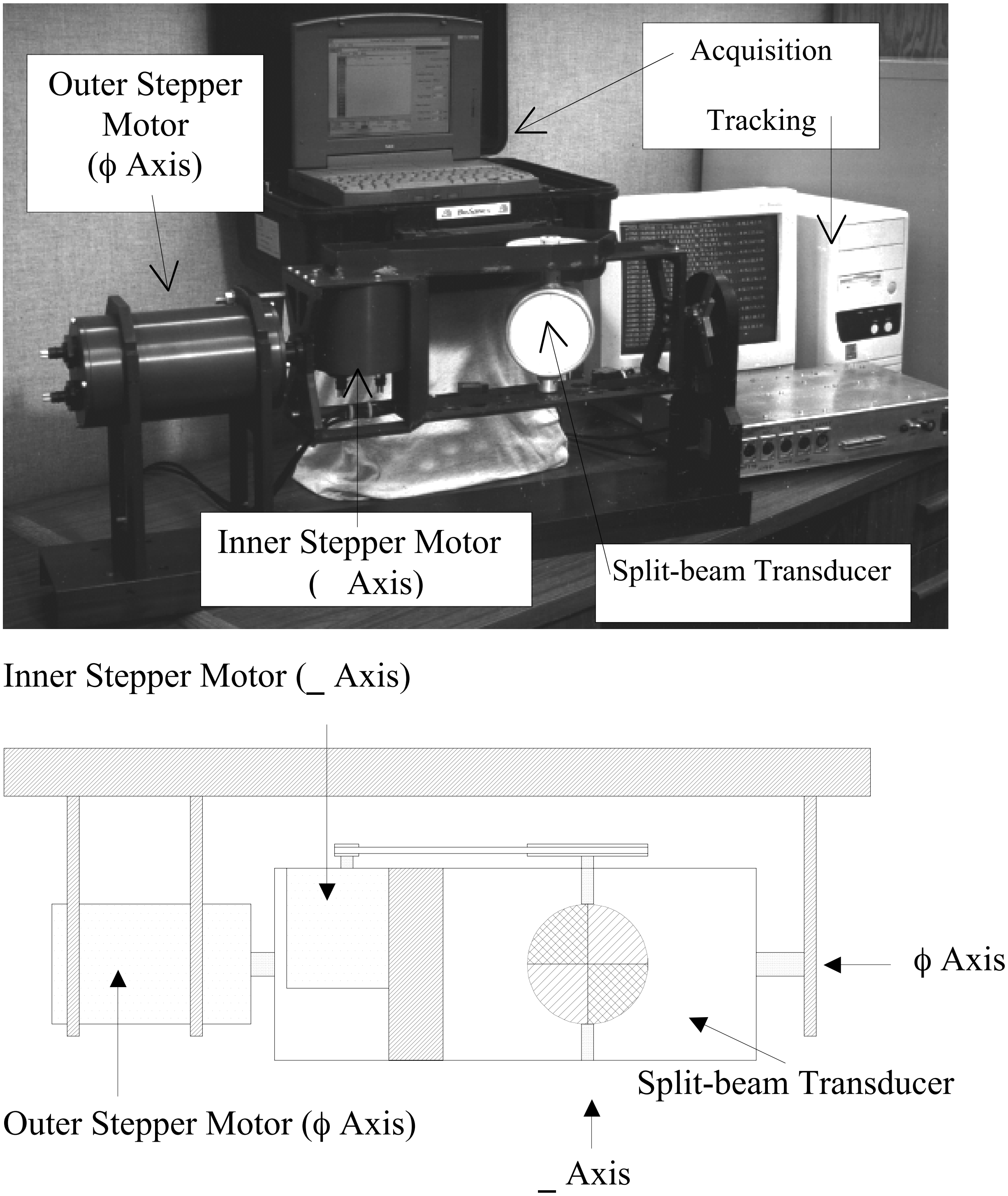

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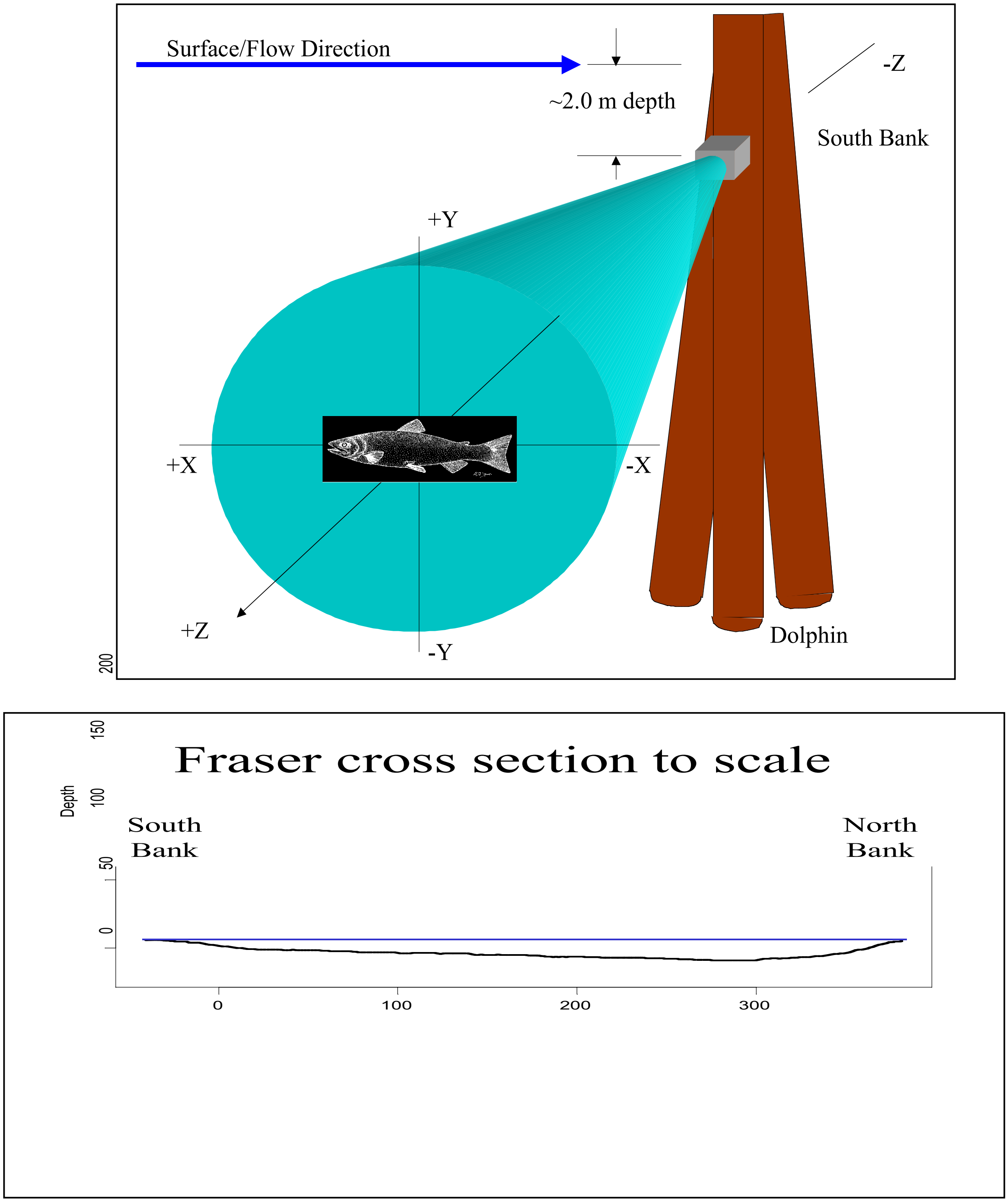

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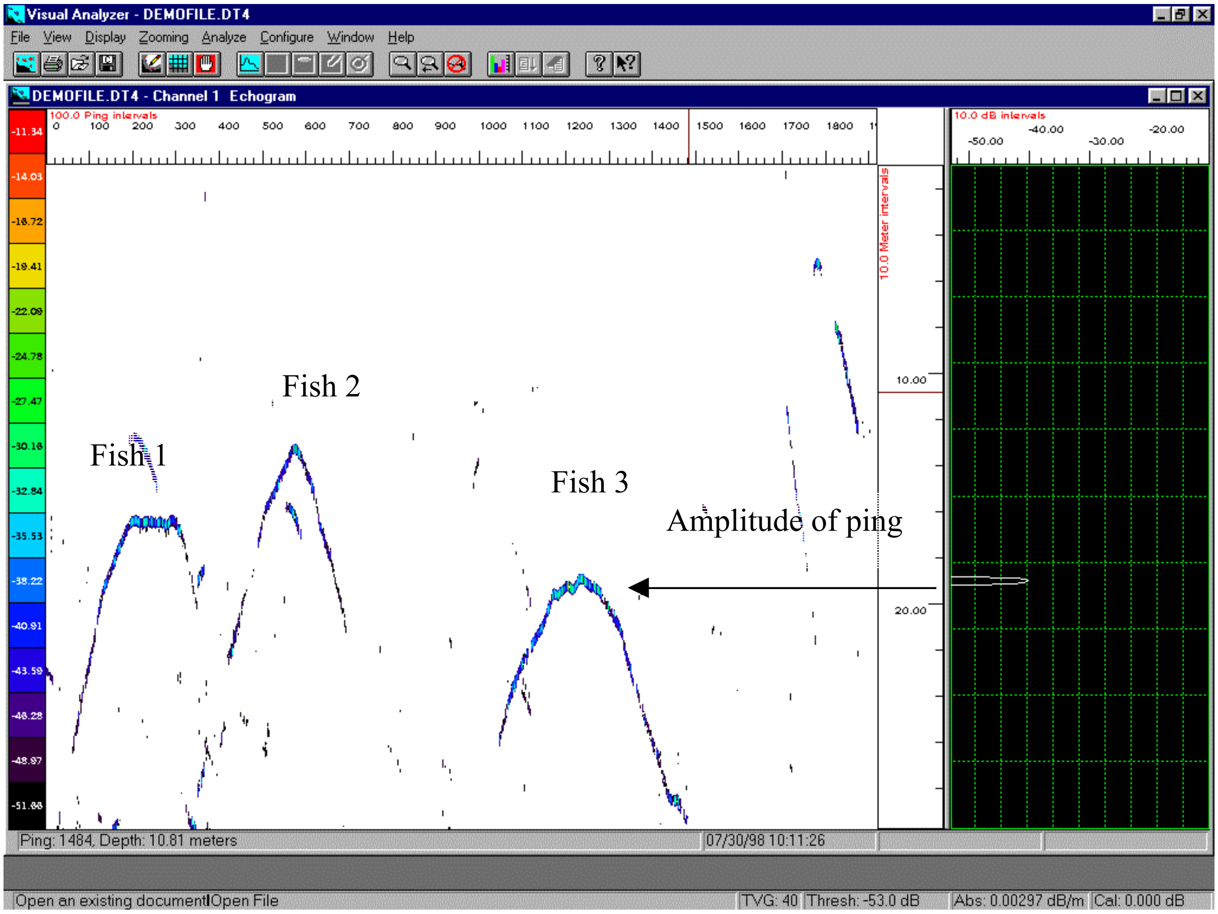

Ping: 1484, Depth: 10.81 meters

07/30/98 10:11:26

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TVG: 40 Thresh: -53.0 dB Abs: 0.00297 dB/m Cal: 0.000 dB

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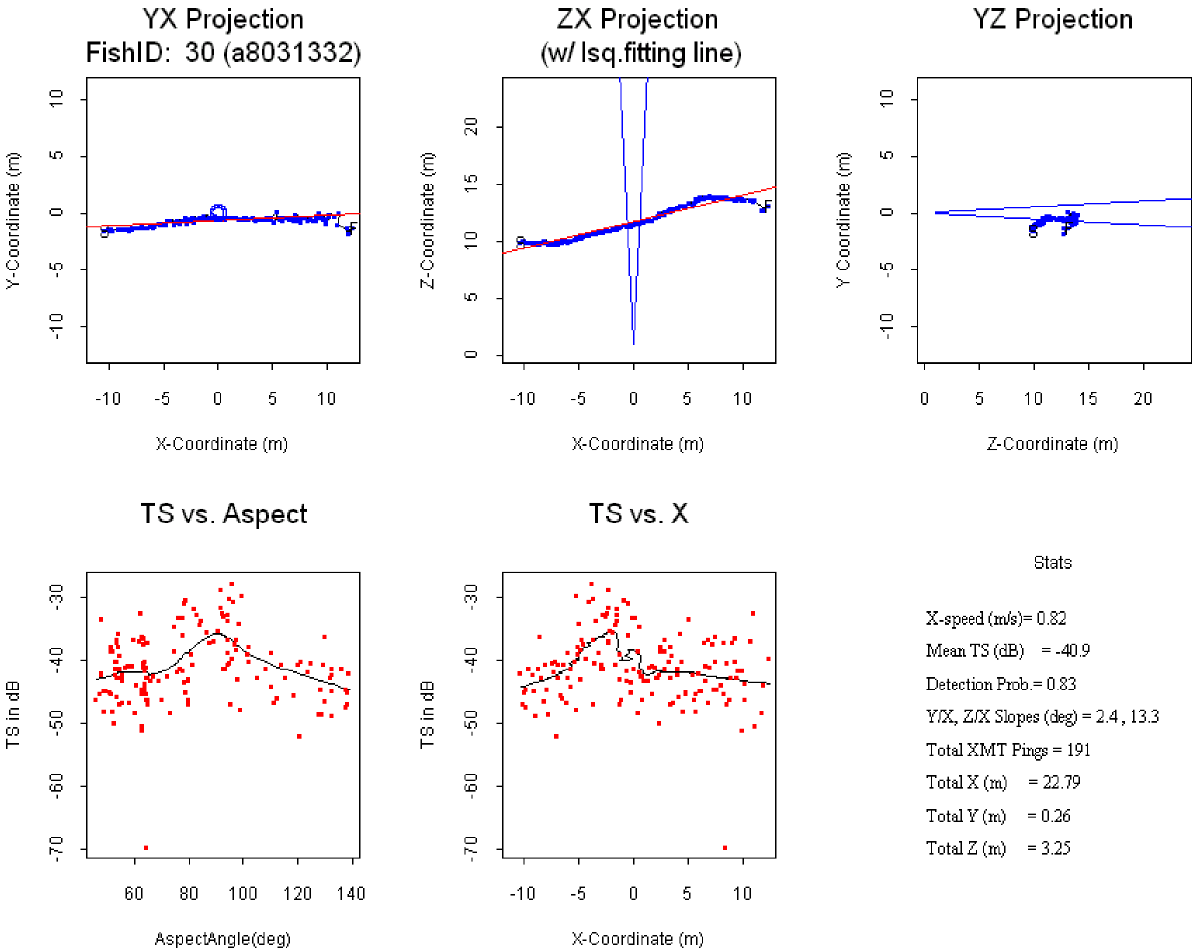

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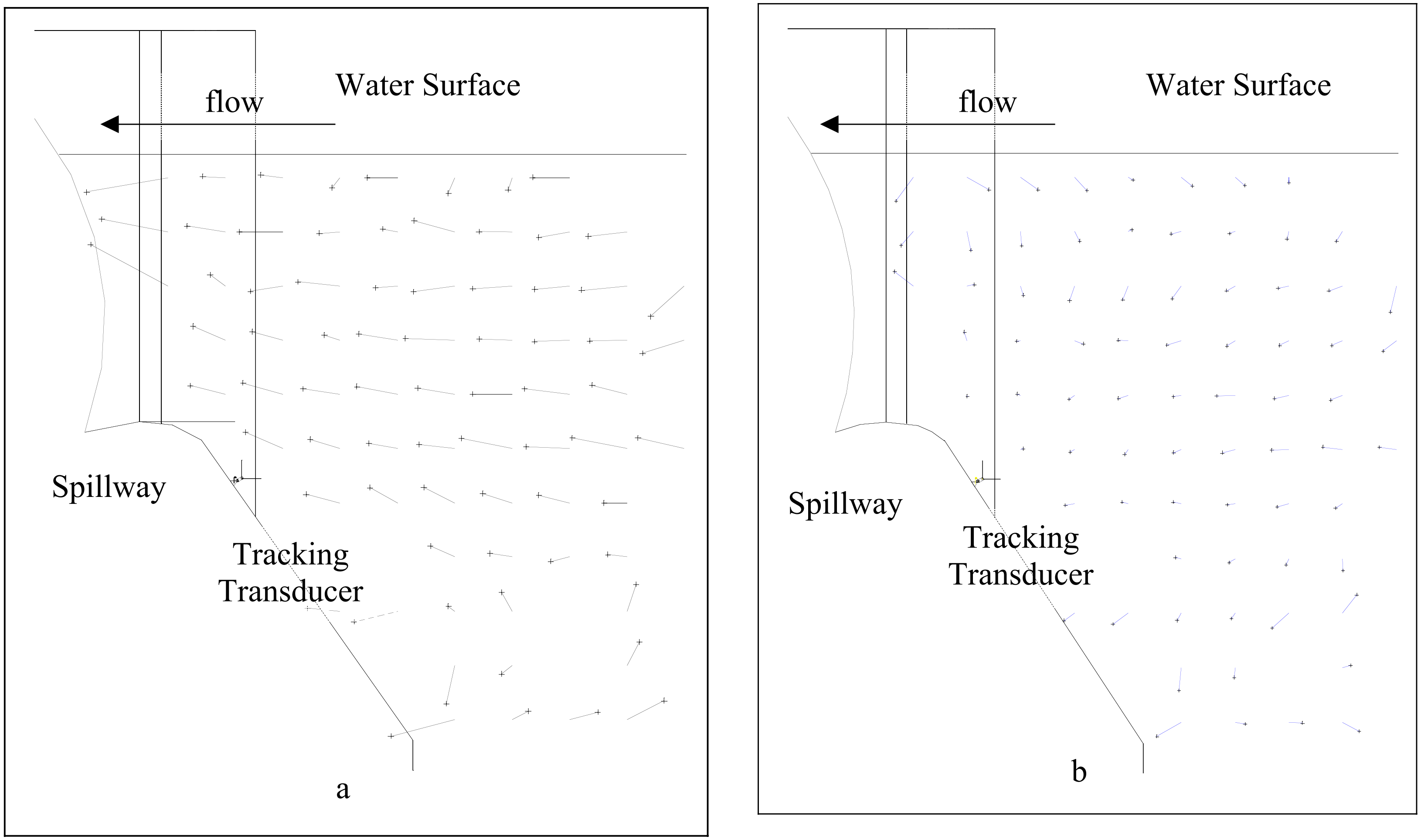

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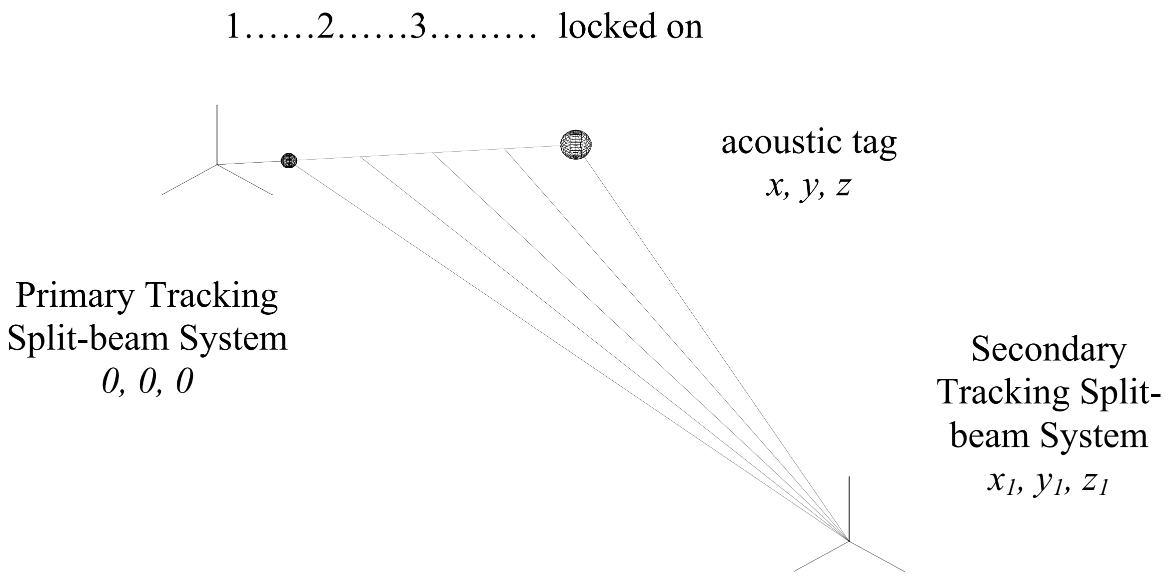

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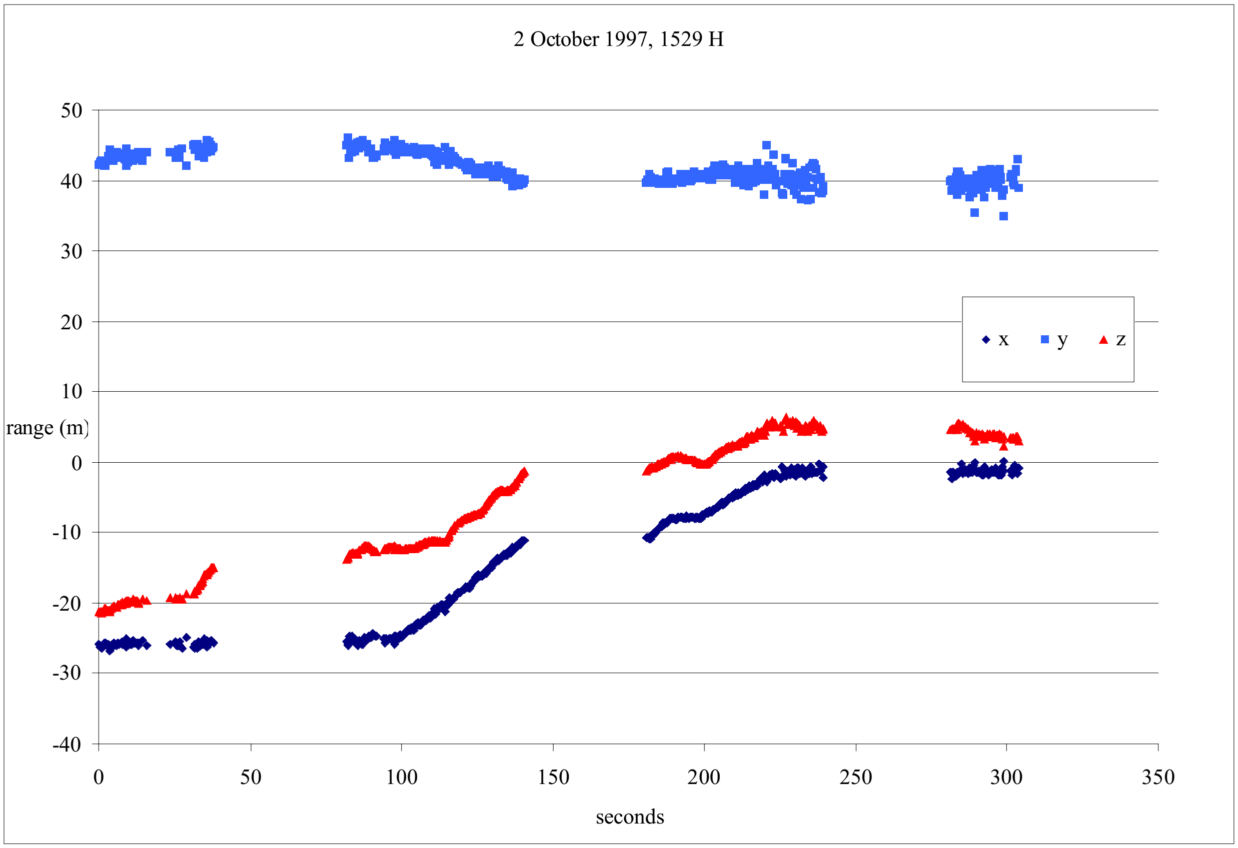

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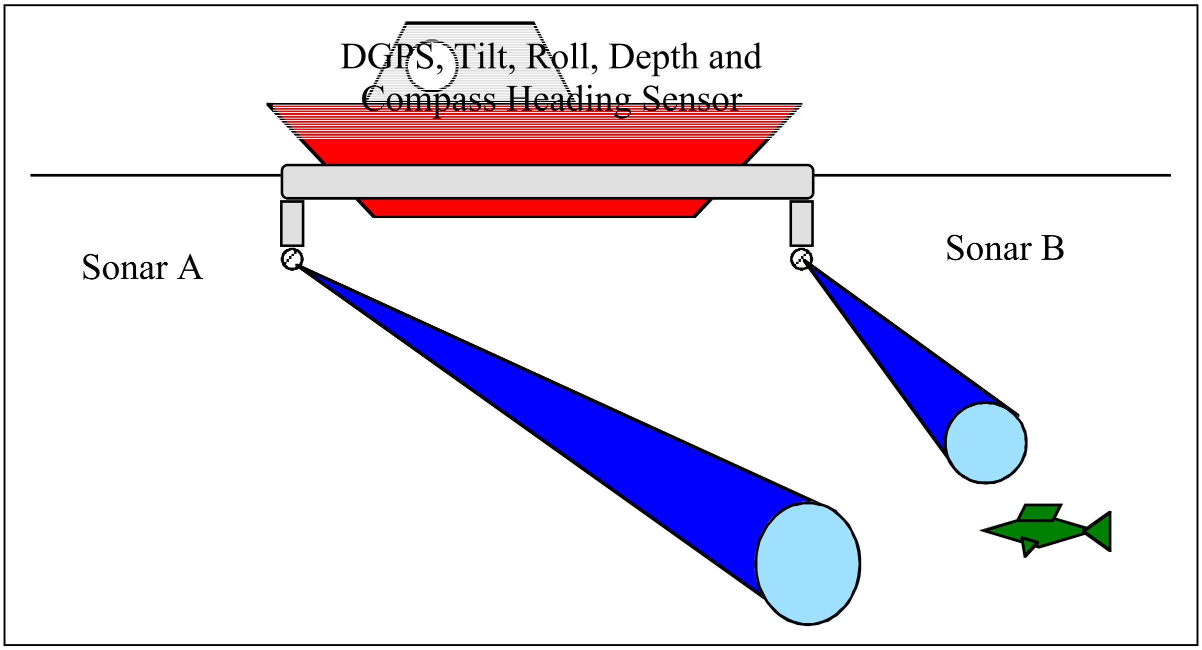

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