NOAA Technical Memorandum NMFS

MAY 1986

THE LIMITATIONS OF FISH TRACKING SYSTEMS: ACOUSTIC AND SATELLITE TECHNIQUES.

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NOAA-TM-NMFS-SWFC-61

U.S. DEPARTMENT OF COMMERCE
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I.G. Priede[1]

INTRODUCTION

The purpose of this paper is to consider the limitations of tracking technology as applied to the problem of tuna migrations. A number of workers have successfully tracked tunas using acoustic transmitters attached to individual fish. This has provided much detailed behavioral information, but long-term tracking beyond a day or two has proved difficult (Hunter et al. 1986). The limitations of acoustic tracking technology will be assessed in the first part of this paper. In the second part the possibility of using satellite locatable radio tags is discussed. Basic information has been collated to enable the non-engineer to interpret specifications of equipment.

ACOUSTIC TRACKING

The normal basic tracking system consists of a transmitter on the fish which emits pulses which can be detected by a directional hydrophone mounted on a ship. The bearing of the fish relative to the ship can be determined and an approximate estimate of range is obtained from signal level. Using such a system it is possible for a ship to follow a fish continually. Primary considerations regarding the transmitter are:

1. range over which the signal can be detected
2. size
3. life of the batteries.

These are determined by the following engineering specifications of the transmitter:

1. source level
2. frequency and range
3. pulse rate and pulse length
4. battery size and chemistry
5. transmitter size
6. tracking performance
7. satellite tracking.

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[2]This review was presented during a technical workshop on existing and new technologies that could be employed to measure tuna movements. The workshop was one of a series of three on tuna movements held in 1985 which were jointly sponsored by the Inter-American Tropical Tuna Commission and the Southwest Fisheries Center of the U.S. National Marine Fisheries Service. For further details regarding the workshops see Hunter et al 1986.

Source Level

In underwater acoustics the source level of a transmitter is usually measured in terms of pressure detected by a hydrophone at a standard distance (1 m) from the source (Figure 1), e.g. 1 Newton/m^2 at 1 m = 1 Pascal (Pa) at 1 m. Normally this is expressed in decibels (dB), a ratio relative to a standard reference pressure. The current international standard for underwater acoustics is a reference pressure of 1 μPa. Thus Source Level (SL):

$$SL = 20 \log_{10} (p/p_o) \qquad (1)$$

When p_o = 1 μPa and p = 1 Pa, then SL = 120 dB. Thus a manufacturer might specify the output source level of the transmitter as: 120 dB re 1 μPa at 1 m. Some manufacturers still use 1 μbar as the reference pressure. 1 μbar = 0.1 Pa; to convert from Db re 1 ubar to Db re 1 μPa add 100 (Figure 1).

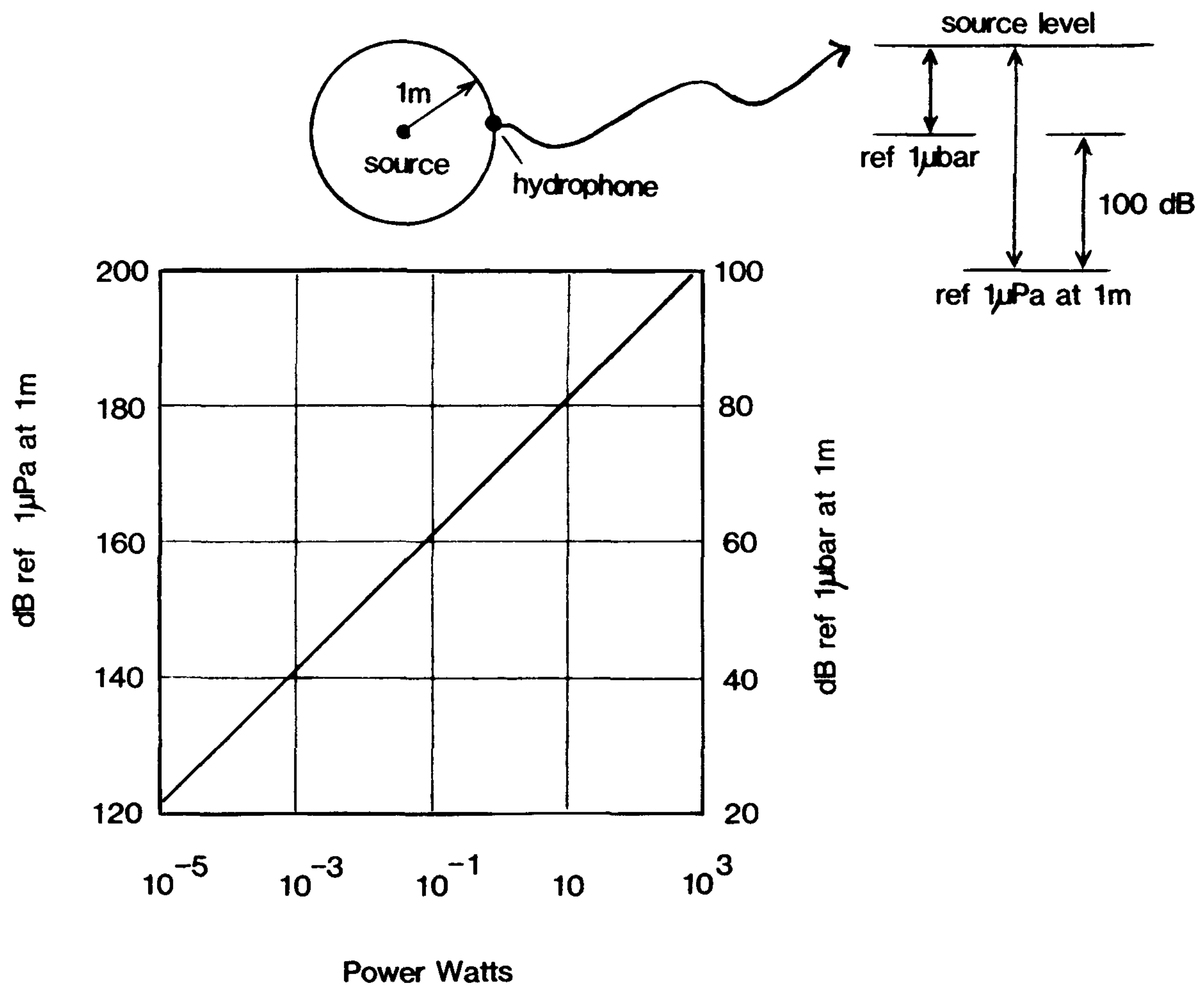

Figure 1. Source levels and power outputs of underwater acoustic transmitters.

The decibel notation is very convenient since all calculations regarding signal levels, attenuation, etc. can be carried out by simple addition or subtraction. Some manufacturers, however, still specify their equipment output power in watts. This has the advantage of being unambiguous, avoiding the confusion arising in decibel notation resulting from use of different reference pressures. To convert from watts acoustic power output (P) to source level dB re 1 μPa at 1 m, the following equation should be used:

$$SL = 170.77 + 10 \log_{10}P \quad (2)$$

Given a transmitter of known source level, it is possible to predict the range at which it can be detected. With a good-quality hydrophone and receiving system the practical limit occurs when the signal cannot be distinguished above ambient sea noise, i.e. a signal-to-noise ratio of 0 dB (Stasko and Pincock 1977). Assuming the signal is emitted omnidirectionally, the power generated spreads out spherically, leading to a fall off in power with range in accordance with the inverse square law. The dB transmission loss (TL) due to spherical spreading is:

$$TL = 20 \log_{10}r \quad (3)$$

where r = range in meters. Since log 2 is approximately 0.3 that gives a 6 dB loss for every doubling in range or 20 dB for every decade increase. The 6 dB rule of thumb is quite accurate at short ranges. As range increases, however, transmission loss due to absorption in seawater becomes significant and Equation 3 must be modified as follows:

$$TL = 20 \log_{10}r + \alpha r\ 10^{-3} \quad (4)$$

where α= absorption coefficient in dB per km. The 10^{-3} term is required to allow for the fact that range (r) is in meters and α is in dB per km. The absorption coefficient varies with temperature, salinity, pressure and frequency. An important consideration from the point of view of acoustic transmitter design is that absorption is proportional to the square of frequency.

Frequency and Range

Figure 2 shows the relationship between absorption coefficient and frequency. In seawater there are important ionic relaxation effects which lead to discontinuities in the basic square law relationship. Figure 3 shows the calculated transmission losses at different frequencies as a function of range. Up to 100 m, loss follows the 20 dB rule; but up to 1000 m, absorption losses become significant, especially at high frequencies.

From the point of view of gaining maximum range with minimum power requirement the lowest possible frequency should be used. In the transmitter the signal is usually generated by a hollow cylindrical piezo-ceramic transducer. Greatest efficiency is achieved if this is driven at its resonant frequency. The resonant frequency decreases with increase in diameter. A popular size is 12.5 mm (1/2 inch) diameter which resonates at

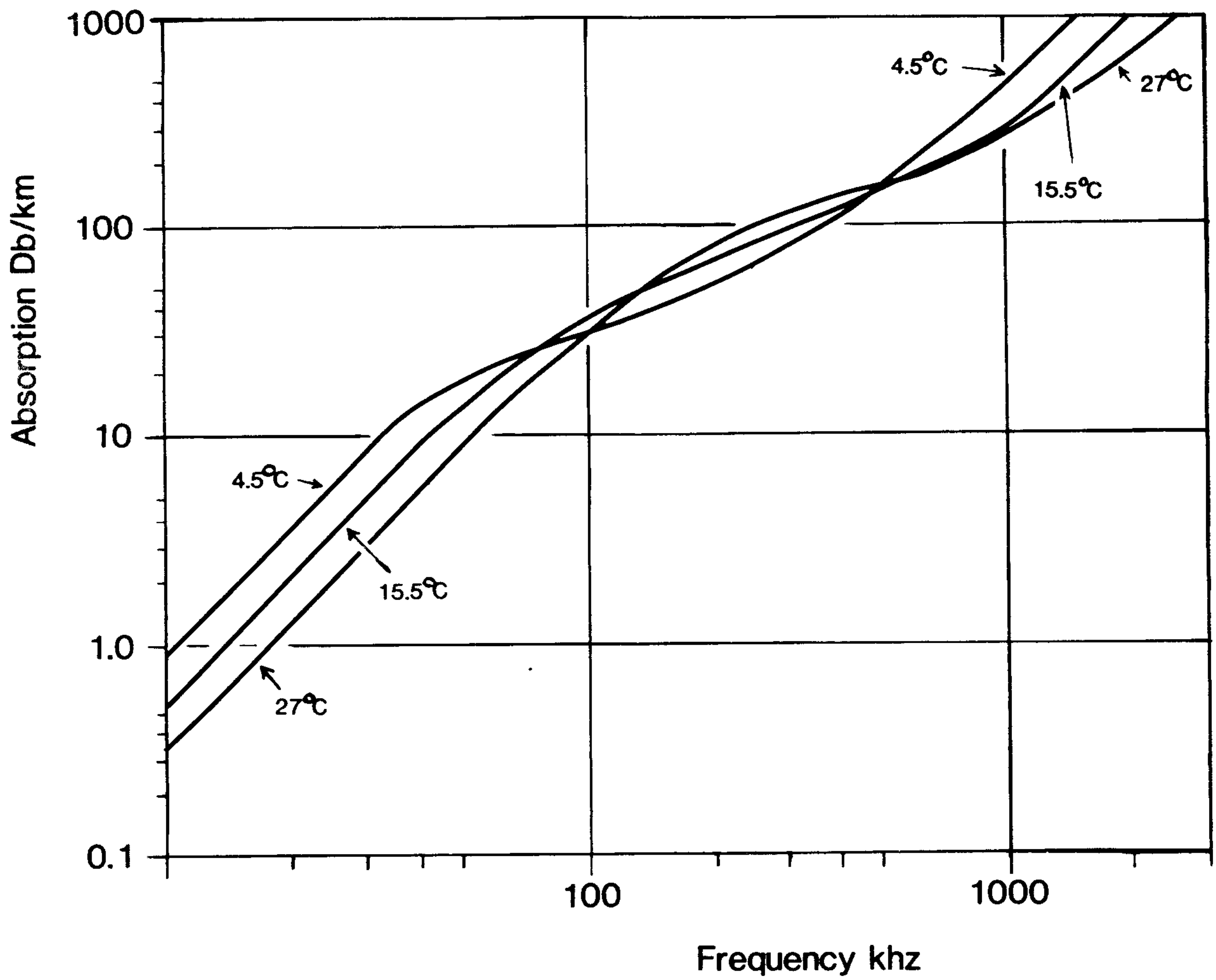

Figure 2. The relationship between absorption coefficient and temperature.

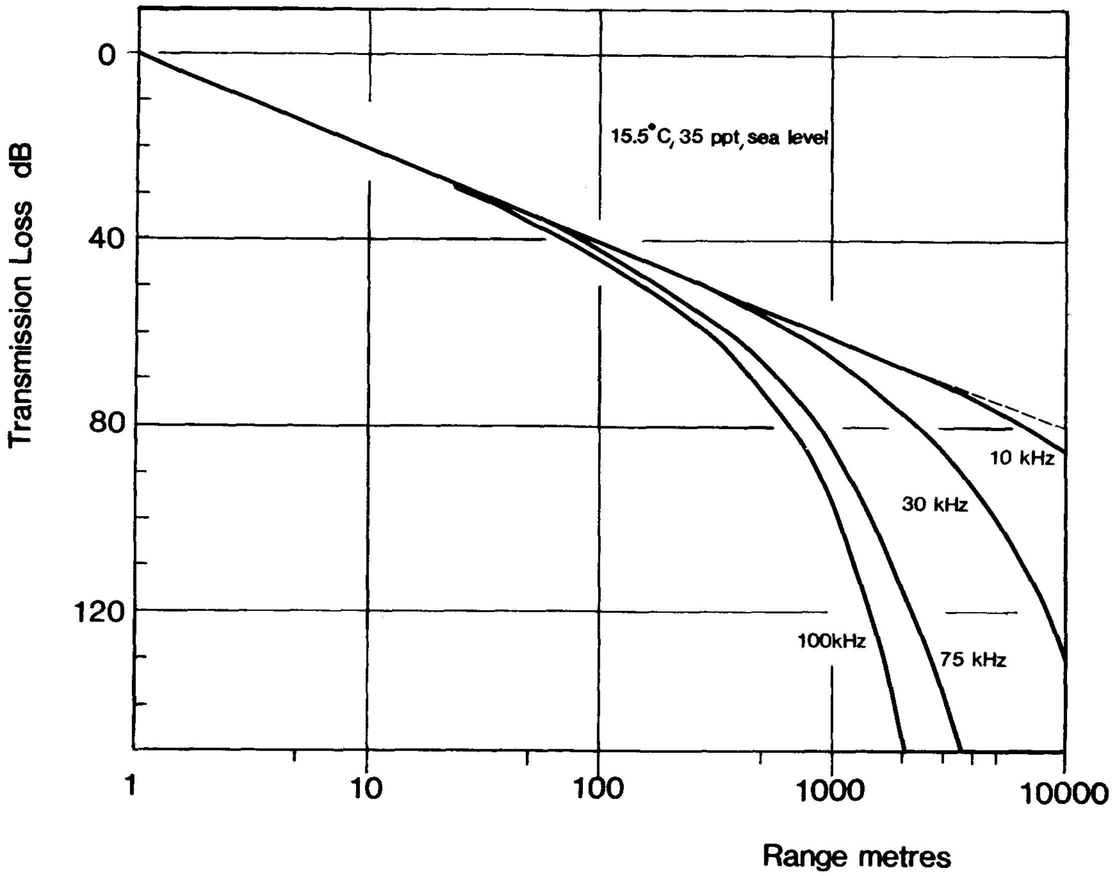

Figure 3. Transmission loss with range at different frequencies.

about 75 kHz and 25.4 mm (1 inch) which resonates at 40 kHz. Figure 4 shows the relationship between frequency and transducer diameter. The choice of frequency therefore immediately begins to define the size of the transmitter. Normally the transmitter is a cylinder just big enough to enclose the transducer and batteries are chosen of a diameter to match the transducer.

Below 20 kHz the diameter is too large to be seriously considered for fish tags. In general frequencies between 30 kHz and 80 kHz are used, although in freshwater with lower absorption coefficients 220 kHz has been successfully used in very small transmitters (Young et al. 1972). Mitson and Storeton-West (1971) used a 300 kHz transmitter for tracking plaice at sea. This was a transponding fish tag, and the frequency was determined by the working frequency of the sector-scanning sonar with which it was used. The working range of this system was not more than about 500 m.

It is possible to take advantage of low absorption characteristics at low frequencies in small transmitters by running a small transducer below resonant frequency. This is generally inefficient, and only low source levels can be achieved. Consideration perhaps should be given to alternative transmitter geometries, getting away from the long cylinder with the transducer aligned coaxially.

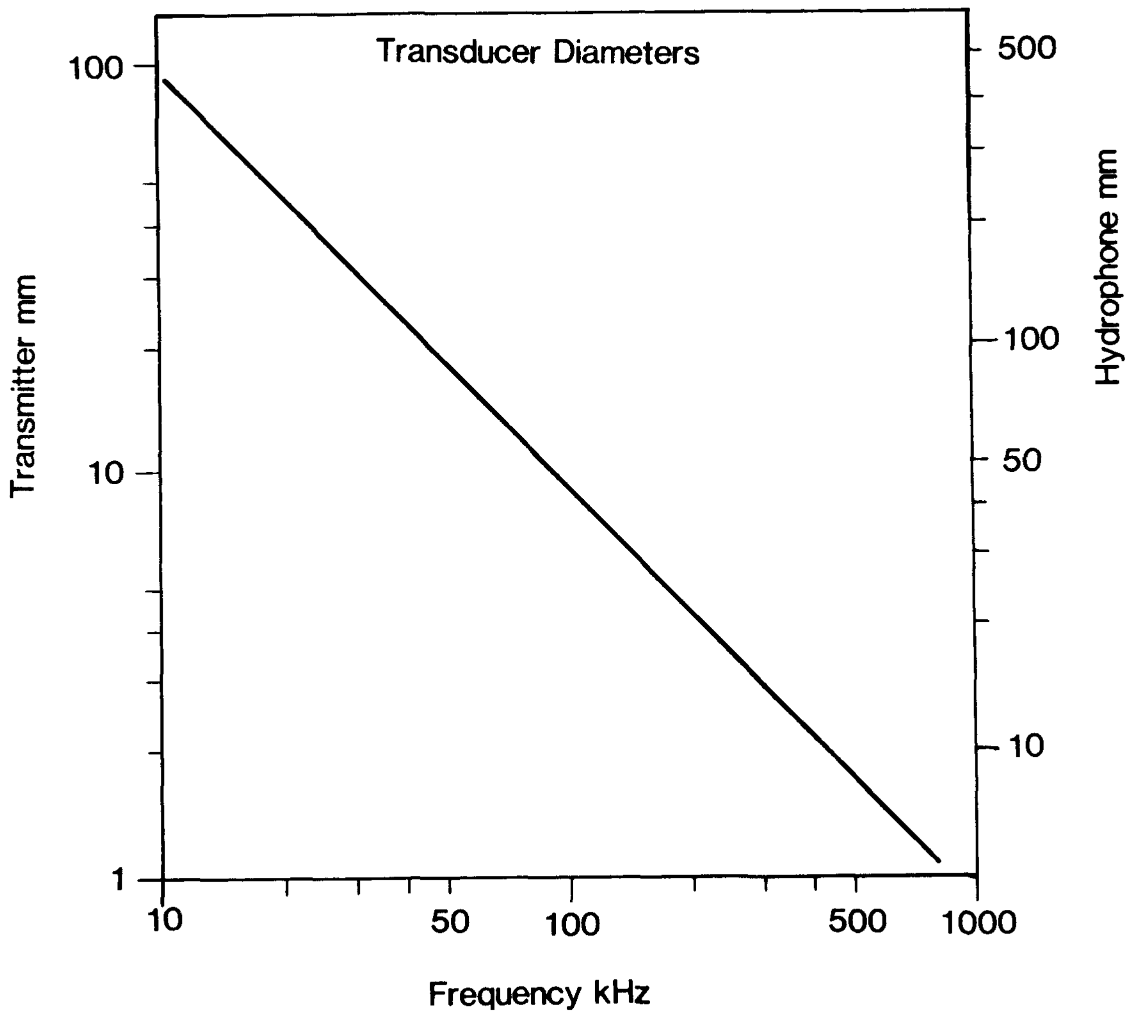

Figure 4. Transmitter transducer diameter (hollow resonant PZT cylinder) in relation to frequency.

Successful tracking depends on a good directional receiving hydrophone. The size of the hydrophone required also increases with decrease in frequency. Figure 4 gives the dimensions of a basic circular piston receiving element with a directivity index of 20 dB (Urick 1967). Larger diameters give improved directivity, but the slope of the relationship remains the same. It can be seen that above 40 kHz it is easy to build compact lightweight hydrophones of appropriate performance, but below 20 kHz hydrophones become large and unwieldy, necessitating special mountings--preferably permanently fitted to the hull of a ship--and with hydraulic servo controls. Below 10 kHz steerable directional hydrophone technology really breaks down, and location would be carried out by measurement of time delays in some sort of spaced receiving array.

A third consideration in choice of frequency is the interference from animals and whether the acoustic signal will be detected by animals, including the fish to which the transmitter is attached. Many fish can detect and produce sounds at up to 10 kHz, but most fish sounds are at low frequencies (Hawkins and Urquhart 1983). The usual fish tracking frequencies of 30 to 100 kHz are unlikely to affect fishes. Marine mammals, however, can produce sounds at up to 100 kHz. I have listened to porpoises in the Bay of Panama apparently trying to communicate with a 75 kHz transmitter being used to track a sea snake. Unfortunately there is no useful acoustic frequency band in the sea which is not utilized by marine mammals.

The detected level (DL) of the signal is determined by the source level and the transmission loss:

$$DL = SL - TL \qquad (5)$$

The detection threshold at extreme range occurs when DL is equal to the noise level (NL). Thus information on ambient noise levels in the sea is required to predict range. Figure 5 shows typical noise levels at the sea surface in deep-sea conditions (Urick 1967; Clay and Medwin 1977) for the frequencies of interest. Above 50 kHz noise is dominated by thermal noise which increases with frequency at 6 dB per octave. Below this frequency sea-surface noise, which decreases at about 6 dB per octave, is dominant. This increases in accordance with wind speed and sea state as indicated. Heavy rain can generate up to 80 dB below 30 kHz. Ship noise can add about 30 dB and generally follows the -6 dB slope in relation to frequency. In coastal regions noise levels would typically be 10 dB above the levels indicated. There is a clear minimum in the noise spectrum in the 50 - 100 kHz band.

The noise level detected by a receiver depends on the bandwidth over which it detects incoming energy. Data in Figure 5 are given in terms of spectrum level/Hz (SPL). The noise level detected is given by:

$$NL = SPL + 10 \log_{10} W \qquad (6)$$

where W = bandwidth in Hz, e.g. for 1 kHz bandwidth:

$$NL = SPL + 10 \log_{10} 1000;$$
$$NL = SPL + 30.$$

Omnidirectional hydrophones detect noise from all around, and therefore require a higher signal level than a directional hydrophone in the same environment. This difference is usually expressed as the directivity index, DI, which is measured in dB and can be regarded as the hydrophone gain. The best directional hydrophones have a directivity index of about 30 dB. Detection threshold depends on numerous factors, including optimum bandwidths and pulse length, as well as hydrophone design. As a first approximation for a typical receiving set, equating noise level and signal level gives a good estimate of maximum range. On this basis maximum range at different source levels for 4 different frequencies is shown in Figure 6.

Figure 6 shows that low frequencies are best for tracking at long ranges. However, also apparent is the fact that high-frequency transmitters are significantly better at short ranges. This is because at

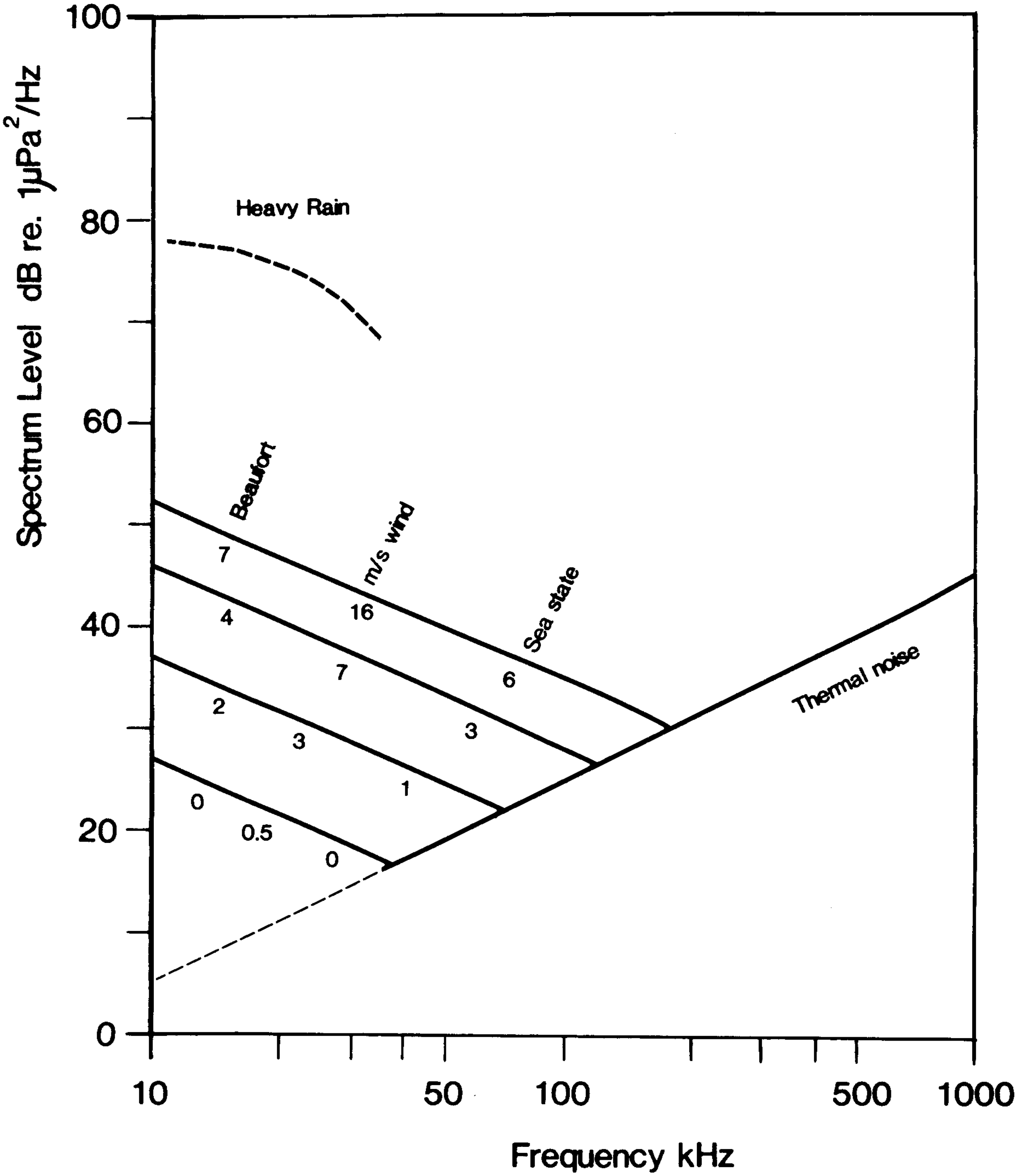

Figure 5. Ambient sea noise spectra.

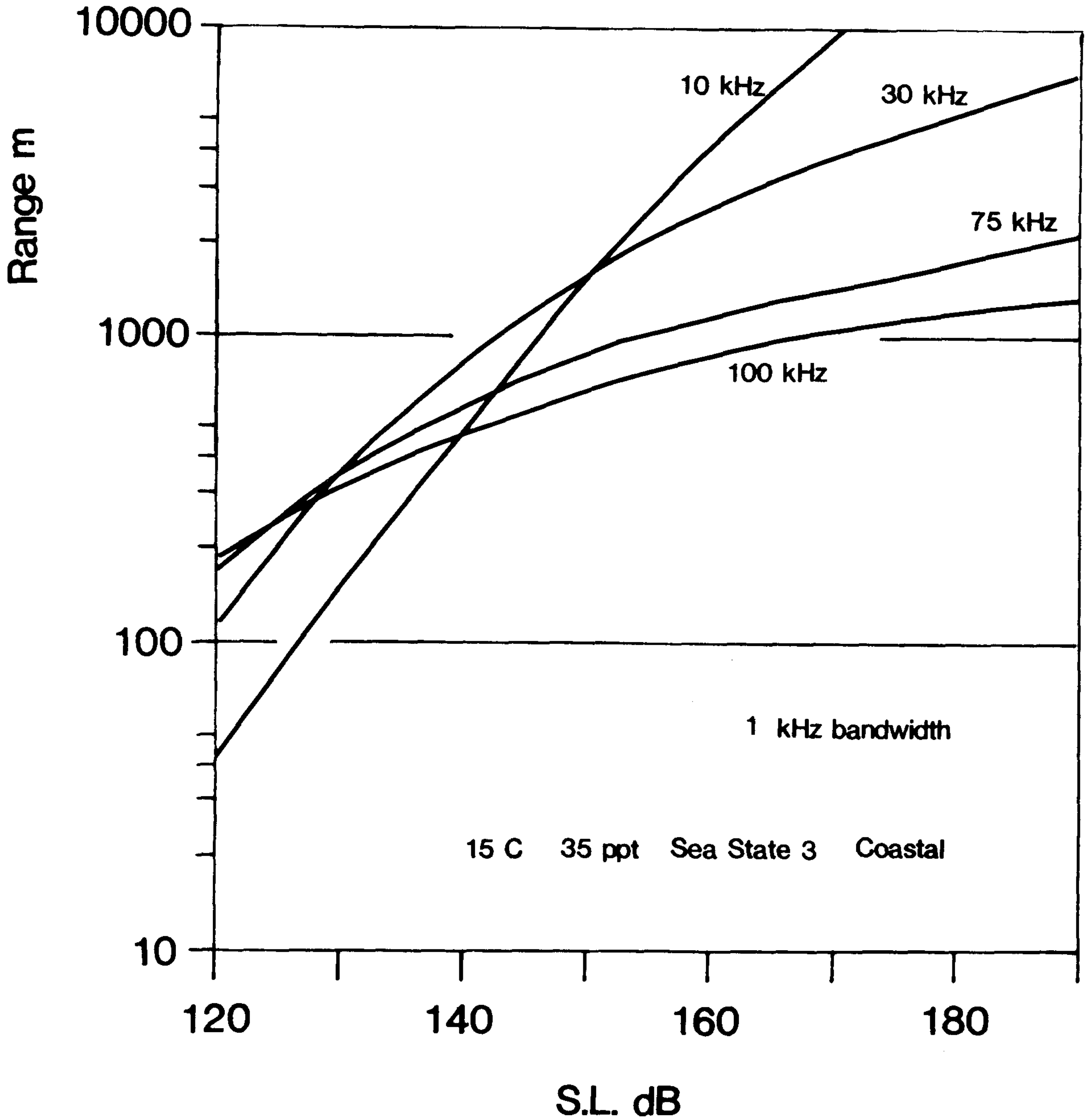

Figure 6. Predicted ranges of different transmitters at different frequencies.

high frequencies there is less noise and at short ranges absorption loss is not significant (Figure 3). This gives rise to an effect that is not widely appreciated: if two transmitters of equal source level are tested close to the ship the larger, low-frequency transmitter will be more difficult to detect. The benefits of low frequency transmitters become apparent only at long ranges. No allowance has been made for ship noise, but unless a very good hydrophone installation is used with a good acoustically transparent dome mounted on the right part of the hull, performance of the low-frequency devices can be disappointing. At ranges of less than 1000 m there is probably no great benefit to be gained from use of frequencies below 50 kHz.

Pulse Rate and Pulse Length

To be trackable a pulse rate of about 1 Hz is necessary. A high pulse rate leads to excessive power consumption, but a pulse rate of much less than 1 Hz makes mobile tracking difficult. Pulse length is typically set at 10 ms, giving a duty cycle of 1% at 1 Hz. Shorter pulse lengths can be used, but usually a higher source level is necessary to ensure detection.

Battery Size and Chemistry

In recent years lithium batteries have resulted in major advances in energy density from 100 Wh/kg for zinc-carbon to over 200 Wh/kg for lithium cells. Many different electrolytes are used, leading to a wide choice of lithium cells. Examples are lithium manganese dioxide, 210 Wh/kg at 2.7V (Duracell), and lithium thionyl chloride, 350 Wh/kg at 3.5V (SAFT). Construction of the cell can also lead to differing abilities to sustain high currents, etc. (Attewell 1985). No major further advance in energy density can be expected for primary cell battery systems; there will be an evolution of lithium systems to meet different specifications for different applications.

Figure 7 gives the energy required at different source levels and transmitter life times at a 1% duty cycle. Any quiescent current is ignored and efficiency of conversion of electrical to acoustic power is assumed to be 17%. A scale of battery sizes assuming 220 Wh/kg energy density is inserted. There are liable to be non-linearities in practice, especially in the smaller sizes. Casing takes up a larger proportion of the weight in a small battery, and small batteries cannot deliver high currents easily even if the theoretical energy density is available.

Transmitter Size

Figure 8 gives information on transmitter dimensions in relation to life and source level. This is intended to give some indication of what to expect when requesting a given performance. There can be wide variation between different manufacturers and, particularly high-frequency transmitters (75 kHz) can be smaller than indicated. The curves predict quite well the size of large transmitters but in small transmitters variations in package design can lead to vast differences in overall size. Given an existing transmitter the curves indicate quite well the rate of increase in size with life. The chart can only be used to indicate trends.

Realistic fish transmitters do not achieve source levels in excess of 170 dB. Cavitation problems limit the maximum power it is possible to radiate from a small transducer; for example, for a 1 cm area, 166 dB is the limit. Maximum efficiency is best achieved well below the cavitation limit. A major source of variation is likely to be transmitter efficiency; if oscillators are carefully tuned to the resonant frequency of individual

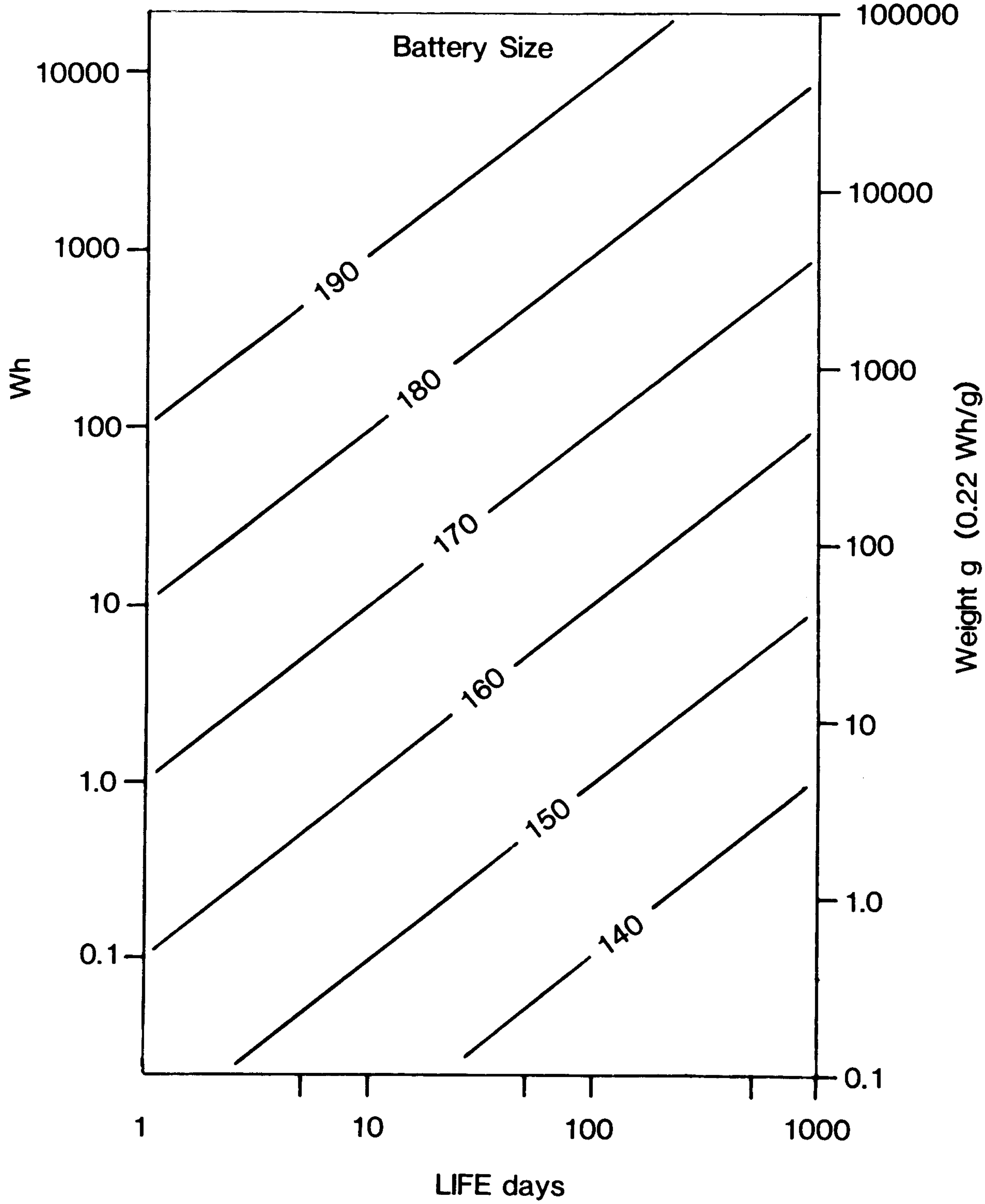

Figure 7. Energy required for 1% duty cycle at different transmitter source levels.

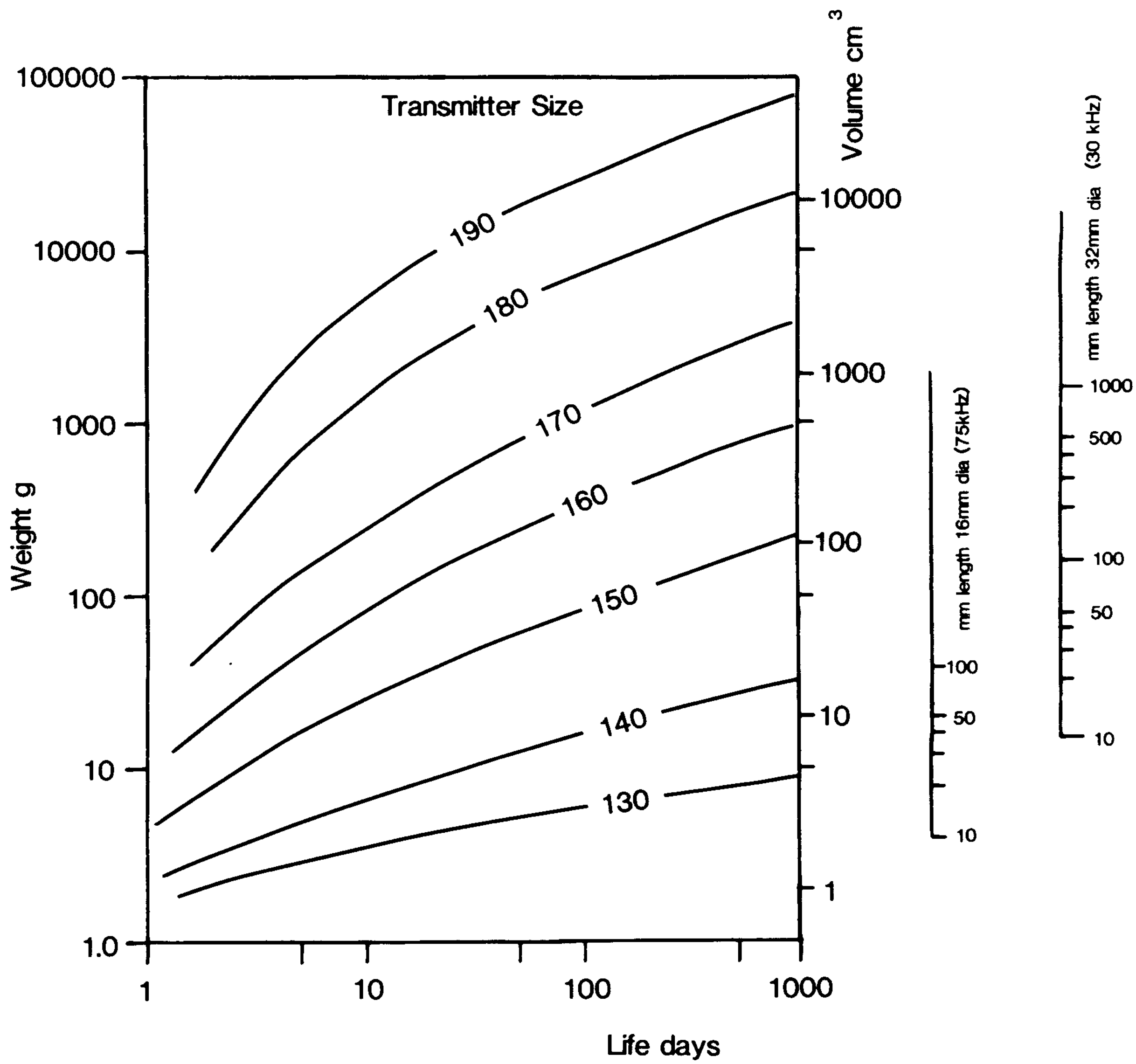

Figure 8. Approximate transmitter sizes for two different source levels dB re 1 uPa at 1 m.

transducers, great improvement in efficiency can be achieved. In series production this is not usually possible and transmitter frequency is set to a standard crystal frequency disregarding individual transducer characteristics. There will, therefore, be significant individual variation in transmitter efficiencies.

Tracking Performance

To ensure good tracking performance the system should be designed to provide good feedback on fish location to enable commands to be issued for maneuvering of the ship. Detection of bearing is usually not a problem. It is, however, easy to loose contact with the fish as it moves radially away from the ship. A 1-m fish moving at 5 body lengths per second can escape to 1000 m in 200 seconds (3.3 minutes), so an immediate response is necessary from the ship to keep in touch.

Range is usually detected by change in signal strength as the fish moves away. Figure 9 shows this effect at two favored tracking frequencies, using the data from Figure 3 plotted on a linear range scale. If it is assumed that a 10-dB change is required for detection at 400 m, then a 50 m change in range is required at 75 kHz. At 30 kHz much larger changes are necessary. While the low-frequency transmitter can be detected at 3000 m, it is difficult to interpret what is going on. The fish can move out of range without the operator being aware of the fact until it is too late or it can disappear into shadow zones created by the thermocline.

For small fish the 30 kHz transmitter is probably too large. In larger fish there are benefits to be gained in terms of range, but tracking may remain difficult. Consideration should, therefore, be given to using transponding systems which would give range and bearing information. Greer-Walker et al. (1971) were able to track plaice at sea with a working range of only a few hundred meters using transponder fish tags in conjunction with a sector scanning sonar providing an instantaneous visual display of fish location relative to the ship. A transponding system working at 30 kHz would give the benefits of long range but with vastly improved range resolution. More extended tracking may then be possible.

A serious limit to long-term acoustic tracking is crew fatigue. To achieve more than a few days continuous tracking requires immense dedication and perseverance on the part of the ship's crew.

Satellite Tracking

Priede (1984) first successfully tracked a fish by satellite using the ARGOS data collection and location system carried on board NOAA satellites. The species chosen, the basking shark (<u>Cetorhinus maximus</u>), is ideal for satellite tracking since it has the habit of basking near the sea surface for long periods of time, and at an adult length of over 7 m is capable of carrying very large transmitter packages. Locations were obtained whenever the animal was on or near the sea surface. An ARGOS transmitter was built into a buoyant package towed by the animal. Eventually this package broke loose and continuous locations by ARGOS (12 per day at latitude 57°N) indicated the last known location of the animal.

The question immediately arises as to whether this technology can be adapted to build a "pop-up" tag for tunas which would break loose after a predetermined time interval to give a single location. Implementation of such a pop-up tag using conventional VHF radio location is discussed by Nelson and McKibben (1981).

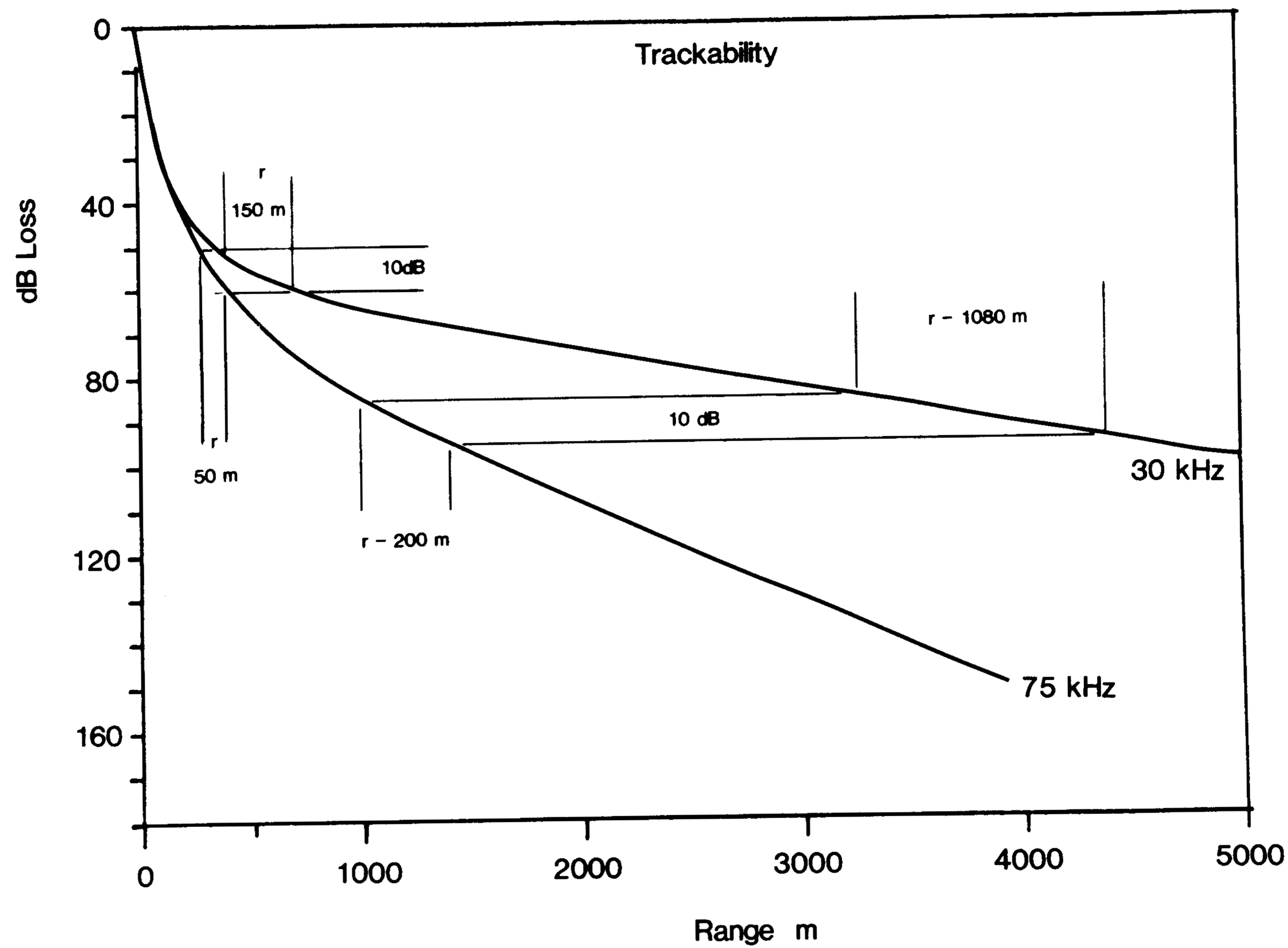

Figure 9. Use of detected signal level as an indicator of range.

The principles of satellite location systems are discussed fully by Priede (1983, 1985) and success depends critically on a very stable transmitter oscillator frequency. Radiated power is about 2 W with a minimum message length of 360 ms emitted approximately every 60 seconds During one satellite overpass at least 4 messages spread over 420 s must be received by the satellite receiver. Studies on animal tracking in the past have been hampered by poor transmitter performance leading to uplinks but subsequent rejection of messages for location calculations due to excessive frequency drift, etc. It is possible, however, with careful design to match and exceed the minimum performance characteristics demanded by Service ARGOS.

Since the successful track of a shark, work in Aberdeen has concentrated on realizing small ARGOS transmitters for use on birds (French 1984, 1986). The smallest ARGOS certified transmitter so far has a volume of 85 cm^3 for transmitter components and 33 cm^3 for batteries with 8 days life. This is configured in a flat disc 100 mm in diameter for attachment to a bird. If this were reconfigured in a cylindrical package it would be the size indicated in Figure 10.

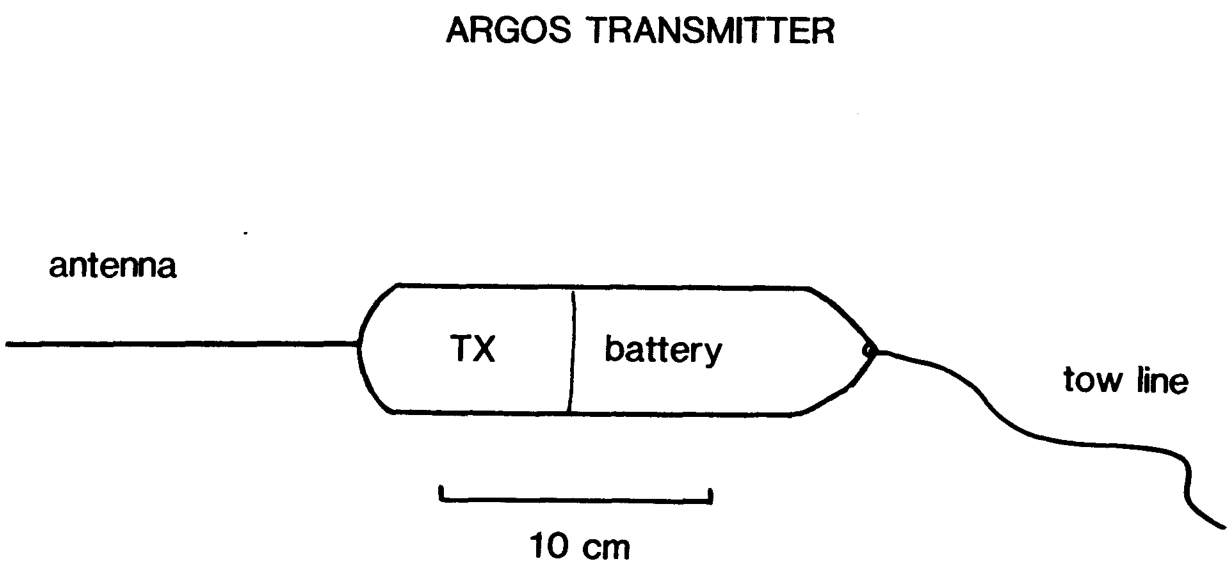

Figure 10. Probable size of a towed satellite locatable radio tag using existing technology.

Gradual size reductions can be expected given significant investment in Mini-ARGOS PTT technology. Two-point satellite tracking of the larger tunas seems feasible in the foreseeable future.

REFERENCES

ATTEWELL, A.
1985. Power sources. In R. Mitson (editor), Animal Telemetry in the Next Decade, p.32-39, summaries of papers from a meeting held at the Fisheries Laboratory, Lowestoft, England on 9-10 January 1985.

CLAY, C.S. and H. MEDWIN.
1977. Acoustical Oceanography. Wiley and Sons, New York, 544 p.

FRENCH, J.
1984. Tracking birds. Argos Newsletter 19:11-12. (Service Argos, Toulouse)

FRENCH, J.
1986. Satellite technology for tracking birds and sea mammals. Ph.D. Thesis. University of Aberdeen, Scotland.

GREER-WALKER, M., R.B. MITSON, and T. STORETON-WEST.
1971. Trials with a transponding acoustic fish tag tracked with an electronic scanning sonar. Nature (Lond.) 299:196-198.

HAWKINS, A.D. and G.G. URQUHART.
1983. Tracking fish at sea. In A.G. MacDonald and I.G. Priede (editors), Experimental Biology at Sea, p. 103-166. Academic Press, New York.

HUNTER, J.R., A.W. ARGUE. W.H. BAYLIFF, A.E. DIZON, A FONTENEAU, D. GOODMAN, and G. SECKEL.
1986. The dynamics of tuna movements: an evaluation of past and future research. FAO Fish. Tech. Pap. (In press)

MITSON, R.B. and T.J. STORETON-WEST.
1971. A transponding acoustic fish tag. Radio Electron. Eng. 41: 483-489.

NELSON, D.R. and J.N. McKIBBEN.
1981. Timed-release, recoverable, ultrasonic/radio transmitters for tracking pelagic sharks. In F.M. Long (editor), Proc. Third Inter. Conf. Wildl. Biotelemetry, p. 90-104. ICWB, University of Wyoming, Laramie, Wyoming.

PRIEDE, I.G.
1983. Use of satellites in marine biology. In A.G. MacDonald and I.G. Priede (editors), Experimental Biology at Sea, p. 3-50. Academic Press, New York.

PRIEDE, I.G.
1984. A basking shark tracked by satellite together with simultaneous remote sensing. Fish. Res. (Amst.) 2: 201-216.

PRIEDE, I.G.
1985. Satellite systems and tracking of animals. In R.B. Mitson (editor), Animal Telemetry in the Next Decade, p. 51-56. Summaries of papers from a meeting held at the Fisheries Laboratory, Lowestoft, England on 9-10 January 1985.

STASKO, A.B. and D.G. PINCOCK.
1977. Review of underwater biotelemetry, with emphasis on ultrasonic techniques. J. Fish. Res. Bd. Canada 34:1261-1286.

URICK, R.J.
1967. Principles of Underwater Sound for Engineers. McGraw-Hill, New York, 384 p.

YOUNG, A.H., P. TYTLER, F.G.T. HOLLIDAY and A. MacFARLANE.
1972. A small sonic tag for measurement of locomotor behaviour in fish. J. Fish Biol. 4: 57-65.

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