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Evaluation of a stimulus-response method for distinguishing out-migrant salmonids from drifting debris for sonar counts in the Trinity River, California

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Abstract − A method for discriminating fish from debris in sonar counts of out-migrant salmonids was tested in the Trinity River, California. The method used induced fish movements to distinguish fish from drifting debris. Electricity and light served as stimuli and video and split-beam sonar were used to measure movements of fish (mainly juvenile chinook salmon) and debris (mainly tree leaves). Differences in fish and debris behavior were clearly observable with underwater video. Many fish darted or slowed and most fish dove, whereas debris drifted passively. Fish responded to the electric field inconsistently, and an apparent positive phototaxis was the most consistent response to stimuli. Lack of matched sonar and video observations of individual targets prevented direct testing of sonar's ability to differentiate fish and debris in the Trinity River. However, analysis of sonar data from a similar situation in the Seton River, British Columbia, indicate that fish responses measured in the Trinity River by video were within the resolution of split-beam sonar. Split-beam position measurement error averaged ≤ 0.06 m within 5° of the acoustic axis, compared to a mean diving reaction of 0.11 m by salmonids observed with video. Proper transducer deployment, improved sonar analysis methods, and perfection of stimuli to elicit obvious and consistent fish responses are key to the success of this technique. With suitable development and validation, the stimulus-response method could become a useful tool for apportioning sonar counts among fish and debris. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

split-beam riverine sonar / video / chinook salmon / smolt

Résumé − Évaluation d'une méthode de réponse à un stimulus pour distinguer les saumons migrateurs des débris dérivants lors de comptages acoustiques sur le fleuve Trinité, en Californie. Une méthode pour différencier les poissons des débris dans les comptages acoustiques des saumons migrateurs est testée dans le fleuve Trinité en Californie. La méthode utilise la lumière réfléchie par les mouvements des poissons pour distinguer les poissons des débris dérivants. L'électricité et la lumière servent de stimulus ; un sonar monofaisceau et la vidéo sont utilisés pour mesurer les mouvements des poissons (principalement des saumons chinook juvéniles) et des débris (principalement des feuilles). Des différences entre le comportement des poissons et celui des feuilles ont clairement été observées en vidéo subaquatique. Beaucoup de poissons s'élancent ou ralentissent et la plupart plongent, tandis que les débris dérivent passivement Les poissons répondent au champ électrique de façon incohérente, et une phototaxie positive semble être la réponse au stimulus la plus courante. Le manque d'observation simultanée avec une caméra vidéo et un sonar n'a pas permis de tester directement la capacité du sonar à différencier les poissons des débris dans le fleuve Trinité. Cependant, l'analyse de données du sonar en situation similaire, sur le fleuve Seton en Colombie Britannique, indique que les réponses des poissons mesurés dans le fleuve Trinité par vidéo relevaient de la gamme de résolution du sonar. Les erreurs de mesure de positionnement étaient inférieures ou égales à 0,06 m pour un angle de 5° par rapport à l'axe acoustique, comparés aux réactions de plongées moyennes de 0,11 m pour les saumons observés en vidéo. Le déploiement d'un transducteur approprié, qui améliore les méthodes d'analyse du sonar, et la précision du stimulus pour obtenir des réponses évidentes et cohérentes, sont les clés du succès de ces techniques. Après développements adéquats et validation, cette méthode de stimulus pourrait devenir un outil utile pour distinguer les poissons des débris dans les comptages faits au sonar. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

sonar en petit fond / vidéo / saumon chinook / smolt

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1. INTRODUCTION

Estimating out-migrant salmonid abundance is a cornerstone of fisheries management in the Trinity River and other northern California streams. Traps and nets, the traditional methods for counting out-migrants, have been criticized because their capture probabilities often vary widely and inexplicably (Krakker, 1991; Roper and Scarnecchia, 1996). In an effort to improve out-migrant abundance estimates, a study was performed from 1996 to 1998 to evaluate the feasibility of using sonar to count out-migrant salmon and trout in the Trinity River. Early findings showed that debris from surrounding forests offered a formidable challenge to this task. Large amounts of debris, mainly oak and madrone leaves, were regularly deposited in the stream by afternoon thermal winds, presenting many spurious sonar targets to account for if accurate estimates of fish passage were to be achieved. Echo traces of fish and debris were not easily distinguishable because: 1) juvenile salmonids and leaves were very similar in target strength (TS); 2) leaves and fish were mingled in the water column; and 3) both moved mainly downstream.

However, fish often respond to external stimuli with movements that might be used to differentiate them from passively drifting debris. Examples of attraction or repulsion of fish by light, sound, and electricity abound in the fisheries literature (Hoar et al., 1957; Reynolds, 1983; Dunning et al., 1992; Nemeth and Anderson, 1992; Carlson, 1995). Additionally, split-beam hydroacoustics has been used to quantify fish behavior and measure fish movements in a variety of situations (Brede et al., 1990; Brandt, 1996; Mulligan and Kieser, 1996; Daum and Osborne, 1998). We hypothesized that induced fish movements, if sufficiently large and in some way recognizable, might be used to distinguish living fish from inert debris using split-beam sonar measurements of echo traces. We refer to this as a stimulus-response method of sonar target identification. This paper presents results from a test of stimulus-response methods conducted in the Trinity River in 1998. Electricity and light were used as stimuli while underwater video and split-beam sonar served to measure behavior of fish and debris. Split-beam sonar data from a similar situation in the Seton River, British Columbia, Canada, have also been included for comparison. Although experimental data did not allow all desired analyses, they were sufficient to demonstrate the potential promise of this new technique. Within these limitations, objectives of this paper are to: 1) examine electricity and light for stimulating fish movement; 2) describe responses by which fish could be distinguished from debris; 3) measure the type and size of fish and debris movements; 4) examine the effect of split-beam position measurement error on the ability of sonar to detect fish responses.

2. METHODS

2.1. Trinity river

Sampling was conducted in the Trinity River from 21h00 to 01h00 hours of July 24 and 25, 1998, to coincide with a high abundance of hatchery chinook salmon (*Oncorhynchus tshawytscha*) out-migrants and favorably low, clear water. The study site was near the town of Hoopa, California, where the river gradient was moderate, with small, widely spaced riffles during summer low-flow, and bottom substrate ranging from sand to cobble. On July 27, 1998, the river width was 60 m and its discharge was 71 $m^3 \cdot s^{-1}$ at the study location. Fish captured concurrently in a 1.5 m EG Solutions rotary screw-trap at the study site were 92 % juvenile chinook salmon, averaging 87.3 mm in fork length, 2% juvenile coho salmon (*Oncorhynchus kisutch*), 2% juvenile rainbow trout (*Oncorhynchus mykiss*), 2% lamprey (*Lampetra* sp.), and 2% other miscellaneous species. Screw trap data and related underwater video observations showed that these fish migrated downstream almost exclusively between dusk and dawn (Stables, 1999).

Split-beam sonar data were obtained using a 420 kHz BioSonics DT6000 echo sounder with a single 6° circular transducer. Echo sounder settings were: source level 218.8 dB//µPa@ 1 m, receiver sensitivity –130.3 dB//V/µPa@ 1 m, data threshold –54.5 dB, 10 $pulses \cdot s^{-1}$, pulse width 0.4 ms, and 40 log R time-varied-gain (TVG). Data were monitored on echograms and an oscilloscope throughout sampling and digital data files were stored to computer disk for later processing. The system was calibrated in the laboratory before and after field work.

Video recordings were made with a Deepsea Micro-SeaCam 1050 black and white submersible video camera with a 2.8 mm, f2.8, wide-angle lens with a sensitivity of 0.27 lux. Data were recorded to standard T-120 VHS tapes with a Toshiba KU7168A time lapse video cassette recorder (VCR) at A2 tape speed (120 min per tape). A field calibration was performed with a 19 mm diameter tungsten steel sphere to determine range of visibility and dimensions of the field of view for an object similar to a small fish. The range of visibility was 1.9 m and the field of view was 52° vertically by 63° horizontally. Night observations were illuminated with a 250 W submersible pool light filtered to pass visible light with wavelengths exceeding 690 nm (red light). This light also served as a stimulus to fish movement.

A Smith-Root model BP-1.5 programmable output waveform barrier pulser was used to generate an underwater DC electric field as another source of stimulus to fish movement. Settings for operation were a nominal voltage of 244 V, pulse width 0.5 ms, and 5 $pulses \cdot s^{-1}$, resulting in a measured instantaneous electric field strength of up to 3.6 $V \cdot cm^{-2}$. Although out-migrants reacted visibly to this field, it was similar

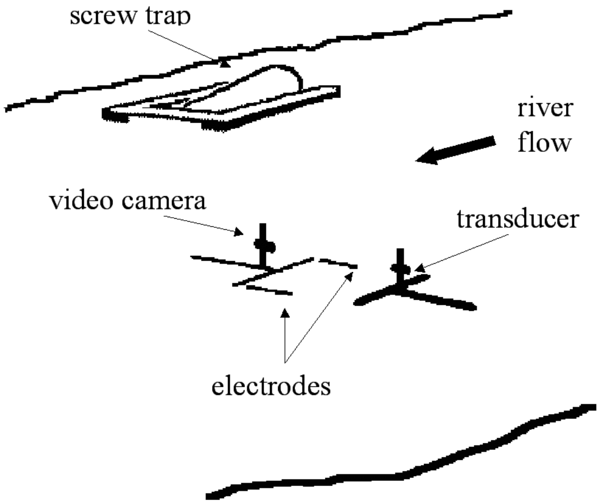

Figure 1. Opposing transducer and video camera configuration used in stimulus-response test, Trinity River, July 1998. The camera and transducer faced each other 11 m apart.

to those often used to divert fish from hazards such as power plants, and was considered harmless to them.

Tests were conducted near the left riverbank where a sand bottom sloped uniformly toward center channel. The transducer and video camera were aimed horizontally, opposing each other, with a separation of 11 m, and were aligned perpendicular to the river flow (*figure 1*). The transducer was 0.4 m beneath the surface in water 1 m deep, while the video camera was 1 m beneath the surface in water 2 m deep. Water velocity was 0.8 $m \cdot s^{-1}$ at the camera lens. The transducer was aimed 3° below the horizontal plane and the video camera was aimed up 3° from horizontal. Each was mounted on an adjustable frame of steel pipe and a buoyant target was used to align sonar and video fields of view so that they overlapped within 2 m of the camera. The electrodes from the barrier pulser (two 1.3×0.04 m steel pipes) lay on the river bottom in front of the video camera mount and generated the electric field in the area mutually sampled by sonar and video. The submersible light was mounted beneath the camera to illuminate this area.

Sonar data were processed in the laboratory using BioSonics Visual Analyzer version 3.1.1 and Vtrack version 0.9.8.1 software to measure echo characteristics and to group echoes into fish traces. Only targets that passed over the electrodes (9–11 m from the transducer) were used for analysis. Processing settings were: data threshold –54.5 dB, beam pattern threshold 6°, ping gap 5, and 3–30 echoes per trace. These echo tracking settings were chosen so that automatic tracker results approximated those from manual processing of test echograms by a skilled analyst. Vtrack software automatically computed several variables describing target movement, including net movement in x, y, and z dimensions, relative net movement in any two dimensions, and net versus total upstream and downstream movement. Editing of automatically tracked fish was not possible with Vtrack software. Attempts to match individual sonar targets with video observations were unsuccessful, so analysis of sonar data was limited to comparison of target characteristics (fish and debris combined) under various experimental conditions.

Video tapes were replayed in the laboratory while an observer tabulated behaviors including burst swimming, slowing, and vertical movement for both fish and debris. Precise identification of objects was not always possible, so they were categorized simply as salmonids, lampreys, or leaves. Behaviors were classified according to the observer’s judgment, except for vertical movement, as explained below. Range of each target from the video camera was roughly estimated as near, medium, or far, based on image brightness and clarity, apparent target size, and speed of passage (objects close to the lens appeared clearer, brighter, larger, and faster moving than similarly sized but more distant ones). Only near and medium range targets (0.1 to 1.3 m from the camera) were used in subsequent analysis. The net vertical movement of each target was measured as a percentage of the video screen height, which was roughly converted to meters with the formula:

$$V_m = V_{\%} \times H_{range} \qquad (1)$$

where: V_m = net vertical movement in meters, $V_{\%}$ = net vertical movement as % of screen height, and H_{range} = mean height (m) of the video camera field of view by range category (near = 0.32 m, medium = 0.97 m).

2.2. Seton River

The Seton River, in British Columbia, Canada, flows from Seton Lake to the Fraser River by way of Seton Dam and a system of canals. It is a migration route for several salmonid species, including juvenile sockeye salmon (*Oncorhynchus nerka*), the subject of a sonar study conducted in spring 1999. Sonar data presented in this paper were collected in the canal approaching the dam, immediately upstream from the dam face and beside an experimental fish guidance louver. These data were obtained from 22h00 to 03h00 hours, May 11–12, 1999.

Split-beam sonar data were collected using a 200 kHz BioSonics DT6000 echo sounder with a single 6° circular transducer. The transducer was in a fixed position 10 m upstream from the dam and 0.5 m beneath the water surface. It was aimed downstream toward the dam face and 7° downward from the horizontal plane. Water depth and velocity were 4 m and 0.5 $m \cdot s^{-1}$, respectively, at this location. Settings for data collection were: source level 214.0 dB//µPa@ 1 m, receiver sensitivity –115.1 dB//V/µPa@ 1 m, data threshold –62 dB, 10 $pulses \cdot s^{-1}$, pulse width 0.3 ms, and 40 log$R$ TVG. The system was calibrated in the laboratory before the study and data quality was monitored on echograms and an oscilloscope during sampling. Digital data files were stored to computer disk for later processing. No underwater video data were collected at Seton Dam.

Sonar data from the Seton River were processed in the laboratory using BioSonics Visual Analyzer version 3.1.1 and Vtrack version 1.0.0 software to measure echo characteristics and to group echoes into fish traces. Settings used for processing were: data threshold –62 dB, beam pattern threshold 5.5°, maximum ping gap 7, 7–100 echoes per trace, and ping concentration 40–100% (ping concentration within a trace = detected echoes/total insonifications). Echo tracking settings were again chosen to approximate those from manual processing by a skilled analyst. The software did not allow editing of automatically tracked fish and the same variables were computed as for Trinity River data.

Error in position measurements by split-beam sonar will affect its ability to distinguish fish from debris; i.e., large measurement error will require large differences in target behavior for successful discrimination of target types. To examine this relationship, we estimated random position measurement error of sonar data from the Seton River for comparison to fish movements measured with video in the Trinity River. A high number of multiple-echo traces made the Seton data amenable to this analysis. Three-dimensional coordinates of echoes were calculated in MS Access and error in position measurements was estimated for the vertical dimension (y) of each echo within a trace (first and last echoes excluded) with the formula:

$$D_i = \left| y_i - \left(\left(y_{i-1} + y_{i+1} \right)/2 \right) \right| \qquad (2)$$

where, for each echo i within a trace, D_i is the deviation of its measured location from an expected value estimated by linear interpolation between the immediately adjacent echoes. Coordinates and error estimates were in meters relative to the acoustic axis. This method assumes that the trajectory between any three adjacent echoes within a trace should be nearly linear, and that the deviation from this linearity is an estimate of random position measurement error.

3. RESULTS

Video observations in the Trinity River showed that most leaves passed through the camera's field of view on a straight trajectory at uniform speed, while most fish darted, slowed, or dove. Ninety five percent of fish observed were juvenile salmonids, of which 21–58% showed burst swimming whether the electric field was on or off, suggesting that the electric field was not the only cause of such behavior (*figure 2a*). The percentage of salmonids showing burst swimming was consistently about 10% higher with the field on, however, this difference was not statistically significant ($X^2 = 3.63$, $p = 0.057$, $n = 193$). From 14–70% of salmonids also slowed noticeably when passing the camera, whether or not the field was activated (*figure 2b*). At dusk, a significantly higher proportion of salmonids ($X^2 = 4.86$, $p = 0.027$, $n = 49$) slowed with the field off (70%) than with it on (38%). At night more slowed with the field on (23%) than with it off (14%), a difference that was not significant ($X^2 = 0.13$, $p = 0.71$, $n = 143$). Only 0.5% of leaves and no lamprey showed behavior classed as burst swimming or slowing. Most salmonids dove actively, while most leaves passed through the view-field without changing depth or with slight upward movement (*figure 3*). Diving behavior of salmonids did not differ significantly with the electric field on or off (Mann-Whitney-U, $z = 0.49$, $p = 0.62$, $n = 137$). Mean vertical movement of salmonids (–0.11 m) was significantly different (Mann-Whitney U, $z = 10.4$, $p < 0.001$, $n = 298$) from that of leaves (0.02 m, *table I*).

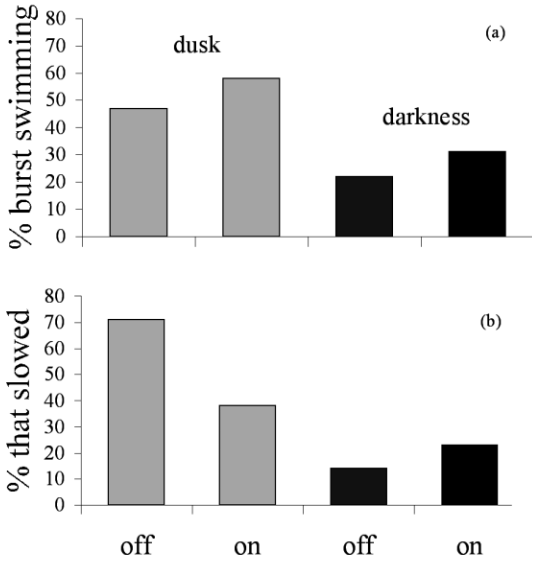

Figure 2. Percent of juvenile salmonids showing burst swimming or slowing behaviors, by time of day and electric field status (on or off). From video observations, Trinity River, July 1998.

Split-beam sonar measurements of target behavior (fish and leaves combined) in the Trinity River showed little effect of electric field operation (*table II*); mean values for most variables describing net movement in x, y, and z dimensions, or relative movement in any two dimensions, showed no significant difference with the field on or off (t-test, $\alpha = 0.05$). Only milling (net versus total upstream and downstream movement) showed a significant difference, and was greater with the electric field off ($t = 2.07$, $p = 0.04$, $n = 123$).

Random error of split-beam position measurements was estimated for 2 419 echoes from the Seton River. This error, which appeared as a saw-tooth pattern in fish traces (*figure 4*), was consistently ≤ 0.06 m

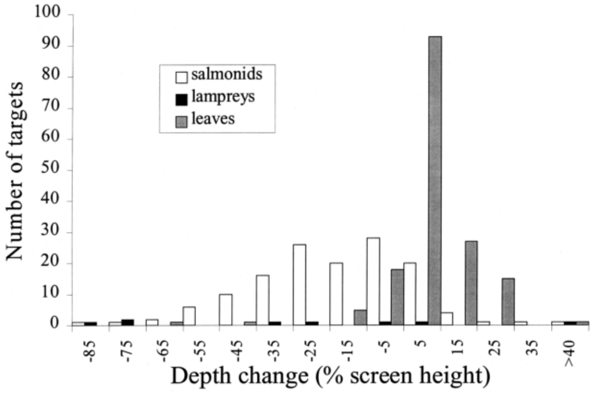

Figure 3. Frequency distributions of depth change by fish and leaves passing the video camera, Trinity River, July 1998.

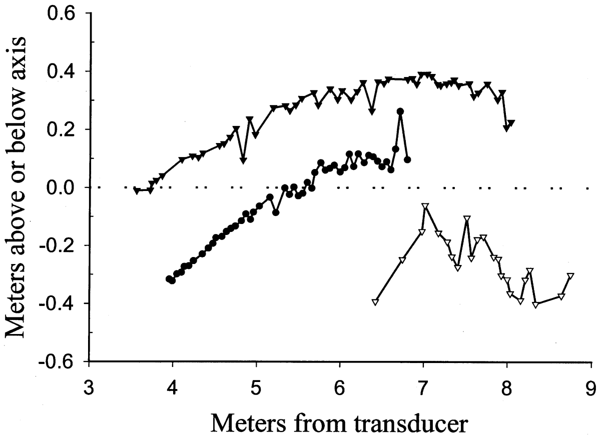

Figure 4. Fish traces from split-beam sonar in the Seton River, May 1999. Coordinates are relative to the central axis of the sonar beam.

(SD ≤ 0.08) within 5° of the sonar beam's acoustic axis (*table III*).

4. DISCUSSION

Our initial tests indicate that a stimulus-response method for differentiating fish from debris may prove useful with further development. Differences in fish and debris behavior were clearly visible with underwater video. Many fish darted or slowed, and most dove measurably, whereas debris drifted passively with few exceptions. Responses to electricity were slight and inconsistent, while an apparent positive phototaxis was the most constant reaction to stimuli, with most salmonids and lampreys diving toward the light source. Although our experiment did not measure fish movements without illumination, and therefore cannot conclusively show that diving was due to light, it is likely that light affected this behavior. Salmonids are light-sensitive visual feeders (Higgins et al., 1995) and attraction of juvenile chinook salmon to constant light has been documented elsewhere (Nemeth and Anderson, 1992). Reliable application of stimulus-response methods will require consistent reactions from most or all fish involved, so light was judged the more useful stimulus in our experiment. The underwater video methods we used were primitive but sufficient to demonstrate differences between fish and

Table I. Mean vertical movement by salmonids, lamprey, and leaves, estimated from video observations in the Trinity River, July 24 and 25, 1998.

	Depth change (m)				
				95% CL of mean	
Target type	Mean	SD	*n*	lower	upper
lampreys	–0.14	0.19	8	–0.27	0.00
leaves	0.02	0.08	161	0.00	0.03
salmonids	–0.11	0.17	137	–0.14	–0.08
Total	–0.04	0.14	306	–0.06	–0.03

Table II. Split-beam sonar measurements of target movements (fish and leaves not differentiated) in the Trinity River with the electric field on and off, July 24 and 25, 1998*.

	Net x		Net y		Net z		Net y/ Net x		Net z/ Net x		Net y/ Net z		Milling	
Item	off	on	off	on	off	on	off	on	off	on	off	on	off	on
Mean	0.41	0.46	0.52	0.56	0.14	0.14	1.77	1.77	0.47	0.39	5.50	6.14	3.78	2.87
Variance	0.07	0.05	0.12	0.10	0.01	0.01	3.19	3.79	0.40	0.18	24.82	35.25	16.51	4.78
Observations	123	82	123	82	123	82	123	82	123	82	123	82	123	82
df	189		183		170		163		203		153		195	
t Stat	–1.50		–0.84		–0.20		0.00		1.00		–0.80		2.07	
P(T ≤ *t*) two-tail	0.136		0.403		0.838		1.000		0.317		0.425		0.040	
t critical two-tail	1.97		1.97		1.97		1.97		1.97		1.98		1.97	

* Distances in meters. Coordinate system: x = horizontal and parallel to river flow, y = vertical, and z = horizontal and perpendicular to river flow. Net movement = (maximum – minimum); milling = (total x/net x).

Table III. Error in split-beam sonar vertical position measurements within target traces, S≤eton River, May 1999.

Angle off-axis (degree)	Mean error (m)	SD	*n*
<1	0.06	0.06	708
1–2	0.06	0.06	593
2–3	0.06	0.07	425
3–4	0.06	0.08	229
4–5	0.02	0.06	464
Combined	0.05	0.07	2 419

debris behavior, and to roughly measure movements of objects in two dimensions. More sophisticated video techniques could provide much better measurements of target behavior in three dimensions for comparison to three dimensional split-beam sonar data (Hughes and Kelly, 1996). Our inability to match video and sonar observations of individual fish and leaves coupled with processing limitations of early generation echo tracking software prevented direct testing of sonar's ability to distinguish fish from debris in the Trinity River.

The capacity for split-beam sonar to measure fish movements in three-dimensional space is its chief advantage over single and dual-beam acoustics as a tool for behavior studies. However, to be useful for stimulus-response methods, sonar must have sufficient resolution to measure fish movements that occur in the environment of interest. Comparison of split-beam position measurement error estimates from the Seton River with video observations from the Trinity River suggest that fish reactions seen in the Trinity River were within the resolution of split-beam sonar in a shallow, riverine environment. Salmonids passing the video camera dove an average of 0.11 m, whereas mean split-beam position measurement error was = 0.06 m (SD = 0.08) within 5° of the acoustic axis. Sonar's ability to detect fish reactions would likely be improved by placing the transducer in a lower noise environment or by increasing the acoustic beam's sampling volume, if possible, by using a wider angle transducer or by increasing the range to targets of interest. A larger sampling volume could enhance performance in two ways: 1) by increasing the number of echoes within the angular limits of high accuracy, and 2) by increasing the physical distance that fish are tracked, thereby improving the chance of detecting deviations from a regular trajectory. However, background noise also increases with range and beam angle, which could offset these advantages by reducing target detectability and increasing position measurement error. Orientation of the transducer with respect to direction of fish travel also affects the distance that fish can be tracked, and a sonar beam aimed downstream or obliquely to the current is likely to track downstream moving fish for a greater distance than a beam aimed perpendicular to the flow. However, because out-migrants typically orient their body's long axis parallel to the river flow, a downstream or oblique transducer orientation could result in unfavorably low signal to noise ratios for fish (Love, 1977; Kubecka, 1994). In summary, it appears that split-beam sonar resolution is sufficient to detect observed reactions of out-migrants in the Trinity River, and that its ability to discriminate fish from debris will be enhanced by judicious transducer deployment and testing.

Other observations made during the Trinity River study point to additional recommendations about stimulus-response methods. River flow at the measurement location should be laminar, so that velocities and trajectories of passively drifting debris will appear uniform compared to those of active fish. If the chosen stimulus is an attractant such as a steady light, the water velocity should be high enough that fish cannot hold position near the stimulant, which would confound results through multiple detections of individual fish. In the Trinity River, out-migrant chinook salmon did not hold in velocities $> 0.5\ \mathrm{m \cdot s^{-1}}$. In our video observations of fish, several measurable behaviors were noted (slowing, burst swimming, and diving). If a similar variety of responses can be detected with sonar, a test statistic using a combination of behaviors (e.g. discriminant analysis) should be more powerful for distinguishing fish from debris than a statistic based on a single behavior.

Many questions remain about the practicality of stimulus-response methods for apportioning sonar counts among fish and debris as part of a day-to-day out-migrant monitoring program. Their development will require thorough experimentation and validation if accurate and reliable results are to be obtained. The evolution of split-beam sonar methods for monitoring sockeye salmon escapements in the Fraser River, Canada, which involved extensive behavioral studies and validation of sonar measurements with video observations, is a well documented example of the systematic effort that would be necessary to properly develop stimulus-response methods (Enzenhofer and Cronkite, 1998; Enzenhofer et al., 1998; Mulligan and Kieser, 1996).

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