Equipment and Methods for
RADIO TRACKING FRESHWATER FISH

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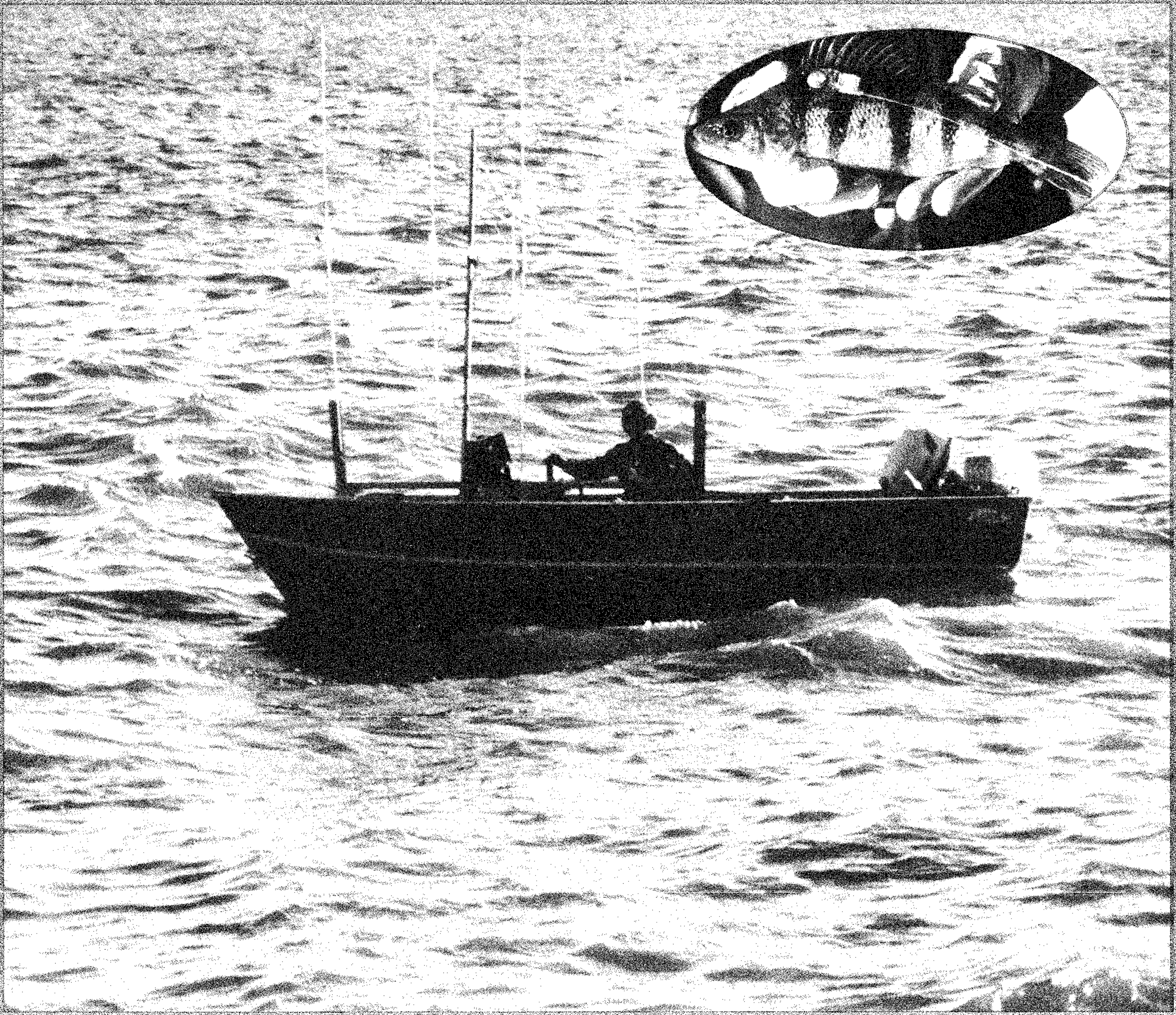

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About the Authors

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INTRODUCTION

Aquatic animal tracking had its origins in the late 1950's (Trefethen 1956, Trefethen et al. 1957, and Johnson 1960). Initially, ultrasonic transmitters in the 30-300 KHz frequency range were developed because low frequency, long wave signals travel well through water and are minimally affected by the water's conductivity. The history and development of ultrasonic tracking equipment has been recorded in the *Underwater Telemetry Newsletter* (1971-1977). About the same time that aquatic ecologists were developing ultrasonic transmitters, terrestrial ecologists were developing radio transmitters in the 27-300 MHz range as described by Slater (1963, 1965) and Brander and Cochran (1971).

In 1969 the University of Minnesota's Cedar Creek Bioelectronics Laboratory began radio tracking fish (Winter et al. 1973). Initially, we tracked carp and northern pike in a stream (W. Hadley, unpublished data) using an automatic tracking facility (Cochran et al. 1965) and largemouth bass in a northern Minnesota Lake (Winter 1976, 1977). Since then we have tracked steelhead in Lake Superior (Winter 1976), yellow perch in the thermal plume from a power plant (Ross 1978), and salmon near hydroelectric dams on the Snake River, Washington (Haynes 1978). It is clear that an ecologist can now choose to track aquatic animals with either radio or ultrasonic equipment depending on the requirements of the project.

Underwater radio telemetry has many important features. The first is that the equipment is relatively inexpensive. One can purchase a high quality receiver for less than $1000 (U.S.) and a yagi antenna, which gives the best range, for about $50. Components for a transmitter cost about $20 and an assembled transmitter sells for under $100. Although transmitters cost more than simple marking tags, the cost-information ratio decreases rapidly as greater quantities of data are collected and becomes lower than in mark-recapture studies.

Second, radio transmitters can be designed with low current drain to give long life. For example, a transmitter with a 0.5 ma current drain and powered by a 42 milliampere-day (Mallory, RM-1) battery will transmit about 3 months. Longer life can be achieved by lowering the current drain or using a larger capacity battery.

Another important feature is that radio-tagged animals can be located without making contact with the water. Since ultrasonic signals are highly attenuated in air, they must be detected with a receiver connected by a cable to a stationary submerged hydrophone or a hydrophone suspended from a boat. Attenuation of radio signals, on the other hand, is much less in air than in water and therefore, transmitters can be monitored by mobile antennas from shore, boat or airplane.

In addition, since radio transmitters use crystals to minimize frequency changes, many individuals can be distinguished at the same location and time because each tag

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transmits on a different frequency. Although ultrasonic transmitters can be built using crystals for frequency control, cost and bulk have usually precluded their use. Consequently, ultrasonic telemetry must use elaborate decoding techniques to identify individuals or must limit the number of tags used in the same vicinity. The number of transmitters that can be distinguished in the same vicinity by simple decoding methods is about 10 to 20 ultrasonic tags and over a hundred radio tags.

Furthermore, radio signals are not affected by some of the factors that interfere greatly with ultrasonic signals. For example, aquatic vegetation or a thermocline can absorb or deflect ultrasonic signals (Ziebell 1973). In addition, air bubbles from turbulent water (Schiefer and Power 1972) or algal growth on hydrophones can interfere with hydrophone reception.

Finally, radio telemetry is versatile. The same receivers and antennas can be used to monitor both aquatic and terrestrial animals. Thus, if an institution cannot afford to have both an ultrasonic and a radio tracking system, the latter will suffice for terrestrial work and many aquatic projects.

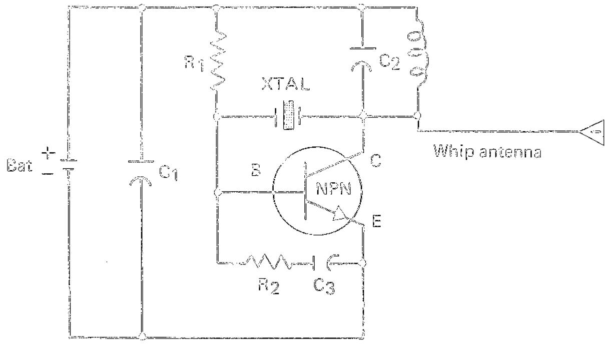
Although there are many advantages, there are also limitations for underwater radio telemetry. Radio signals attenuate with increasing conductivity and depth. This limits radio tracking to freshwater species or to marine animals that surface periodically. Ultrasonic transmitters, on the other hand, are well suited for tracking animals in salt water or deep water. Secondly, radio signals may be deflected by large metal objects, terrestrial vegetation or terrain; however, an experienced tracker can usually surmount such difficulties. In addition, both tracking systems may receive interference from powerlines, unshielded ignition systems and citizen's band radio.

This paper describes the application of radio tracking technique to aquatic animals. Terrestrial radio tracking literature is summarized and the equipment and methods that have been used to track freshwater fish are described. It is hoped that this information will aid fisheries biologists, who may not be familiar with the wildlife literature, to establish radio tracking programs with a minimum of literature search.

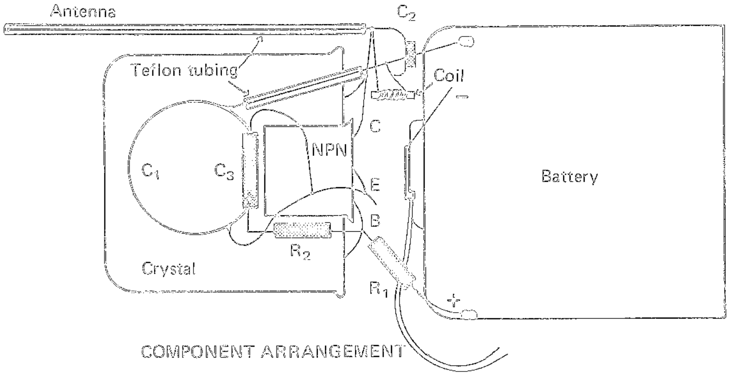
Transmitters

The basic transmitter circuit (figure 1) is similar to that described by Cochran and Lord (1963), but most of the components are different (table 1). The original design was for a continuous-wave ("whistling") signal; however, we added capacitor (C_3) and resistor (R_2) to form a squegging circuit. This causes the transmitter to emit a pulsing signal. Continuous-wave signals were easier to distinguish from background noise than pulsing-signals and therefore, were

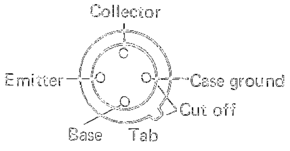
Figure 1. Transmitter circuit diagram and component arrangement.



Circuit diagram



COMPONENT ARRANGEMENT



Transistor lead configuration
Amperex A415

detected at greater distances. It was also easier to detect animal activity with continuous-wave signals because animal movements caused the frequency and amplitude of the signal (antenna orientation) to vary slightly so that a wavering signal was produced (Cochran and Lord 1963, Marshall and Kupa 1963). Consequently, signal or activity patterns can be recorded on strip charts (Gilmer et al. 1971, Siniff, et al. 1971) or 16 mm film (Cochran et al. 1965).

Pulsing-signals reduced power consumption and therefore increased transmitter life. Pulse width (on-time) of our transmitters was .02-.025 seconds and the pulse rate was set between 60 and 120 pulses per minute. The duty cycle or the ratio of on-time to total time was 3% ± 1%. Pulsing-signals can also be used to transmit physiological and environmental information. By constructing transmitters (Tester and Siniff 1976) so that the period between pulses varies as a function of temperature or water pressure (depth), we have been able to measure these parameters with free-ranging fish.

Transmitters were powered by 1.4 volt mercury cells or 2.8 volt lithium batteries used singly or in series for more power. The types of mercury batteries available and their usefulness for biotelemetry have been described by Kuechle (1967). We used certified mercury cells for greater reliability because they are manufactured to rigid specifications and are inspected at each stage of construction. Most sizes had to be special ordered, but the costs for sizes other than the widely used RM-1 and RM-640 were prohibitive unless ordered in very large quantities (>1000).

Lithium batteries are a recent development and show much promise for underwater telemetry. They have half the weight in water and twice the voltage of an equivalent volume mercury cell. Compared to mercury cells with the same milliampere-hour (mah) rating, lithium batteries have 2.5 times greater volume; however, because of the higher voltage of lithium cells, smaller cells can be used at a lower current drain to produce the same power and life as a mercury cell. Lithium batteries also have better cold temperature performance. At the present time the smallest lithium cell available is 14 mm diameter by 23 mm and weighs 4.3 gm (air) which is too bulky for small fish. However, smaller lithium cells will probably be available in the near future.

Transmitter life depended mainly on battery dimensions, weight and current drain. The approximate transmitter life

Table 1. Aquatic radio transmitter components (53 MHz).

	Component	Comments
Crystal	Holder type HC18/U, (International Crystal Co., 10 North Lee, Oklahoma City, Oklahoma 73102	determines the operating frequency of the transmitter
Transistor	Amperex A415	provides feedback to sustain the oscillation
Capacitor C_1	0.01 pf ceramic 10 volt	(bypass capacitor) eliminates the influence of the battery and the leads on transmitter operation
Capacitor C_2	10 - 35 pf, silver mica: CDE CD6 Series	(final tuning capacitor) restricts the oscillator to operate on the correct overtone of the crystal. Use the least capacitance (critical step) which initiates pulsing with the antenna under water.
Capacitor C_3	2 - 10 pf, Sprague 162D series	controls pulse width and rate along with R_2
Resistor R_1	.3 to .8 ma at 56 KΩ to 20 KΩ, 100 KΩ typical; 1/8 or 1/10 watt	(current drain resistor) is selected to give the desired current drain
Resistor R_2	1 KΩ to 2.2 KΩ, 2.2 KΩ typical; 1/8 or 1/10 watt	controls pulse width and timing along with C_3
Coil	Belden #32 enameled wire	20 turns on 3 mm form for C_2 between 15 and 35 fpf
Whip Antenna	.5 mm stainless steel wire in teflon tubing or 26 gauge Teflon-coated electrical wire	length depends on fish length
Attachment Wire	Teflon-coated electrical wire (26 gauge)	provides a ground plane for the antenna
Battery	certified mercury cell (1.4 volt) or 2.8 v lithium cell (Power Conversion, Inc.)	

under ideal conditions was computed by dividing the manufacturer's milliampere-hour (mah) rating for a battery (q.v. Kuechle 1967) by the average current drain of the transmitter.[1] For most of our steelhead and largemouth bass tracking we used certified Mallory RM-1 mercury cells with a 1000 mah capacity rating. Average current drain was usually between 0.5 ma and 0.7 ma. The expected and observed transmitter life was between 60 and 83 days. Our smallest transmitters for perch had a 160 mah (Mallory RM-675) battery and a 0.2 ma current drain. Actual transmitter life was 30 ± 5 days. Higher current drains produce a non-linear increase in signal range but an almost linear decrease in battery life.

The size of the underwater transmitter was determined largely by the size of the battery. Transmitter components, without the battery, weighed only 2.5 gm. With a 2.0 gm RM-675 battery, a package was made suitable for 300 gm yellow perch. This package weighed 3.3 gm in water (6.5 gm dry) and measured 30 mm by 10 mm 5 mm. By using miniature components, the transmitter could be made smaller, but at greatly increased cost. In water, the transmitter (Scotchcast epoxy encapsuled) weight with a mercury cell was 50 to 60 percent of the dry weight whereas it was only 40 percent with a lithium battery. For example, steelhead transmitters (RM-1 battery) had a dry weight of 26 gm and weighed about 15.6 gm in water. Dimensions were 17 mm in diameter and 40 mm long. We feel that the transmitter weight in water should not exceed 1 to 1.25 percent of the fish's weight out of water. With this package weight, a fish regains his equilibrium within minutes after tagging and total habituation time is kept to a minimum. Therefore, the desired transmitter size, life and range must be matched to each other and the demands of the project.

Transmitters were encapsulated in Scotchcast #5 electrical resin (3M Co.). This two-part epoxy was found to be very durable and was compatible with transmitter components. Hardening time was reduced by heating the resin (A) to 60 C before hardener (B) was added. Transmitters were potted in molds made by pouring a silicone rubber compound (RTV-30, General Electric) into a box around a smooth dummy transmitter or by carving hardened RTV-30 with a scalpel. Scotchcast was poured over the components and an identification label in the mold and heat was applied briefly to eliminate air bubbles. After removing the transmitter, excess epoxy was removed with an electric hand grinder.

Signal Transmission

Although there are a number of theoretical papers concerning the transmission of radio waves in water, they are difficult to interpret and apply to fish tracking (King et al. 1974, Lee and Smith 1975, and Shen et al. 1976). Marshall (1960) reported that "a transmitter (150 MHz) with antenna was tried underwater and the distance of reception was cut down to a few inches." Our success with underwater radio transmitters is partly due to tuning (capacitor C_2) the transmitter with the antenna underwater by choosing the smallest capacitance which initiates pulsing. This results in the transmitter working well in water but poorly in air. We also connect a capacitance wire to the battery which provides a ground plane for the dipole antenna. This capacitance wire is also used in attaching the transmitter.

Saran and Held (1960) found that the field strength received at a submerged dipole antenna was attenuated exponentially with increasing depth. Our calculations show that a signal transmitted by a submerged dipole antenna will also be attenuated exponentially with increasing depth. Attenuation tests (figure 2) were conducted on two lakes that are representative of the low conductivity water in eastern Minnesota and moderate conductivity water of central Minnesota. Since the signal range was 35 to 45 percent less when the transmitter antenna was broadside to the receiving antenna, we kept the transmitter antenna horizontal and pointed at the receiver. Additional tests with a signal strength meter have confirmed the elliptical pattern of transmission. Transmitter range was determined by ear and the range at each depth was expressed as a percentage of the surface or maximum range. In Lake Superior we lost 50 percent of the range at 8 m depth but received the signal down to 50 m. In Lake Bemidji, 50 percent of the signal was lost at 4 m. The shapes of the curves (figure 2) suggest that underwater radio signals are attenuated exponentially with depth. They also indicate that attenuation is greater in water of higher conductivity. The top curve has an exponential shape but does not start at 0 meters because of a probable surface range error. In addition, our tracking observations indicated that a thermocline or ice had little effect on the signal.

We chose 53 MHz as our operating frequency because the data available suggested that this frequency travels through water better than higher v.h.f. signals. This has not been supported by theoretical calculations; however, we recently found that 53 MHz signals attenuate less than 164 MHz signals in a lake during the winter (figure 3). Calculations also indicated that the advantages of signals less than 53 MHz were offset by the need for a bulkier receiving antenna. Furthermore, the transmitting antenna would be a smaller fraction of the wave length.

Receivers

Radio receivers for animal tracking can be purchased from commercial sources (BIAC 1967). There are several factors to consider when choosing a receiver. The receiver should have a sensitivity such that a signal can be detected to -143 dbm by listening. Good receivers have this sensitivity, which probably is also near the theoretical limit. Secondly, to obtain the best range, signal selectivity should be high so that much noise is filtered; that is, an intermediate band (i.f.) width about 1 KHz. In addition, the frequency selector should be accurate and the receiver capable of handling many transmitters. Often many animals with close frequencies will be in the same vicinity and there should be no difficulty in distinguishing them. Next, a receiver must permit quick searching of frequencies. This is necessary in tracking from an airplane because the high speed does not allow much time to find a specific frequency. A field receiver should use rechargeable batteries; thus, the duration of charge, battery life, availability and cost are important. Furthermore, the receiver should be capable of working with little protection over a wide temperature range (−25° C to

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[1] $\frac{\text{mah battery rating}}{\text{average current drain (ma)}}$ = expected life in hours

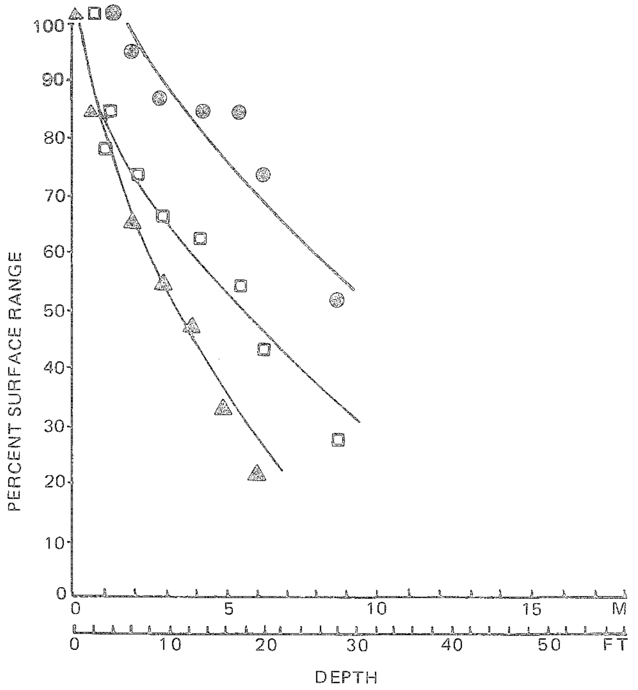


Figure 2. Attenuation of radio signals with increasing depth in lakes with different conductivities. Curves marked with dots and squares are from Lake Superior (80 μ mho/cm) and triangles are from Lake Bemidji (300 μ mho/cm).

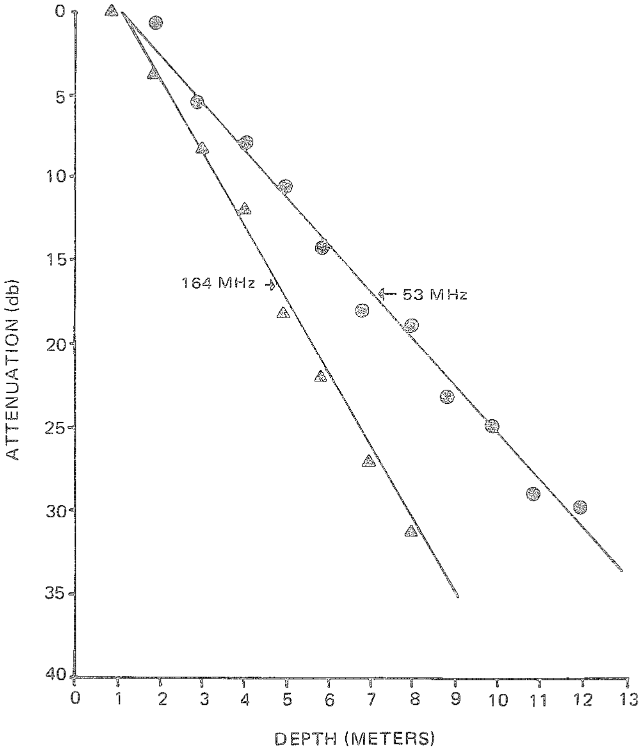


Figure 3. Comparison of attenuation with increasing depth of 53MHz and 164 MHz radio signals in water of 70 μ mho/cm conductivity.

50° C). If the receiver will be hand-carried in the field, it should be light and small. Last, since receivers inevitably break down at inopportune times, the supplier should have a good service policy. Ideally, the supplier should be near and/or have a receiver loan policy.

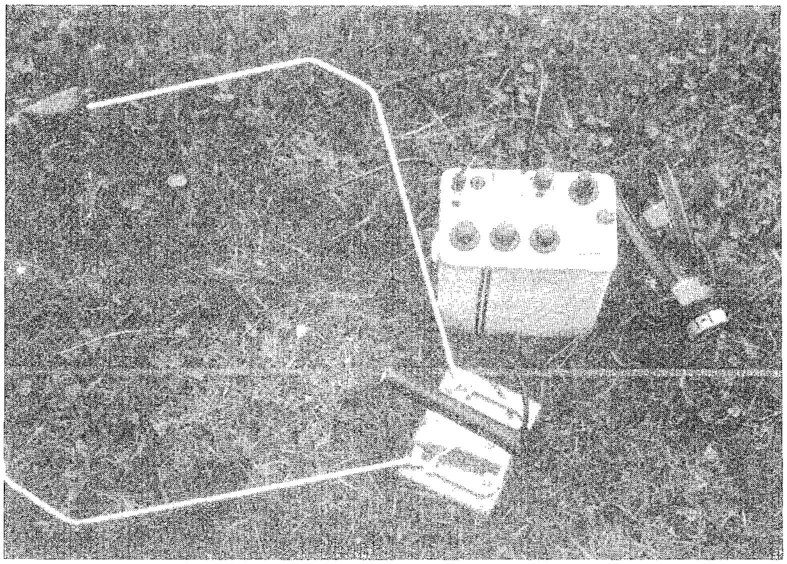
Our receivers were designed and constructed at the Cedar Creek Bioelectronics Laboratory of the University of Minnesota. The first receiver we used, which was simple and inexpensive ($125 U.S.), was essentially an automobile "radio" modified for tracking purposes (Kuechle et al. 1971). This receiver was a portable, hand-held unit (13 cm by 18 cm by 13 cm) with a detachable loop antenna and jack for connecting other antenna systems (e.g. yagi). Different transmitter frequencies were used for each animal and up to 30 individuals (33 KHz apart) were distinguished, provided the animals were not close to the receiving antenna.

Our latest receiver is a double conversion using a frequency synthesizer for tuning where all channels are phase-locked to a single crystal (Tester and Siniff 1976). It can be built to cover any 1 MHz frequency range depending on the choice of the first converter. Instead of a "radio dial" tuner, specific frequencies are selected by three detent switches which allow 1 KHz channel spacing. Over 100 different transmitter frequencies spaced 5 to 10 KHz apart can be easily distinguished. The receiver has a signal sensitivity of −143 dbm, an i.f. band width of 1.2 KHz and a noise figure of about 4 db. Since it measures 21 cm by 13 cm by 17 cm high and weighs 1.8 kg, it is easily hand-carried in the field. Additional receiver specifications and operator control functions are listed in the appendix.

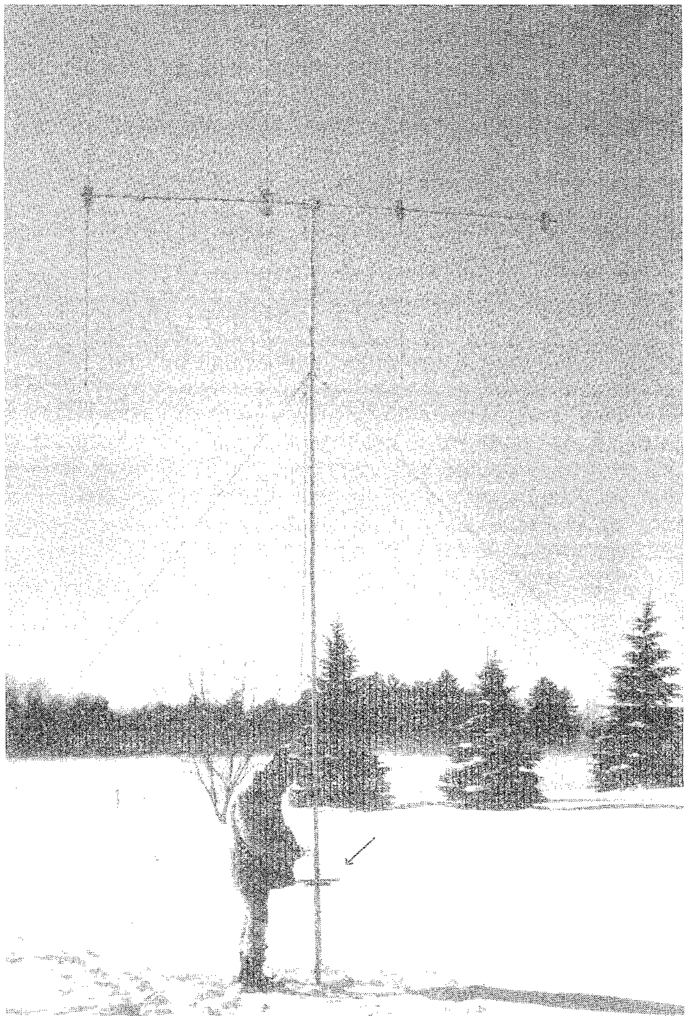
A memory option can be incorporated into the basic receiver design (Tester ans Siniff 1976). In addition to the three front panel frequency selectors, frequencies can be programmed into a memory and later recalled by a single selector switch or scanned automatically by an internal timer (q.v. appendix). The receiver presently can scan up to 64 channels or pre-selected frequencies. Since a programmed frequency can be recalled quickly by a single switch, this receiver is valuable in airplane tracking where many frequencies have to be searched in a short time. Furthermore, this receiver is useful in unattended monitoring to scan and record the signal from the frequencies that have been programmed into the memory. For example, the signal from a temperature or pressure tag is fed from the receiver through a pulse decoder which measures the period between pulses. Pulse period can be read as a digital readout on the decoder or a line on a Rustrak strip chart recorder.

Methods of Tracking

Underwater radio transmitters were monitored from shore, by boat or airplane. Most tracking involved plotting the animal's location on a map from compass bearings, visual bearings or a combination of the two. Compass bearings were taken on the transmitter direction from locations that were recognizable on a map or in some cases (eg. when tracking from an airplane or boat) from the animal's position to landmarks. The compass bearings were plotted on a map and the point where the lines intersected was the animal's calculated position. Visual bearings on the transmitter direction were used when the observer was close to the animal and when the animal was near good landmarks. In addition,



4. A radio receiver with channel selecting tuning, headset and a hand-held loop antenna.



5. A semi-permanent tower with yagi antenna and compass rose, which is indicated by an arrow.

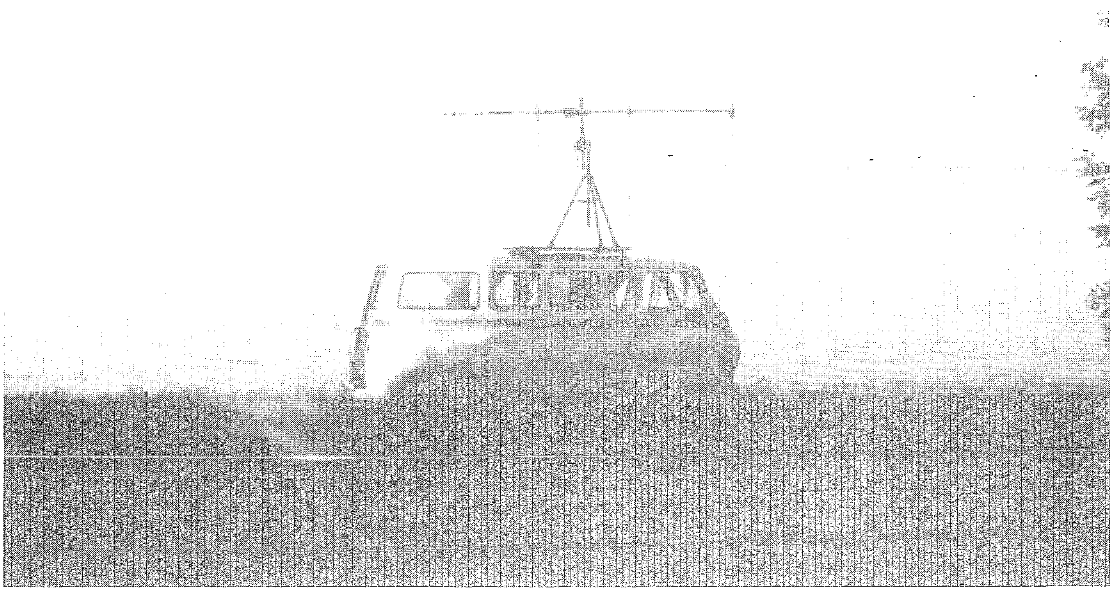
line of sight and compass bearings were used together in grid systems established around largemouth bass home ranges. Markers were placed at 6 m intervals on shore and 15 m offshore.

Shore tracking was done with a portable hand-held receiver, a semi-permanent tower, or a mobile unit. The advantages of shore tracking were that it could be done during stormy weather or at night and it did not disturb the fish. Diamond-shaped, bi-directional loop antennas (figure 4) were used with the hand-held receiver. For this equipment a minimum or null signal occurred when the plane of the antenna was perpendicular to the transmitter direction, and a maximum signal occurred when the sides of the loop were pointed at the transmitter. Since the null was easier to distinguish than the maximum signal, the null was generally used for taking bearings (Cochran and Lord 1963). The maximum working range of the loop antenna was .8-1.2 km.

A temporary tower was useful for projects on small lakes, on aquatic animals with small home ranges, and on specific areas of a lake or river such as near a thermal effluent or dam (figure 5). Temporary towers have been described by Marshall and Kupa (1963), Houseknecht (1970), and Brander and Cochran (1971). We made the temporary tower base by welding a metal plate to one end of a 1m long, 4 cm diameter pipe and a compass rose to the other end. A yagi antenna was mounted with the elements vertical on a 6 m long, 3 cm diameter T.V. mast. The T.V. mast was inserted into the base pipe and was guyed with wires to a slip-ring which allowed the mast to be rotated. A pointer was attached to the mast just above the base pipe and in the same direction as the antenna reception so that bearings could be read on the compass rose. The azimuth to the transmitter was determined by finding the mid-point between the two null points (Marshall and Kupa 1963). We found that the range of the yagi antenna was up to three times greater than the loop antenna. If temporary towers are used in pairs, fixes can be taken simultaneously with the aid of two-way radio communication. Furthermore, temporary towers can be used to automatically record data such as presence of a signal, animal activity, water temperature or pressure by connecting them to scanning receivers plugged into strip chart or tape recorders (Gilmer et al. 1971, Siniff et al. 1971 and Ross 1978).

A mobile tracking unit was valuable for scouting along rivers or around a lake with good access (figure 6). Verts (1963) described a mobile tracking unit with a loop antenna. Marshall and Kupa (1963a) built a mobile unit with greater range by using a tip-up yagi antenna. The design of a mobile

Figure 6. Mobile tracking vehicle with a yagi antenna and antenna rotors.



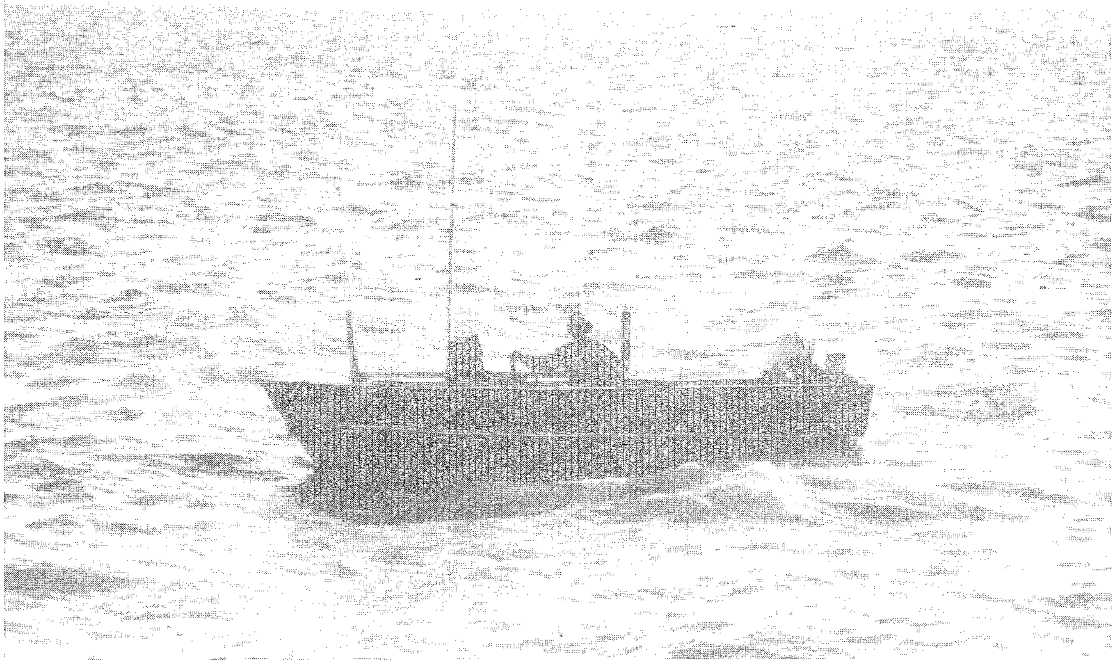


Figure 7. A yagi antenna mounted on a telescoping mast in a boat.

tracking unit depends on antenna size, type of vehicle, overhead obstructions, and the number of locations used in tracking.

Along Lake Superior we were faced with many stops which made a tip-up or telescopic mount too time consuming. Since a 53 MHz yagi antenna is large, overhead obstructions presented problems. To overcome these problems a system was built to turn the antenna to a horizontal position for travel. The tracking vehicle was a van with a (1 m high) television tripod mast-mount bolted to a plywood sheet attached to car-top carriers. A television antenna rotor was attached to a 1 m mast and another rotor to the antenna beam. When traveling, the antenna was carried with the elements horizontal. To monitor fish, the beam rotor turned the yagi to vertical and the mast rotor rotated the antenna. Rotors were powered by a 12 v to 110 v power converter. For extremely rough terrain, steel tubes were inserted into the aluminum yagi elements for reinforcement (Haynes 1978). The range of the mobile unit with yagi antenna was 2 to 3 times greater than a loop antenna.

A boat with a yagi proved most effective for searching a small area thoroughly. We mounted the yagi on a 4 m telescopic mast in a 5.5 m long boat (figure 7). The boat-mounted yagi, like the mobile unit, was primarily used to initially locate signals. Once the signal was localized, a loop antenna was used. When a fish was close to shore, we obtained two bearings that intersected at 90° with one of the bearings aligned with a landmark. When a fish was far from

shore, we approached the fish until the signal became loud and omni-directional. This indicated that we were within 20 m of the fish. The location was determined by taking compass bearings on landmarks or measuring two adjacent horizontal angles between three landmarks on shore with a navy Mark II sextant (McCleave and Horrall 1970). Sextant bearings were obtained more quickly than compass bearings, were less affected by rough water or metal and were very accurate (± .5°). Angles were set on a three-arm protractor and aligned with landmarks on an aerial map. The origin of the angle marked the calculated location of the fish.

Tracking from an airplane was useful on large lakes (>125 to 250 km²) and for nomadic species. Loop antennas were usually made from aluminum rods (6 mm) but copper tubing (1.3 cm) was more durable for extensive high-speed airplane searches. Antennas were insulated from and bolted to pieces of aluminum (75 mm by 300 by 3 mm) bent in a 45° angle. The aluminum brackets were attached to airplane struts by hose clamps and the antennas were mounted under each wing perpendicular to each other (figure 8). A switch allowed the tracker to listen to both antennas at the same time, which gave wide reception, or to each separately to determine signal direction. To detect weak signals a plane with the ignition noise suppressed must be used. In addition, noise inside the airplane was reduced by padded stereophonic headsets that fit tightly around the ears.

After the animal was initially located, the aircraft was flown in circles of decreasing circumference and the receiver volume and sensitivity were reduced until the signal was received only over a small area. An alternative method was to listen for the maximum signal and then a decrease as the airplane passed over the fish. Compass bearings were taken on landmarks from the fish's location. Maximum transmitter range was slightly better at higher altitudes but locations were determined more accurately at lower altitudes. Average ranges from various altitudes expressed as a per cent of maximum range were as follows: 150 m altitude, 60 percent; 300 m, 75 percent; 450 m, 75 percent; 600 m, 93 percent, and 750 m, 100 percent. Transmitter locations were determined as accurately as 100 m radius providing that good landmarks were near (1 to 3 km).

A disadvantage of airplane tracking was that the speeds flown (>96 km/hr) allowed only a short time to listen for individual transmitters. Furthermore, the high cost of airplane rental limited tracking to periods when many fish were radio tagged or to occasional searches for missing fish.

Antenna Accuracy

Tests were conducted on the accuracy of yagi and loop antennas. Two 6 m high temporary towers were located near the thermal discharge of a power plant. The receiving end of the yagi was oriented 90° to 180° from the plant for tracking and accuracy tests. Transmitters were placed in the water near locations recognizable on an aerial photograph. Bearings on each location were close together (S.E.<.45°) with 2.0° to 5.0° difference between the highest and lowest bear-

Table 2. Accuracy of Yagi Antennas.

Distance m	Tower	Trials	Bearing range in degrees	Mean bearing error in degrees*	S.E. in degrees	Mean bearing error in m*
138	1	10	5.0	6.25	.45	16.0
275	1	10	4.0	.25	.38	2.0
338	2	10	3.0	2.85	.37	16.5
438	2	10	2.5	3.55	.22	27.0
438	1	10	2.0	1.70	.23	10.5
450	2	9	4.0	1.11	.27	3.0
463	1	10	5.0	1.90	.29	16.0
575	2	10	4.0	5.35	.34	52.0
738	2	10	4.0	3.05	.40	35.0

*without correction factors for the systematic errors: tower #1, −2°; tower #2, ±3°

Figure 8. A loop antenna attached to an airplane strut by hose clamps.

ings (table 2). Mean bearing error for each distance ranged from .25° to 6.25°; however, tower errors were systematic. Therefore, the bearings were corrected to within ±3° by adding 3.0° to tower #2 and subtracting 2.0° from tower #1. Distance errors using the correction factors were less than 5 m at 100 m and 43 m at 800 m. From a van-mounted yagi, the mean bearing error was approximately 14 m from 200 m and about 28 m from 400 m. These results compared closely with yagi accuracy tests conducted by Marshall (1962, 1963) in a wooded area and by Slade et al. (1965) on grasslands.

Loop antennas were very accurate at close ranges and were useful in recovering transmitters. Cochran and Lord (1963) found that they could locate an animal with a loop antenna to within a 3 m radius (no distance specified). Verts (1963) reported that triangulations from his truck-mounted loop antenna were ±7.6 m from 400 m and about ±23 m from 800 m.

Many locations recorded in our studies were made with a hand-held receiver and loop antenna from distances less than 100 m. Accuracy tests on transmitters submerged in an aquatic grid system suggested that maximum triangulation errors were about ±1.5 m from 15 m, ±3 m from 30 m and ±6 from 60 m. Further tests on the accuracy of a portable loop antenna were conducted on a football field (table 3) with easily computable bearings to a transmitter submerged in water in a plastic container. Test bearings were taken with a Silva Ranger compass. The mean bearing error ranged from .3 m (5 to 15 m distance class) to 4.81 m (76 to 92 m distance class). However, at very close ranges the signal was so strong that the exact direction was difficult to determine or the directivity of the loop antenna was reversed. Antenna reversal occurs theoretically at a distance equal to ¼ wave length which is 1.4 m at 53 MHz (Cochran 1967). We have detected antenna reversal starting at 4.6 m and becoming complete at 2.7 m for 53 MHz. Consequently, the smallest distance class in the accuracy study was 5 to 15 m which reduced wild fixes and better approximated field tracking conditions.

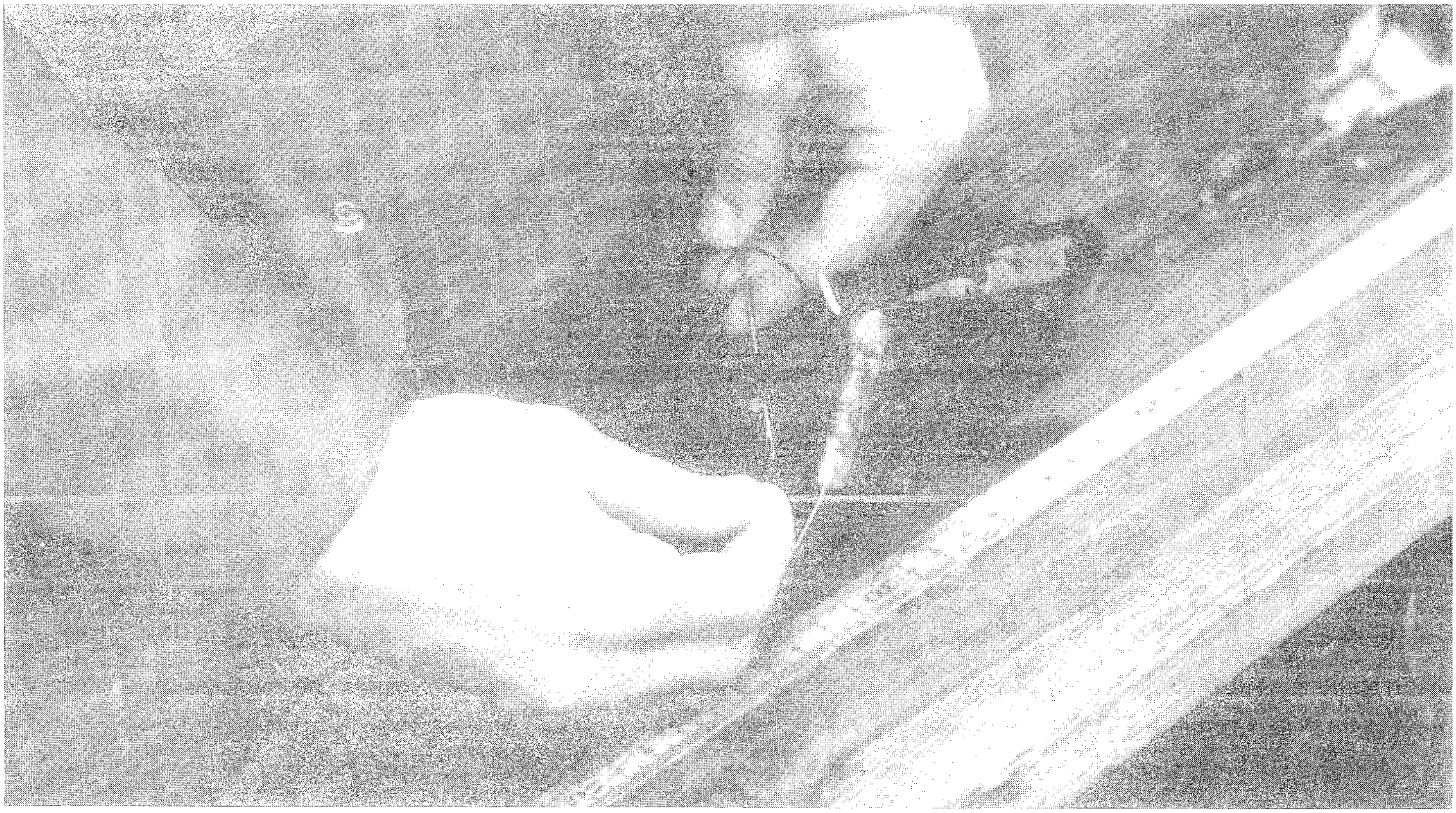
Theoretical triangulation error was determined by plotting the mean and maximum degree errors from points representing distance classes on two lines intersecting at right angles. Right angles were chosen because the highest accuracy for triangulation occurs when the bearing lines intersect at 90° on the perpendicular bisector between two tracking stations (Tester 1971, Heezen and Tester 1967). A tracker should move to positions to obtain bearings intersecting near 90°. The calculated maximum triangulation error ranged from 2.1 m (5 to 15 m distance class) to 10.7 m (76 to 92 m distance class) and the calculated mean triangulation error ranged from .79 m to 6.49 m. Discussions of factors causing errors in radio-location data can be found in Tester 1971; Marshall 1962, 1963; and Slade et al. 1965.

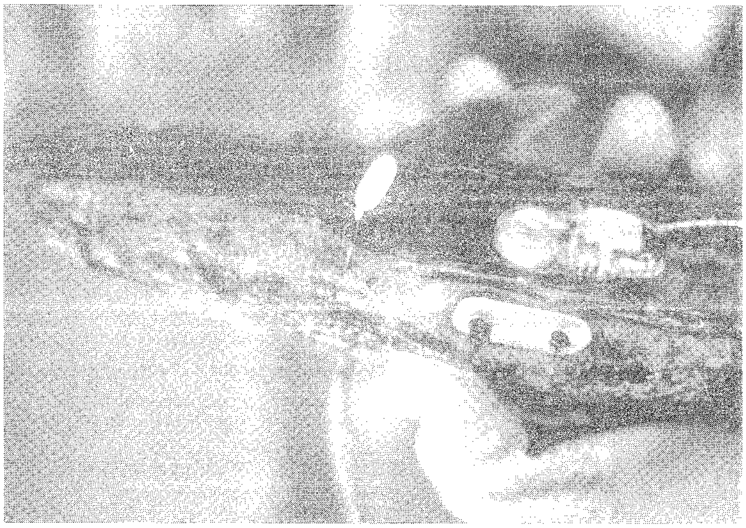
Attaching Radio Transmitters

There is no universal attachment method for all species and all tracking situations. Attachment methods depend on the morphology and behavior of the species, the nature of the aquatic ecosystem and the objectives of the project. Radio transmitters can be attached externally on the back or internally in the body cavity or stomach. External attachment is quicker and easier than implanting and can be used for spawning and feeding fish. The disadvantages of external attachment are that transmitter movement can erode larger holes in the skin around the attachment wires which could lead to fungal infection. Furthermore, external transmitters can become snagged in vegetation and increase the drag on the fish. Transmitter drag may not affect movement patterns but could affect swimming speed or energetics. The only published study on transmitter drag (McCleave and Stred 1975) was unfortunately conducted with very bulky transmitters (17 mm diameter) on small (106 gm) fish.

Table 3. Accuracy of loop antenna.

Distance class meters	Number of trials	Mean distance of trials	Mean bearing error degree	S.E. in degrees	Mean bearing error in meters	S.E. meters	Triangulation theoretical error maximum °	m	mean °	m
5 - 15	16	8.8	1.92	.382	.30	.06	±5	2.1	±2	.79
16 - 30	13	25.6	2.62	.311	1.26	.14	±4	3.2	±2.5	1.82
31 - 45	10	41.1	3.89	.564	3.01	.46	±6	7.5	±4.0	4.39
46 - 60	8	55.2	3.07	.735	3.14	.63	±5.5	9.1	±3.0	4.66
61 - 75	7	68.3	2.17	.654	2.64	.80	±5	10.4	±2.0	3.78
76 - 92	13	86.3	2.94	.412	4.81	.60	±4.5	10.7	±3.0	6.49





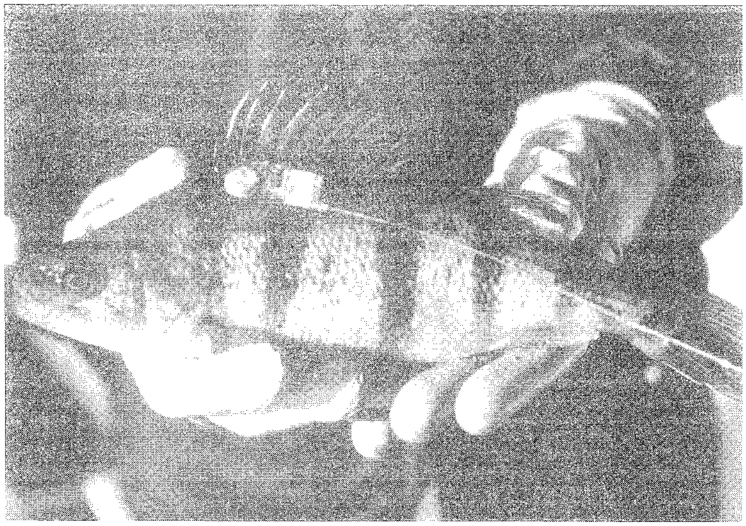


Figure 9. Threading an attachment wire through a hypodermic needle under the dorsal fin.

Figure 10. Dorsal view of a temperature transmitter and soft plastic "washer."

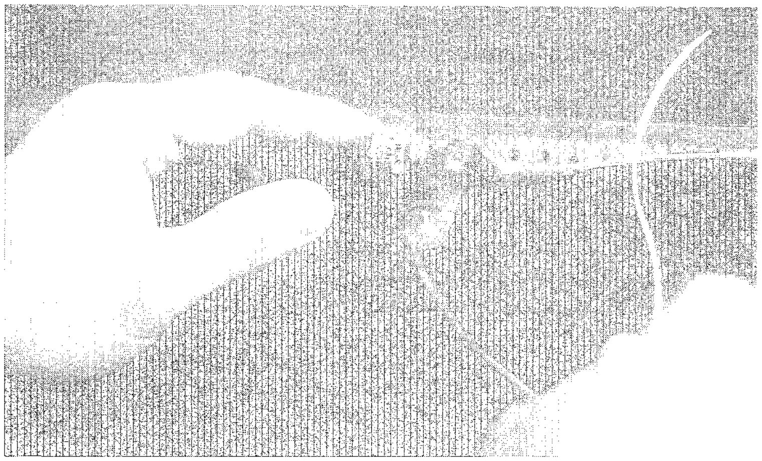
Figure 11. A 340 gm yellow perch with a 3.3 gm (in water) radio transmitter.

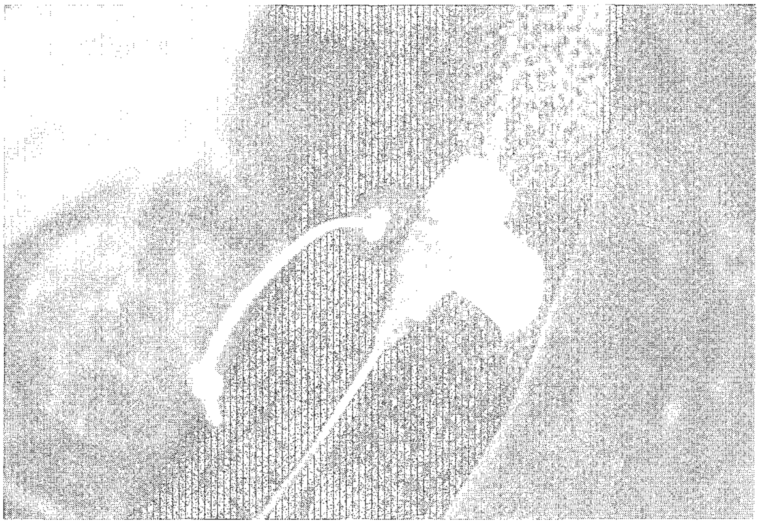
Internal transmitters are less subject to wear, drag and snagging. Since an internal transmitter is below a fish's center of gravity, a heavier package can be used internally without creating balance problems. The disadvantages of surgical implantation are that it takes longer and is more likely to cause infection than external attachment or stomach insertion. In addition, the time necessary for a fish to recover from surgical implantation is much greater than for external attachment or stomach insertion. Transmitters also should not be implanted when the body cavity is filled with eggs. However, surgical implantation is well suited for long term tracking and physiological telemetry. Stomach insertion can be done quickly and probably requires the shortest habituation time by the fish. The disadvantages of stomach insertion are that transmitters may be regurgitated by many species (Hart and Summerfelt 1975) and insertion can rupture the esophagus (McCleave and Horrall 1970). Although stomach insertion worked well on salmon in the lower Columbia River (Wash.), Haynes (1978) found that the mortality of salmon tagged far upstream was much greater for stomach tags than external tags; presumably because of stomach and gut lining atrophy.

We attached radio transmitters by a sub-dorsal fin mount, a mid-dorsal saddle mount, implantation, and stomach insertion. The length of the whip antenna varied with the length of the fish, and was determined before the transmitter was tuned. In general, we feel that an external antenna should not extend beyond the caudal fin.

The sub-dorsal fin mount (figure 9) was best suited for fish with long dorsal fins (eg. Centrarchidae, Percidae, etc.) and little space for an external saddle transmitter without excising part of the dorsal fin. Two teflon coated electrical wires (ground plane) extended from the transmitter. Either a surgical needle or a hypodermic needle was used to thread two teflon coated wires through the supporting tissue under the dorsal fin. The transmitter was snugged to the fish and on the opposite side of the body a soft plastic washer was slid over the wires and against the fish (figure 10). Overhand knots prevented the wire from slipping through the washer. (figure 11).

Most salmonids were tagged with a mid-dorsal saddle mounted transmitter (figure 12). A saddle for 1.5-5.0 kg fish was made from soft (1 mm) plastic measuring 16 mm by 45 mm which was bent in a U-shape by heat or a sharp crease. After two pair of small holes were made on top of the saddle for tying it to the transmitter, the transmitter and saddle were potted together in epoxy. In the field the saddle was trimmed and fitted in front of the dorsal fin. A long surgical needle was used to thread the teflon coated ground plane wire through one side of the saddle, under the skin and connective tissue of the back, and through a hole in the other side of the saddle (figure 13). The saddle was drawn snug on the fish's back and two overhand knots were tied on the wire. A whip antenna trailed along the fish's body (figure 14).





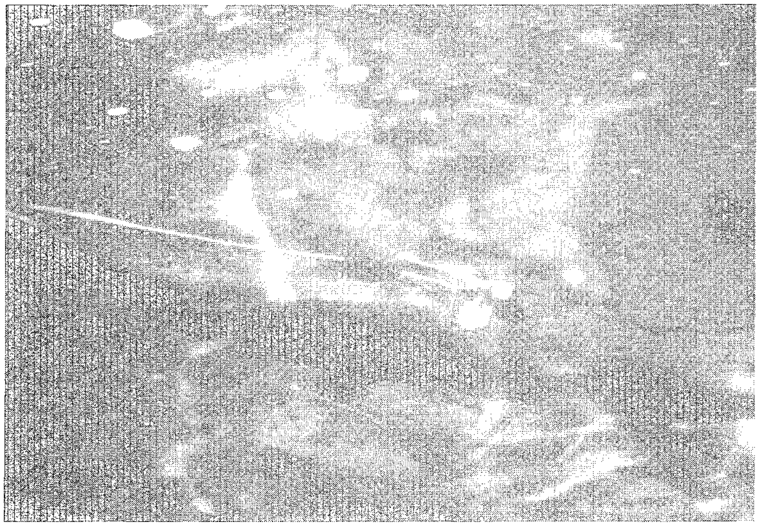


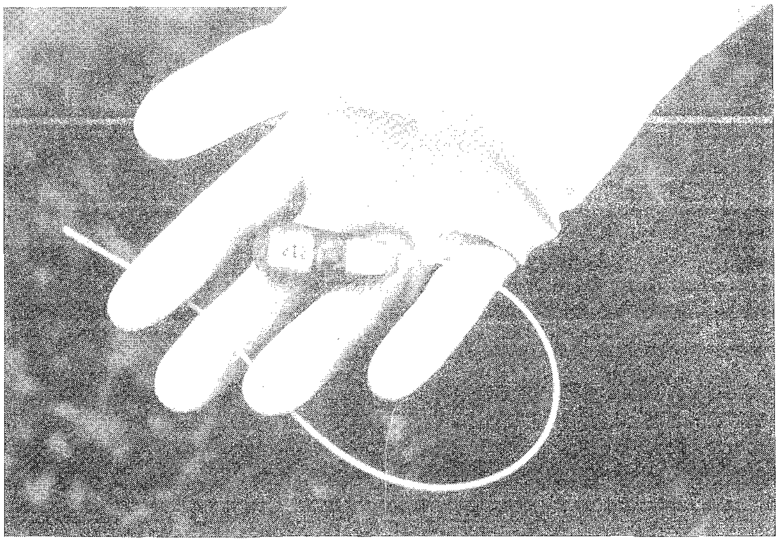
Figure 12. A surgical needle was used to thread the attachment wire through the fish and saddle.

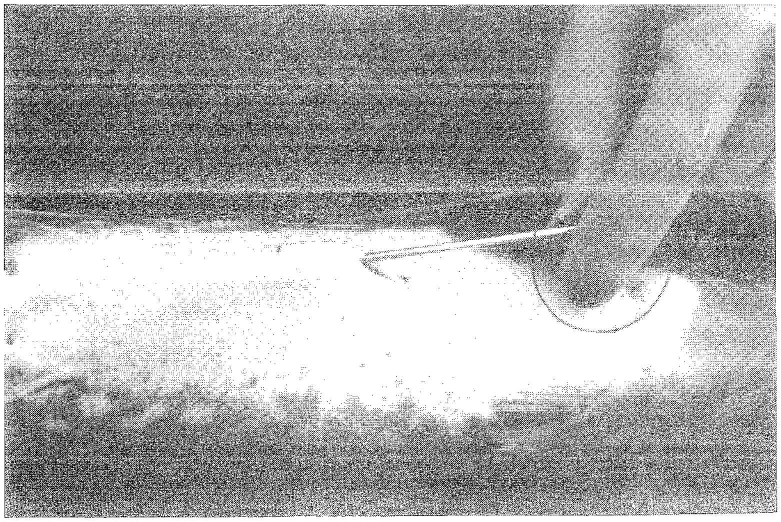
Figure 13. Dorsal view of a saddle-mounted radio transmitter on a 1.7 kg steelhead. The wire on the left is the attachment or ground plane wire and the antenna is to its right.

Figure 14. A 60 cm long radio tagged steelhead swimming upstream.

Figure 15. An internal transmitter with flexible whip antenna.

Figure 16. Making a tunnel under the skin for the whip antenna. The antenna is connected to the tunneling tool by a thread and follows the tool into the tunnel.





We have also implanted radio transmitters (figure 15) using surgical procedures similar to those described by Hart and Summerfelt (1975). Our tests indicated that very little (10%) of the radio signal was absorbed by the fish's body. Transmitter antennas were made from flexible teflon-coated electrical wire. The fish was placed in a tilted V-shaped trough with its head immersed in water containing an anesthetic (MS-222) but its body out of water. A small longitudinal incision was made in front of the pelvic fins. The transmitter antenna was tied by thread to a small diameter (#1) knitting needle which was used to tunnel under the skin (figure 16). As the needle was pulled through the tunnel and out a hole near the anal fin, the antenna followed into the tunnel (figure 17). We are presently trying another method (Peter Johnsen, Univ. of Wisconsin) in which an incision is made behind the pelvic fins lateral to the midventral line so that the transmitter does not lay on the stitches. The antenna is extended under the skin to the pectoral fins. Incisions may heal slowly in fish; therefore, non-absorbable suture should be used. Radio transmitters with loop antennas can be implanted easier than those with whip antennas (R. W. Larimore, Illinois Natural History Survey); however, the range of the loop antenna is shorter and the signal more directional.

Radio transmitters were inserted into the stomachs of salmon through a hollow plastic tube such that a whip antenna extended through the esophagus into the mouth. The antennas, which were made from teflon-coated electrical wire, were anchored by two methods. In most fish, the antenna was passed with a surgical needle through the tissue behind the maxillary and a crimp was placed over the wire (Haynes 1978). If the antenna was not cut at the crimp but left to trail, the transmitter range was greater. A second method was to anchor the wire to the roof of the mouth with a plastic barb (G. Monan, National Marine Fisheries Service, Seattle). Since the gut lining atrophies in spawning salmon, Haynes (1978) recommends placing the transmitter in the posterior portion of the esophagus rather than in the stomach.

Summary

Freshwater fish were tracked by radio telemetry which was well suited for use in turbulent and shallow freshwater. Radio signals attenuated exponentially with increasing salinity and depth. The signal was not affected greatly by aquatic vegetation, ice or a thermocline. Fish were tracked from shore with a hand-held loop antenna or with yagi antennas mounted on temporary towers or trucks. They were also tracked by loop antennas mounted on an airplane and a yagi antenna attached to a boat. Many individuals were distinguished and tracked at the same time because each transmitter broadcasted on a different frequency be-

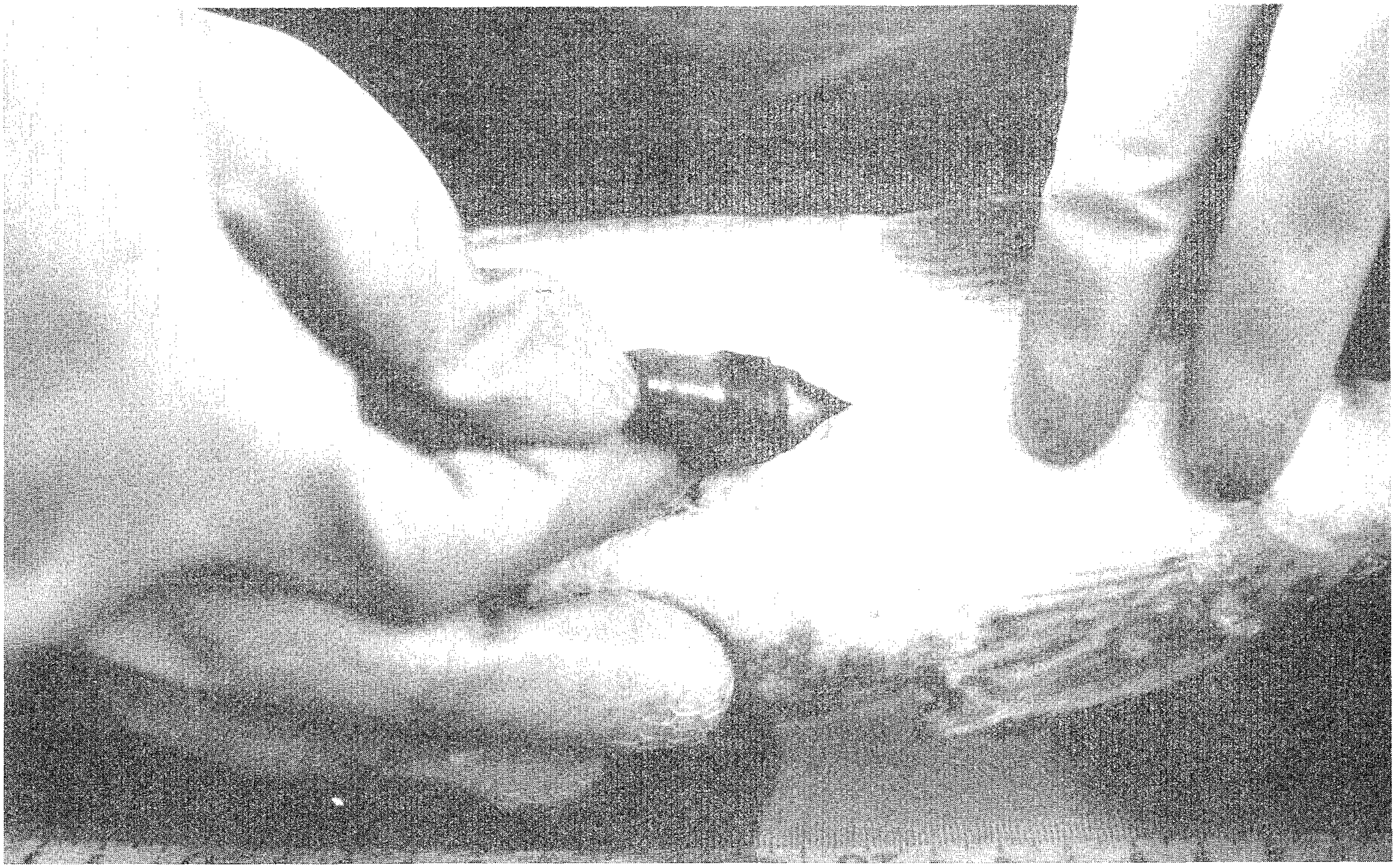


Figure 17. Implanting the transmitter into the body cavity in front of the pelvic fins.

tween 52.5 to 53.5 MHz. Because of a low current drain, transmitters operated for periods ranging from 30 ±5 days for small fish (yellow perch) to several months for larger fish.

Transmitter parts cost about $20 (U.S.). The pulse rate was set between 60 and 120 pulses per minute. Pulse width (on-time) was .02 to .025 seconds and the duty cycle (on-time:total time) was 3 percent ±1 percent. Pulsing-signals can be used to transmit information on water temperature and pressure (depth). Whip antennas of varying lengths were constructed from .5 mmm stainless steel wire for external transmitters and from teflon-coated electrical wire (26 gauge) for internal transmitters. Transmitters were powered by certified mercury cells (1.4 v) or lithium batteries (2.8 v) used singly or in series for more power. The battery was the largest component and was chosen with regard to fish size, and transmitter range and life requirements. We feel that the transmitter weight should not exceed 1 to 1.25 percent of the fish's weight out of water. Mallory RM-675 batteries were used on yellow perch transmitters, which measured 30 mmm by 10 mm by 5 mm and weighed 3.3 gm in water (6.5 gm dry). Steelhead transmitters (Mallory RM-1) weighed 15.6 gm in water (26.0 gm dry) and measured 17 mm diameter by 40 mm. Scotchcast #5 electrical resin (3M Co.) was used to cover the components. Transmitters were attached along side the dorsal fin or on the back with a saddle mount and internally in the body cavity or stomach.

An automobile "radio" was modified into a portable tracking receiver with detachable loop antenna and jack for connecting other antenna systems. Parts for this receiver cost about $125 (U.S.). A more complex, channel selector receiver was developed which can distinguish over 100 different transmitter frequencies spaced 5 to 10 KHz apart. This receiver can also be built with a 64 channel memory and an internal timer for scanning channels to automatically record data on temperature and pressure (depth).

Maximum signal ranges in water of 80-300 μ mho/cm conductivity were: loop antennna, .8 to 1.2 km; yagi, 2.4 to 3.6 km; and loop on airplane, 4.5 km. Mean bearing error for a loop antenna was ±.3m from 5 to 15 m to ±4.8 m from 76 to 92 m. Yagi antenna bearings were accurate to ±3.0° or ±5 m from 100 m to ±43 m from 800m.

Acknowledgments

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Literature Cited

BIAC. 1967. Biotelemetry equipment source directory. AIBS Information Module M12. 19 pp.

Brander, R. B. and W. W. Cochran. 1971. Radio-location telemetry. In: *Wildlife Management Techniques*, R. H. Giles, Jr., Editor, Washington, D. C. Wildlife Society, 1971. pp. 95-103.

Cochran, W. W. 1967. Some notes on the design of a directional loop antenna for radio tracking wildlife. BIAC Information Module M4. 4pp.

Cochran, W. W. and R. D. Lord, Jr. 1963. A radio-tracking system for wild animals. *J. Wildl. Manage*. 27(1):9-24.

Cochran, W. W., D. W. Warner, J. R. Tester, and V. B. Kuechle. 1965. Automatic radio-tracking system for monitoring animal movements. *BioScience*, Feb. 1965. pp. 98-100 (BIAC Information Module M1).

Gilmer, D. S., V. B. Kuechle and I. J. Ball, Jr. 1971. A device for monitoring radio-marked animals. *J. Wildl. Manage*. 35(4):829-832.

Hart, L. G. and R. C. Summerfelt. 1975. Surgical procedures for implanting ultrasonic transmitters into flathead catfish (*Pylodictis olivaris*). Trans. Am. Fish. Soc. 104(1):56-59.

Haynes, J. M. 1978. Movement and habitat studies of chinook salmon and white sturgeon. Ph.D. Thesis. Univ. Minnesota. 166 pp.

Houseknecht, C. R. 1970. Biotelemetry as a technique in disease ecology studies. *J. Wildl. Diseases*. 6:414-417.

Johnson, J. H. 1960. Sonic tracking of adult salmon at Bonneville Dam, 1957. U.S. Fish Wildlife Serv., Fish Bull. 176:471-585.

King, R. W. P., K.-M. Lee, S. R. Mishra, and G. S. Smith. 1974. Insulated linear antenna: theory and experiment. *J. Appl. Phys*. 45(4):1688-1697.

Kuechle, V. B. 1967. Batteries for biotelemetry and other applications. AIBS/BIAC Information Module M10. 15 pp.

Kuechle, V. B., R. A. Reichle, and R. J. Schuster. 1971. Construction details for an animal tracking receiver. Univ. of Minnesota. 16 pp. multilithed.

Lee, K.-M. and G. S. Smith. 1975. Measured properties of bare and insulated antennas in sand. IEEE Transactions on Antennas and Propagation, Sept. 1975. p. 664-670.

Marshall, W. H. 1960. Development and use of short wave radio transmitters to trace animal movements. Progress Report, Univ. of Minn., 27 pp. (multilithed).

Marshall, W. H. 1962. Development and use of short wave radio transmitters to trace animals movements. Progress Report, Univ. of Minn. 18 pp. (multilithed).

Marshall, W. H. 1963. Studies of movements, behavior and activities of ruffed grouse using radio telemetry techniques. Progress Report, Univ. of Minn. 30 pp. (multilithed).

Marshall, W. H. and J. J. Kupa. 1963. Development of radio-telemetry techniques for ruffed grouse studies. Trans. 28th No. Am. Wildl. and Nat. Resources Conference. pp. 443-456.

McCleave, J. D. and R. M. Horrall. 1970. Ultrasonic tracking of homing cutthroat trout (*Salmo clarki*) in Yellowstone Lake. J. Fish. Res. Bd. Canada 27:715-730.

McCleave, J. D. and K. A. Stred. 1975. Effect of dummy telemetry transmitters on stamina of Atlantic salmon (*Salmo salar*) smolts. J. Fish. Res. Board Canada. 32(4):559-563.

Ross, M. J. 1978. Winter distribution of fish and temperature preference of yellow perch, *Perca flavescens*, in the thermal plume of a power plant as determined by radio telemetry. M.S. Thesis. Univ. Minnesota. (in preparation).

Saran, G. S. and G. Held. 1960. Field strength measurements in freshwater. J. Research NBS 64D, 5:435-437.

Schiefer, K. and G. Power. 1972. Tracking in a turbulent river. *Underwater Telemetry Newsletter*. 2(1):14-15.

Shen, L. C., R. W. P. King, and R. M. Sorbello. 1976. Measured field of a directional antenna submerged in a lake. IEEE Transactions on Antennas and Propagation, Nov. 1976. p. 891-896.

Siniff, D. B., J. R. Tester and V. B. Kuechle. 1971. Some observations on the activity patterns of Weddell seals as recorded by telemetry. Antarctic Research Series, Vol. 18, Antarctic Pinnipedia. pp. 173-180.

Slade, N. A., J. J. Cebula, and R. J. Robel. 1965. Accuracy and reliability of biotelemetric instruments used in animal movement studies in prairie grasslands of Kansas. Trans. Kansas Acad Sci. 68(1):173-179.

Slater, L. E. 1963. *Bio-telemetry*. 327 pp. Pergamon Press Inc., N.Y.

Slater, L. E. 1965. Editor. A special report on bio-telemetry. *Bio Science*, Feb. 1965. pp. 81-157. (AIBS/BIAC Information Module M1).

Tester, J. R. 1971. Interpretation of ecological and behavioral data on wild animals obtained by telemetry with special reference to errors and uncertainties. Symposium on biotelemetry, CSIR, Pretoria, S. Africa, pp. 385-408.

Tester, J. R. and D. B. Siniff. 1976. Engineering design and development, p. 6-36. In: Vertebrate behavior and ecology, annual progress report for period ending 30 June 1976. Submitted to ERDA under contract No. E(11-1)-1332 (Univ. of Minnesota, Minneapolis).

Trefethen, P. S. 1956. Sonic equipment for tracking individual fish. U.S. Fish & Wildl. Service, Special Scientific Report, Fisheries No. 179. 11 pp.

Trefethen, P. S., J. W. Dudley and M. R. Smith. 1957. Ultrasonic tracer follows tagged fish. Electronics 30(4):156-160. April.

Underwater Telemetry Newsletter. 1971-1976. Ed. A.V. Stasko, Fisheries and Marine Service, Biological Station, St. Andrews, N.B., Canada EOG 2X0. 1976-present. Ed. C. C. Coutant, Environmental Sciences Divison, Oak Ridge National Laboratory, Oak Ridge, TN. 37830.

Verts, S. J. 1963. Equipment and techniques for radio-tracking striped skunks. J. *Wildl. Manage*. 27(3):325-339.

Winter, J. D., V. B. Kuechle, and D. B. Siniff. 1973. An underwater radio tracking system. *Underwater Telemetry Newsletter*. 3(2).

Winter, J. D. 1976. Movements and behavior of largemouth bass (*Micropterus salmoides*) and steelhead (*Salmo gairdneri*) determined by radio telemetry. Ph.D. thesis. Univ. Minnesota. 200 pp.

Winter, J. D. 1977. Summer home range movements and habitat use by four largemouth bass in Mary Lake, Minnesota. Trans. Am. Fish. Soc. 106(4):323-330.

Ziebell, C. D. 1973. Ultrasonic transmitters for tracking channel catfish. Progr. Fish-Cult. 35(1):28-32.

Appendix

Description of Radio Tracking Receivers

Receiver specifications:

Frequency range	Any 1 MHz range as determined by the first converter.
Tuning method:	three detent switches.
Channel spacing:	1 KHz. Unit may be tuned more accurately by use of fine tune control.
Sensitivity:	Signal detectable to -143 dbm by listening.
I.f. band width:	1.2 KHz.
Power supply:	Internal Ni-Cad, 8 hours mic. use of full charge, or external 12 volt, negative ground.
Frequency drift:	0.01%.
Outputs:	0-1 ma signal indicator, output jack in series with meter for 0-1 ma recorder.
Output impedance:	2000 ohms or 8 ohms switch selectable, standard phone jack.
Dimensions:	21 cm × 13 cm × 17 cm high.
Weight:	1.8 kg.

Function of Operator Controls:

1. Headset Impedance Switch. This switch selects the best impedance match between the 2000 ohm Telex headsets which are normally used and the 8 ohm Koss headsets which are used if ambient or wind noise is a problem.

2. Headset Jack. Provides receptacle for headset or other listening device. Standard monouarl plug fits. Standard stereo plugs may be used if both head pieces are wired to the tip.

3. Battery Charge/External Power; Optional Input/Output. Provides receptacle for input power to recharge internal batteries and to provide power from external 12 volt power supply. Extra pins may also be used as optional input/outputs.

4. Antenna Input. Female BNC connector to provide for 50 ohm antenna input.

5. Fine tune. Allows shifting the first converter crystal frequency to provide fine tuning between the 1 KHz increments of the frequency synthesizer. It allows the operator to tune to the frequency that can be heard best or is the most comfortable.

6. On/Off - R.F. Gain. Turns power on and off from internal batteries or external power supply. The variable resistance control varies the r.f. gain in the input pre-amplifier to prevent signal overload on strong signals. This prevents spurious signals from being generated by intermodulation and cross modulation. R.f. gain is maximum when the control is fully clockwise.

7. Audio Gain. Controls the audio level in the headset. This control has very little effect on detectability of a signal. Maximum signal level is with the control fully clockwise.

8. Battery Status Indicator. Indicates voltage level of internal rechargeable batteries or external power source. It should be in the white area for proper operation.

9. 0-1 ma External Recorder Jack. Allows insertion of an external meter in series with the internal meter to record signal strength on an external paper recorder.

10. Signal Strength Meter. Provides an integrated indication of the audio signal level.

11. Frequency Selectors. The three switches select which frequencies are to be passed through the receiver and which are blocked. Frequency can be selected in 1 KHz increments over a 1 MHz range. The 1 MHz range is determined by selection of the preamp and first converter.

Function of Operator Controls with Memory Unit.

12. Frequency Indicator. Three digit display of the frequency. In the manual mode the display will be the same as the frequency selector switches (11). When in the memory active mode it will display the frequency of the active channel.

13. Display on/off Switch. Turns off the display to save power when the display is not needed.

14. Memory Channel Selector. Sixteen position switch to address which channels are to be written or read into the frequency selector.

15. Memory Bank Selector. In 32 channel receiver the switch selects channels 0-15 in position (A) or 16-31 in position (B).

16. Memory Active/Bypass Selector. This switch determines whether the receiver frequency is selected by the memory (ACTIVE) or by the frequency selectors (11) on the front panel.

17. Memory Read/Write Selector. This switch is used to transfer a frequency selected by front panel switches (11) into the memory channel selected by (A).

18. Memory Auto Manual Selector. Selects whether the memory is to be scanned by means of the channel selector (14) or automatically by an internal timer.

19., 20. Memory Scan Interval Control. Controls the rate of the interval timer for the auto scan mode.

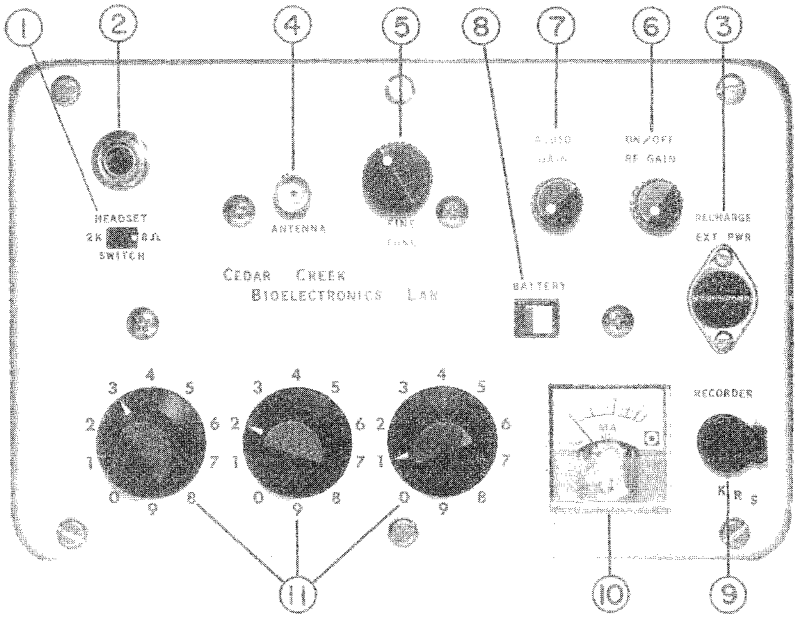
21. Signal Search Control. (Optional) With this signal in the lock mode the receiver will scan until a signal is found. It will then remain locked on that channel as long as a signal is present.

22. Auto Scan Channel Indicator. Lights indicate which channel is active in the auto scan mode. It is in binary code and can be converted to decimal by adding the number below the lights that are on.

23. Signal Indicator From Phase-locked-loop. Indicates a signal is present when the light is on.

24. Auxiliary Outputs. (Optional).

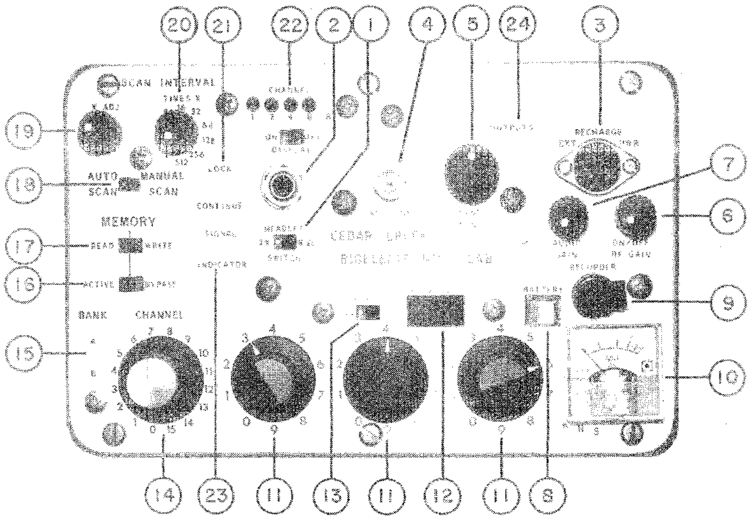
Front Panel Controls, Connectors And Indicators



(1) Headset Impedance Selector
(2) Headset Jack
(3) Battery Charge/External Power/Auxiliary Output
(4) Antenna Input Connector
(5) Fine Tune Control
(6) On/Off RF Gain Control
(7) Audio Gain Control
(8) Battery Status Indicator
(9) External 0-1 ma Recorder Jack
(10) Signal Level Meter
(11) Frequency Selector Switches (reads 53.321 MHz)

Front Panel Controls, Connectors And Indicators

(1) Headset Impedance Selector
(2) Headset Jack
(3) Battery Charge/External Power/Auxiliary Output
(4) Antenna Input Connector
(5) Fine Tune Control
(6) On/Off RF Gain Control
(7) Audio Gain Control
(8) Battery Status Indicator
(9) External 0-1 ma Recorder Jack
(10) Signal Level Meter
(11) Frequency Selector Switches
(12) Frequency Indicator
(13) Display On/Off Switch



(14) Memory Channel Selector
(15) Memory Bank Selector
(16) Memory Active/ Bypass Selector
(17) Memory Read/ Write Selector
(18) Memory Auto/ Manual Selector

(19) (20) Memory Scan Inter-val Control
(21) Signal Search Control
(22) Auto Scan Channel Indicator
(23) Signal Indicator From Phase Lock Loop
(24) Auxiliary Outputs