A STUDY TO DETERMINE THE BIOLOGICAL FEASIBILITY OF A NEW FISH TAGGING SYSTEM, PART I:

Evaluation of Potential Passive Acoustic Tag Systems

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Edmund P. Nunnallee, Earl F. Prentice, and Sandra L. Downing

Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
2725 Montlake Blvd. East
Seattle WA 98112-2097

to

Division of Fish and Wildlife
Bonneville Power Administration
U.S. Department of Energy
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EXECUTIVE SUMMARY

We investigated the technical feasibility of developing two types of passive acoustic tags, each with a read range of up to 10 m. The first tag evaluated was an acoustic passive integrated transponder (A-PIT) tag. Our initial evaluation addressed the attenuation of acoustic energy as it propagates through the body of a fish in order to determine the range of viewing aspects from which tags could be effectively read. A test transducer was placed in the coelomic cavity of fish, and results showed a wide range in attenuation values for the frequencies of interest (50 and 500-kHz) in relation to aspect or viewing angle.

The data suggested that a fish's body and air bladder would significantly attenuate acoustic signals at most viewing angles except ventrally and to a limited extent laterally. In addition, due to the narrow dimensions of the beam at short range, fish rapidly passing near the energize/receive transducer may not remain within its interrogation field long enough for the tag to be energized or for the return signal to be received completely.

Two separate sound fields were proposed for use with the A-PIT tag system: one at 50 kHz (a continuous energizing field) and the other at 500 kHz (tag response frequency). The strengths of the 50- and 500-kHz sound fields were estimated at 207-213 dBµPa@1 m and 120-126 dBµPa@1 m, respectively. Thus, during operation of an A-PIT system, fish and other animals could be exposed to strong sound fields. A literature review showed that the energy field required to energize the A-PIT tag could, under some conditions, cause behavior modification and/or damage some animals.

We concluded that technically, the A-PIT tag could be developed. This was confirmed by an independent non-government contractor who reviewed the potential system. However, based upon the signal attenuation data showing limited operational viewing aspects, and the literature review showing a potential risk to fish and other animals from the continuously transmitted tag-energizing field under some potential operating conditions, we recommend that the tag not be developed. These factors, in addition to potentially high system developmental cost, outweigh any potential advantages of the system over currently used tagging systems.

Similarly, upon investigation of the technical feasibility of a resonating sphere tag, it became apparent that the tag could be developed (confirmed by an outside non-government contractor) but that its application would be limited, and there would be a potential risk to animals confined in close proximity to the tag energizing system.

Factors identified as potentially limiting system performance included use with small fish only, diminishing tag-detection ability as a fish grows, limited "tag codes" (resonating frequencies) because of tag size limitations in relation to fish size, ambient noise reducing tag-detection ability, limited viewing aspects because of a fish's physical characteristics, and the acoustic spectral characteristics of fish.

Calculations showed that the strength of the acoustic energizing field for a resonant sphere tag system could, as with the A-PIT tag, potentially cause behavior modification or damage to fish or other animals. Based on this information, we recommend that development of a resonating acoustic sphere tag for use in the Columbia River Basin not take place at this time.

A review of literature covering the effect of sound on animals strongly suggested that the interrogation or insonification sound-field strength of either of the proposed tag detection systems could, under certain conditions, cause harm and/or behavior modification to fish and aquatic mammals. However, the ability of some animals to detect and avoid a potentially damaging sound field prior to damage taking place reduces this concern. To reduce the risk of harm, the systems would thus need to be operated in situations that do not confine animals (i.e., use in open water and not in fish ladders).

CONTENTS

INTRODUCTION: EVALUATION OF POTENTIAL PASSIVE ACOUSTIC TAG SYSTEMS

Fisheries agencies use a variety of marking systems to identify groups or individual fish. One such system is the radio frequency passive-integrated-transponder (RF-PIT) tag, which obtains its operating power from an electromagnetic field (EMF) and subsequently "transmits" its unique identification code to a receiver (Prentice et al. 1990). The major shortcoming of this passive tag is its limited operating range.

In 1992, NMFS proposed to Bonneville Power Administration (BPA) that the technical feasibility of developing a new generation of small passive tags and tag detection systems, suitable for use with juvenile salmonids, be investigated. As proposed, the tags would operate using acoustic rather than electromagnetic energy, thus increasing their detection and read range over existing tags. Theoretically, these systems would be able to detect acoustic tags to a range of up to 10 m or more.

The investigative work took place during the period of 1994 through 1996 as a work element within Project 83-319, "*A Study To Determine The Biological Feasibility Of A New Fish Tagging System, Part III: Development and Evaluation of PIT-tag Technology*." Two types of passive sonic tags and the potential effect of acoustic energy (acoustical field intensities proposed to energize tags and transponder tag data) on biota were investigated and are discussed in three separate papers within this report.

TECHNICAL FEASIBILITY OF AN ACOUSTIC PIT-TAG

Introduction

The first tag the NMFS proposed to investigate was an acoustic passive integrated transponder (A-PIT) tag. As proposed, the tag would have the following features:

- Passive (i.e., having no power source of its own)
- An operating range of up to 10 m
- Energized with one acoustic frequency and transmit data on another
- Individually coded
- Suitable for implanting into the coelomic cavity of juvenile salmonids

A multi-phased plan to investigate the technical feasibility of such a tag was formulated. Since the proposed tag would lie in the coelomic cavity of a fish, its design necessitated that it be energized and respond through the fish body. Thus, the first steps in the investigation were to determine acoustic energy attenuation through the bodies of fish to estimate acoustic power levels needed to operate and detect the tag, characterize the limitations of the tag performance, and to develop a prognosis of the applicability of the tag for field research.

Methods and Materials

In this study, attenuation of acoustical energy through fish bodies was measured for body aspect angles throughout pitch, roll, and yaw planes (Table 1, Fig. 1). Attenuation for each aspect (viewing) angle was unique with respect to the tissues and structures encountered along that path of sound propagation. Factors affecting attenuation included how fully the swim bladder was inflated, the thickness and composition of bone and musculature, and frequency-dependent effects. Attenuation was measured using a small test transducer (underwater speaker/microphone) that was inserted into the coelomic cavity of fish at approximately the position where an injected A-PIT tag would lie.

Calibrated laboratory transducers were used to transmit to and receive transmissions from the test transducer. Measurements were made using two frequencies, 50 kHz and 500 kHz. Fifty kHz was chosen to represent the tag energizing frequency. Acoustical theory predicts that attenuation through a fish body will be less for 50 kHz than for a higher frequency, which should facilitate energy transfer to a tag.

Table 1. Definitions of the three planes of rotation (with angular references, Fig. 3a-f) used in the study of acoustical attenuation by a fish's body.

Plane of Rotation	Description
Pitch	The plane that divides a fish or the transducer into left and right halves (sagittal plane) (tail-on = 0°, ventral aspect = 90°, head-on = 180°, dorsal aspect = 270°; Figs. 3b, 3e)
Roll	The plane that passes through and normal to the long axis and divides a fish or the transducer into fore and aft halves (transverse or orthogonal plane) (dorsal aspect = 0°, ventral aspect = 180°, side aspect = 90° and 270°; Figs. 3a, 3d). The roll plane intersected the body of a fish near the insertion of the dorsal fin.
Yaw	The plane passing parallel to the lateral lines that divides a fish or transducer into upper and lower halves (or median longitudinal plane) (tail-on = 0°, head-on = 180°, side aspect = 90° and 270°; Figs. 3c, 3f). This configuration was indistinguishable from the pitch plane for the (cylindrical) transducer when viewed alone since its directivity was nearly symmetrical about the roll axis.

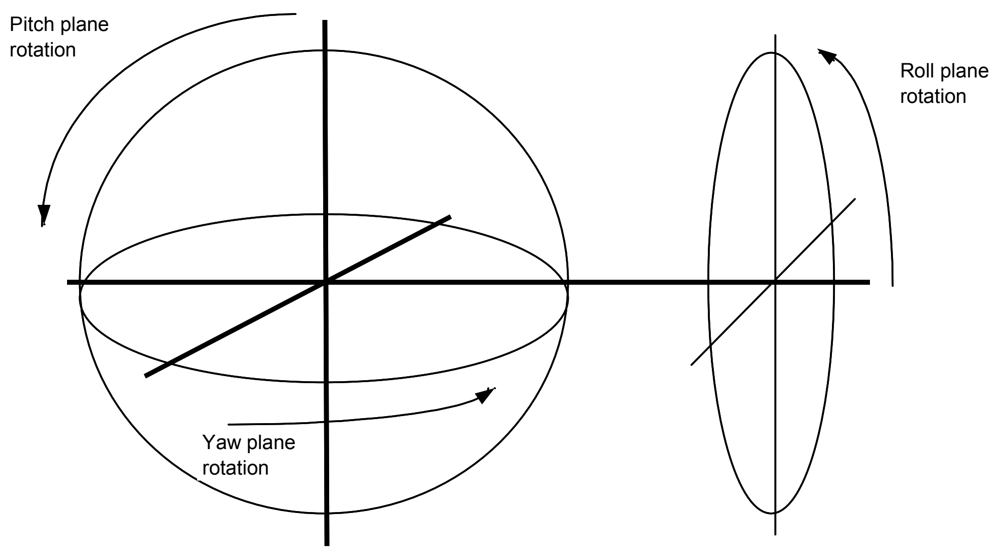

Figure 1. Pitch, roll and yaw planes of rotation used for measurement of baseline transducer directivity and acoustical attenuation effects of fish body structure. Fish were mounted on the horizontal bar, dorsal side up, and facing to the left.

Further, the diameter of a transducer capable of producing the necessary interrogation field intensity would be of a manageable size; less than 10 cm (Kinsler et al. 1982). Five hundred kHz was chosen to represent the tag response frequency because of the necessarily small transducer that would be incorporated into an A-PIT tag. The physical size of a transducer element is inversely related to its resonant frequency (Kinsler et al. 1982). In addition, a high frequency allows a greater rate of tag-code data transfer.

All measurements for this study were made on the University of Washington's acoustics barge (*R. V. Henderson*) while it was moored in 4.3 m of fresh water. The *Henderson* is a self-contained, floating laboratory for underwater acoustics research. It houses a full range of electronic test and measurement equipment, including calibrated transducers (hydrophones). Water temperature throughout the investigation was 7.5°C.

The test transducer used in this study was not calibrated, so it was not practical to attempt to directly measure acoustical attenuation through a fish body. Thus, comparative measurements were made to determine the reduction in acoustical pressure attributable to attenuation. To make these calculations, the directivity (radiation or receiving sensitivity pattern) of the test transducer was measured alone, and measured again when inserted into a fish. A particular set of aspect angles with respect to the physical axes of the transducer were maintained throughout both sets of measurements.

This comparative procedure accomplished two objectives. First, the differences between the two measurement sets constituted a direct measurement of attenuation. Secondly, most of the basic directivity effects of the test transducer were eliminated because only changes in acoustical pressure at particular aspect angles were used to calculate attenuation. Thus, test transducer directivity effects were removed from fish body attenuation measurements. A test transducer having an omnidirectional directivity pattern would have been desirable for these measurements. However, the design of such a transducer is very difficult, and its construction would have been prohibitively expensive.

The test transducer was constructed by the Applied Physics Laboratory (APL) at the University of Washington. It consisted of a single, hollow ceramic cylinder, 5.1-mm long by 2.5-mm in diameter. The finished unit measured 5.6-mm long by 4.0-mm in diameter (after encapsulation) and was attached to a 3.0-m length of RG-147 coaxial cable. Voltages representing acoustical field strengths striking the test transducer were measured at the end of the coaxial cable. Transmissions from the test transducer were measured by calibrated transducers located at a fixed horizontal range of 1.57 m.

All directivity measurements were made either with the test transducer alone or with the test transducer inserted into the coelomic cavity of a fish mounted within an adjustable suspension frame (Fig. 2). The frame was mounted on a rotatable shaft that was lowered to position the test transducer at a 2.1-m depth. Test subjects were positioned within the frame such that when rotated horizontally, a line between the test transducer and the calibrated laboratory transducer described a desired aspect plane (i.e, pitch, roll, or yaw).

The frame consisted of two pairs of metal supports, with each pair fastened together to form symmetrical crosses suspended 2-m apart, one above the other. The supports were suspended using 0.75-mm-diameter, plastic-coated, stainless steel wire. The upper members of the frame were made of 1.2-m lengths of 1.25-cm inside-diameter steel pipe, while the lower members were made of similar lengths of 7.6-cm-wide by 6.0-mm-thick steel flat-bar. The wider dimension of the flat-bar was placed parallel to the water surface. Steel flat-bar was used for the lower support because its additional weight and small cross-sectional area aided in stabilizing the frame when it was submerged and rotated.

Pitch- and roll-plane directivity data sets were collected for the test transducer alone for use as baseline measurements prior to making measurements with the transducer inserted into a fish. Directivity was nearly symmetrical throughout the roll plane of the test transducer, so pitch- and yaw-plane directivity were considered as equivalent. When the test transducer was inserted into the coelomic cavity of fish, its long axis was aligned as closely as possible with the long axis of the fish. Directivity data were then collected throughout pitch, roll, and yaw planes with respect to the axes of the fish (Fig. 1).

Freshly sacrificed fish of two general size groups were used as test specimens. The smaller individuals were sockeye salmon (*Oncorhynchus nerka*) that ranged in fork length from 24.8 to 26.7 cm. The larger fish were Atlantic salmon (*Salmo salar*) that ranged in fork length from 54.6 to 61.0 cm. A fish and/or the transducer was suspended within the test frame using monofilament fishing line (1.8 or 5.5 kg breaking strength depending upon fish size) and fishing hooks (#8-10).

The test transducer was inserted into specimen fish through a 3-mm-long incision in the abdominal musculature located posterior to the pectoral fins and 3 to 5 mm from the mid-ventral line. The coaxial cable leading from the transducer was routed through the opercular slit and out the mouth. Air or water intrusion was reduced by application of petroleum jelly around the coaxial cable entry incision. Fore and aft adjustments of the transducer within the coelomic cavity were made using a reference mark on the coaxial

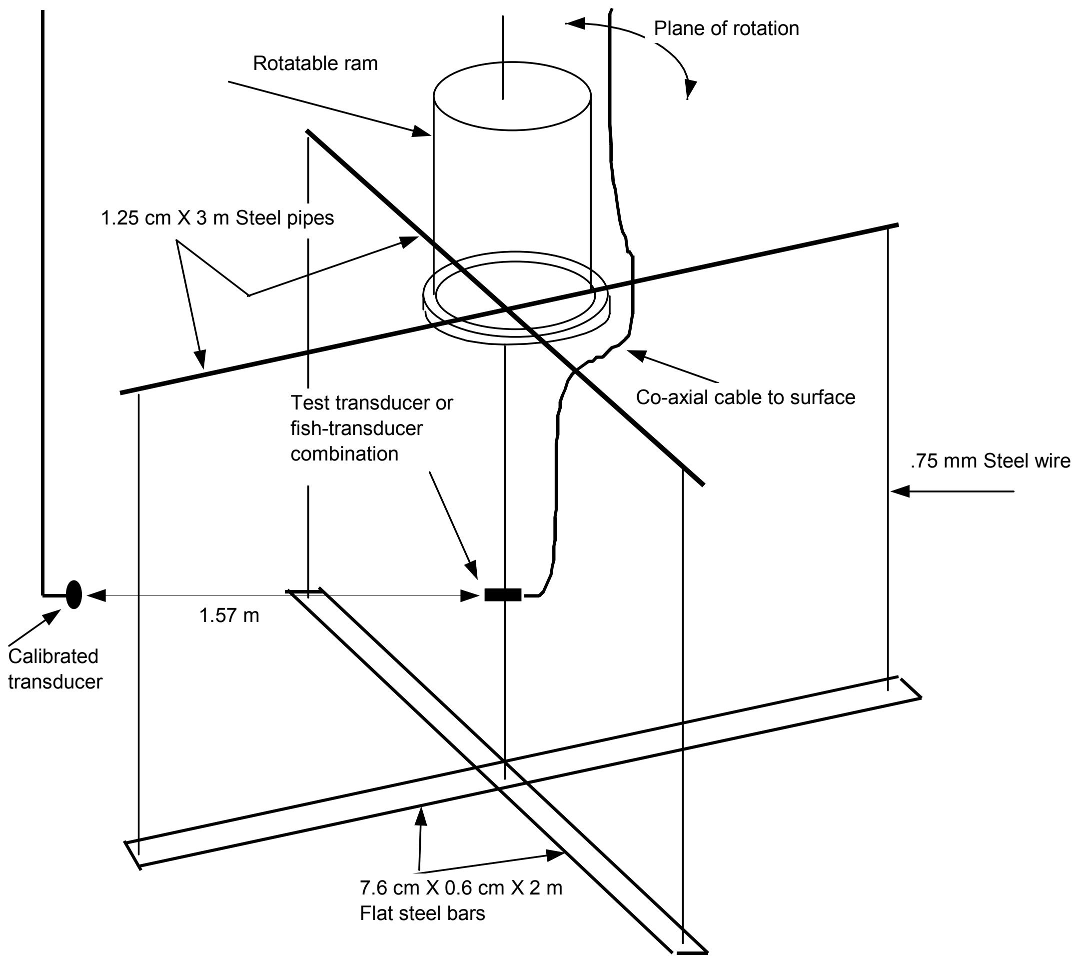

Figure 2. Diagram of the test frame used for measurement of baseline test transducer directivity and acoustical attenuation effects of fish body structure. Fish were mounted within the frame so that when rotated in the horizontal plane, their pitch, yaw or roll planes were presented to the calibrated transducer.

cable. However, dorso-ventral and side-to-side misalignments could not be observed directly and were estimated by the angle at which the cable emerged from the incision.

The test transducer was placed adjacent to the abdominal musculature at the ventral surface of the coelomic cavity, about 2 cm forward from the pelvic girdle. This is the normal location where an A-PIT tag would be placed within a fish. Attenuating effects of air in swim bladders were measured with swim bladders fully inflated, partially inflated, and deflated.

Air volumes were adjusted using a 60-cc syringe attached to a 20.5-mm long, 22-gauge hypodermic needle. The needle and syringe were attached by a 3.0-m length of 1.8-mm (outside diameter) plastic tubing. The needle was inserted into the air bladder and the tubing was routed forward from the needle through the opercular slit and out the mouth to the surface. The hypodermic needle was left in position during all measurements, and the tubing was positioned for least interference to acoustic measurements.

All acoustic measurements consisted of two types. The first type was of the acoustical pressure received by the test transducer from a fixed source at uniformly spaced aspect angles, either alone or within a fish, as it was rotated through 360°. The second type of measurement was of the acoustical pressure received by a calibrated measurement hydrophone, which was radiated by the test transducer at similar aspect angles.

Receive measurements were made with a constant 50-kHz acoustic field level directed toward the test transducer using a calibrated transducer positioned at a fixed location. Similarly, a calibrated transducer at the same location was used to measure the strength of a 500-kHz acoustical field radiated from the test transducer, which was energized by a constant input level.

Measurement values were recorded in decibel units, relative to one micro Pascal (dBμPa). Directivity data sets, as used in this report, consist of groups of acoustical pressure measurements received by or transmitted from the test transducer at incremental angles throughout 360 degrees of rotation within a particular plane. Total attenuation by a fish was calculated as the sum of 50 kHz (simulated tag interrogation field) and 500 kHz (simulated tag transponding field). Attenuation effects differ for the two frequencies when they propagate through different types of tissue (see Kinsler et al. 1982 for a detailed review of frequency-dependent attenuation of sound propagation).

Results and Discussion

With the test transducer implanted within the coelomic cavity of a fish, most measurements of sound attenuation were characterized by wide ranges in values with respect to aspect or viewing angle. The largest source of variability in measured attenuation was related to the physical properties of a fish. These properties are of primary interest since they suggest aspect angles where an implanted A-PIT tag could possibly be detected.

Most repeated directivity data sets for a particular test transducer/fish configuration were similar when no physical adjustment of the fish or transducer was made between measurements. However, physical adjustments (i.e., repositioning of the test transducer or fish on the test frame; lifting the frame out of the water and repositioning it at depth) often resulted in changes in measured directivity. The frame was not sufficiently rigid to maintain or allow precise realignment of the transducer or of a fish. In addition, large differences in directivity values were seen between fish. This resulted primarily from size differences between specimens and individual acoustical characteristics of fish.

Two factors unrelated to the characteristics of fish were identified as contributing to the variability between attenuation measurements. They were misalignment of test transducer/fish combinations on the test frame and uncertainty in swim-bladder inflation. Due to its physical shape, the directivity (radiation and receiving sensitivity patterns) of the test transducer varied considerably with aspect. Likewise, the acoustical attenuating characteristics through a fish body varied for different aspects, depending on the organs and structures through which sound propagated. Thus, moderate misalignments of the test transducer and the fish could result in large apparent changes of attenuation, particularly where large changes in test-transducer directivity occurred over small changes in aspect angle, since directivity effects are additive.

Acoustical theory predicts high attenuation of sound propagation through an air bubble equivalent to the size of a fish swim bladder (Kinsler et al. 1982). However, no clear trend was seen in the degree of swim-bladder inflation and acoustical attenuation during this study. Overall, attenuation was less when the swim bladder was deflated. However, attenuation effects of the swim bladder were not significantly greater than those of the heavy dorsal musculature and skeletal structure of a fish.

Complete deflation of the swim bladder was difficult to achieve. Dissection revealed that the swim bladder did not collapse evenly or fully using the syringe. In all observed cases, some air remained trapped in parts of the swim bladder. Surgical deflation of the swim bladder required that the transducer be removed while the coelomic cavity was opened and the swim bladder was punctured and completely evacuated of air. In addition, lifting the test frame out of the water, and later lowering it back to depth, caused considerable inadvertent misalignment of the transducer and fish, contributing to uncertainty in comparing attenuation measurements.

Although the fore/aft location of the test transducer was known, small changes in its location relative to the pelvic girdle had not been predicted to significantly affect acoustical attenuation. However, for the larger fish, considerably higher attenuation was noted when the internal transducer was positioned about 2 cm forward of the pelvic girdle than when placed directly dorsal of the girdle. The effect probably was related to differences in the size and shape of the swim bladder at the two locations and perhaps to differences in its proximity to the test transducer.

Dorsal aspect attenuation of acoustical pressure amounted to 25-30 dB reduction (94-97%) for 50 kHz and 15-20 dB reduction (82-90%) for 500 kHz, when the test transducer was forward of the pelvic girdle. However, when the transducer was directly dorsal of the pelvic girdle, attenuation was only a 5- to 10-dB reduction (44-68%) for either frequency. Similar measurements were not made using the smaller size fish. It is likely, based on our experience with RF-PIT tags, that under normal conditions some A-PIT tags could migrate between either location. Those positioned just dorsal of the pelvic girdle would be subjected to lower attenuation effects and would have a higher probability of detection.

The sum of acoustical attenuation of 50-kHz energization and 500-kHz response fields through a fish body will determine at which aspect angles an internal A-PIT tag would be detectable. Generalized degrees of attenuation with respect to aspect angle were compiled by comparison of attenuation plots for all fish-size and swim-bladder inflation conditions tested. Predictions of the ranges of aspect angles over which A-PIT tags would be reliably detectable were made using a composite of this data.

These predictions are based on the assumption that for a 10-m maximum range, tag detection would be unlikely if total (2-way; energization + response) fish-body attenuation was more than 24 dB (94% reduction). This somewhat arbitrary threshold was chosen to reflect the source level and sensitivity of a typical echo-sounding system and a practically attainable tag-response source level. The aspect angles where attenuation was greatest for large and small fish were similar. High attenuation values were common in pitch and roll planes to at least 45 degrees fore/aft or left/right from the dorsal aspect. In addition, high attenuation was consistent within 10-20 degrees of the tail-on aspect.

Attenuation at the near head-on aspect was less than at the tail-on aspect, but was still sufficiently severe that the likelihood of reliable A-PIT tag detection would be marginal. Qualitative predictions of pitch, roll, and yaw plane aspect angles where A-PIT tagged fish would most likely be detectable are given in Table 2. Attenuation plots typical of those used to predict reliable tag detection are shown in Figures 3a-f. Attenuation, when presented as a polar plot, shows variations with aspect angle throughout a plane of rotation. Attenuation levels of 0, -6, -10, and -20 dB are equivalent to sound pressure reductions of 0, 50, 69, and 90%, respectively. Note that the plots in Figures 3a-f are only typical of directivity measurements and may not correspond precisely with the ranges of predicted tag-detection ability in Table 2.

Even though there was considerable uncertainty in the measurements made during this study, it was shown that high acoustical attenuation was typical over much of the dorsal aspect of fish for all sizes tested. Attenuation levels were shown to be severe enough to significantly limit the usefulness of an A-PIT tag detection system using a downward directed interrogation beam pattern. Therefore, installations of interrogation and receiving transducers on the hull of a vessel would probably not yield reliable results.

Conversely, low levels of attenuation were found over most near-ventral aspect angles, showing that an upwardly directed acoustical beam could probably detect tags with acceptable reliability. Transducers mounted on the floor of a fish ladder or on the bed of a stream would probably yield satisfactory results. However, if the fish routinely approached close to the transducer, tag detection could be difficult due to the narrow width (small sampling volume) of the beam at very short range.

Acoustical attenuation through a fish body is not the only factor that would limit the detectability of A-PIT tags. Ambient noise and bubbles created by wind, turbulence, waterfalls, etc. would interfere with tag detection in at least two ways: acoustical noise would obscure recognition of some tag responses, and bubbles would attenuate sound fields traveling to and from a tag. It is not known how sensitive A-PIT tag decoding would be to environmental noise interference. Therefore, custom installation would be required at each interrogation site to overcome these potential problems.

An independent review of the data sets collected during this investigation was made by GRD Associates (1994, Appendix A). The author concluded that development of a system that could reliably detect implanted A-PIT tags to a range of 10 m could be accomplished, but concurred that there are aspect angles in which a tag may not be detectable.

Table 2. Predicted ranges of aspect angles where one-way acoustical attenuation through the body of a salmonid would allow A-PIT tag energization (50 kHz) or tag response detection (500 kHz). Note that total (two-way) attenuation equals the sum of energization plus response frequency attenuation. A-PIT tags would be detectable only within overlapping angle ranges for the two frequencies, for each aspect plane listed below. Angles are referenced to those in the attenuation plots shown in Figure 3a-f.

	Frequency	
Viewing aspect	50 kHz (range)	500 kHz (range)
Dorsal aspect		
Pitch plane	[a]	[a]
Roll plane	[a]	[a]
Ventral aspect		
Pitch plane	30°-190°	55°-125°
Roll plane	85°-275°	80°-280°[c] 40°-320°[d]
Side aspect		
Yaw plane	30°-150°	40°-140°
Roll plane	10°-180°	10°-180°
Head-on aspect		
Pitch plane	140°-200°	[b]
Yaw plane	150°-210°	[b]
Tail-on aspect		
Pitch plane	10°-200°	[b]
Yaw plane	20°-340°	[b]

a Undetectable for > 45 degrees.
b Could not be reliably determined due to nulls in the test transducer directivity pattern at this particular aspect.
c Inflated swim bladder.
d Deflated swim bladder.

GRD Associates presented several suggestions for improving tag-detection ability. These included design of a tag with increased transmitting power, design of an active-when-interrogated tag using an internal battery to supplement transmitting power, and increased tag-energization field strength. GRD Associates also suggested that tag detection would be more reliable if interrogator receiving sensitivity could be increased and the maximum required operating range (10 m) were reduced. Implementation of some of these suggestions would change various characteristics of the A-PIT tag as currently envisioned. The tag would have to be larger to contain an internal battery, developmental costs would be probably increase, and the interrogation system would be more complex.

Based on measurements of acoustic field attenuation by fish bodies, and the independent review of the results of our measurements, we recommend that development of an A-PIT tag detection system not be undertaken at this time. The aspect angles for viewing the tag are too restrictive for broad research application in the Columbia River Basin. In addition, environmental noise would further complicate operation of the tag system in most areas of interest.

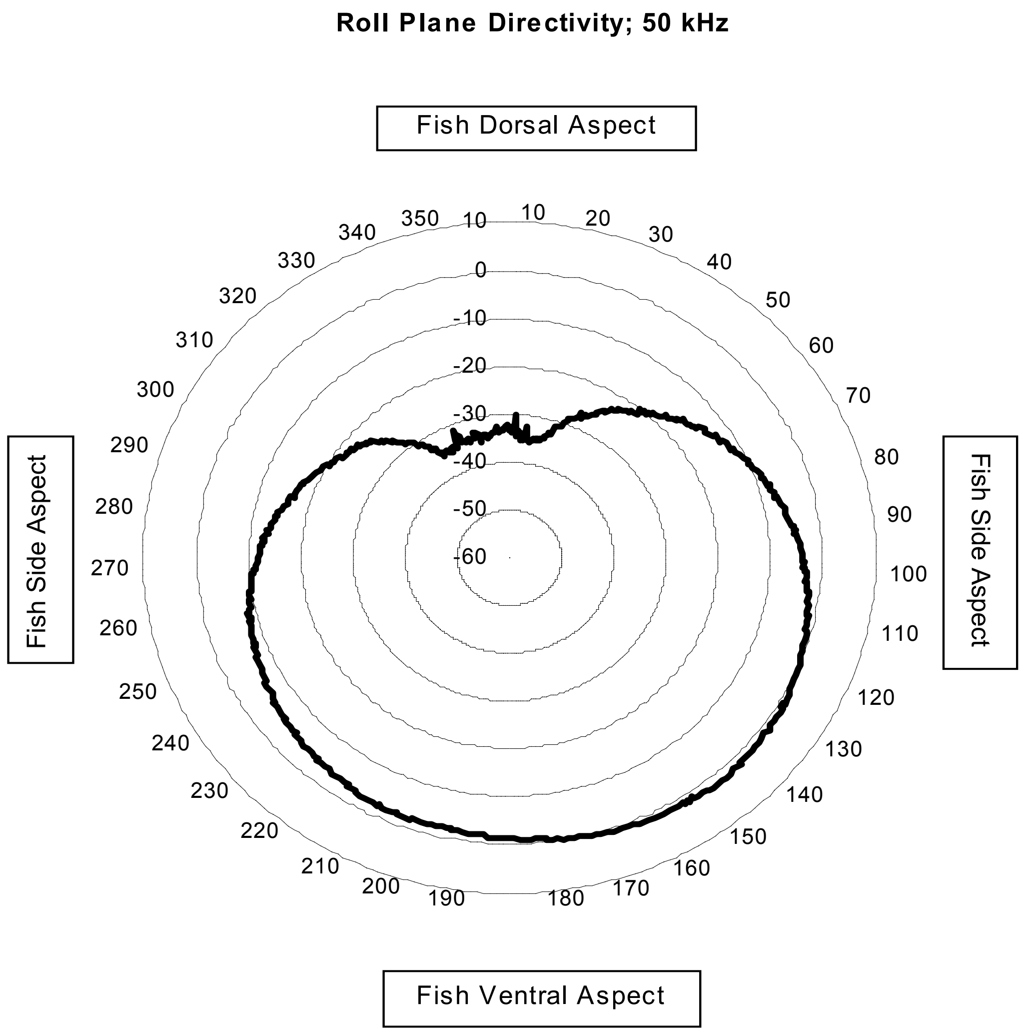

Figure 3a. Typical directivity plot of roll plane acoustical attenuation due to a fish body for 50 kHz; measured with the test transducer inserted into the coelomic cavity of a fish, at a location where an A-pit tag would be expected to lie.

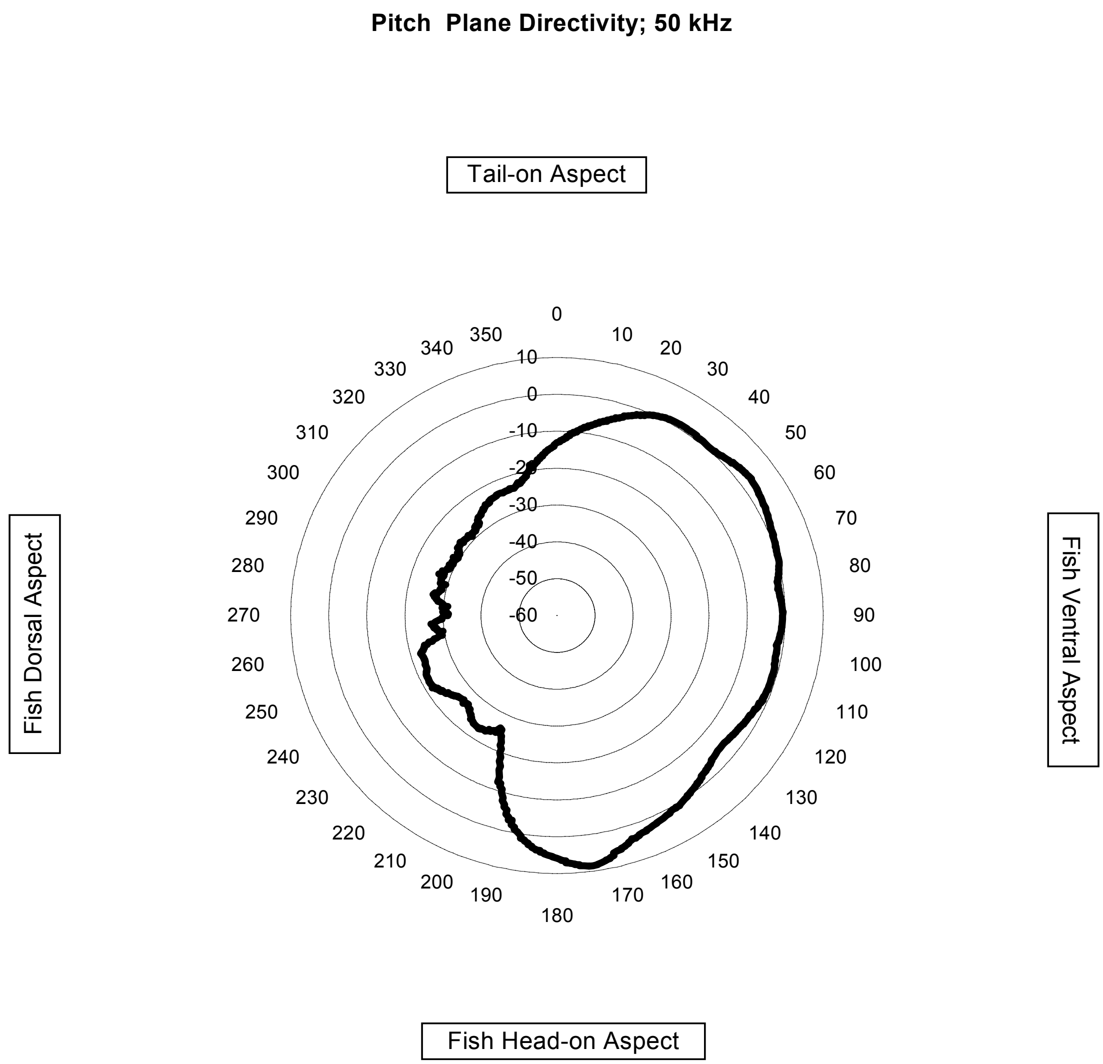

Figure 3b. Typical directivity plot of pitch plane acoustical attenuation due to a fish body for 50 kHz; measured with the test transducer inserted into the coelomic cavity of a fish, at a location where an A-pit tag would be expected to lie.

Yaw Plane Directivity; 50 kHz

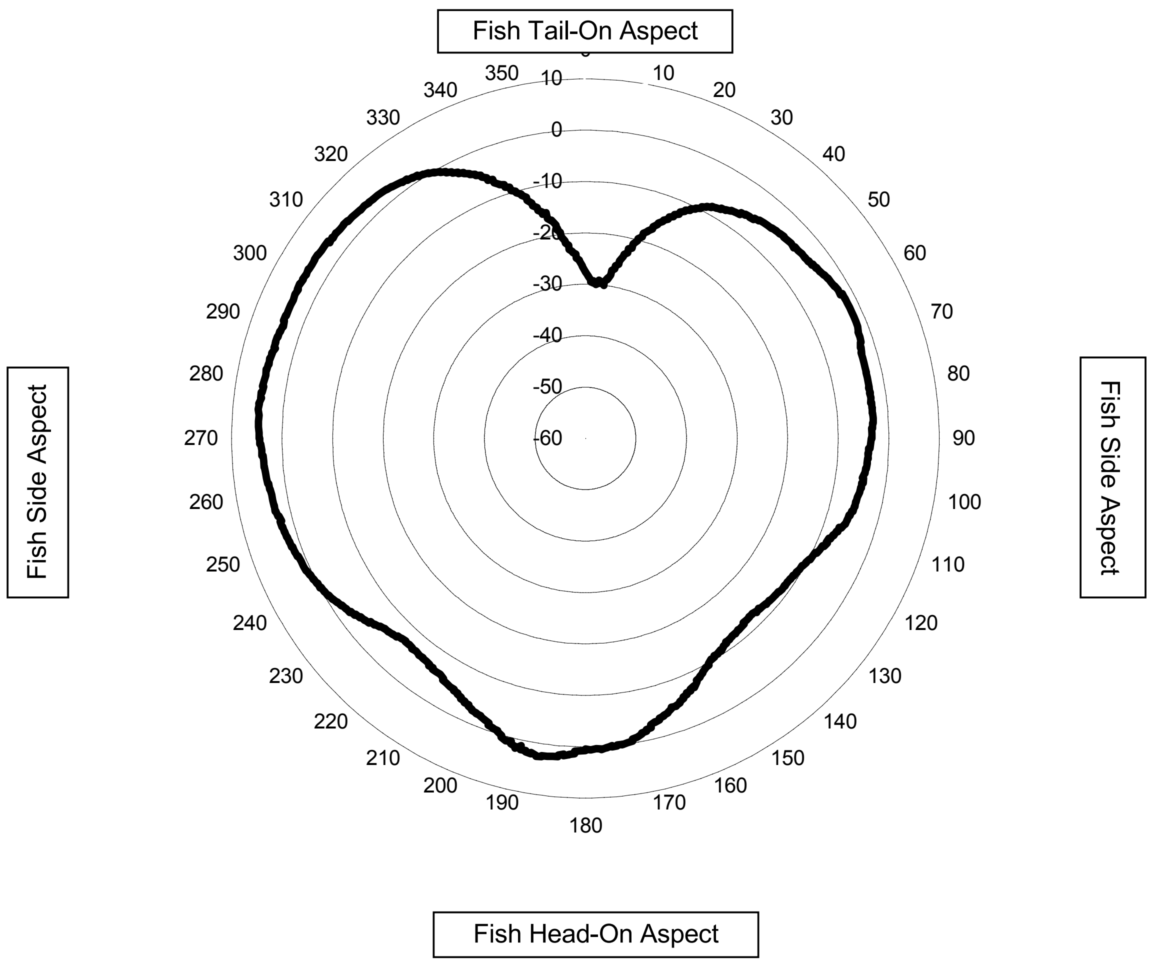

Figure 3c. Typical directivity plot of yaw plane acoustical attenuation due to a fish body for 50 kHz; measured with the test transducer inserted into the coelomic cavity of a fish, at a location where an A-pit tag would be expected to lie.

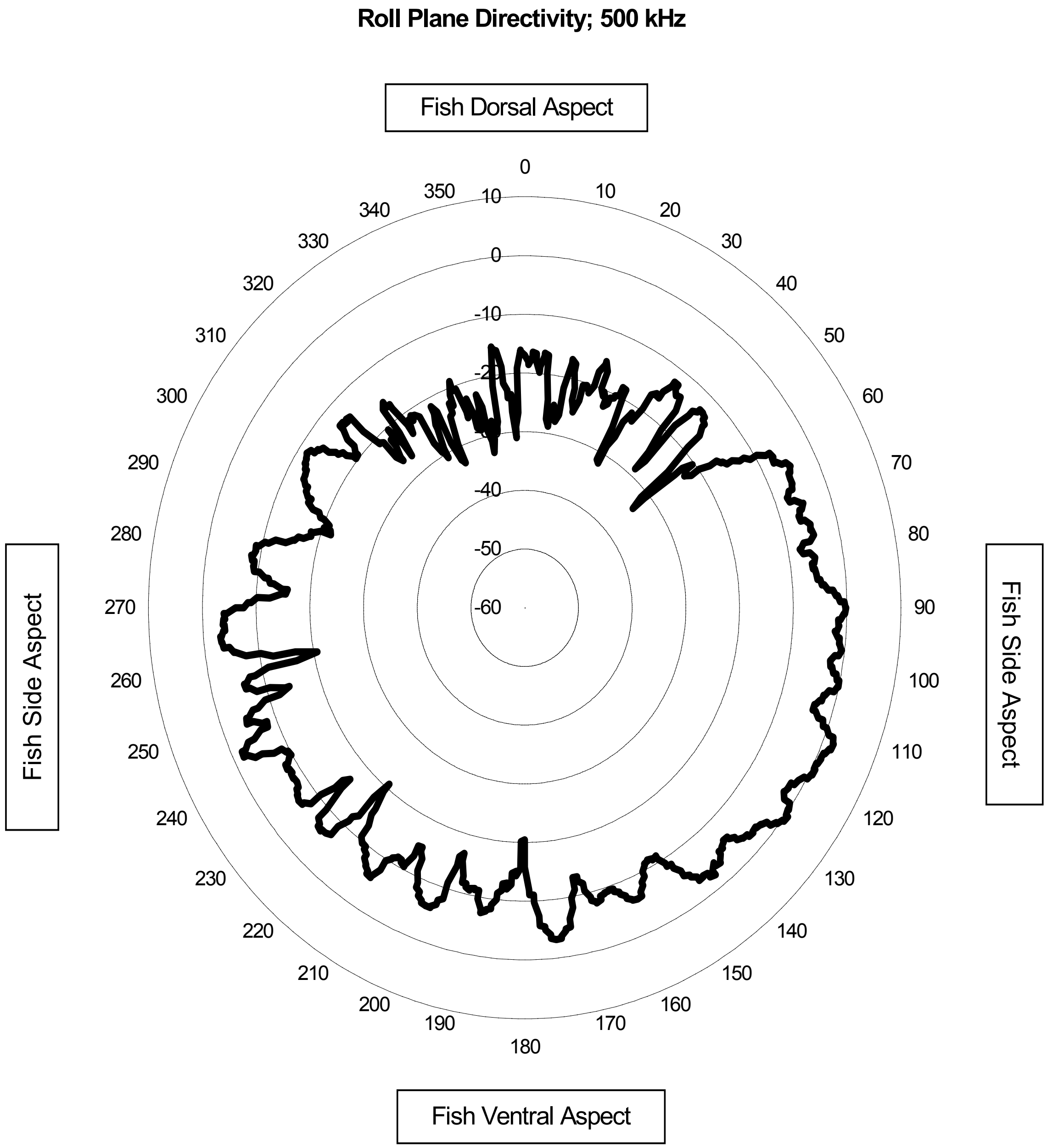

Figure 3d. Typical directivity of roll plane acoustical attenuation due to a fish body for 500 kHz; measured with the test transducer inserted into the coelomic cavity of a fish, at a location where an A-pit tag would be expected to lie.

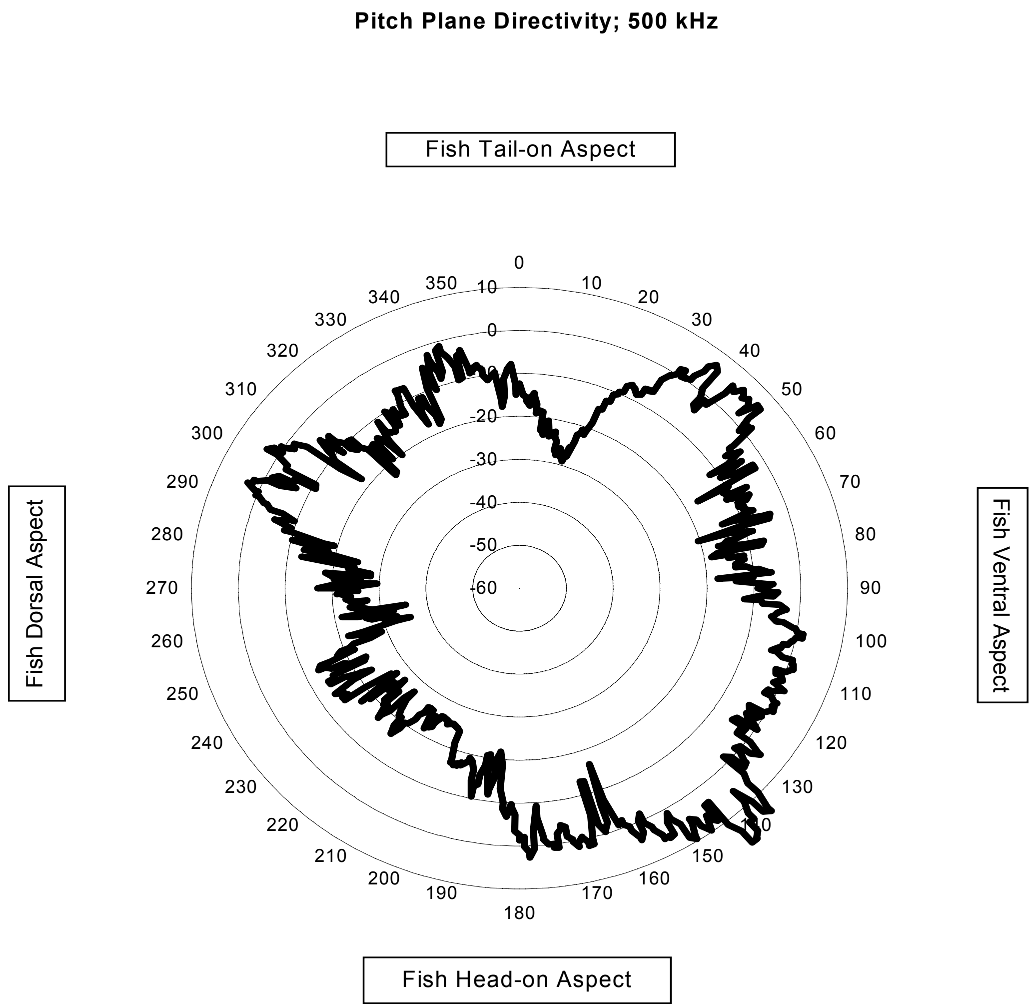

Figure 3e. Typical directivity plot of roll plane acoustical attenuation due to a fish body for 500 kHz; measured with the test transducer inserted into the coelomic cavity of a fish, at a location where an A-pit tag would be expected to lie.

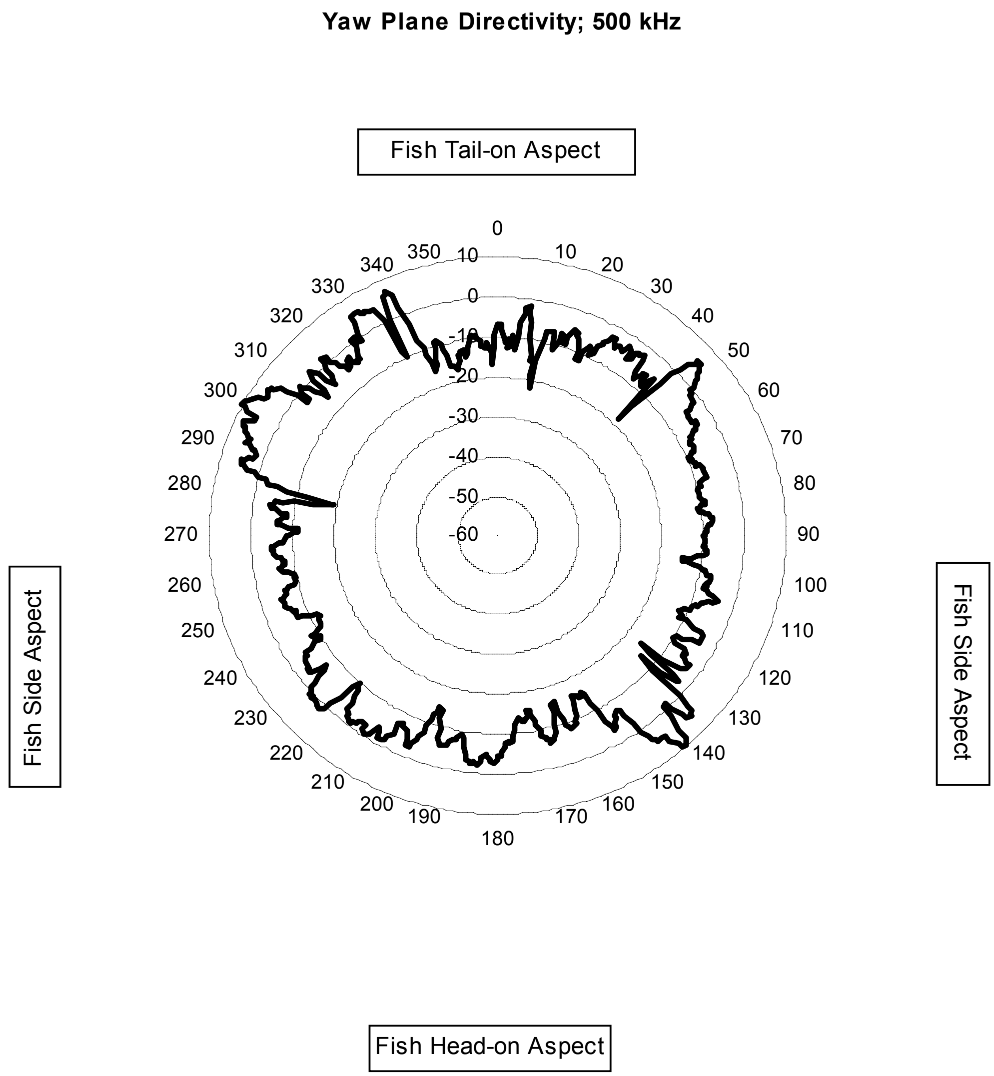

Figure 3f. Typical directivity plot of yaw plane acoustical attenuation due to a fish body for 500 kHz; measured with the test transducer inserted into the coelomic cavity of a fish, at a location where an A-pit tag would be expected to lie.

Conclusions and Recommendations

1) Attenuation of 50- and 500-kHz frequencies by the bodies of differing sizes of salmonids was investigated.

2) Calculations were based on the assumption that the tag would operate at a range of up to 10 m from the interrogating/receiving transducer.

3) All measurements of attenuation were made by comparison of acoustical field strengths received or generated by a test transducer operated both outside and surgically implanted in the coelomic cavity of a fish, at similar aspect angles. The test transducer alone or the fish with the implanted test transducer were positioned on an adjustable support apparatus during all measurements.

4) Wide ranges in attenuation values, in relation to aspect or viewing angle, were observed. Measurement variability was attributed to the following factors, in order of importance: viewing or aspect angle, fish size, location of the transducer within a fish, air-bladder inflation variability, and physical test apparatus.

5) High attenuation values were common to at least 45 degrees from the dorsal aspect of the fish in all directions.

6) High signal attenuation within 10-20 degrees of the tail-on aspect was observed.

7) Attenuation at the near head-on aspect was less than at tail-on aspect but was still marginal for reliable detection.

8) Low attenuation was observed for all fish for the near-ventral aspect angles.

9) Short-range ventral viewing may be difficult because of acoustic beam narrowing very near the transducer.

10) Results suggest that an upward- and lateral-viewing A-PIT tag system could detect tags with acceptable efficiency.

11) Ambient noise will reduce tag detection efficiency because of interference with its weak return signal.

12) An independent review of NMFS data by GRD Associates concluded that development of an A-PIT tag was technically feasible, but when injected into a fish would be limited in the range of aspect angles at which it could reliably be

detected. GRD Associates offered several suggestions for improving the tag, including adding a battery to improve tag return-signal strength. However, this approach changes the tag concept from a passive to an active tag, and as such the tag would have a limited operating life.

13) We concluded, because of the limited viewing aspect angles where tags could be reliably detected and the possible limitations imposed by environmental noise, that the tag not be developed.

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TECHNICAL FEASIBILITY OF AN ACOUSTIC RESONANT TAG

Introduction

A marking tool that will allow remote, non-invasive detection and recognition of tagged fish groups is needed for a variety of fisheries research and management programs. Such a tag must be reliable, stable, and must not impose a significant biological burden. A hollow glass sphere that acoustically resonates could potentially be such a tag. Like passive integrated transponder (PIT) tags, the spheres could be implanted into the coelomic cavity of fish. As envisioned, the resonant tags would be detected by spectral analysis of acoustic echo returns from exposing fish to a swept frequency (limited portion of a broad frequency band) pulse (an acoustical chirp), which would include the resonant frequency of the implanted tag.

The frequency range of the chirp could be selected from a large spectrum, perhaps ranging from 10 to 500 kHz, and would be selected depending upon the characteristics of a particular fish/resonant sphere combination of interest. The reflective contribution or "fingerprint" of the resonant tag would give tagged fish a different spectral pattern than untagged fish. Thus, tagged fish and untagged fish of similar size could be distinguished. This approach would permit identifying, enumerating, and determining the distributions of tagged fish.

In concept, a resonant tag is simple and appealing, but it may be difficult to implement because the tag's "fingerprint" could be masked by the spectral characteristics of the fish or by ambient environmental noise. In addition, an effective resonant sphere for implantation into fish and a resonant-tag detection system do not currently exist and would need to be developed. Furthermore, the acoustical field strength needed for acquisition of sphere echo returns from a 10-m range was estimated at 207-213 dBµPa@ 1-m from the face of the transducer. This level of acoustic energy could have a detrimental effect on biota.

Each of these factors needs to be investigated to determine if the effort is justified. In addition, calculations estimating the acoustical reflectivity or target strength (TS) of fish, TS of resonant spheres, and enhancement of fish TS by an implanted resonant sphere are essential in determining the feasibility of the proposed tag. This paper addresses the enhancement of fish TS.

Methods and Materials

The target strength of an object (i.e., a fish) is calculated as 10 times the logarithm of the ratio of incident to reflected acoustical intensity, at a range of 1 m. By convention, a perfectly reflecting sphere having a radius of 1 m has been adopted as a 0-dB target-strength reference. Since the surface, or back-scattering area of this sphere is 4π m^2, the effective back-scattering area of another reflector can be calculated from its target strength, which is also the ratio of its scattering area to that of the standard sphere. The TS of a fish is directly proportional to its length and indirectly proportional to the frequency of an applied acoustical pressure field (Table 1).

Target strength (in dB), based on scattering area, is defined as follows (Appendix B):

$$TS_{(\sigma)} = 10 \log(\sigma/4\pi) \tag{1}$$

where σ = effective scattering area of a fish (m^2) and
4π = surface area of a 1 m radius sphere.

The target strength of a scatterer such as a fish is related not only to its length, but also to the frequency of the acoustic field used to measure reflectivity. Fish TS may be estimated as below (Appendix B):

$$TS_{(fish)} = 10 \times \log(L^{1.87} \times \lambda^{0.13}) - 27.7 \tag{2}$$

where L = fish length (m) and
λ = acoustic wavelength (m).

The TS of different sized, very thin-walled spheres (thickness ratio = inner radius/outer radius = 0.99), near their resonance frequencies, can be calculated using Equation 3 (from Dahl, Appendix B), as follows:

$$TS_{(sphere)} = 20 \times \log(a)-44 \tag{3}$$

where a = sphere radius (mm).

As with fish, TS of the resonant spheres increases with size (Table 2). At frequencies other than near resonance (> 25% of resonance frequency; Kinsler et al. 1982), the approximate TS of the sphere can be calculated using Equation 1. These calculations are idealized, as neither the effects of fish tissue on sphere resonance nor interference problems due to spectral characteristics of a fish are considered.

Table 1. Theoretical target strengths (TS in dB) of fish in relation to length and frequency (see Equation 2).

Fish length (cm)	Frequency (kHz)			
	10	50	100	500
10	-47.50	-48.40	-48.80	-49.70
30	-38.50	-39.50	-39.80	-40.80
60	-32.90	-33.80	-34.20	-35.10
90	-29.60	-30.50	-30.90	-31.80

Table 2. Target strength, resonant frequency, volume and displacement (buoyancy) of hollow, resonant spheres (air-filled glass spheres; thickness ratio = 0.99).

Sphere radius (mm)	Target strength (dB)	Resonant frequency (kHz)	Sphere volume (mm^3)	Sphere displacement (mg)
0.50	-50.00	391.6	0.5	0.5
1.00	-44.00	195.8	4.2	4.2
1.80	-39.00	108.8	24	24.4
2.00	-38.00	97.9	34	34
5.00	-30.00	39.2	520	520

In conjunction with this study, a contract was issued to the University of Washington Applied Physics Laboratory to investigate the theoretical feasibility of a resonating tag for fisheries. The results of the study are presented in Appendix B and are based upon a fixed set of conditions. These conditions were as follows: fish length of 100 mm; two tag sizes, one with a radius of $\geq$ 1.0 mm for a hollow sphere and one with a radius of $\geq$ 1.8 mm for a solid sphere; and frequencies of 30- to 500-kHz).

Results and Discussion

Three critical factors in the development of a resonant tag are 1) the size range of fish to be tagged, 2) the size range of tagged fish to be detected, and 3) the size of the implanted tag. There is a strong relationship between these factors from both biological and acoustical standpoints. The combined reflectivity of the fish and the resonant sphere is equivalent to their combined scattering areas. As a fish increases in size, its target strength also increases (Equation 3), thus eventually masking the acoustic contribution of a resonant tag.

Target strengths (TS) for fish of various lengths (10, 30, and 60 cm), in relation to an 1.8-mm-radius resonant, hollow glass sphere having a shell thickness ratio of 0.99, are shown in Table 3. Table 3 values were calculated for interrogation at tag resonant frequency using Equations 3, 4 (Appendix B), and 5 (from Johannasson and Mitson 1983).

However, at frequencies greater than those where resonance effects are significant, the TS of the sphere will amount to -44 dB (Equation 1) or 5 dB lower than at resonance. Reflectivity at frequencies below resonance would be considerably less.

$$F_{(res)} = 195.8/a \tag{4}$$

where a = sphere radius (mm).

$$TS = 10 \log((\sigma_{(fish)} + \sigma_{(sphere)})/4\pi) \tag{5}$$

where $\sigma_{(fish)}$ = effective scattering area of a fish (m^2) and
$\sigma_{(sphere)}$ = effective scattering area of an implanted resonant sphere (m^2).

The theoretical enhancement of fish TS values by a 1.8-mm radius resonant sphere, measured at the resonant frequency, would equal 10.3, 3.3, and 1.1 dB for the 10-, 30-, and 60-cm fish, respectively (Table 3). The 10-dB enhancement of a 10-cm fish would probably be measurable, but the 3-dB enhancement would be near the threshold of discrimination by spectral analyses. It is unlikely that the 1-dB enhancement of the 60-cm-long fish TS would be detectable. A larger resonant sphere would enhance detection in large fish, but if implanted in small fish before they grow to larger size, may also impose an unacceptable biological burden.

An implanted hollow resonant sphere may affect a fish's equilibrium because the sphere will be buoyant. The displacement of a hollow sphere in water (disregarding its weight) can be calculated by the equation:

$$D_{(sphere)} = V_{(sphere)}/r \tag{6}$$

where $V_{(sphere)} = 4\pi a^3/3$ (cm^3)
D = displacement (g)
r = density of water (g/cm^3)

Displacement of the swim bladder of a 10-cm-long salmon is about 700 mg, while displacement of an 1.8-mm-radius sphere is 24.4 mg, and would represent about 7% of the fish's body weight in fresh water (Shibata 1970, Johannesson and Mitson 1983). Thus, sphere displacement (buoyancy) would amount to approximately 3% of swim bladder displacement. While this would probably not present a significant biological burden, the buoyancy of a larger resonant sphere might (Table 2). For example, a 5.0-mm-radius sphere would displace 520 mg, which would be equivalent to almost 75% of swim bladder displacement in a 10-cm fish.

The discussion of fish marking with resonant spheres has to this point disregarded the effects of environmental factors on detection of tags. The presence of bubbles, environmental noise, and the viewing or aspect angle for interrogation of tagged fish can all limit the ability to detect tagged fish. Bubbles formed by wind, swift current, and waterfalls would interfere with acoustic sound propagation and thus reduce detection efficiency. Bubbles are excellent reflectors that effectively scatter directed sound, often to the extent that a detection system could be disabled. Further, bubbles similar in size to an implanted sphere could resonate and interfere with tag detection. Sites where a resonant-tag interrogation system could be deployed will have to be carefully selected to reduce the effects of bubbles.

Table 3. Theoretical target strength and TS enhancement (dB) of fish due to an implanted sphere having a radius of 1.8 mm and a resonant frequency of 108.8 kHz.

	Target Strength			
Fish length (cm)	Fish (dB)	Sphere (dB)	Combined (dB)	Enhancement (dB)
10.00	-49.00	-39.00	-38.60	10.4
30.00	-39.50	-39.00	-36.20	3.3
60.00	-33.80	-39.00	-32.70	1.1

Strong ambient noise sources will also interfere with resonant tag detection. Spectral components of noise are indistinguishable from those of target fish or resonant tags when they occur in the same frequency range, and their presence could thus mask tag recognition. Potential noise sources include pumps, power turbines, waterfalls, rain, and boats.

The interrogation viewing or aspect angles from which tagged fish could be recognized will be limited by fish morphology. When interrogated from the dorsal aspect, a fish's swim bladder, dorsal musculature, and vertebral column would be aligned in the propagation path between the resonant sphere tag in the coelomic cavity and the interrogating transducer. The result would be that the interrogating acoustic field strength and the echo from the sphere would be significantly attenuated.

A study of acoustical energy transfer through a fish body indicated that this attenuation could block tag detection for aspect angles within at least 45 degrees from dorsal aspect (see "Technical Feasibility of an Acoustic PIT-Tag" in this report). An interrogation transducer would probably have to be deployed such that fish are insonified from side or ventral aspects to obtain reliable detection.

The theoretical work of the University of Washington Applied Physics Laboratory (Appendix B) concluded that hollow spheres of useable size for use in juvenile salmonids could increase their TS by as much as 6 dB, and thus could theoretically be a useful tool for monitoring salmon movement. A limited discussion of sphere material and construction is presented in Appendix B.

Based upon the theoretical calculations of fish/sphere TS and the independent evaluation of the concept of resonant sphere tags by the University of Washington, the proposed detection system appears to be technically feasible and probably could be developed. However, because of the number of factors discussed that will negatively impact system performance, the resonating sphere tag would have very limited application. Thus, we recommend that a resonant sphere tag detection system not be developed for use in the Columbia River Basin at this time.

Conclusions and Recommendations

We concluded that on a theoretical basis, the detection of resonant spheres implanted within fish is feasible but severely limited by several factors. An independent appraisal of the concept by the University of Washington Applied Physics Laboratory confirmed our conclusion. Factors identified as limiting the performance of the system included:

1) increasing difficulty to detect tags as fish grow;

2) the problem of tag size, which must be considered in terms of biological effect on small fish and loss of detection ability as fish grow larger;

3) sensitivity of tag detection, which may be limited by bubbles in the water, ambient noise, and the spectral characteristics of fish; and

4) blocking of tag detection by bone, tissue, and swim bladder shading.

Even though development of a resonant sphere detection system is technically feasible, the above limitations so restrict its potential use that we recommend it not be developed for use in the Columbia River Basin at this time.

References

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DETRIMENTAL EFFECTS OF ULTRASOUND ON ANIMALS: A LITERATURE REVIEW

Introduction

Two types of passive acoustically energized tags were consideration for potential development by NMFS (see "Technical Feasibility of an Acoustic PIT-Tag" and "Technical Feasibility of a Acoustic Resonant Tag" in this report). The first tag, described as an acoustic-passive-integrated transponder (A-PIT), would acquire its operating power and would respond using acoustical (sound) energy. Sound, as used in this paper, refers to any vibration or displacement of water or air particles in response to a pressure wave.

Two separate sound fields would operate the A-PIT tag system: a continuous 50-kHz field would energize the tag, and a 500-kHz field would be used for its response. An energy budget was estimated for the system based on a receiver threshold of 93 dBμPa (decibels referenced to 1.0 micro Pascal) (power level = 1.3×10^{-7} mW/cm^2), and a tag detectability range of 10 m. Results suggested the 50-kHz energizing sound-field strength should be 207-213 dBμPa@1 m (330-1330 W/m^2) and the 500-kHz response-field strength should be 120-126 dBμPa@1 m (0.67-2.65 mW/m^2). Conversions of acoustical pressure to equivalent electrical power are presented for reference in Table 1. Based on these calculations, the minimum energizing field that must strike the tag would be 186-192 dBμPa. Thus, the process of energizing the proposed A-PIT tag will expose target species and other animals to strong, continuous acoustic fields at 50 kHz.

The second tag proposed was a glass sphere that would acoustically resonate at a specific frequency. Such a tag would be detected by spectral analysis of acoustic echo returns from exposing fish to a pulse from a limited portion of a broad frequency band (i.e., 10-500 kHz). The sound-field strength needed for acquisition of sphere echo returns from a 10-m range was estimated at 207-213 dBμPa@1 m from the face of the transducer. This field strength is similar to that proposed for the A-PIT tag, and as such, would likewise expose biota to strong, pulsed acoustic fields.

Based on the above information, a review of the literature was conducted to investigate possible detrimental effects on biota from acoustic energy. Discussions are focused toward the frequency and field strengths required to operate either of the proposed tags.

Table 1. Conversions of acoustical pressure to equivalent electrical power.

Acoustical Pressure dB μPa	Equivalent Electrical power Watts/m^2
10.00	6.667×10^{-18}
20	6.667×10^{-17}
30	6.667×10^{-16}
40	6.667×10^{-15}
50	6.667×10^{-14}
60	6.667×10^{-13}
70	6.667×10^{-12}
80	6.667×10^{-11}
90	6.667×10^{-10}
100	6.667×10^{-09}
110	6.667×10^{-08}
120	6.667×10^{-07}
130	6.667×10^{-06}
140	6.667×10^{-05}
150	6.667×10^{-04}
160	6.667×10^{-03}
170	6.667×10^{-02}
180	6.667×10^{-01}
190	$6.667 \times 10^{+00}$
200	$6.667 \times 10^{+01}$
210	$6.667 \times 10^{+02}$
220	$6.667 \times 10^{+03}$
230	$6.667 \times 10^{+04}$
240	$6.667 \times 10^{+05}$

Methods and Materials

The literature search conducted was limited in scope, concentrating on major papers that best represent the state of current knowledge in the area of acoustics as related to fish, cetaceans, and terrestrial animals. Literature citations were grouped into six discussion areas. The first two areas provided background information on general mechanisms and abilities of fish to sense sound. The third and fourth areas described some effects of acoustic energy on fish behavior and physiological changes that can be caused when fish are exposed to strong acoustic fields. The fifth area discussed hearing sensitivity of cetaceans and the sound fields they produce, and the final area included literature describing detrimental effects of acoustic fields on terrestrial animals.

Results and Discussion

Sound Sensing Mechanisms of Fish

Some mechanisms fish use to sense sound are similar to those of terrestrial animals, while others are very different. Fish can sense sound vibrations and water particle velocity and acceleration. Together, these abilities allow some fish to create a three-dimensional sound image of their environment. The overall set of organs and structures used by fish to sense sound is called the octavolateralis system. Detailed descriptions of the morphology, mechanism, and application of the various components of the octavolateralis system have been previously published (Alexander 1962; Buekle 1968; Enger and Anderson 1967; Tavolga 1967; Chapman and Hawkins 1973; Sand and Enger 1973; Fay 1974; Fay and Popper 1974, 1975; Sand 1974, 1981; Hawkins and Johnstone 1978; Myrberg and Spires 1980; Buwalda 1981; Platt and Popper 1981; Buwalda et al. 1983; Popper 1983; Saidel and Popper 1983; Rogers and Cox 1988; Kalmijn 1988, 1989; Platt, Popper and Fay 1989; Bleckman 1993; Enger et al. 1993; Popper and Platt 1993; Carlson 1995).

Sound Sensing Abilities of Fish

Sound-frequency and field-sensing thresholds differ considerably among fish species. For salmonids, sound-frequency sensing thresholds are fairly constant, ranging from <1 Hz to about 150 Hz, but rise steeply for higher frequencies. Near-total loss of sound detection occurs at frequencies >380 Hz (Knudson et al. 1992, Kalmijn 1988). Weber and Schiewe (1976) concluded that the lateral line of salmonids is responsive to stimulation by frequencies from 1 to 345 Hz, with maximum sensitivity between 10 and 170 Hz. Contrary to the findings of other investigators, Shabalin (1991) reported rainbow trout (*Oncorhynchus mykiss*) can detect sound at frequencies up to 50 kHz at >100 dB μPa.

Clupeids, such as blueback herring (*Alosa aestivalis*) and shad (*Alosa sapidissima*), are able to detect frequencies ranging from 60 Hz to 150 kHz (Dunning et al. 1992, Pickens 1992, Nestler et al. 1992, Ross et al. 1993). Shabalin (1991) reported golden mullet (*Mugil aratus*) detected sound at frequencies to 4-70 kHz at >92 dBμPa, garfish (*Belone belone*) to 80 kHz at >112 dBμPa, silver carp (*Hypophthalmichthys molitrix*) to 80-95 kHz at >80 dBμPa, and common carp (*Cyprinus carpio*) to 125 kHz at >114-124 dBμmPa. Shabalin found that the transducer he used to generate underwater sound also produced an electromagnetic field (EMF).

After investigating this, he reported that the common carp can detect EMFs from 10 Hz to 160 kHz and can sense changes in EMF levels of 12 dB for field strengths of at least 10^{-4} V/cm. Shabalin also reported that all of his study species had some sensitivity to EMFs. Similar findings have not been reported by other investigators. However, it has been shown that cochlear hair cells of some fish and animals are sensitive to electrical current (Brownell and Kachar 1985, Ashmore and Brownell 1986, Jen and Steele 1987).

The above investigations show that the 50-kHz tag-energizing frequency produced by an A-PIT system could be sensed by some fish species, including perhaps salmonids. However, the 500-kHz tag-response frequency is higher than any reported to be detectable by fish. In addition, the sound field produced by the tag (response field) is low (120-126 dBμPa@1 m) and is only present after the tag has been energized. It is not known if a transducer used to produce an A-PIT energizing sound field would also produce an EMF, how strong such a field might be, or how sensitive fish might be to the exposure.

The operating frequency of the proposed resonating sphere tag system would lie between 10 and 500 kHz. As with the A-PIT-tag system, the lower operating frequencies may be audible to fish under certain conditions, since the energizing field strength would be high (207-213 dBμPa@1 m).

Fish Avoidance of Sound Fields

There is concern that fish behavior may be modified by sound fields produced by the proposed A-PIT system and the resonant sphere detection system. If fish are repelled or attracted, tag detection data could be biased. This section is a condensed review of sound field levels and frequencies reported to affect fish behavior.

Knudson et al. (1992) reported consistent avoidance by Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) to a 10-Hz sound field in a pool; no habituation was noted. The authors stated that at 5-10 Hz, particle acceleration values should be at least 0.01 m/s^2 to elicit an avoidance response in salmonids. Enger et al. (1993) reported that migrating Atlantic salmon smolts consistently avoided a 10-Hz sound field. The effective range was approximately 3 m, within which particle acceleration was greater than 0.01 m/s^2. However, no behavioral response was noted for a 150-Hz sound field, even when the fish approached to within <10 cm of the sound source.

Particle acceleration at 10 cm from the source was more than 114 dB greater (factor of 500,000) than the measured hearing threshold for Atlantic salmon for frequencies between 5 and 10 Hz (Knudson et al.,1992). VanDerwalker (1967) reported short-range avoidance (0.6 m) by juvenile chinook salmon (*Oncorhynchus tshawytscha*) responding to sound fields at frequencies of 30 to 150 Hz, but awareness dropped off at frequencies higher than 150 Hz. The fish did not appear to habituate to the sound.

Clupeids are sensitive to higher frequencies and to lower sound levels than salmonids. Pickens (1992) and Nestler et al. (1992) reported initial reactions by blueback herring and shad when exposed to sound-field frequencies between 60 and 500 Hz. However, they quickly acclimated to repeated exposure. Both species were attracted to a continuous sound frequency of 80 Hz, but were repelled by frequencies of 100-110 kHz. They were most sensitive to frequencies near 130 kHz, and continuous noise over a band of 100-150 kHz was strongly avoided. Experimentation determined that a 130-kHz sound-field level of 176 dBμPa@1 m caused both species to move at least 7.7 m (158 dBμPa@7.7m).

Effective avoidance to 61 m was obtained when the 130-kHz sound-field level was increased to 183 dBμPa@1 m (reduces to 147 dBμPa@61 m). Dunning et al. (1992) found that blueback herring were repelled to a distance of 60 m by 124.6- and 130-kHz sound fields having a source level of 187 dBμPa@1 m (reduces to 151 dBμPa@60 m).

Reduced response was seen for frequencies below 110 kHz or above 140 kHz. Finally, Carlson (1995) reported that blueback herring showed strong avoidance to a 120-kHz sound field of 200 dBµPa@1 m, with some individuals within 2 m of the source (194 dBµPa@2 m) being stunned or killed.

The reported reactions of fish to various sound-field levels supports the notion that the A-PIT or the resonating sphere tag systems could affect some species of fish when near the sound source. Blueback herring and shad could sense the energizing sound fields of the proposed tags and would very likely react to them. The 50-kHz energizing frequency for the A-PIT tag is below either fish's maximum frequency sensitivity (130 kHz), but some sphere tag frequencies could be within the range of maximum sensitivity for either species.

In addition, the proposed energizing field strength for both tags is very high (207-213 dBµPa@1 m); nearly 70 times higher than levels that repel either shad or blueback herring (176 dBµPa@1 m; Pickens 1992; Nestler et al., 1992). The energizing sound-field levels proposed for both tag systems are greater than those reported to have stunned or killed either species when very near a sound source (Carlson 1995). It is unlikely however, that any fish species would react to a 500-kHz tag response frequency of the A-PIT tag. This frequency is higher than that reported to cause fish avoidance, and the sound-field level is low (120-126 dBµPa@1 m) (Pickens 1992, Nestler et al. 1992, Dunning et al. 1992) and would only be present after a tag was energized.

The 50-kHz A-PIT-tag energizing field or the range of frequencies proposed for resonating sphere tags would unlikely elicit any reaction by salmonids, since both are higher than frequencies generally reported to be detectable by these fish (VanDerwalker 1967, McKinley and Patric 1987, Knudson et al. 1992, Enger et al. 1993). However, Shabalin (1991) reported that rainbow trout (*Oncorhynchus mykiss*) could detect frequencies up to 50 kHz at >100 dBµPa. If this is indeed the case, then some salmonids would be able to detect the proposed tags and thus could respond.

Effects of Exposure to Strong Sound Fields

Exposure to intense sound fields can result in tissue and cellular damage in addition to physiological and neurological trauma to animals. A limited review of pertinent literature is presented below. Intense sound fields, under certain conditions, can produce bubbles, cell wall rupture, and tissue heating. Limited research has been conducted using fish as test subjects, but a wide range of literature describing experiments using terrestrial animals is available. The results of these studies may be applicable to some fish because of similarities in their inner ear and tissue morphology.

Ter Haar and Daniels (1981) reported that guinea pigs (*Cavia cobaya*) exposed for 5 minutes to 750 kHz at an intensity of 150 mW/cm^2 (213.5 dBµPa) developed 10-µm-diameter bubbles in their blood. They did not detect bubble formation for exposure intensities < 80 mW/cm^2 (210.8 dBµPa). Other investigators have shown that high-intensity sound fields will damage cellular structures. Dooley et al. (1983) reported that about 60% of rat lymphocytes in suspension were damaged by continuous 10-minute exposures to 500 kHz at 2 W/cm^2 (224.8 dBµPa). Pulsed ultrasound at the same frequency and equivalent average temporal intensity, but with peak intensity values of 30 W/cm^2 (236.5 dBµPa), resulted in about the same level of cell damage.

Other than causing direct mechanical damage, exposure to a strong sound field can cause frictional heating in tissue. Martin et al. (1982) found that tails of plattyfish (*Xiphophorous maculatus*), when exposed to 780 kHz at 2.6 W/cm^2 (225.9 dBµPa), increased in temperature by 2.2 to 3.5°C after 30 seconds. Blood flow increased when the tails were exposed to 780 kHz at 10 mW/cm^2 (201.8 dBµPa). Maximum blood flow was reached after 5-10 minutes.

No data clearly shows that the energizing sound field of either of the proposed tags would cause tissue heating in fish. Sound-field/frequency combinations reported to cause significant tissue heating were of levels and frequencies higher than those of the proposed tag systems.

The energizing field level (207-213 dBµPa@1 m) of the proposed tags is of equal strength to a 750-kHz field that was shown to cause bubble formation in tissue by cavitation (Ter Haar and Daniels 1981). Cavitation occurs more readily at 750 kHz than at lower frequencies, but fish may approach much nearer to either of the proposed tag system transducers than 1 m. For instance, exposure level at 10 cm from the transducer could be 10 times greater than at 1 m (227-233 dBµPa@10cm) (Kinsler et al. 1982) and may be sufficient to cause bubble formation.

The lateral line of salmonids can be severely disabled by gas bubble disease. Weber and Schiewe (1976) found that steelhead trout exposed to water with a gas pressure of 118% of saturation showed effects of gas bubble disease in the lateral line within 2-6 hours. Further, progression of bubble formation resulted in increased loss of lateral-line functioning to the point of near-total unresponsiveness. Recovery following return of the fish to equilibrated water required 16-20 hours (Weber and Schiewe 1976). Gas bubble formation in fish caused by exposure to an intense sound field may result in symptoms similar to those of gas bubble disease, or exposure may aggravate a preexisting condition.

Exposure of fish to intense sound fields can result in effects ranging from temporary or permanent loss of sound-detection sensitivity to stunning and death. Hastings (1990) stated that the literature has no reports concerning morphological damage to the lateral-line system caused by intense underwater sound. However, Weber and Schiewe (1976) found that the lateral line of salmonids can be temporarily disabled by high-intensity sound (no sound level reported). Since salmonids have limited ability to detect sound-pressure fields, due to minimal coupling between their inner ear and swim bladder, their ability to avoid potentially damaging conditions is likewise limited.

Other species, so-called "hearing specialists" (eg., goldfish, *Carassius auratus*), are much more sensitive to sound-pressure fields and are susceptible to inner-ear damage by intense sound (Alexander 1962; Buekle 1968; Enger and Anderson 1967; Tavolga 1967; Chapman and Hawkins 1973; Sand and Enger 1973; Fay 1974; Fay and Popper 1974, 1975; Sand 1974, 1981; Hawkins and Johnstone 1978; Myrberg and Spires 1980; Buwalda 1981; Platt and Popper 1981; Buwalda et al. 1983; Popper 1983; Saidel and Popper 1983; Rogers and Cox 1988; Kalmijn 1988, 1989; Platt, Popper and Fay, 1989; Bleckman 1993; Enger et al. 1993; Popper and Platt 1993; Carlson 1995).

Popper and Clark (1976) exposed a hearing-specialist species (e.g., goldfish) to a sound field of 149 dBμPa at frequencies of 300, 500, 800, and 1000 Hz for 4 hours. They measured a temporary shift in hearing thresholds at 500 and 800 Hz immediately after exposure, but all thresholds returned to normal within 24 hours. Hastings et al. (1986, 1987) and Hastings (1990) reported that goldfish were killed, and the otolith organs of other species were severely damaged, by 0.5- to 2-hour exposures to 250- and 500-Hz sound fields of 182-204 dBμPa. At 250 Hz, physical damage to the otolith organs began at a field strength of 189 dBμPa, and at 500 Hz, damage began at 197 dBμPa.

Scanning electron microscopy (SEM) revealed that these sound-level exposures resulted in destruction of hair cell cilia on the maculae of the saccular otolith organ. Some hair cell cilia that appeared (SEM inspection) to be physically undamaged were also injured. At least a 10-dB increase in the sensitivity threshold of nerve fibers was observed for fish subjected to the lowest field strength exposure (182 dBμPa) for the experiment. Transient stunning also occurred, but its physiological mechanism and threshold values were unknown.

Gourami (*Colisa* sp.) were immobilized by 8- to 30-minute exposures to 150- and 400-Hz sound fields of 98 and 92 dBμPa (Hastings 1990). Hastings also reported that post-exposure behavioral characteristics and conditions of the gouramis ranged from lethargy and loss of equilibrium to internal hemorrhaging. In addition, some apparently unaffected fish sustained physical damage to their inner ear. Hastings (1990) concluded that sound-pressure levels <150 dB dBμPa are not harmful to fish, while exposure to sound levels >180 dBμPa is harmful to many fish. Further, those species with the swim bladder closely associated with the inner ear are most susceptible. Hastings did not report predictions as to damaging sound-level thresholds related to frequency. Enger (1981) found that when cod (*Gadus morhua*) were exposed for 1-5 hours to 50 and 400 Hz at a field strength of 180 dBμPa, ciliary bundles on the saccular maculae of the inner ear were destroyed.

Very strong underwater sound fields that will kill fish can be produced using explosives. Norris and Mohl (1983) state that lethal exposure thresholds for explosives with a short rise-time begin at 229 dBμPa. Similarly, MacLennan and Simmonds (1992) reported lethal thresholds of 229-234 dBμPa@1 m. Fast explosives such as dynamite and TNT had lethal effects for sound levels 5-10 dB lower than for slower-igniting explosives.

The proposed energizing field strength for the two proposed tags (207-213 dBμPa@1 m) falls well within the range of levels reported to damage fish at ranges from the transducer of 10 m or less (Chapman and Hawkins 1973; Popper and Clark 1976; Enger 1981; Hastings et al. 1986, 1987; Hastings 1990; MacLennan and Simmonds 1992; Carlson 1995). In addition, calculation of sound-field levels at 10 cm from the energizing transducer shows that field strength could be as much as 20 dB (10 times) greater than at 1 m (227-233 dBμPa@10cm).

Fish passing within 10 cm of the energizing transducer could be subjected to about the same sound-field strength as considered lethal when produced by explosives (MacLennan and Simmonds 1992, Noris and Mohl 1983). However, the energizing field for the A-PIT tag would be continuous, and may not be as damaging as pulsed sound. In contrast, the high-energy, pulsed energizing field for the resonating sphere tag may be comparable to pulses produced by explosives, and thus may cause damage to animals at short range (e.g., <1 m) (Dancer et al. 1980, Price 1983).

Hearing Sensitivity of Cetaceans and the Sound Fields they Produce

The proposed A-PIT and resonant sphere systems could potentially be used in areas such as the Columbia River estuary where cetaceans may be exposed to their energizing and response sound fields. Cetaceans present an enigma in that their hearing is very sensitive to a wide range of sound frequencies, but they do not appear to suffer damage from intense sound-field levels produced by themselves or by others in their social groups.

Au and Snyder (1980) conducted an experiment designed to measure the echo-locating ability of bottlenose porpoise (*Tursiops truncates*). They found that this porpoise could produce a 120-kHz sound level of 160 dBμPa@1 m and could detect, with 50% success, a water-filled steel sphere of -41.6 dB target strength at a range of 113 m. The echo level from the sphere at that range amounted to 76.3 dBμPa. Detection success at 100 m (2 dB greater echo level) was 91%.

Other cetaceans are able to produce much higher sound levels. Norris and Mohl (1983) presented convincing evidence that whales are able to stun or debilitate prey from great distances (no distances reported) by emitting sonic beams in the 1-5 kHz band with sound levels of 230 dBμPa@1 m. Similar observations were reported by Hult (1982), but no measurements of source levels were reported. Taylor (1986) also stated that whales are apparently able to stun prey. Most cetaceans can produce and sense high-frequency sound fields (Backus and Shevill 1966, Diercks 1972).

The operating frequency range (30-500kHz) of the proposed tag systems would be audible to some cetaceans, but it is not known if the energizing field strength (207-213 dBμPa@1 m) would present a hazard. Many cetaceans produce echo-location field strengths of nearly the same level, and some produce levels many times as strong (Norris and Mohl 1983). In addition, cetaceans within a social group or pod can apparently withstand exposure to strong sound fields produced by other individuals without suffering injury.

Damaging Sound Field Level Exposures for Terrestrial Animals

Some aquatic or semi-aquatic animals such as otters or beavers may be exposed to the strong energizing sound field of the proposed A-PIT or resonant sphere tag systems if the systems were deployed in streams or lakes. Little is known about the sensitivity of these animals to the effects of strong sound fields. However, it is well documented that when animal subjects are exposed to excessive noise, temporary and/or permanent reductions in hearing sensitivity can occur.

Continuous exposures to moderate-level noise will cause asymptotic hearing thresholds shifts (ATS) within 18-24 hours. Permanent threshold shifts (PTS) depend upon the level, frequency, and duration of exposure. Below a "critical level" of about 115 dB//20μPa (141 dBμPa), PTS and hair cell loss in the cochlea are generally related to the total energy received during a continuous exposure. Periodic rest periods inserted in an exposure schedule reduce hearing loss and cochlear damage (Clark 1991).

Several reports have detailed the effects of exposure to strong sound-field levels for short durations (>126 dBμPa) in behaviorally trained animals (Ward and Duval 1971; Lonsbury-Martin and Martin 1981; Borg 1982a,b; Buck et al. 1984). Generally, the noise exposures used in these studies were sufficient to produce PTS after only a few minutes to a few hours. In addition, a correlation was noted between measured permanent hearing loss and the extent and location of damage to sensory cells. Intense, short rise-time sound pulses are more damaging to hearing than equivalent sound-energy exposures to pulses having a more gradual increase in level (Dancer et al. 1980, Price 1983).

The proposed 500-kHz A-PIT-tag response frequency is probably far beyond the hearing range of terrestrial animals, but the sound field (120-126 dBμPa@1 m) approaches levels reported as harmful for long-term exposure (>126 dBμPa, several hours to several days). However, a tag response would be generated only during tag energizing, when an animal would also be subjected to the much stronger 50-kHz A-PIT energizing sound field. This energizing sound field may be audible to some animals. In addition, its field strength (207-213 dBμPa@1 m) is many times greater than the reported threshold for injury (126 dBμPa). If an aquatic mammal were to remain submerged within the A-PIT energizing field for more than a brief period, hearing damage would most likely occur. Similarly, the calculated sound field (207-213 dBμPa@1 m) required to operate the spherical resonating tag creates the same concern for animals.

Conclusion and Recommendations

A review of literature covering the effect of sound on animals strongly suggested that the sound-field strength of either of the proposed tag-detection systems could, under certain conditions, modify behavior or cause harm to fish, and perhaps also to some aquatic mammals.

Two separate sound fields would be produced by the proposed A-PIT-tag system: the first would be a continuous field at 50 kHz (energizing frequency), and the second at 500 kHz (response frequency). The strengths of the 50- and 500-kHz sound fields will be 207-213 dBµPa@1 m and 120-126 dBµPa@1 m, respectively. The proposed resonating sphere tag system would operate at a frequency between 10 kHz and 500 kHz (pulsed field), and would produce an energizing field strength of 207-213 dBµPa, as measured at a range of 1 m from the transducer. Based on this information, during operation of either of the proposed tag-detection systems, fish and other animals would be exposed to strong sound fields. Some fish and mammal species would be able to sense the 50-kHz acoustic frequency of the A-PIT tag, but its 500-kHz response frequency would probably be beyond detectable limits.

Reported reactions of fish to strong sound-field levels justifies the concern that fish behavior may be modified by the sound fields produced by either tag system. However, salmonids are unlikely to react to the higher frequencies, as most investigators report that frequencies > 400-500 Hz are beyond the upper limit of their sensitivity. Clupeids (blueback herring and shad) and some other fish species would be able to not only sense the 10-kHz or higher sound field, but would likely react to it. The frequency of maximum sensitivity for blueback herring and shad is near 130 kHz. The proposed energizing sound-field level for either tag detection system would be greater than that reported to have stunned or killed blueback herring and shad near a sound source. It is unlikely fish would react to the 500-kHz A-PIT-tag response frequency or to resonant sphere interrogation frequencies greater than about 250 kHz.

The sound fields produced by either of the proposed tag systems would be audible to some cetaceans, but it is not known if the sound would cause them to alter their behavior or if the sound-field levels would present a significant hazard. Many cetaceans produce echo-location field strengths equal to or greater than the interrogation field strength, and individuals within a social group or pod must often be exposed without suffering injury.

Exposure to intense sound fields can result in reduction of sensitivity to sound, damage to the inner ear, gas bubble formation in tissues, tissue heating that can cause cellular damage, stunning, and death to fish or mammals. The proposed energizing field strength for the A-PIT and the resonating sphere tag system fall well within the range of levels reported to cause injury to fish, in some instances even to a range of as much as 10 m from the transducer. Fish exposed at very short range (10 cm or less) could be subjected to about the same sound-field levels as those produced by explosives. If a mammal were to remain submerged near (10 m) a transducer producing an energizing field for more than a very brief period, hearing damage could occur. However, unlike an explosion-produced sound pulse, fish and other animals may be able to avoid the energizing sound field produced by the tag systems through early detection.

Overall, the literature suggests that some animals could detect and be harmed by the sound fields produced by the proposed tag detection systems. This suggestion is based primarily on information derived from the response of test animals held in a confined area during testing. However, the ability of an animal to detect and avoid a potentially damaging sound field would dramatically reduce its risk. On the other hand, if the proposed tag systems were used in situations where animals could not easily escape potentially damaging sound-field levels (i.e., a fish ladder), damage and/or behavior modification could result.

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CONCLUSIONS AND RECOMMENDATIONS

The technical feasibility of developing an acoustic passive integrated transponder (A-PIT) tag was investigated. The initial evaluation addressed the attenuation of acoustic energy by the body of a fish. Placing a test transducer in the coelomic cavity of fish produced wide ranges in attenuation values for the frequencies of interest (50 and 500-kHz) in relation to aspect or viewing angle.

The data suggested that a fish's body and air bladder would significantly attenuate the system's acoustic signals at most viewing angles except for those viewed ventrally and to a limited extent laterally. It was also suggested that if the fish was rapidly swimming very near to the transducer that the narrow beam of the system's transducer at that point would not allow sufficient time to energize the tag.

Two separate sound fields would be produced by the proposed A-PIT tag system; a continuous energizing frequency at 50 kHz and a response frequency at 500 kHz. The strengths of the 50 and 500 kHz sound fields were estimated at 207-213 dBµPa@1 m and 120-126 dBµPa@1 m, respectively. Thus, during operation of an A-PIT system, fish and other animals could be exposed to strong sound fields. A literature review showed that the energy field required to energize the A-PIT-tag could under some conditions cause behavior modification and/or damage to some animals.

Technically the A-PIT tag could be developed. This was confirmed by an independent review of the potential system concept. However, based upon the signal attenuation data showing limited operational viewing aspects and the literature review showing a potential risk to fish and other animals from the tag energizing field under certain operating conditions, we recommend that the tag not be developed. The potential advantages of the A-PIT tag system, and the limited number of applications where it could be applied do not warrant the developmental expense or potential risk to animals.

Similarly, upon investigating the technical feasibility of a resonating-sphere tag, it became apparent that the tag could be developed (confirmed by independent review of the concept), but its application would be limited and there would be a risk to animals confined in proximity to the tag energizing system. Factors limiting system performance included its feasibility for small fish only, its diminishing detection ability as a fish grows, the limited codes (resonating frequencies) available because of tag size in relation to fish size, reduced tag detection ability due to ambient noise, limited viewing aspects because of a fish's physical characteristics, and the acoustic spectral characteristics of fish.

Calculations showed the strength of the acoustic energizing field for the tag could, as with the A-PIT tag, potentially cause behavior modification or damage to fish or other animals under certain conditions. Based on this information we do not recommend the development of a resonating acoustic sphere tag at this time for use in the Columbia River Basin.

The review of literature covering the effect of sound on animals strongly suggested that the interrogation sound field strength of either of the proposed tags could under certain conditions cause harm and or behavior modification to fish and mammals. However, the ability of an animal to detect and avoid a potentially damaging sound field prior to damage taking place reduces this concern. To reduce the above risk, the systems would thus need to be operated in situations that do not confine animals (i.e., use in open water and not in fish ladders).

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APPENDIX A: Review and Comments on the A-PIT Tag Tests Conducted at the APL/UW Acoustic Calibration Test Barge 7-10 Feb, 1994

Review and Comments on the A-PIT Tag Tests Conducted at the APL/UW Acoustic Calibration Test Barge 7-10 Feb, 1994

Report to National Marine Fisheries Service

by

GRD Associates
4621 78th PI SW
Mukilteo, Wa. 98275
(206) 347-5297

15 October 1994*

*Revised 23 February, 1995 at request of NMFS to remove specific reference to a proprietary proposal previously submitted to the government for consideration.

Introduction and Summary

During the period from 1-10 February 1994, an experiment was conducted at the University of Washington APL acoustic test barge located on the Lake Washington Ship canal. The purpose of the experiment was to "determine the effects of the body of a fish on the directivity and the degree of attenuation of acoustical energy transmitted from and received by a transducer implanted in the coelomic cavity of a salmonid."

Two species were used, sockeye salmon and atlantic salmon. The experiment was conducted to gather critical information needed to assess the feasibility of possible future development of an Acoustical Passive Integrated Transponder (A-PIT) tag. One proposed approach for an A-PIT tag concept was provided in response to reference [1]. The purpose of this report is to comment upon the experimental data in the context of that proposed approach.

In summary, we found that the signal attenuation through the fish flesh varied considerably over the span of the experiments. In some cases, little or no attenuation (even some occasional signal reinforcement) was observed. However, in a large number of cases, substantial signal attenuations were measured. The higher attenuation levels (10-20 dB over bare transducer measurements) occurred primarily at overhead and head-on aspects to the fish host.

The case of 20 dB signal attenuation stresses the proposed design. Although there is sufficient design margin with the proposed approach to accommodate these losses, the large attenuations observed in the experimental measurements increase the development risks if the system is required to accommodate these worst case losses under all circumstances. Nevertheless, there *is* enough design margin in the proposed approach to accommodate the 20 dB signal attenuation losses suggested by the experimental data (see section 4 of this report) .

Finally, we note that a battery assisted A-PIT tag concept was included in reference as a back-up risk reduction approach in case that development problems for a purely passive tag proved insurmountable. This concept provides a 60 dB design margin on the interrogation link and provides reliable transmit power for the reply link which does not require energy storage at all. In view of the risk reduction alternatives included in the proposal, we consider that the development risks are manageable for an A-PIT tag concept.

1.0 Data Description and Preliminary Observations

There were a number of apparent discrepancies with the acoustic data that indicates that measurement and/or calibration errors are present in the data. Most of these are within 3 dB or so, and therefore are not overly significant (at least as long as we do not expect the answers to be more accurate than this.) Some of the discrepancies, however, are much larger (more than 6 dB). In those cases, we tend to believe that the data is faulty and should be disregarded. There are a few in-between cases in which the errors seem to be in the 3-6 dB range. Normally, we would tend to discount the data in this case as well. Unfortunately these discrepancies are in the calibration plots on the bare transducer. Since these plots have been used as ground truth in all subsequent comparisons, these discrepancies are somewhat troublesome. Some discussion of this problem is provided below in the section on "Bare Transducer Calibration Plots."

Index to Data Sets

In making comparisons, the following table is useful in identifying the appropriate data sets. These references apply to the master data collection log provided by NMFS which indicates what the experimental conditions were for each measurement set. This table allows us to cross reference the various plots by measurement set # , file #, or plot # which are the three ways the sets are referenced in the data log, EXCEL plots, and data plots respectively.

Meas. Set	File No.	Plot No.	Meas Axis	Xducer Config	Bladder Cond	Fish Length	Group
1	XDR-H-R.50	1944	Pitch	Bare	NA	NA	1
2	XDR-H-R.500	4188	Pitch	Bare	NA	NA	1
3	XDR-H-T.500	1947	Pitch	Bare	NA	NA	1
4	XDR-V-T.500	1948	Roll	Bare	NA	NA	2
5	XDR-V-R.500	4189	Roll	Bare	NA	NA	2
6	XDR-V-R.50*	4190	Roll	Bare	NA	NA	2
7	F-1-V-R.50	4191	Roll	External	Def (?)	24.8	3
8	FlA-V-R.50	4192	Roll	External	Def (?)	24.8	3
9	F1B-V-R.50	4193	Roll	External	Def (?)	24.8	3
10	F1C-V-R.500	4194	Roll	External	Inflated	24.8	3
11	F1D-V-T.500	1949	Roll	External	Inflated	24.8	3
12	F1E-V-T.500	1950	Roll	External	Inflated	24.8	3
13	F1F-V-R-500	4195	Roll	External	Inflated	24.8	3
14	F1G-V-R.50	4196	Roll	External	Inflated	24.8	3
15	F2A-V-R.50	4197	Roll	Internal	Inflated	26.7	4
16	F2B-V-R.500	4198	Roll	Internal	Inflated	26.7	4
17	F2C-V-T.500	1951	Roll	Internal	Inflated	26.7	4
18	F2D-V-T.500	1952	Roll	Internal	Pt Def	26.7	4
19	F2E-V-R.500	4199	Roll	Internal	Pt Def	26.7	4
20	F2F-V-R.50	4200	Roll	Internal	Pt Def	26.7	4

21	F3A-N-R.50	4201	Yaw	Internal	Inflated	26.7	5
22	F3B-N-R.500	4202	Yaw	Internal	Inflated	26.7	5
23	F3C-N-T.500	1954	Yaw	Internal	Inflated	26.7	5
24	F3D-N-T.500	1955	Yaw	Internal	Deflated	26.7	5
25	F3E-N-R.500	4203	Yaw	Internal	Deflated	26.7	5
26	F3F-N-R.50	4204	Yaw	Internal	Deflated	26.7	5
27	F3G-H-R.50	4205	Pitch	Internal	Inflated	26.7	6
28	F3H-H-R.500	4206	Pitch	Internal	Inflated	26.7	6
29	F3I-H- T.500	1956	Pitch	Internal	Inflated	26.7	6
30	F3J-H- T.500	1957	Pitch	Internal	Pt Def	26.7	6
31	F3K-H-R.500	4207	Pitch	Internal	Pt Def	26.7	6
32	F3L-H-R.50	4208	Pitch	Internal	Pt Def	26.7	6
33	F3M-H-R.50	4209	Pitch	Internal	Deflated	26.7	6
34	F3N-H-R.500	4210	Pitch	Internal	Deflated	26.7	6
35	F3O-H-T.500	1958	Pitch	Internal	Deflated	26.7	6
36			-------Missing Data Set--------				
37	F4A-V-T.500	1960	Roll	External	Inflated	54.6	7
38	F4B-V-R.500	4211	Roll	External	Inflated	54.6	7
38a	F4C-V-R.50	4212	Roll	External	Inflated	54.6	7
39	F4D-V-R.50	4213	Roll	Internal	Inflated	54.6	8
40	F4E-V-R.500	4214	Roll	Internal	Inflated	54.6	8
41	F4F-V-T.500	1961	Roll	Internal	Inflated	54.6	8
42	F4G-V-T.500	196	Roll	Internal	Deflated	54.6	8
43	F4H-V-R.500	4215	Roll	Internal	Deflated	54.6	8
44	F41-V-R.50	4216	Roll	Internal	Deflated	54.6	8
45	F5A-V-R.50	4218	Roll	Internal	Inf(?)	61.0	9
46	F5B-V-R.500	4220	Roll	Internal	Inf(?)	61.0	9
47	F5C-V-T.500	1963	Roll	Internal	Inf(?)	61.0	9
48	F5D-V-T.500	4221	Roll	Internal	Inf(?)	61.0	9
49	F5E-V-R.500	4222	Roll	Internal	Inf (?)	61.0	9
50	F5F-V-R.50	4223	Roll	Internal	Inf (?)	61.0	9
51	F5G-V-R.50	4224	Roll	Internal	Inf (?)	61.0	9
52	F5H-V-R.50	4225	Roll	Internal	Deflated	61.0	9
53	F5I-V-R.500	4226	Roll	Internal	Deflated	61.0	9
54	F5J-V-T.500	1964	Roll	Internal	Deflated	61.0	9
55	F5K-N-T.500	1965	Yaw	Internal	Inflated	61.0	10
56	F5L-N-R.500	4227	Yaw	Internal	Inflated	61.0	10
57	F5M-N-R.50	4228	Yaw	Internal	Inflated	61.0	10
58	F5N-N-R.50	4229	Yaw	Internal	Deflated	61.0	10
59	F5O-N-R.500	4230	Yaw	Internal	Deflated	61.0	10
60	F5P-N-T.500	1966	Yaw	Internal	Deflated	61.0	10
61	F5Q-H-T.500	1967	Pitch	Internal	Deflated	61.0	11
62	F5R-H-R.500	4231	Pitch	Internal	Deflated	61.0	11
63	F5S-H-R.50	4232	Pitch	Internal	Deflated	61.0	11

Note: The data file indicated for this set in the NMFS master data log was XDR-V-R.500 We believe this was in error.

The groupings in the last column are intended to group measurement sets which are similar with respect to Measurement Axis, Transducer Configuration, and Fish Size. The conditions for inflation/deflation of the air bladder are suspect in many cases because of the difficulty in determining the exact condition of this organ. The table does not attempt to indicate exact transducer placements within or on the fish for internal and external transducer configurations. Some additional details are available in the NMFS data log. See the individual writeups in the NMFS data log for additional comments and details on the conditions of the air bladder, on transducer placement within the fish body cavity, and other details of the measurement sets which we could not summarize in tabular fashion.

2.0 General Remarks

This section provides some general observations as to the apparent validity of the measurement sets. The bare transducer calibration plots (measurements sets 1-6) show Some discrepancies (approximately 6 dB) which are troublesome. Furthermore, they are not consistent with some of the early bare transducer measurements taken by APL/UW prior to beginning the actual tests; i.e. those indicated as "Test Transducer Measurements" and labeled with the acronym NMFS on the plots. Specifically these include plot numbers (1940, 1942, 1943, 4182, 4183, 4184, and 4185). Plot number 1941 appears to be missing in our data set. There were no details on the conditions under which these earlier measurements were taken. We believe that they were not taken in the same support frame as were all of the other measurements, but we’re not certain. Hence, these measurements have not been included in our index to the data sets. The plots were, however, included in the data package forwarded by NMFS and we have included these in our comments below.

Bare-Transducer Calibration Plots (Measurement Sets 1-6)

Measurement sets 1 through 6 represent calibration plots for the bare transducer. Data sets 1 and 6 compare the 50 kHz receive patterns about the transducer pitch and roll axes respectively. The roll-axis is along the longitudinal axis of the cylindrical transducer and the pitch axis is at right angles. We would expect the roll pattern to be omnidirectional. This is, in fact, the case. The roll-pattern is omnidirectional within a dB or so. We would expect the two patterns to have the same value at the 90 and 270 degree points; i.e., the points at which the roll and pitch axis measurements present the same transducer orientation to the measurement setup. We see that this is, in fact, the case (at least within a couple of dB or so).

Measurement sets 2 and 5 show the same receiver pattern comparisons but at 500 kHz rather than 50 kHz. These comparisons are not nearly as good as the 50 kHz results. The roll-axis pattern is not very omnidirectional. It has a 5 dB dip at about a 120 degree aspect. Furthermore it does not agree with the "NMFS Test Transducer Measurements" taken by APL/UW prior to the beginning of the test series. These earlier bare-transducer plots show a maximum-to-minimum roll-axis variation of only 2.5 dB by comparison (e.g., see plot 4183 as compared to measurement set #5). A second problem is indicated by the pitch axis pattern (measurement set #2) which shows an approximate 10 degree orientation registration error. This is probably indicative of a misalignment within the support frame. The earlier NMFS measurement (plot 4184) dos not show a similar misalignment. If there is a possibility of this much misalignment in the data measurements using the support frame, the difference patterns between the in-fish and bare-transducer measurements are probably misleading. Misalignments with respect to a null in the bare-transducer pattern could show an apparent gain with respect to the "in-fish" measurement when compared on the basis of difference patterns. This is apparent in several of the difference measurement sets (e.g., sets 22-25, 28-31, 34-35 and 56 are prominent examples). The apparent gains (as much as 15-20 dB) shown in the difference patterns for these sets are probably not real gains, but are very likely an artifact of orientation misalignments between pattern nulls in the two sets of measurements. Finally, we note that the roll-axis pattern does not agree with the pitch-axis pattern at the 90 and 270 degree orientations, as it did at 50 kHz. Even with axis misalignments, we would expect that the peaks in the pitch and roll patterns should agree, since both the pitch and roll axis measurements must cross the transducer’s "equator" twice in each rotation. The peaks differ by about 6 dB, indicating a 6 dB discrepancy in these two data sets. This is somewhat disturbing, since these are the bare-transducer calibration plots used for all of the latter comparisons (i.e., in-fish vs bare-transducer comparisons).

Measurement sets 3 and 4 show the same comparisons at 500 kHz but for the transmit patterns instead. These patterns show virtually identical characteristics. This at least shows that transmit/receive reciprocity comparisons are probably valid. Unfortunately it sheds no further light on the discrepancies indicated above. It is possible that the support frame is affecting the patterns. It is also possible that the roll axis measurements were not made at an angle which is precisely perpendicular the transducers longitudinal (roll) axis. This would be a possible explanation for the discrepancies if the roll-axis measurements were off-perpendicular by a constant 15-20 degrees or so; e.g., if the source and receive hydrophones were at different depths by about 1 foot. We don’t think that this was a likely event. Furthermore, these same characteristics were not seen in the earlier APL/UW measurements. It would be interesting to know how these earlier measurements were taken; i.e., with or without a frame. If no frame was used, how was the transducer supported? In any case, we apparently must accept the possibility that the calibration pattern measurements used for comparisons may be in error by as much as 6 dB (a somewhat troublesome prospect).

Reciprocity Comparisons

One of the ways to check the calibration is to compare the transmit and receive data for the in-fish measurements with the corresponding results for the bare transducer. We performed eyeball comparisons with all of the available receive/transmit data sets. The approximate reciprocity discrepancies are indicated below. These are only approximate, and represent only an overall eyeball judgement of the transmit and receive pattern relative differences.

Data Set Pairs	Reciprocity Discrepancy(dB)
10/11	0 dB
12/13	0
16/17	0
18/19	0
22/23	0
24/25	3
28/29	2
30/31	2
34/35	3
37/38	0*
40/41	2
42/43	1
46/47	3
48/49	2
53/54	1
55/56	2
59/60	3
61/62	3

* Note: There initially appeared to be a 12 dB discrepancy in the EXCEL plot comparisons for this set (37/38). Fortunately this was due to the use of the wrong calibration pattern for data set No.38 in the EXCEL plots. When the correct pattern is used, the results are in very close agreement.

These discrepancies have a mean value of 1.5 dB with a standard deviation of 1.25 dB. We consider these to be reasonable comparisons and would say that the reciprocity comparisons are within the allowable measurement errors for the indicated test setup.

3.0 Observations on Similar Measurement Sets

In the following subsections, we have grouped measurements into similarity categories which have the same frequency (either 50 or 500 kHz), measurement axis (pitch, roll or yaw), and transducer configuration (internal or external). These are groupings for which the pattern measurements relative to those of the bare transducer would be expected to be similar. We did not group according to air bladder characteristics or to fish size, since we did not see a consistent correlation with either of these variables. We did not differentiate between transmit and receive patterns because of the close agreement with the reciprocity comparisons discussed above. The measurement sets which fall into the same similarity categories by this criteria, listed by the group index (last column) in our master index, are:

Group	Similarity Category
1	Bare Transducer Pitch-Axis Measurements
2	Bare Transducer Roll-Axis Measurements
3, 7	External Transducer Roll-Axis Measurements
4, 8, 9	Internal Transducer Roll-Axis Measurements
5, 10	Internal Transducer Yaw-Axis Measurements
6, 11	Internal Transducer Pitch-Axis Measurements

Groups 1 and 2 represent the bare transducer only, and are used as the calibration measurements (ground truth) in the absence of the fish structure. The last four similarity groups are discussed individually below for the 50 kHz and 500 kHz measurement sets respectively.

External Transducer Roll-Axis Measurements at 50 kHz

The measurement sets which fall into this general category are: 7, 8, 9, 14, and 38a. With the exception of set 38a, the measurements are very similar and do not show drastic or dramatic signal degradation relative to the bare transducer measurement (set # 6). The maximum degradation is about 10 dB and degradations of this magnitude only occur over relatively small azimuth sectors. The azimuth sectors at which the fish seems to attenuate the signal are not consistent among the plots. We did not know on which side of the fish the transducer was mounted for these measurements. There does not seem to be much correlation with air bladder inflation. A dramatic change is seen in measurement set # 38a. This plot shows a large reduction (10 to 30 dB) in signal receive sensitivity over all azimuths. This particular measurement seems to be at odds with all of the others. We tend to discount this particular measurement set as being unreasonable. If this is a valid measurement, we do not understand the mechanism by which this large signal degradation arises.

Internal Transducer Roll-Axis Measurements at 50 kHz

The measurement sets which fall into this general category are: 15, 20, 39, 44, 45, 50, 51, and 52. Once again, these measurements are fairly consistent with one notable exception. They generally show that the signal is significantly degraded (10 to 30 dB) on one side, typically when the air bladder is between the transmitter and receiver. The response on the other side is not significantly reduced and in some cases the response is slightly increased. Once again, we have a dramatic exception to these general results, namely set # 15. This plot shows a large reduction (15 to 30 dB) in signal receive sensitivity over all azimuths. Again, this seems to be a flyer. We have no explanation as to the mechanism that would result in this kind of signal absorption at all azimuths; particularly when all other measurements show no indication of this characteristic. We tend not to believe set # 15. No particular correlation with signal degradation and the degree of air bladder inflation is noted.

Internal Transducer Pitch-Axis Measurements at 50 kHz

The measurement sets which fall into this general category are: 27, 32, 33, and 63. They show a large signal degradation (on the order of 20 dB) from above and directly head-on to the fish. The signal reduction below the fish is non-existent for two of the sets (33 and 63) and is moderately significant (5-10 dB) in sets (27 and 32). This data is consistent with the roll-axis measurements discussed above. The largest reductions occurred with an inflated air bladder (one case only).

Internal Transducer Yaw-Axis Measurements at 50 kHz

The measurement sets which fall into this general category are: 21, 26, 57, and 58. They show a large signal degradation (on the order of 20 dB) for a directly head-on aspect to the fish. The signal reduction to the sides of the fish vary from as much as 10 dB in set # 21 to a signal reinforcement of as much as 5 dB in sets # 57 and #58. Once again these measurements are consistent with the roll and pitch-axis measurements discussed above. No particular correlation with signal degradation and the degree of air bladder inflation is noted.

External Transducer Roll-Axis Measurements at 500 kHz

The measurement sets which fall into this general category are: 10, 11, 12, 13, 37, and 38. The first four sets are consistent and show very little difference in transducer response with and without the fish present. The patterns show considerable fine scalloping presumably due to coherent combinations of reflections from the internal fish structure. There seems to be no correlation with fish bladder inflation and hence the internal reflections do not appear to be dominated by the air bladder. Measurement sets #37 and #38 show quite different results with average degradations of 5 to 10 dB or more. We have no explanation for the apparent difference of these results with the previous ones unless it has to do with the detailed placement of the transducer within the fish cavity. A more careful look at these results with respect to detailed transducer placement may be warranted.

Internal Transducer Roll-Axis Measurements at 500 kHz

The measurement sets which fall into this general category are: 16, 17, 18, 19, 40, 41, 42, 43, 46, 47, 48, 49, 53, and 54. The first four plots show a very consistent pattern with significant signal degradation (10-20 dB) when the fish is viewed from above. There appears no real difference with air bladder inflation other than a slight reduction of the degradation from above when the bladder is deflated. The remaining measurements are more variable and show scattered regions of signal degradation and reinforcement. No correlation with air bladder inflation is noted.

Internal Transducer Pitch-Axis Measurements at 500 kHz

The measurement sets which fall into this general category are: 28, 29, 30, 31, 34, 35, 61, and 62. These plots all show significant signal degradation at most aspects, particularly from above the fish (typically 10-20 dB). They also show significant degradation at tail-on aspects. Signal degradation below the fish is not as pronounced but is still significant in some cases and varies from 5-10 dB. No correlation with air bladder inflation is noted.

Internal Transducer Yaw-Axis Measurements at 500 kHz

The measurement sets which fall into this general category are: 22, 23, 24, 25, 55, 56, 59, and 60. These plots show a relatively consistent 5-10 dB signal degradation directly to the sides of the fish. This seems a little strange since there should be no strong absorption or scattering mechanisms in these directions. Furthermore, this is not what would be expected from the roll axis measurements at this same aspect. No correlation with air bladder inflation is noted.

4.0 Implications for the A-PIT Tag Concept

In this section we briefly discuss the implications of these measurement data relative to the acoustic passive integrated transponder (A-PIT) tag concept which was a proposal presented in response to reference [1]. That concept was a completely passive miniaturized acoustic tag capable of being activated and energized by an acoustic interrogation signal operating at 50 kHz. The tag replies with a unique encoded response at 500 kHz for fish identification and censusing purposes. The baseline proposal was a completely passive tag using a single transducer. Various alternatives were presented as backup approaches as part of the overall risk mitigation plan. These included a dual transducer concept using PVDF for improved receive sensitivity as well as battery-powered and battery-assisted options. Components were identified and preliminary evaluations presented for each option to ensure a low-risk alternative to the baseline approach.

The two primary problems to overcome with the A-PIT tag approach were:

1) Providing a sufficiently intense interrogation signal at 50 kHz to energize the tag, and
2) Providing a sufficiently strong reply signal at 500 kHz to propagate a signal back to the census station receive array.

We'll consider these two problems separately below. In the following discussions, we'll take the measurements at face value and assume them to be correct. We'll ignore the 6 dB discrepancies noted previously in the bare transducer measurements at 500 kHz.

The 50 kHz Interrogation Problem

The measurement data indicate that the tag receive response at 50 kHz is relatively highly attenuated (up to about 20 dB or so) at overhead and head-on aspects to the fish. At most other aspect angles, the signal shows much less attenuation or no attenuation at all. In some cases the response is enhanced by the fish presence, but seldom by more than about 3 dB. Nevertheless, a problem still exists in some situations wherein the tag must be energized at overhead or head-on aspects.

The proposal recognized the interrogation link as the critical portion of the system. For this reason a number of alternative schemes were considered to ensure the adequacy of the design in this respect. One of the principal features of the proposed approach was to include multiple interrogation arrays to ensure that the fish would be ensonified at multiple aspects. A properly designed interrogation setup with multiple interrogation arrays would not allow fish passage without providing an interrogation signal at a favorable aspect. The measurement data set supplied by these experiments provides a suitable database for planning an appropriate interrogation setup geometry.

If the multiple interrogation array approach is impractical or unacceptable, the use of a dual transducer concept could be considered. The proposed design opted to use a single PZT transducer ceramic for both transmit and receive. It proposed a system with sufficient design margin to support proper tag operation using the PZT ceramic for both functions. PZT is preferred for transmit but not for receive. An alternative is to transmit on the PZT ceramic and receive on a separate PVDF ceramic which has a receive sensitivity approximately 20 dB higher than PZT. This approach provides 20 dB additional receive sensitivity to compensate the 20 dB fish flesh attenuation losses indicated by the measurement data. If this approach is considered, additional analysis is required to ensure that the energy transfer relationships and transducer impedance characteristics adequately support completely passive tag operation for this configuration.

Finally, battery-assisted operation was considered in which the interrogation signal serves only to trigger the tag. The power necessary to respond would be provided by an internal Lithium Carbon Mono-Fluoride battery, the commercial version of which has a 10 year shelf life with less than 1 percent per year dissipation. Battery dimensions are 2.2 mm by 10 mm. With this approach, the 50 kHz interrogation signal only needs to be sufficient to trigger the tag. The design margin in this case is in excess of 60 dB. This completely offsets the 20 dB fish flesh attenuation losses indicated by the measurement data and still provides more than a 40 dB design margin on this link. Although this approach does not represent a completely passive tag, it does provide a very attractive alternative to achieve transponder mode operation in a tag which will likely outlast the lifetime of the fish host.

The 500 kHz Reply Problem

The measurement data indicate that the tag transmit response at 500 kHz can also be attenuated (up to about 20 dB or so) at overhead aspects. This is not always the case, but appears to occur often enough that 20 dB losses cannot be considered completely atypical. Fortunately, we have considerable design margin on this link. The PZT ceramic transducer is capable of transmitting a 143 dB source level. (Note that the APL/UW transducer provided 145-147 dB source level at 500 kHz as shown in Test Transducer Measurement plot #1942). The proposal, however, showed that the required source level is only 123 dB for a 10 meter range. This figure includes a conservative 10 dB design margin as well. Increasing the tag source level another 10 dB (to 133 dB) provides the additional margin necessary to overcome the apparent 20 dB fish flesh attenuation losses indicated by the measurement data. This still leaves us with a 10 dB design margin since the maximum transducer source level capability is 143 dB. The increase in transmit power necessary to raise the transmit source level to 133 dB is not prohibitive. This is because the bulk of the required tag power goes into the electronics rather than into acoustic energy in the water. An increase in source level of 10 dB requires only a 2.2 dB increase in overall tag power requirements. Hence this approach is very practical.

A final alternative which works on both links is to reduce the maximum operating range (R). Signal strength increases inversely as $20 \log (R) + \alpha R$. Hence halving the range increases the signal level by more than 6 dB. This may not be a desirable method to recover the entire 20 dB. Nevertheless, it may be reasonable to use this approach to recover a portion of the loss, especially in the overhead (or depth) dimension, which is the primary direction in which fish flesh attenuation seems to be a problem. A full 10 meter range in this dimension may not be necessary .

Conclusion

Even though the measurement data indicate that considerable fish flesh attenuation may exist for both 50 kHz and 500 kHz transmissions, the proposed A-PIT Tag concept is still viable. The proposed approach provided very conservative design margins and a number of alternative approaches as part of the risk mitigation plan. We see that a number of alternatives are available to offset the apparent signal losses that may be present on the 50 kHz interrogation link and that sufficient design margin is available to offset apparent signal losses on the 500 kHz reply link as well. These may be used individually or in combination to provide sufficient margin to offset these losses. Even though the measurement data indicate that significant losses may exist for internally placed acoustic tags at certain aspects, these results do not imply that the proposed A-PIT tag concept is infeasible.

References

[1] Federal Solicitation Number 52ABNF300018 ("Development of Acoustic PIT Tag System"), NOAA, Oct 30, 1992

APPENDIX B: A Study on the Feasibility or Using Small Spheres to Enhance Fish Target Strength

A Study on the Feasibility or Using Small Spheres to Enhance Fish Target Strength

by Peter H. Dahl

Letter Report to NMFS, September 1994
Applied Physics Laboratory
University of Washington
Seattle, Washington 98105

1. Introduction

This report summarizes findings of a study to address the feasibility of placing small spheres inside salmon smolts, in order for the fish to be identified acoustically. The basic idea is that a fish which has implanted within it a sphere (referred to as tagged fish), will exhibit a significantly higher acoustic target strength (*TS)* than untagged fish. This *TS* enhancement would occur only at select acoustic frequencies known to excite the acoustic resonances of the sphere. Different spheres sizes and therefore different interrogation frequencies could then be used to distinguish different fish populations.

Spheres are considered because their scattering properties are independent of the direction of incoming acoustic radiation. The sphere acts as a passive transponder: scattering acoustic radiation only when excited by its resonance frequency. Implanted transducer material would not work for this purpose, since good transducer radiation properties do not equate to good passive scattering properties.

The scope of this study is limited to feasibility only. Biological issues (such as fish mortality when tagged) and manufacturing issues (such as costs and availability of spheres) are not addressed.

The study concludes that spherical shells made of glass with radius $a \geq 1$ mm, or solid spheres made of polystyrene with radius $a \geq 1.8$ mm, can increase the *TS* of salmon smolts by 6 dB or more. Therefore this method of tagging fish is a potentially useful technique. Recommendations for the next stage of this project are also made.

2. Target Strength of Salmon Smolts

We assume the salmon smolts are nominally 100 mm in length. For frequencies between 30 and 500 kHz the fish length (L) to acoustic wavelength (λ) ratio varies between 2 and about 30. A simple model for fish target strength averaged over all aspects and which spans this L/λ ratio is (Love, 1977)

$$TS = 10\log(L^{1.87}\lambda^{0.13}) - 27.7 \qquad (1)$$

where L and λ are in meters, and *TS* is in dB. Using $L = 0.1$ m, Eq. [1] gives $TS \approx$ -49 dB, with very little frequency dependence over the frequency range of interest. We thus adopt -49 dB as a nominal value for the *TS* of a 100 mm salmon smolt. We also have confidence in this estimate as it applies to salmonids since actual measurements of salmonid *TS* at 420 kHz (Dahl and Mathisen, 1983) are predicted to within ±2 dB using Eq. [1].

3. Enhanced Fish Target Strength Using Implanted Sphere

Assuming incoherent acoustic scattering, then a fish with $TS \approx$ -49 dB which has within it implanted a small sphere of $TS =$ -44 dB will show an increase in target strength about 6 dB. We are seeking at least a 6 dB enhancement in fish target strength, thus small spheres with a $TS \gtrsim$ -44 dB are of interest. Note that more reliable discrimination between tagged and untagged fish would occur if the *TS* difference was 10 dB or more. To realize a 10 dB difference in *TS* the sphere *TS* must be -39 dB.

4.Target Strength or Small Spheres

In this section results of a parameter study on the target strength of small candidate spheres are presented. Both solid spheres and hollow spherical shells are considered. The spherical shell calculations were made by Dr. Steve Kargl of the Applied Physics Laboratory, based on the work contained in Kargl and Marston (1991). Using the notation from this reference, the sphere target strength is defined as

$$TS = 10\log\frac{|F|^2 a^2}{4} \tag{2}$$

where $|F|$ is the magnitude of the complex scattering amplitude (in steady-state) of the form function, in the backscattered direction, and a is the sphere radius in meters. Large values of $|F|$, and therefore TS, exist with certain combinations of frequencies and sphere radii associated with acoustic resonances of the sphere.

A critical parameter is the radius a of the sphere (in m if used in Eq. [2]). For example, PIT tags of a maximum dimension equal to 2 mm have been implanted within salmon smolts with fish remaining viable. Other parameters are the sphere material, and in the case of hollow spherical shells, the shell thickness. The shell thickness is defined by the ratio of the inner radius to outer radius. For example, if the radius a equals 1 mm, and thickness ratio equals 0.9, then the shell thickness is 100 µm. The hollow spherical shells offer some advantage because they will in general display a large monopole resonance, like an air bubble. The closer the thickness ratio is to unity (or the thinner shell is), the more the sphere behaves like an acoustic bubble.

Three candidate materials were studied: stainless steel, glass, and polystyrene. These were chosen because of their availability, cost, and that these materials are all likely to be biologically inert. Figs. 1-4 show $|F|$ vs ka for glass and polystyrene material spheres. Stainless steel spheres did not offer any advantage over spheres made of glass or polystyrene, and was not considered further. Note that k is acoustic wavenumber which we convert to acoustic frequency assuming a sound speed of 1500 m/s.

Results for a glass spherical shell with thickness ratio = 0.99 (Fig. 3) show a maximum $|F|$ = 12.42 at ka = 0.82, which upon using Eq. [2] translates to

$$TS = -44 + 20\log a_{mm} \tag{3}$$

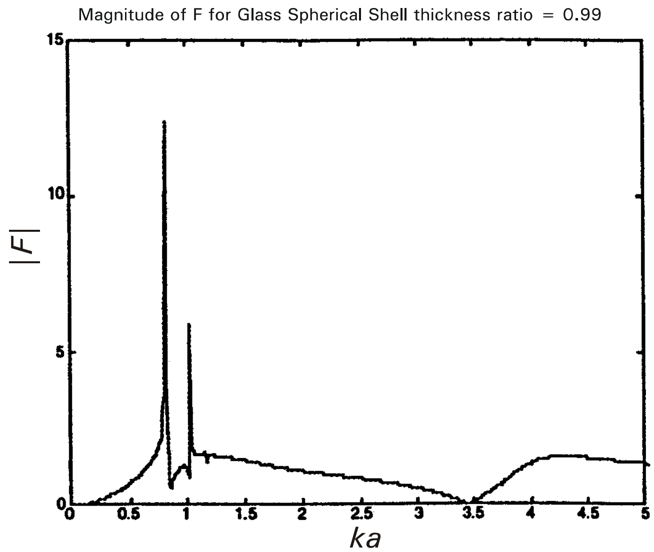

Figure 1: Magnitude of form function F for glass spherical shell vs *ka*. Material density = 3600, longitudinal speed = 5260, transverse speed = 2960 (MKS).

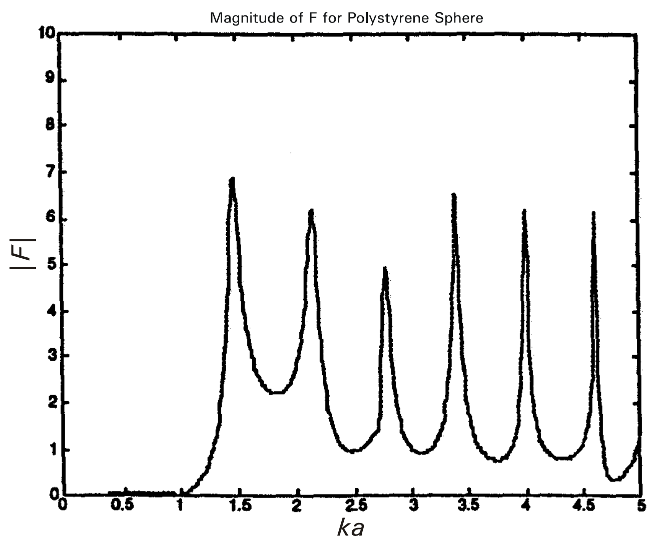

Figure 2: Magnitude of form function F for solid polystyrene sphere vs *ka*. Material density = 1056, longitudinal speed = 2350, transverse speed = 1120 (MKS).

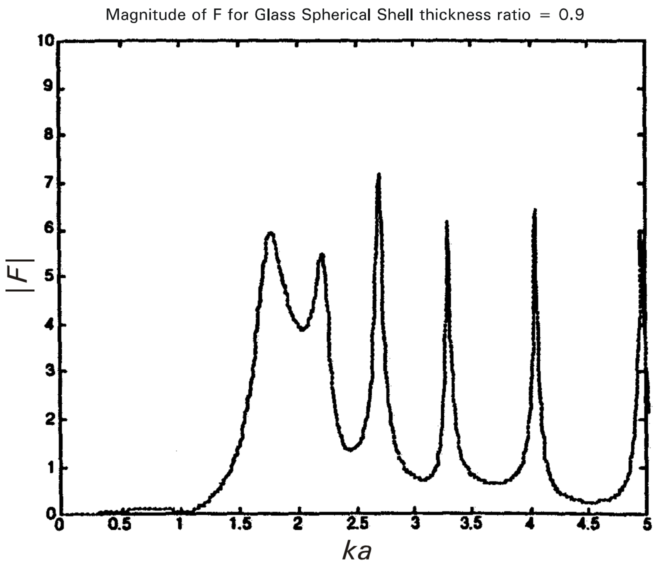

Figure 3: Magnitude of form function F for glass spherical shell vs *ka*. Material density = 3600, longitudinal speed = 5260, transverse speed = 2960 (MKS).

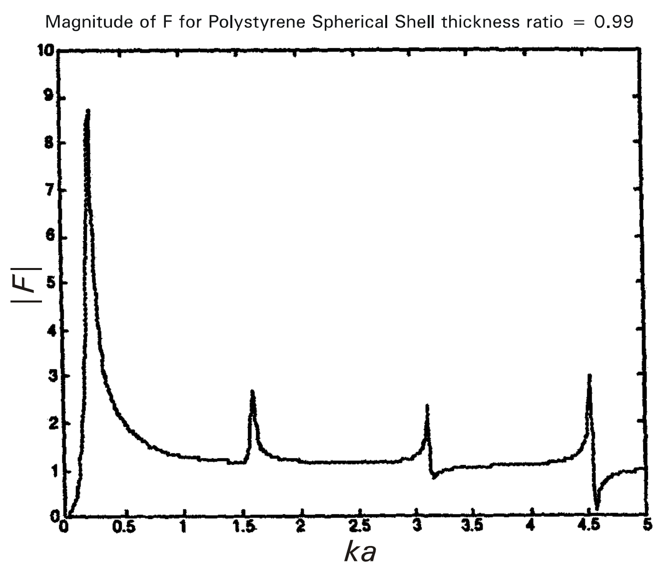

Figure 4: Magnitude of form function :F for polystyrene spherical shell vs *ka*. Material density = 1056, longitudinal speed = 2350, transverse speed = 1120 (MKS).

in dB, where a_{mm} is spherical radius is now expressed in mm. For particular radius, a_{mm} the maximum *TS* will occur at a frequency *f* (in kHz) equal to $195.8/a_{mm}$. For example, with sphere radius of 1 mm, the *TS* is -44 dB at a frequency of 195.8 kHz. Increasing the radius to 1.5 mm gives a *TS* of -40 dB at a frequency of 130.5 kHz. The -40 dB *TS* value is certainly the more desired scattering level, but it comes at a cost of the spherical radius slightly exceeding the maximum tolerable value as suggested by experience with the PIT tags.

The solid polystyrene sphere data (Fig. 2) is of special interest because one may imagine this type of sphere to be extremely easy to manufacture while also maintaining consistency. The resonance peak of $|F| = 6.91$ at $ka = 1.47$, will produce a *TS* that exceeds -44 dB only for $a_{mm} > 1.8$. Although this radius exceeds the maximum tolerable radius, a more exhaustive search of materials may point to other materials similar to polystyrene which produce sufficiently high scattering with smaller spheres.

Another possible candidate is a glass sphere with thicker shell ratio = 0.9 (Fig. 3). Three resonant peaks for $ka < 3$ may be exploited. The thicker glass shell may also be easier to manufacture. Finally, spherical shells made of polystyrene (Fig. 4) do not seem to offer a significant advantage over solid polystyrene.

In practice, the observed *TS* will be the result of integration in the frequency-domain of *S*, the incident signal spectrum; *F*, as defined above; and *H*, the receiver frequency response function (Foote, 1983). The backscattering intensity *I* is thus proportional to

$$I \propto \int_0^\infty |SFH|^2 \, df \tag{4}$$

Our computations using the results in Figs. 1-4 are based on a narrow band pulse that approximates a single frequency. Since a typical fisheries sonar operates with a relatively narrow bandwidth H ≈2-kHz, then *I* is approximately proportional to $|F|^2$ evaluated at the center frequency. In the follow-on study (outlined below) the exact integral in Eq. [4] should be evaluated to obtain a more precise value of the sphere *TS*.

5. Summary and Recommendations for Next Stage

This study has demonstrated that implanted small spheres inside salmon smolts can increase the *TS* of the fish by 6 or more dB. Hollow spherical shells seem the most promising at this stage, e.g., a hollow glass sphere of thickness ratio = 0.99 giving a monopole resonance at $ka = 0.83$. But there is the possibility that solid polystyrene (or other plastic-like material) spheres may be also be useful, particularly if the maximum allowable sphere radius can be increased. The increased *TS* , occurring only at a frequency corresponding to the resonances of the sphere, may be used to distinguish different populations of smolts.

We recommend that a more detailed parameter study combined with experimental test be undertaken. The parameter study would seek to optimize sphere material, and geometrical properties such as radius a and spherical thickness, vis-a-vis manufacturing costs and biological constraints. The methods described in Kargl and Marston (1990) would be used for this purpose. The goal of this study would be to produce precise specifications of the prototype sphere, and predictions of *TS* enhancement. Also the issue of damping due to the sphere being encapsulated in fish tissue would need to be addressed; in the present feasibility study we have assumed this to be a small effect.

The experimental test would confirm the results of the parameter study. The test could be made at the Applied Physics Laboratory's Research Barge (R/V Henderson). A simple cage of the type described in Weibe, et al. (1990), which was used to measure the *TS* of encaged zooplankton, could be used for this purpose. The *TS* of both individual fish, and groups of fish, with and without implanted spheres would be measured in order to demonstrate final proof-of-concept.

6. References

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