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EVALUATION OF HYDRO-ACOUSTICS AS A MEANS TO ASSESS SPAWNING STOCKS OF BLUEFIN TUNA IN THE GULF OF MEXICO

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SUMMARY

The present stock assessment of bluefin tuna relies on data obtained from commercial and recreational fishermen, limited egg and larval surveys, and biological studies. Many parts of the life history data base are missing (e.g., spawning information and bio-environmental relationships). Existing hydro-acoustic systems were reviewed as a means to aid assessment activities. Theoretical calculations were performed to identify an optimum system. The conclusion was existing systems are not adequate but a system could be designed if additional information were available.

RESUME

Les évaluations actuelles du thon rouge dépendent des données obtenues des pêcheurs commerciaux et sportifs, d'une prospection limitée des oeufs et larves, et d'études biologiques. De nombreux segments de la base sur le cycle vital manquent (par exemple, information sur la ponte et rapports biologie-milieu). Les méthodes hydro-acoustiques actuelles sont passées en revue en tant que moyen de faciliter les activités d'évaluation. Des calculs théoriques sont effectués pour définir un système optimum. La conclusion en est que les méthodes actuelles ne sont pas adéquates, mais qu'un système pourrait être élaboré si une information complémentaire était disponible.

RESUMEN

En la actualidad, la evaluación de la población de atún rojo se basa en datos obtenidos de la pesca comercial y de la de recreo, en prospecciones larvarias y de huevos - limitadas - y en estudios biológicos. Hay muchas lagunas en la base de datos históricos del ciclo vital (por ej., información sobre el desove y las relaciones bio-ambientales). Se revisaron los sistemas hidroacústicos existentes, como medio de apoyo a las actividades de evaluación. Se hicieron cálculos teóricos para identificar un sistema óptimo. Se llegó a la conclusion de que los actuales no eran adecuados y que, con información adicional podría diseñarse un sistema nuevo.

with large areal coverage. A second objective based on the failure of the first to provide a positive answer was pursued. This objective was to develop parameters necessary to define a system that would adequately satisfy the requirements set forth in the first objective.

PROBLEM STATEMENT

Tuna are described as a schooling fish, but spatial distribution within the schools is seldom mentioned. When addressed spatial distribution is described in terms such as "the larger fish are frequently below the smaller ones" or "large migratory bluefin passing the Cat Cay area in the Bahamas . . ., traveling northward in loose schools . . ." (Mather, 1963). Available aerial photographs imply a neighbor-to-neighbor spatial distance of greater than one fish length for giant bluefin.

Using classifications defined by Rivas (1978) and fecundity studies by Baglin (1982), spawning stocks may be divided into medium and giant tunas. These data identify target sizes of interest as: medium tuna (age 6-8) are 130-190 cm in length and weigh 66-136 kg; and giant tuna (age ≥ 9) are > 190 cm in length and weigh > 136 kg. Therefore, the minimum size of an individual fish with spawning potential is 130 cm and 66 kg. Known facts and assumptions concerning required data necessary to define characteristics of bluefin tuna in development of hydro- acoustic system are identified in Table 1.

Accurate use of hydro-acoustics in fish population assessment requires target verification. Common practices include net or handline sampling, and visual confirmation. There has been limited success reported by Hester (1966) and Yuen (1971) using target discrimination from acoustic returns only. Initial acoustic images, however, must be confirmed by positive identification of the targets to develop pattern recognition techniques. A supposition by Mather (1963) that tunas are subject to predation by cetaceans (blackfish) and killer whales, coupled with the observed presence of finback whales and porpoise intermingled with tuna schools makes the discrimination problem more severe, since these species probably have similar target strength characteristics.

AVAILABLE HYDRO-ACOUSTIC TECHNIQUES

The sector scanning sonar is a commercially available hydro-acoustic tool for finding fish. This system transmits a pulse of acoustic energy in all directions around the transponder and electronically scans segments of the transponder to provide direction information. The scan rate can be made fast enough to eliminate targets lost due to vessel motion and rotation of the transponder in a searchlight pattern. The directivity of this system is limited by the physical geometry of the transducer. Commercially available systems have beam widths of around 12° and ranges of approximately 1,000 m for large targets (approaching 0 db). Consistent single target discrimination range is probably limited to around 300 m for a 1 m tuna.

Continuous transmission frequency modulated (CTFM) sonar systems derive range information from the frequency difference between the reflected energy and the transmitted energy. The transmitted signal varies in frequency with time. Yuen (1971) reported some success in target discrimination using this technique. The CTFM system design does not lend itself to long-range operation because responses are masked by short-range surface reverberations. A range of less than 1,000 m can be expected. The electrical power required for continuous transmission also is a limiting factor (assuming surface reverbation at short ranges could be overcome).

Vertical sounders are typified by the commercially available fish finder. Several varieties are available, ranging from the simple rotary light display fish finder to fully adjustable scientific sounders with calibration capability and accurate attenuators. The major differences are the methods used for processing and displaying echo returns and cost. All are limited by the fixed physical orientation (vertical) and are not as efficient for searching as scanning -type sonars. The area covered by a vertical sounder is limited by beam width and the speed of the vessel on which it is mounted. Beam width design presents a conflict between the desire for large areal coverage (wide beam width) and the need for target discrimination (narrow beam width). The search area of a vertical sounder is limited to the cone of sound immediately below the sounder's transducer.

Processing of hydro-acoustic signals covers a broad range of techniques. Most signal processing methods are well-defined and covered in detail by Tucker and Gazey (1966) and Urick (1977). Four signal processing techniques have been or could be adapted to fisheries applications: echo integration; dual beam target strength measurement; doppler shift measurement of tail beat frequency; and echo spectra analysis.

Echo integration is the summing of selected echoes over a specific area (or volume). The summation operation and volume determination is easily handled by available electronics and ships' navigation gear. The specification of which echoes to sum and which to reject is complicated by: the target aspect with respect to the acoustic transponder; the finite beam width of the acoustic system; the variance of sound transmission through the sea due to temperature, salinity, and density differences within the media; background noise, and system noise.

Commercial echo integrators are expensive, complicated to operate and the areal coverage is restricted by the use of a vertical sounder. Despite these problems Nishimura and Shibata (1966) and Yamanaka, et. a. (1977) have reported success in counting tuna and related species. Truskanov and Zapherman (1977) also reported success in echometric survey work by carefully examining the problem of target verification and restricting efforts to well-known, densely schooled fish. Burczynski (1979) describes the basics of sonar use in estimating fish biomass using the echo integration concept and the problems associated with equipment calibration and maintenance.

System calibration with respect to specific targets of interest is a particular problem. Ehrenberg (1984) describes a unique method of in situ calibration using a dual acoustic beam technique. This scheme effectively removes the beam pattern factor from the echo of a single target. The beam pattern factor is the error that arises due to the displacement of the target from the centerline of the beam. Removal of the beam pattern factor is accomplished by transmitting the acoustic energy with a narrow beam transponder whose axis is essentially coincident with a wide beam receiver. The single target echo is received by both the wide and narrow beam transponder simultaneously. The narrow beam pattern is then extracted from the echo and the individual backscattering values may be computed.

Doppler shift measurement of tail beat frequency is based upon the modulation of the target echo due to the movement of the fish's tail with respect to its body. This movement produces a shift in frequency of the echo signal component that arises from backscattering of the moving tail. Tail beat frequency, coupled with swimming speed appears to be a valid means of classifying fish (Bainbridge, 1958). Experimental data for the species of interest, however, must be developed.

Echo spectra analysis use for fish target discrimination, as proposed by Altes (1981), consists of experimentally classifying against stored digitized spectral data received from fish target echoes. A mechanism for varying echo integration time, and range interval for the integration should be provided, and the data digitized for spectrum analysis. Independent verification of the target must be made to allow completion of the classification file. The primary problem is target verification. This file should be built from controlled experimental data such as captured species of interest impounded and insonified.

FEASIBILITY ANALYSIS

A basic design concern for an acoustic system to survey spawning bluefin tuna in the Gulf of Mexico is the amount of area to be covered and the restrictive time frame to provide reasonably precise and biological sound population estimates. The time frame can be estimated to be about 60 days based on work by Rivas (1975). The coverage area, however, is much less certain, but if one assumes a surface area in the Gulf of Mexico of about 1.2 x 10^6 km^2 and half of this area is eliminated from the survey based on historical fishing data, the required survey area reduces to about 6 x 10^5 km^2. Then if one further assumes 10 percent of the reduced area has to be insonified based on a predetermined sampling design (e.g. line transect theory), the required coverage area would reduce to about 6 x 10^4 km^2. These latter estimates are admittedly arbitrary, but probably resonable first approximations. Given that a survey period of 20 days is considered optimum to fit within the estimated 60-day spawning period, and that weather and sea conditions permit an average vessel survey velocity of about 6 km/hr, the sonar system would have to have an effective insonification range of about 20 km.

A 20 km range is an order of magnitude greater than that obtainable from presently available commercial sonar systems. Altes (1981) proposed a low frequency sonar system with a predicted range of 27 km. To obtain this range Altes made some assumptions such as target strength calculation based upon schools of fish numbering 1400 to 2800 over an area of 1.4 to 4.5 km width. An estimated school size of Atlantic bluefin tuna of spawning age may be 64 fish in an area of 10 x 10 m, assuming a 1.5 m neighbor-to-neighbor spacing and a three dimensional matrix (4 x 4 x 4 fish) with equal fish distribution in all directions. Altes (1981) estimated range resolution of 1.4 - 4.5 km would be decreased to an estimated 10 m. This difference in target characteristics imposes severe bandwidth dependences upon the system required for Atlantic bluefin tuna assessment.

Another consideration is the difference in target strength between tunas and the fish schools described by Altes. The target strength return calculated for 200 fish each with a target strength of -30 db is + 3 db whereas the same calculation for a school of 50 tunas yields a target strength return of -13 db; a difference of 16 db. Even allowing for the greater size of bluefin tuna and using maximum target strength (from Table 1) of -22 db, the expected target strength (TS) is -5 db; a decrease of 8 db.

Areal restrictions associated with a vertical echo sounder eliminate this system from consideration as a search tool for Atlantic bluefin tuna. The potential accuracy available from a vertical sounder indicates a potential use as a counting system, if the fish school can be approached close enough to allow the vertical sounder to obtain data. Use of continuous transmission frequency modulated (CTFM) sonar for long-range fish detection is limited by surface reverbation effects and reported maximum ranges of less than 1 km (Yuen, 1971) are not adequate. Specified ranges of commerical sonars (2-3 km) are not adequate to efficiently cover the area of concern in Atlantic bluefin tuna assessment.

SYSTEM DEFINITION

Problems associated with defining a hydro-acoustic system for assessing bluefin tuna can be shown by several sample calculations. The basic sonar equation (Urick, 1977) to be used is:

$$SL - 2TL + TS = NL - DI + DT$$

where:

NL = Noise level
DI = Receiving directivity index
DT = Detection threshold
SL = Source level
TL = Transmission loss
TS = Target strength

TS, NL and TL are determined by the physical properties of the target (TS) and the physical properties of the transmission media (sea water). NL and TL are frequency dependent, exhibiting a wide variation depending upon the frequency selected for transmission of acoustic energy. A high operating frequency (50 - 60 kHz) will enable the transducer design to be more compact, while it is beneficial to use the lowest possible frequencies (5 - 10 kHz) to enhance the transmission of sound through the sea. Therefore, assume 50 kHz and 10 kHz, respectively, in the following calculations. The values or terms in the sonar equation can be expected to fall within the following limits.

TS = -22 to -30 db
NL @ 50 kHz = -40 to -80 db
NL @ 10 kHz = -50 to -90 db
TL = α + R

where:

α = attenuation of seawater
α @ 50 kHz = 19 db/kyd
α @ 10 kHz = 1 db/kyd

and: R = spreading loss (intensity decrease with range (r)) = 20 log r

Using a 24.1 km range, (26.4 kyd):

TL @ 50 kHz = (19) (26.4) + 88.4 = 590 db
TL @ 10 kHz = (1) (26.4) + 88.4 = 114.8 db

DI is a function of the physical design of the transducer. Select a DI value of 30 db to correspond with the design of a 25.4 cm circular array at 50 kHz and DI of 15 db at 10 kHz.

DI @ 50 kHz = 30 db
DI @ 10 kHz = 15 db

SL (source level) is desired at about 125 db and relates to systems available commercially.

SL = 125 db

DT (detection threshold) is the ratio of signal power to noise power and incorporates the receiver operating characteristics and an acceptable false alarm probability. Select:

DT = 30 db

Using the sonar equation, SL can be calculated based on the preceding values.

SL = NL - DI + DT + 2TL - TS
SL @ 50 kHz = -40 - 30 + 30 + (2) (590) - (-30) = 1170 db
= -80 - 30 + 30 + (2) (590) - (-22) = 1122 db

Therefore, the required source level (SL) at 50 kHz will be 1122 - 1170 db.

SL @ 10 kHz = -50 - 15 + 30 + (2) (115) - (-30) = 225 db
= -90 - 15 + 30 + (2) (115) - (-22) = 177 db

Therefore, the required source level (SL) at 10 kHz will be 177 - 225 db.

The source level calculation at 50 kHz results in a required source level in excess of 1,000 db which exceeds reasonable design requirements. Normally cavitation occurs well below this level for any reasonable number of array elements. The SL of 177 - 225 db for 10 kHz is more realistic, although the design of the transponder is complicated by the physical size required to obtain a directional transponder at the lower frequency. These simple, rough calculations are presented to illustrate the multitude of design trade-offs and judgemental decisions required to formulate a set of sonar system design parameters. These calculations are based on assumptions and provide only approximation of source level requirements.

Another element of the design criteria is the analysis of required responses in relation to expected reverberation levels. Altes (1981) addresses this analysis but the results deviate from the desired system by 8 - 16 db in target strength estimates. A rough estimate of surface reverberation level may be obtained using the following equation (Urick, 1977).

$RL_s = SL - 40 \log r + S_s + 10 \log A$

Select: $S_s = -45$ db
$A = 1.797 \times 10^7$ If: $r = 26.4$ kyd
$\Delta r = 2.6$ kyd
$\Phi = 15^\circ = 0.26$ rad

then: $10 \log A = 7.25$
SL = 225 db
$40 \log r = 176$
$RL_s = 225 - 176 + (-45) + 7.25$
$= 11.25$ db

Using the sonar equation, solve for DT using the best case of SL = 225 db.

DT = SL - 2TL + TS - NL + DI
= 225 - 230 + (-30) - (-90) + 15 = 70 db
= 225 - 230 + (-22) - (-50) + 15 = 38 db

These calculations result in a detection threshold (DT) of 38 - 70 db and a surface reverberation level (RL_s) of -11.25 db. Therefore, the reverberation level is below the detection level in either case further demonstrating assumptions made on the best available information are not within the tolerance required to develop a viable assessment system for bluefin tuna.

CONCLUSIONS AND RECOMMENDATIONS

Bluefin tuna characteristics and assumptions identified in Table 1 were used in a series of hypothetical calculations to determine the feasibility of using available sonar systems and the development of design criteria for an optimum system. This brief analysis raised a number of questions which are addressed in Table 2.

A long-range sonar required for a reasonable coverage of the Gulf of Mexico would have to be designed and developed. This system would give the best, most thorough and accurate results in addition to being usable for many other areas of fisheries research and management. It is recommended this development be pursued.

Limited success can be expected using commercially available scanning sonars. The primary restriction is the short range (2-3 km) of these systems. A theoretical sampling design would require areal coverage of approximately 6×10^4 km ^{2} within an estimated 60-day spawning period. Further, a survey period of 20 days is considered optimum. Therefore, the survey of spawning stocks of Atlantic bluefin tuna in the Gulf of Mexico is not feasible with available short-range hydro-acoustic systems. Development of long-range sonar systems to hunt these near-surface fish does appear feasible if sea surface reverberation can be overcome, tuna targets can be accurately discriminated, and *in situ* target strength measurement techniques can be developed.

Table 1. Summary of the pertinent characteristics of spawning size tunas for determining a set of design parameters for hydro-acoustic assessment.

Size	: > 130 cm (length)	
Weight	: > 66 kg	
Swim Speed	Normal	Excited
Minimum :	3 knots	--
Maximum :	8 knots	40 knots
Assume :	6 knots average	
Number per school		
Usually	: 6 to 20	
Sometimes	: 50 to 100 +	
Assume	: 64 average	
Spacing	: 130 cm to 190 + cm	
Assume	: 1.5 m average	
Target strength	: -22 db to -30 db	
Assume	: -26 db average	
Depth	: Surface to 100 fm	
Tailbeat frequency	: 2 to 12 beats/sec	
Assume	: 6 beats/sec average	

Table 2. Information necessary to develop design criteria or identify an existing optimum hydro-acoustic system for assessment of bluefin tuna.

QUESTION	PROPOSED SOLUTION
TARGET CHARACTERISTICS	
Number of fish in a school and neighbor-to-neighbor spacing	The expected average number of Atlantic bluefin tuna in a school and their neighbor-to-neighbor should be estimated and experimentally confirmed.
Target strength of a single tuna	Target strength is necessary to define design constraints for a sonar system. This parameter has such a large variation with fish aspect to the sonar beam that "a number" for a particular species is probably not feasible. Effort should be directed toward schemes of *in situ* determination of target strength not repeated determination of specie dependent data.
Tail beat frequency of bluefin tuna	Tail beat frequency studies of yellowfin tuna have been productive. Confirmation of swim speed (body length/time) versus tail beat frequency for bluefin tuna would aid in use of Bainbridge's (1958) equations to explore doppler shift techniques.
Maximum swim speed of tuna	Maximum swim speed data of tuna is necessary to evaluate the amount of lost data due to system designs that do not encompass the full speed range. These data also would be useful in determining swim speed discrimination criteria.
DEFINITION OF MOST EFFICIENT SURVEY TRACK	
Horizontal range	Determination of tuna's horizontal range is necessary to optimize the survey track and develop a required sonar swath width.
Vertical dispersion (regarding thermocline)	Vertical distribution of tuna in the water column is necessary to develop sonar design criteria. An existing system may be used to confirm this parameter.

Table 2. (Continued)

EXPERIMENTAL PROOF OF TARGET DISCRIMINATION TECHNIQUES	
Doppler shift as a function of tail beat frequency	Measurement of shift as a function of fish tail beat is necessary to determine the feasibility of target identification, classification or discrimination, and confirm calculations by Altes (1981).
Echo spectra analysis classification	Experimental proof of echo spectra classification is necessary to justify incorporation of this feature in the design criteria.
Dual beam classification applied to long-range systems	Dual beam use for *in situ* target strength determination was demonstrated by Ehrenberg (1984). The feasibility of applying this technique to long-range (20-30 km) sonar systems should be evaluated.

LITERATURE CITED

Altes, R.A. 1981. Detection and identification of fish schools from sonar echoes. Final Technical Report. National Science Foundation. PB82-247933:95p.

Baglin, R.E., Jr. 1982. Reproductive biology of western Atlantic bluefin tuna. Fishery Bull. U.S. 80(1):121-134.

Bainbridge, R. 1958. The speed of swimming of fish as related to size and to the frequency and amplitude of the tail beat. Jour. Exp. Biol. 35(1): 109-133.

Burczynski, J. 1979. Introduction to the use of sonar systems for estimating fish biomass. FAO Fisheries Technical Paper No. 191:89p.

Ehrenberg, J.E. 1984. The BioSonics dual-beam target strength measurement system. Submitted to FAO February 1984. 14 p.

Hester, F.J. 1966. Identification of biological sonar targets from body-motion doppler shifts. Proc. of Second Symp. on Mar. Bio-Acoustics, American Museum of Natural History. New York. April 13-15, 1966. 2:59-74.

Mather, F.J., III. 1963. Tunas (Genus *Thunnus*) of the western North Atlantic. Part III. Distribution and behavior of *Thunnus* species. Symp. on Scombroid Fishes (1):1-16.

Nishimura, M. and K. Shibata. 1966. Echo-survey of tuna fishing ground. La mer; Bull. de la Societe Franco-Japanaise d'Oceanographie. 4(3):155-168.

Richards, W.J. 1975. Sqawning of bluefin tuna (*Thunnus Thynnus*) in the Atlantic Ocean and adjacent seas. ICCAT Collective Volume of Scientific Papers V(2):267-278.

Rivas, L.R. 1978. Preliminary models of annual life history cycles of the North Atlantic bluefin tuna. The Physiological Ecology of Tunas.:369-393.

Truskanov, M.D. and M. L. Zapherman. 1977. Some characteristics of hydroacoustic methods of determination of fish abundance in sound scattering layers. Rapp. P.-v. Reun. Cons. int. Explor. Mer. 170:245-247.

Tucker, D.G. and B. K. Gazey. 1966. *Applied Underwater Acoustics*. Pergamon Press. Oxford.

Urick, R.J. 1977. *Principles of Underwater Sound for Engineers*. McGraw-Hill Book Company, New York.

Yamanaka, H., M. Yukinawa and J. Marita. 1977. Acoustic fish counting systems for tuna and related species. Rapp. P.-v. Reun. Cons. int. Explor. Mer. 170:174-184.

Yuen, H.S.H. 1971. An evaluation of a continuous-transmission, frequency-modulated sonar in fishery research. Modern Fishing Gear of the World. 3(1):141-144.