STUDIES

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DEVELOPMENT OF SATELLITE-LINKED METHODS OF LARGE CETACEAN TAGGING AND TRACKING IN OCS LEASE AREAS -- FINAL REPORT

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ABSTRACT

The movements and behaviors of most whales are poorly understood. Tracking whales by radio can help. 1) identify critical habitats (feeding areas, breeding areas, calving areas, and migration routes), 2) determine the importance of oceanographic features (bottom topography, ice, thermal gradients, currents, upwellings) to navigation and feeding, 3) and define the daily and seasonal patterns in diving which relate to feeding, resting and active swimming. Technical developments and data from whale studies using both conventional (VHF) and satellite-monitored radio tags are presented. The longest distances and durations of tracking whales by both techniques were accomplished during this study. The evolution and utility of the Argos (satellite-based) Data Collection and Location System is traced during the period from 1979 to 1987.

Before satellite-monitored tags, the duration of experiments to monitor the movements of whales was limited. Tracking pelagic whales was difficult because the short range of conventional transmitters required constant (labor-intensive) monitoring and expensive ships. The development of a new subdermal attachment system for surface-mounted tags was demonstrated in 1979 by VHF tracking a gray whale at least 6,680 km from Mexico to Alaska. The tagged animal was relocated by radio off California, Oregon and Alaska 5 times over a 94 day period. This is still the longest distance and duration of any VHF whale tracking effort. Data from untagged whales showed no affects from tagging. This was the first direct measurement of a whale over an entire migration route (monthly average speeds up to 127 km/day).

Argos locations are determined by Doppler shift calculations which require multiple transmissions in the 15 min. period of a satellite passing overhead. However, Argos transmitters cannot transmit through water, so the patterns of 11,080 dives by 10 gray whales tagged with VHF radios in 1980 were analyzed to determine that whales would surface frequently enough to be located by satellite. Available Argos transmitters were too large for whales because of power requirements for keeping sensitive oscillators in a temperature stable environment. Working with Telonics, an Argos transmitter was developed which was small enough to attach to whales and incorporated a saltwater switch to initiate transmissions when the whale surfaced. The first successful track of a large whale by satellite was a 6 day experiment in 1983 tracking a humpback whale for 700 km off the Newfoundland (Atlantic) coast. The whale moved from the nearshore to a convergence area offshore frequented by other humpback whales. In 1984, a gray whale was tagged with a modified transmitter which provided dive profile (depth) data.

A more energy efficient oscillator was redesigned for the transmitter and a duty-cycle function was added to allow transmissions only during pre-programmed times when satellites would be passing overhead. This technology and specialized software to analyze Argos location and dive data were applied to an independent study of endangered manatees. Using a caudal peduncle attachment and a tethered bouy to house the electronics, manatees were tracked for up to 300 days with an average of more than 2 locations/day.

The improved transmitter in a new pressure housing was applied twice to individual humpback whales (1986 and 1987), but was poorly attached in both instances. Nonetheless, excellent data were received for the 22 and 71 hr periods of attachment, demonstarting the performance of the new transmitter software, the new pressure housing and an ability to locate whales up to 6 times/day. The same transmitter was attached to a pilot whale in 1987 with a molded dorsal fin pack. The transmitter slightly exceeded its predicted battery life, resulting in 479 locations over a distance of at least 7,588 km in 95 days. The average speed was 3.3km/hr (80 km/day), but speeds as high as 16 km/hr were maintained for periods >3 hours. All dives for the period were counted (average of 2,020/day) and measured (average of 40 s in duration). Deep diving only occurred at night when the deep scattering layer rises and brings squid near enough to the surface to be fed on efficiently. Most surface resting occurred right after sunrise on a 4-7 day cycle (the first evidence of cyclic surface resting in a cetacean). This is the longest distance and duration for tracking a whale by any means. It is also the most intimate description of any whale's movements and dive habits. While further analysis remains, there appear to be significant correlations in the whale's activities and movements with time of day, thermal gradients and bathymetry.

The utility and limitations of conventional and satellite telemetry are discussed. Recommendations are made for future studies. Attachment and deployment techniques for tagging large whales deserve further research attention, but should get easier in the future as the improved electronics get smaller and more effecient. The use of other satellite systems is discussed and some developments of the Argos system are predicted. In general, satellite telemetry is extremely cost effective ($12/day for data capture) compared to conventional telemetry. The feasiblity of tracking whales by satellite has now been demonstrated and has resulted in an unprecedented amount of information. It is the most promising available technique for the future evaluation of whale habits and critical habitats.

Executive Summary

Little is still known of the normal movements, behaviors and dive patterns of free-ranging whales because they are difficult to identify as individuals and observe over long periods of time. The habits of individual whales are important because collectively they describe what their population does. Satellite-monitored radio tags can now track virtually any number of tagged whales simultaneously anywhere in the world and send data which can interpret the animal's health and habits.

The feasibility of satellite tracking began in 1979 when Minerals Management Service (MMS) funded a whale tracking study using conventional, very high frequency (VHF) radio tags. A radio tagged gray whale moved at least 6,680 km from Mexico to Unimak Pass, Alaska in 94 days, at an average speed of 85 to 127km/day (3.5 to 5.3 km/hr). Only the nearshore migratory habits of this species allowed the low powered (short range) transmitter to be monitored from shore without involving expensive ships and aircraft. In offshore studies, widely dispersed animals must be tracked individually because of the short reception range. The new "barnacle" attachment was so successful that consideration of longer duration studies and larger tags needed for satellite tracking began. At least 5 messages were needed to determine the location of special satellite-monitored transmitters and signals could not be transmitted through seawater. So, in 1980 VHF tags were again used to determine dive durations and pattern data from 11,080 gray whale dives to estimate that whales do surface frequently enough during the 15 minute duration of a satellite pass overhead to make satellite location and tracking feasible. The VHF study was typical of conventional telemetry work, requiring 10 people to work 3 months to tag, track and log data from whales.

Argos is the only satellite system presently available which can provide locations for whales equipped with specialized transmitters. Prior to 1983 these transmitters were too large and power consumptive for whales but, in cooperation with Telonics, an experimental transmitter was developed which now provides satellite-monitored data from free-ranging whales and other marine mammals. Extremely accurate locations (90% within 1 km) are achieved by using very stable ultra-high frequency (UHF) transmitters. Positions are calculated from Doppler shift data (the change in frequency heard by the satellite receiver resulting from its speed as it passes the transmitter). Argos receivers are carried on two polar-orbiting NOAA weather satellites, which jointly pass over all portions of the earth from 7 (tropical) to 24 (polar) times daily. Transmitters send a 2-watt signal which the satellite can receive up to 2,500 km away. To conserve battery power, a saltwater switch was developed to initiate transmissions only when the transmitter surfaces and during pre-programmed times when satellites are overhead.

The first successful tracking of a whale by satellite occurred in 1983 when a humpback whale off Newfoundland, Canada was tracked 700 km during 6 days. The whale's location was calculated 10 times and showed an average movement of 5.9 km/hour (similar to the migrant gray whale speed) to an area offshore where the cold Gulf Stream and the warm Labrador currents converged. This area, like an upwelling, was characterized by high productivity and was often used by humpback whales feeding on concentrations of spawning capelin. This was the first documentation of a nearshore animal moving directly offshore to another whale feeding area. It is not known whales know where to find food (memory, sensing favorable oceanographic factors, or listening to other whales vocalize) and navigate to it (dead reckoning, magnetic headings, or celestial cues). This prototype transmitter had an operational life of only 30 days as most of its energy was used to keep the oscillator circuit warmed up, whether it was transmitting or not.

In January 1984, a female gray whale with a modified Telonics transmitter collected depth information every 15 seconds and reported information about dive duration, temperature and depth profile with each transmission. The experiment lasted for only a few days probably as a result of breeding activity. The tagged whale spent 45 minutes of the first hour after tagging in vigorous mating behavior with 2 males. The tag did not appear to inhibit the whale's behavior.

Although not funded by MMS, the next significant development in satellite tracking marine mammals was built upon the progress of the MMS studies. A 1985 collaboration between the U.S. Fish & Wildlife Service and Oregon State University resulted in tracking a free-ranging manatee (an endangered species) in Florida for 100 days with a battery change half way through the experiment. A similar 1986 experiment tracked a female manatee with a calf for 300 days. The calf went through normal development and was weaned. This was the first study by any means to demonstrate the daily movements and natural foraging range of a free-ranging marine mammal over such an extended period. At the end of the 300 day experiment, the transmitter was replaced and the same animal was tracked for another 10 month period.

The first long term satellite-monitored study of a free-ranging whale took place during 1987 in the North Atlantic. An immature pilot whale, stranded in December 1986, was rehabilitated by the New England Aquarium and released on 29 June 1987 carrying a Telonics transmitter. The whale was tracked by satellite for 95 days and covered a distance of at least 7,588 km between 479 satellite-determined locations. The average daily movement (80 km/day) and a maximum movement of 234 km in 24 hours suggest how wide ranging small cetaceans can be. Every dive was counted ($\bar{x}$ = 2,020/day) and its duration measured. The average dive lasted 40 seconds. The number of dives in a 12-hour period varied from 636 to 1433, reflecting changes in the animal's activity patterns and metabolic rate. Swimming speeds averaged 3.3 km/hr for the entire 95 day period. Average speeds in excess of 16 km/hr were maintained for periods >3 hrs.

Important correlations of the animal's movements and dive patterns were made by comparing transmitter temperatures (down to 6°C) with sea surface temperatures (14°C to 30°C). The whale encountered temperatures up to 12°C cooler than surface temperatures during deep dives, which occurred primarily before sunrise and secondarily just before sunset. Deep dives coincided with the nocturnal rise in the water column of the deep scattering layer and of the pilot whale's favorite prey, squid. Few deep dives were recorded during daylight hours. If daytime feeding occurred, it was a completely different strategy. This was the first direct documentation of the importance of night feeding to this species. The highest swimming speeds were also observed at night and just before sunset suggesting that this whale either traveled fast in pursuit of prey or moved quickly to search for other prey patches. Surface resting activity lasted up to 15 minutes and was most common during the first 3 hours after sunrise. Surface resting occurred on a 4 - 7 day cycle. These data represent the first long-term evidence of cyclic on surface resting patterns for a free-ranging cetacean.

The feasibility of tracking marine mammals has now been proven and these examples show its utility over relatively long periods. A February 1987 Marine Mammal Commission workshop (sponsored by MMS), summarized whale radio telemetry studies and recommended satellite-monitored radio tags as the most promising tool for the long-term study of pelagic whale movements. The most challenging problems will be attachment and deployment techniques. Once successfully deployed, satellite tags will be a cost effective means of gathering whale data. Tags cost about $4,000 (approximately the same as a single day of vessel charter) and are satellite-monitored for $12/day. Some behaviorial observations will still be desirable, but relatively inexpensive because observers will be able to find tagged whales easily during good weather with satellite-determined locations.

The successful monitoring of a single whale by satellite for even a few days can provide insights into the species' diving behavior, movements, diurnal rhythms, and energetics. While the daily dive patterns and energetics of whales are of interest, the longer term movements within foraging areas, breeding grounds and along migration routes are also important to assess potential impacts of offshore development. For instance, satellite-monitored tags could be used on bowhead whales to gather information on: 1) the foraging range (and site tenacity) of individual whales during their Beaufort Sea occupancy; 2) the importance of certain areas for feeding, staging and migration; 3) what diurnal and geographic differences in dive habits reflect differences in behavior; 4) the speed of movements between feeding areas and during migration; 5) the relationship of whale distributions to environmental factors such as sea surface temperatures, bathymetry and ice coverage; and 6) the amount of time whales spend at the surface, which affects how often they are sighted during aerial surveys and affects the interpretation of existent aerial survey data. It may also be possible to conduct experiments with tagged whales along their migration route to determine if whales avoid specific sounds. If tags remained operational for longer periods or whales were tagged in other regions, it would be possible to identify the complete fall migration route through the Beaufort, Chukchi and Bering Seas to learn something about the wintering grounds of the bowhead. Recent isotopic studies suggest that these winter areas may be important parts of the bowhead's feeding range. In the future, satellite-monitored radio tags are likely to provide much of the oceanographic data which describes why certain habitats are preferred by endangered whales.

Additional attention needs to be devoted to deployment methods. Further development of attachments and packaging for recently minaturized transmitters will greatly reduce hydrodynamic drag and extend the duration of operation.

Initial efforts in tagging bowheads should take advantage of the more "open water" nature of the late summer feeding season in Beaufort. Tags should be applied as early in the open water season as practical to provide as much time as possible for follow-up observations of behavior and the tag attachments. The tag should provide large numbers of messages (transmitting perhaps four 2 h periods/day) during the 10 week open water season to maximize the daily locations and then shift to a low intensity transmission schedule (1 h/3 days) to collect information on attachment longevity. Five to 10 whales should be tagged to fairly evaluate any new PTT and there should be an emphasis on compacting PTT-analyzed data into a short message format. A first-time deployment should not involve manipulative experiments (such as noise avoidance) so that natural variability and possible seasonal changes can first be understood.

It is important that future studies have adequate time to develop and test new equipment before field operations commence. Adequate lead time will also be necessary for interagency coordination and to assure that data on important environmental variables (currents, ice coverage, sea surface temperatures, winds, cloud cover, etc.) are collected concurrently.

It is likely that PTTs can provide significant amounts of physical oceanographic data as well as information on whales.

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INTRODUCTION

This report covers the research and development of radio tags for the tracking of large whales funded by the Bureau of Land Management Outer Continental Shelf Program and the Minerals Management Service (MMS) intermittently from 1979 through September 1987. The experiments and data reported here involve ten tagging efforts at least partially funded by MMS on four whale species and five variations of electronics on two principal themes: 1) low power very high frequency (VHF) radio tags, and 2) satellite-monitored ultra-high frequency (UHF) radio tags, often referred to as platform transmitting terminals (PTT). The latter are monitored by the Argos Satellite System onboard sun-synchronous polar orbiting TIROS-N weather satellites. Data are also reported for manatee experiments conducted in cooperation with the U.S. Fish and Wildlife Service because they developed as a direct result of the MMS-sponsored work on satellite-monitored tags. The time-line below summarizes the chronological development of events and milestone achievements during this contract. This report is largely a chronological account of MMS-funded developments and experimental applications of whale tags directed to the ultimate tagging of bowhead whales.

VHF	1	2	3	4				12	
	1979	1980	1981	1982	1983	1984	1985	1986	1987
SATELLITE					5, 6	7, 8	9	10, 11	13, 14

1. 3 gray whales; one whale monitored over a 94 day period from Mexico to Alaska (6,680 km)

2.* 13 gray whales: 11,080 dives monitored, movements in and out of calving lagoon, movements between lagoons, identification of new feeding area, analysis of dive pattern variability between whales, comparison of tagged and untagged whales

3. Evaluation of humpback whales entangled in fishing gear for future tagging efforts

4. One humpback whale tagged: fast movement offshore

5. Gray whale tagged in Mexico: tag electronics failed

6.* Humpback whale tagged in Newfoundland: 6 day track (700 km) to offshore convergence area

7. Gray whale tagged in Mexico: dive profiles collected for short period, no interruption of breeding behavior

8. Software written for analysis of satellite-acquired tagging data

9.* One manatee tagged and tracked for 100 days: electronic improvements and miniaturization, critical habitats, navigation, home range, travel speeds, site tenacity-foraging

10.* Three manatees tagged and tracked for up to 300 days; long-term marine capability demonstrated, normal mother/calf behavior

11.* One entrapped humpback whale tagged: improved electronics, reduced size, redesigned housing and attachment, tag attachment damaged at release, one day duration with 4 locations (134 km)

12. Bowhead whales: assisted in tagging 2 whales, developed successful approach technique for projectile tags

13.* One humpback whale tagged: attachment incomplete, 70 hr duration, 16 locations

14.* Pilot whale tracked for 95 days (7,588 km), 187,000 dives measured, movement, nocturnal feeding habits, surface resting, search patterns, speeds

* Partial or complete funding supplied by another agency.

BACKGROUND

Nineteenth-century whalers recognized the seasonal movements of some large whales (Scammon, 1874) from spears and harpoons. In the 1930's scientists began applied shotgun "discovery" tags to find out about their movements (Brown, 1978). The numbered shafts were recovered from harvested whales linking the tagging location with the harvest area, but with no information on where the whale had been in the interim (often many years). During the last 15 years natural marks on many species have been used to successfully identify individual whales returning to specific breeding and feeding grounds (Kraus and Katona, 1977; Darling, 1984) and long term social bonds in killer whales (Balcomb, 1978). Using this technique, the calving intervals of southern right whales, killer whales, humpback whales and gray whales have been determined.

Radio tags have several advantages over visual methods for finding, tracking and recording whale movements and behaviors: 1) observations can be made day or night; 2) observations are less dependent upon weather; 3) identification of individuals is not limited by the necessity of viewing certain portions of the whale's anatomy; 4) distance from which observations can be made is greater and, thus, possibly less disturbing to normal whale behavior; and 5) positive identification can be made in real time (versus later comparison of detailed photographs or descriptions). During the last quarter of a century radio tags have been used to track several species of whales (Evans, 1974; Watkins et al., 1978, 1981; Mate and Harvey, 1981; Goodyear, 1981).

The earliest successful radio tag for large whales was developed by Schevill and Watkins (1966). The technique used a shotgun-fired projectile high frequency (HF) radio tag which has been reduced in size and used on humpback, fin and brydes whales. Fired from a modified shotgun, the tag is imbedded in the skin and blubber of the whale with only the antenna protruding. Sweeney and Mattsson (1974) and Evans (1974) surgically attached a VHF transmitter to a yearling gray whale when it was released after one year in captivity. Norris and Gentry (1974) and Norris et al. (1977) attached a VHF transmitter to a gray whale calf with a harness system. Goodyear (1981) used a suction cup device for the short-term attachment of VHF tags in humpback whale studies. These examples of conventional telemetry all require monitoring efforts at relatively close range and are, therefore, reasonably labor intensive for full time data recovery.

Two VHF tags were developed during this project and are described in this report: umbrella and barnacle tags. Although each tag is applied differently, both rely on subdermal attachments to secure the transmitter to the surface of the whale's back. The transmitters and receivers were electronically identical to those used successfully in tracking harbor seals in the Pacific Northwest (Brown and Mate, 1983). Gray whales were the initial subjects for tagging because of their accessibility in certain Mexican calving lagoons and the relative ease of documenting long-range movements due to their nearshore migration.

Concurrent with the development of the VHF radio tags, the NIMBUS Satellite System for locating special UHF transmitters (PTT's) was being further developed by NASA. Early attempts at satellite tracking of animals were largely unsuccessful due to the considerable weight of batteries needed to keep the transmitter's temperature constant for frequency stability. The large size of the earliest wildlife transmitter for tracking an elk made the experiment unsuccessful (Craighead et al. 1972). Attempts many years later to equip dolphins with PTT's were also unsuccessful (Jennings and Gandy, 1980). Technical advances which allowed hybridization of circuits, further miniaturization of other components and the development of temperature-stable oscillators have now made it possible to create small satellite-monitored radio tags and success can be reported. This project was responsible for the first success in satellite-tracking a fully aquatic marine mammal and has stimulated numerous examples of both marine and terrestrial long-term tracking.

This report is divided into two basic sections: VHF radio tags and satellite-monitored PTT's. The VHF section reviews the MMS-funded development of VHF radio tags, subdermal attachments, and data produced by these tags. The section on satellite-monitored radio tags reviews: 1) the background of the Argos satellite system; 2) the development of of satellite-monitored transmitters, attachments, housings and software; and 3) data collected from humpback, gray, bowhead and pilot whales during the course of this project. Finally, a projection of future potential applications and recommendations is offered.

PART I - VHF TAGGING (1979 AND 1980):

Background

This study began as an attempt to understand the diving and surfacing patterns of gray whales and the timing of their migration along the western coast of North America. Gray whales are modest sized baleen whales (up to 15 m) with limited blubber thickness which precluded the consideration of existent projectile VHF tags. However, 1977 studies in San Ignacio lagoon (Figure 1) of oxygen uptake measurements (Sumich, 1986) involved working closely with free-ranging gray whales. Because many gray whales were quite approachable and even appeared to solicit physical contact with small boats, two attachment systems were ultimately designed which could be deployed at very close range (Mate et al., 1983a). Both systems emphasized laterally deployed subdermal attachments and a restricted depth of penetration.

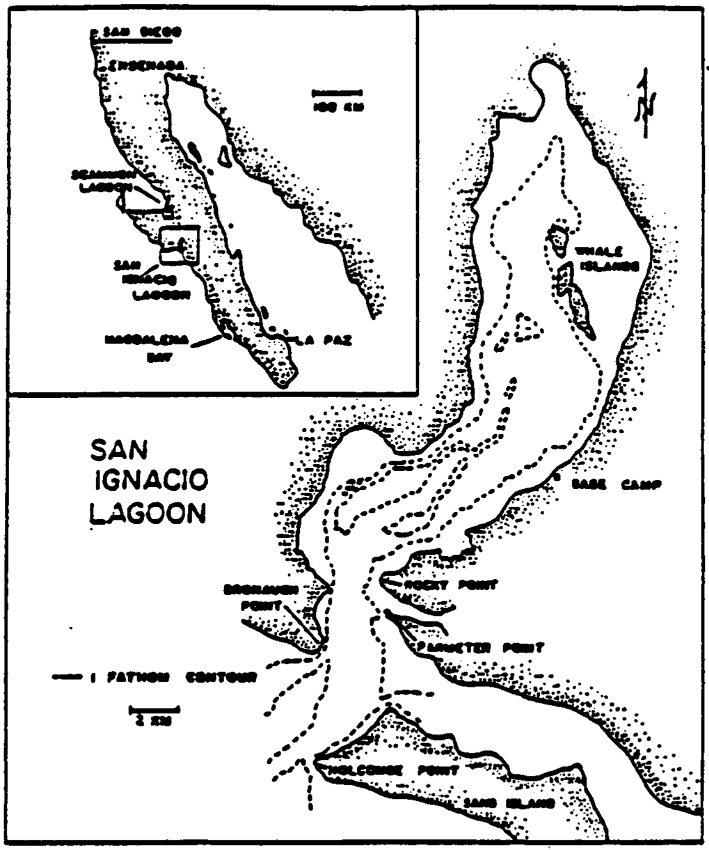


Fig. 1. San Ignacio Lagoon, Baja California Sur, Mexico was the location of all tagging activities. A base camp and field camp at Bronaugh Camp were established to monitor radio-tagged whales. The lower lagoon was arbitrarily demarcated from the ocean by bearings originating from Bronaugh Point to Hoicombe Point.

Materials and Methods

The umbrella tagging system consisted of two major components, a radio transmitter on an attachment plate and a tag applicator. Radio transmitters used were model L2B5 (Telonics, Mesa, AZ) and measured 3.8 cm x 3.6 cm x 2.5 cm. The transmitters emitted 30-msec pulses every 430 msec on discrete frequencies in the 148-149 MHz range. Two different antenna designs were used. One quarter-wave whip antenna consisted of a 46 cm flexible stainless steel cable that was insulated and stiffened with shrink tubing to achieve a vertical orientation. Later models used a truncated helix antenna that consisted of a 22.9 cm long stainless steel spring (0.6 cm diam.) embedded in polyurethane. With 1 mw (milliwatt) peak effective radiated power, each transmitter had an estimated operational life of 3.5 months. To aid in visual identification of tagged whales, a 1.0 m x 7.5 cm colored plastic and nylon streamer was mounted beneath the transmitter. Both the transmitter and streamer were riveted to the center of a 17.5 cm x 3.75 cm x 0.25 cm stainless steel attachment plate.

The attachment plate (with radio transmitter and streamer) was secured to a whale by two umbrella anchors (Figure 2). Each anchor consisted of a cylindrical piston of surgical-quality inconel metal 2.1 cm in diameter and 1.9 cm high. Two grooves were machined around the circumference of the piston. One groove held a rubber O-ring and the other, in combination with a spring-loaded detent, held the piston in the tag applicator. Six spring inconel wires (8 cm long x 2 mm diam.), curved to form an arc of constant radius, were pressed into holes drilled through the piston and silver-soldered. The six wires passed through slots at each end of the attachment plate. The distal end of each wire was beveled inward.

The tag applicator consisted primarily of two cylinders mounted on a stainless steel plate (Figure 3). The piston end of an umbrella anchor was pushed with a 20 cm long screwdriver into the plate end of each cylinder. This required compressing the distal ends of the wires from a relaxed diameter of 7.0 cm to a diameter of 2.5 cm. To retain the anchor in the fully compressed position, a spring-loaded detent in the cylinder pressed into the groove of the piston. The anchors were ejected by electrically actuated pressure cartridges (350 mg load; manufactured by Holex, Hollister, CA) screwed into the top of each cylinder. The transmitter was riveted to the attachment plate and secured to the underside of the tag applicator with breakable nylon bolts. The applicator, with attached tag, was suspended from the end of a 5 m long aluminum or fiberglass pole.

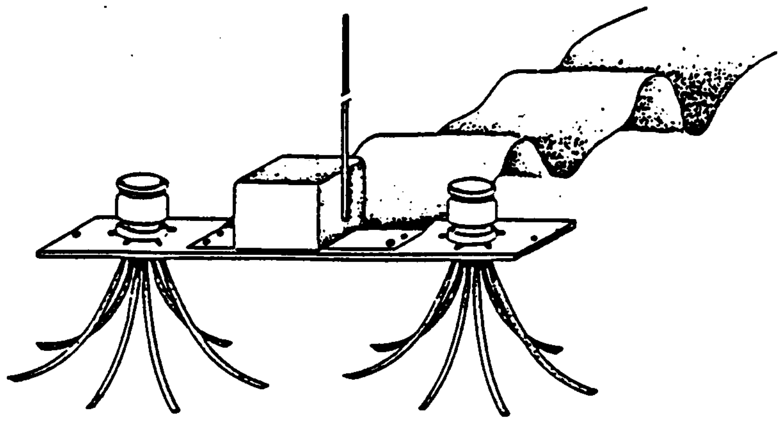


Fig. 2. Umbrella tag showing transmitter (square box) with its antenna, visual identification streamer and two umbrella attachments mounted on a base plate.

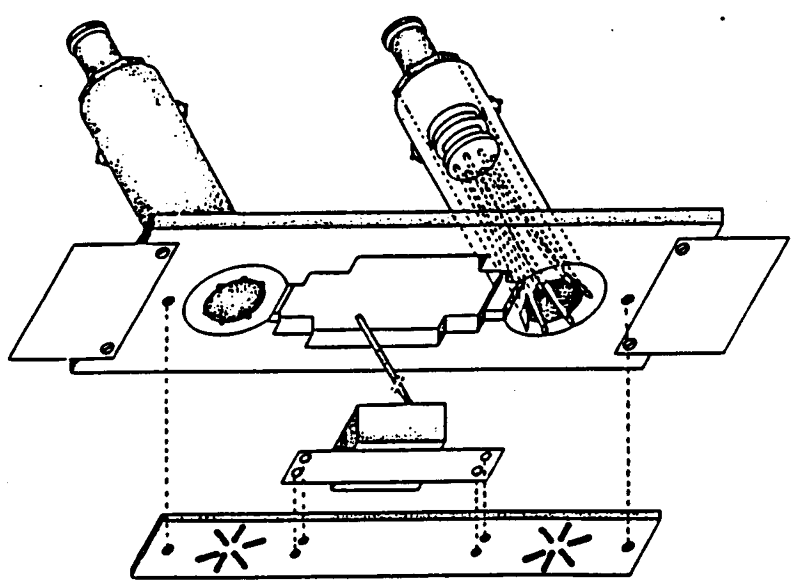


Fig. 3. Tag applicator with cutaway view of 1 umbrella anchor withdrawn and held in a cylinder by a detent. The radio-tag attachment plat is held to the applicator with nylon bolts. The pressure cartridges are screwed into the top of each cylinder and are wired in series with microswitches (not shown) above the tabs placed at each end of the applicator's base.

Two flexible stainless steel tabs were bolted to the ends of the applicator and bent downward so the ends were 0.5 cm below the bottom plane of the applicator. Two microswitches were screwed to the end of the applicator above the tabs so that as the applicator contacted a flat surface, the tabs bent upwards, closing the microswitches. When lowered onto the dorsal surface of a whale the simultaneous closure of the microswitches (wired in series) actuated a solenoid-controlled 12-volt battery to fire the pressure cartridges. The requirement for simultaneous closure of the two microswitches assured that the device was flat on the whale's back when the tag was applied. The two pressure cartridges (Holex #6300) forced the umbrella anchors out of the cylinders of the applicator and the wires into the skin and blubber of the whale. When the pistons hit the attachment plate, the nylon bolts broke to free the tag from the applicator. Preliminary tests were conducted in 1979 on two samples of gray whale skin and blubber taken from dead beach-cast animals.

Barnacle tags used eight curved inconel wires to hold a 7.6-cm diameter circular plate to the surface of the whales. The transmitter was attached to the upper surface of the plate and embedded in a hemisphere of polyurethane resin (Figure 4). A sliding ring held the distal ends of the wires in an 8-cm diameter circle prior to deployment. A truncated helix antenna was attached to the hemisphere of polyurethane. This projectile tag was shot by means of a compound bow at distances up to 8 m. A hollow arrow shaft covered the antenna and fitted into a molded recess at its base.

Two inflatable boats were used to approach whales for tagging. Precautions were taken to assure good tag placement with both techniques. The surfacing and movements of tagged whales in the lagoon were monitored with Telonics TR-2 scanning receivers and by direct observation from inflatable boats and land based camps at Base Camp, Rocky Point and Bronaugh Point (Figure 1). Additional, manual and automated, monitoring occurred from receiving stations at La Jolla, California; Newport, Oregon, Unimak Pass, Alaska; and during aerial surveys in a Cessna 182 airplane. The plane was equipped with a Telonics TR-2 scanning receiver, two strut-mounted, two-element Yagi antennas, and a Telonics direction finder receiver (DF) using two belly-mounted DF antennas. During 1979, only one aerial survey (in early May) was conducted to locate tagged whales along the Washington, Oregon, and California coasts. During 1980, aerial surveys were flown principally along the Baja shoreline north and occasionally south of San Ignacio Lagoon in the process of supplying the camp and were the only source of whale movement information in Baja outside San Ignacio Lagoon. The four automated scanning receiver sites in 1980 used a volume-activated relay to turn on a tape recorder so the pulse interval of the transmitters could be measured to confirm the identification of each passing whale.

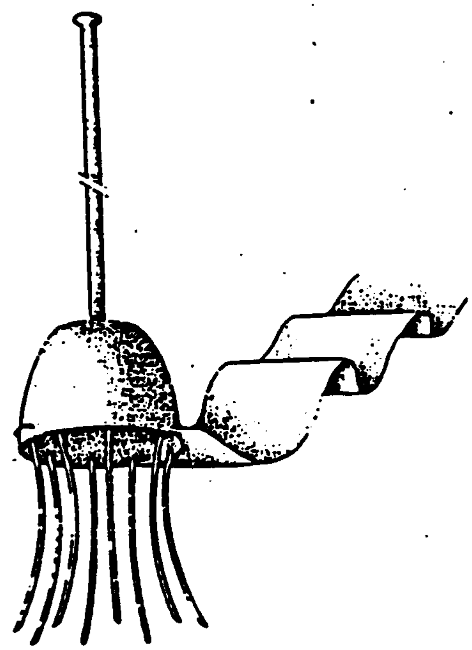


Fig. 4. Barnacle tag with eight metal legs showing hemisphere of resin surrounding transmitter, antenna and visual streamer. The retaining ring is not shown.

Results

The in vitro tests in 1979 revealed that there was an adequate charge to drive the umbrella anchors fully into the blubber layer. Noise from the pressure cartridges was similar to firing a .22 caliber rifle. Each wire of the anchors followed a predescribed arc through a single entry in the whale's skin to avoid tearing the tissue. Lateral penetration was achieved by the beveled distal ends, curvature of each wire, and lateral force exerted by the compressed wires. The wires retained their basic curvature but bent at the piston base, resulting in shallower penetration (6 cm) and more lateral spreading than the unused anchor's configuration. Tags were placed on unrestrained whales 1 - 2 m behind their blowhole along the mid-dorsal line. The coated cable antennas were used in 1979 and on the first 6 whales tagged in 1980. These antennas worked well on single animals. The first 2 tags applied to females with calves in 1980, however, had the antennas broken off within 10 min of tagging. No antenna failures were observed with the more flexible truncated helix antennas.

Deployment

Three (1979) and 11 (1980) umbrella tags were applied to gray whales in the two years: 3 adult females (without calves), 2 adults of unknown sex, and 9 females with calves. Whales did not react visibly to tagging with umbrella tags; instead, they continued their inquisitive behavior as before tagging. Only one whale was tagged that did not exhibit inquisitive behavior. This female was sleeping at the surface with her calf nearby and was tagged during a quick approach. She awoke as the tag was attached and reacted with a vigorous fluke slap and rapid swimming. The calf was able to keep up with its mother and both were observed swimming slowly in the lagoon the next day.

Some difference was noted in the pressure needed to fully attach umbrella tags to adults with calves in comparison to those without calves. The pressure provided by a 350 mg Holex pressure cartridge provided complete attachment on several adults without calves but was insufficient for at least 8 of 9 adults with calves. Females with calves may use up enough of their lipid reserves in the blubber layer during the development of a fetus and subsequent lactation to make the blubber a more compact layer of connective tissue and hence more resistant to penetration. The 1980 production of attachments were also made with slightly less arc to the individual umbrella "wires" than those made for the 1979 experiment.

A barnacle tag was applied to each of 4 females with calves during 1980. Two of the barnacle tags hit the water before reaching the whales, did not fully deploy and came off almost immediately. The other two barnacle tags attached fully. The very low angle from which barnacle tags were applied resulted in a dorsolateral placement and a poor antenna angle. Vertical antenna orientation is preferred for the best signal output and is possible with a mid-dorsal placement if barnacle tags are applied from a higher vantage point, such as from the bow of a larger vessel.

Transmitter Performance

Transmitters could be heard on a line-of-sight basis which limited their usefulness to 9.5 km for observers onshore at sea-level or out in a boat on the lagoon. The range from the plane was up to 105 km from 1800 m altitude. The ADF was useful only to distances of 4 km from shore when used with an Adcock antenna on a 5 m mast.

Retention

On 4 adults without calves, umbrella tags remained attached with operative transmitters for at least 6, 40, 50 and 94 days. The latter animal was seen 810 days after tagging with the tag still attached. Incompletely attached umbrella tags remained attached on 4 females with calves for at least 2, 12.5, 18 and 20 days. Barnacle tags remained attached for at least 20 days.

Whales tagged in 1980 were observed and remained approachable as long as they were in the lagoon (up to 20 days after tagging). One whale lost its tag after 11 days of continuous tracking. Close inspection of this animal within 5 hours after tag loss revealed no lacerations, but slight swelling was observed in the area of the lost tag. The tag was seen 24 hours before it was lost and appeared as secure as on the day it was attached. It is likely that incomplete deployment of the anchors and constant physical contact of the calf against the female were responsible for the loss of the tag. One whale, photographed one year after tag loss, had two small "rosettes" each composed of 6 white dots where the wires had originally penetrated. This was the only visible sign of having been tagged (Swartz, pers. comm.).

Dive Duration

Ten whales stayed in the lagoon long enough to provide dive duration data from which dive patterns were also analyzed (Harvey and Mate, 1984). In total, 303.7 hours of whale diving which encompassed 11,080 dives in San Ignacio Lagoon were monitored. The mean duration of dives varied between whales from 0.96 to 2.58 min. The overall mean was 1.57 +/- 0.02 min. Ninety-nine percent (99%) of all dives were less than 6 min and 49% of all dives were less than 1 min long (Figure 5). The longest dive was 25.9 min.

All dives longer than 12 min in the lagoon were associated with resting animals, typified by a whale floating at or slightly below the water surface for periods of up to 51.6 min and then submerging for 12 to 26 min. These dives and surface durations were 2 to 250 times longer than those recorded for active whales in the lagoon and were not similar to patterns of traveling animals. Wyrick (1954) and Evans (1974) reported maximum dive durations for migrating gray whales of 12 and 16.5 min respectively.

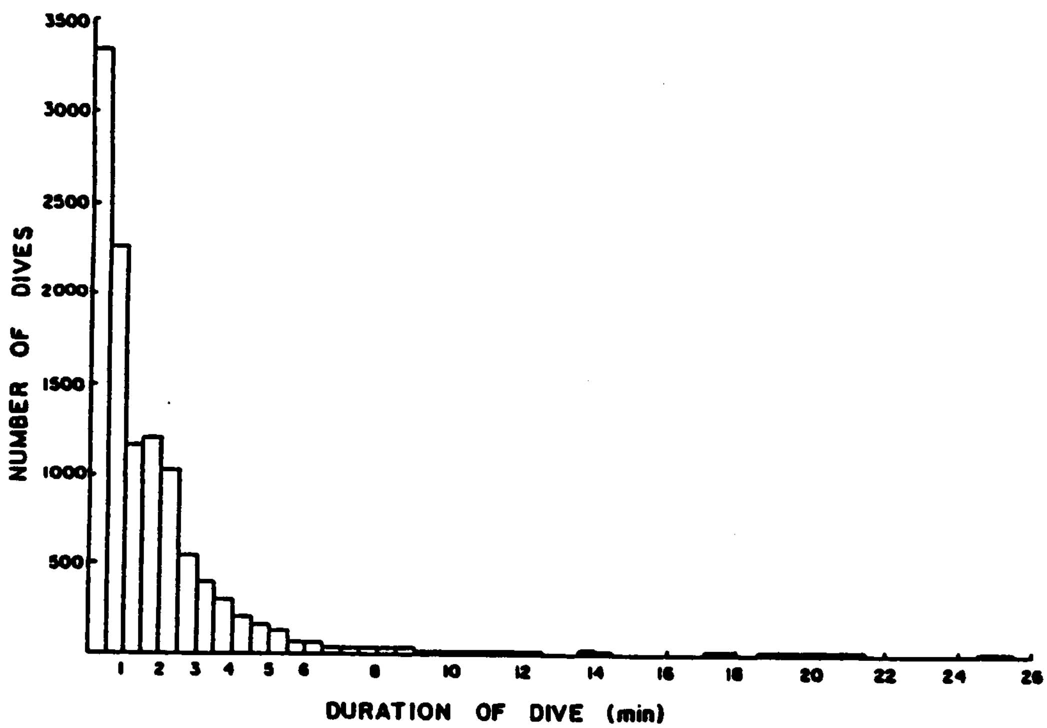


Fig. 5. The frequency of distribution of 11,080 dive durations from 10 different radio-tagged whales monitored for 303.7 hr in San Ignacio Lagoon. The mean is 1.57 ± 0.02 (SE) min.

Over half of the monitored dive data in the lagoon was taken from a female with a calf (designated 100R) which was monitored for 154.3 hours and had a mean dive duration of 1.51 +/- 0.02 min. An analysis of the diving patterns for 100R revealed variations in the daily mean dive duration from 1.14 to 1.66 min

(Table 1). Although no changes in whale behavior were apparent, it is interesting to note that the daily mean dive duration for Whale 100R was lowest on the day of tagging ($\bar{x}$ = 1.14).

Table 1. Summary of Dive Data Collected from Whale 100R.

Date	Time monitored (hr)	Total surface time (hr)	Total dive duration (hr)	n	Mean dive duration (min)	Time at surface (%)
Mar. 19	2.26	0.06	2.21	94	1.14	2.7
Mar. 20	9.56	0.35	9.21	349	1.58	3.7
Mar. 23	14.7	0.77	13.93	529	1.58	5.2
Mar. 24	12.3	0.36	11.99	457	1.57	2.9
Mar. 25	15.45	1.38	14.07	509	1.66	8.9
Mar. 26	16.00	0.92	15.08	657	1.38	5.8
Mar. 27	20.38	0.96	19.42	778	1.50	4.7
Mar. 28	16.49	0.84	15.65	675	1.39	5.1
Mar. 29	14.30	0.31	13.99	527	1.59	2.2
Mar. 30	13.79	0.56	13.23	536	1.48	4.1
Mar. 31	12.01	0.64	11.37	469	1.45	5.3
	147.3*	7.15	140.15	5580	1.51	4.9

*Does not include 7 hr of data collected during periods of less than 10 min duration.

The mean duration of time spent at the surface was 4.4 s +/- 0.6. The mean rate of surfacing for tagged whales was 35.6 +/- 0.8 surfacings per hour and varied from 19.4 to 62.5 surfacings per hour for individual animals. There were significantly more surfacings during the day ($\bar{x}$ = 37.1 +/- 1.3) than at night ($\bar{x}$ = 30.3 +/- 1.5 surfacings per hour). Norris et al. (1977) recorded a breathing rate of 50 breaths per hour for one female gray whale with a calf in Baja de Magdalena. The mean dive duration of a single whale was generally longer than that of females with calves. Calves surfaced twice as frequently as adults during the first several weeks after birth.

There was, however, no significant variation in the mean surfacing rate between morning, midday and afternoon (weighted ANOVA, P > .05). The longest continuous surfacing was 51.62 min by a female without a calf resting at the surface. While the percentage of time spent at the surface varied from 1.5 to 16.3 percent, overall tagged whales spent 4.5 percent of their time at the surface.

The combination of surfacing rates and time spent at the surface may be useful for other investigators in developing sighting correction factors for aerial- and shore-based surveys. While factors such as weather, elevation, speed of the sighting platform and behavior affect whale sightings, surfacing to breathe is the most important sighting cue in virtually all surveys.

The surfacing rates of tagged whales were generally consistent throughout the day. Lower surfacing rates (15 to 20 per hour) were associated with resting animals and not with animals actively diving for long times. Swartz and Jones (1980) have reported a midday reduction in whale activity near the mouth of San Ignacio Lagoon. This change in observed whale activity may have been a change in the use of that area of the lagoon during that time of day.

Dive durations, surface durations and surfacing rates could be combined frequently to provide behavioral information. For instance, long dive durations, extremely long surface durations and low surfacing rates were observed for whales resting at the surface. Whale 80Y, which had the longest average dive duration (2.58 min) and the lowest surfacing rate (16.6 surfacings per hour), was found to be resting 7 of the 20 hours that the whale was monitored. Surfacing patterns for other whales indicated rest periods up to 4 hours duration. Short average dive and surface durations and high surfacings rates were indicative of directed swimming. Whale 50B swam at a moderate speed (4 km per hour) for 2 of 7 hours monitored, with an average dive duration of 0.96 min and a surfacing rate of 59.3 surfacings per hour.

Dive Patterns

Idealized diving and surfacing patterns were modeled for each of three discernible patterns as a first order Markov process; using transition matrices Harvey and Mate, 1984). The three patterns used were: 1) "regular-long," regularly spaced dives greater than 1 min in duration; 2) "regular-short," regularly spaced dives less than 1 min in duration; and 3) "clumped or clustered," a dive greater than 1 min in duration followed by 2 to 6 shorter dives of less than 1 min each (Figure 6). An additional category termed "irregular or unpatterned" was established as a catchall category for dives that did not fit the criteria of the 3 defined patterns. The dive pattern data were summarized from a series of 7 dives at a time. The computer program calculated the probability that an observed series of dives fit a particular pattern by comparing the series of 7 dives with the modeled idealized dive patterns.

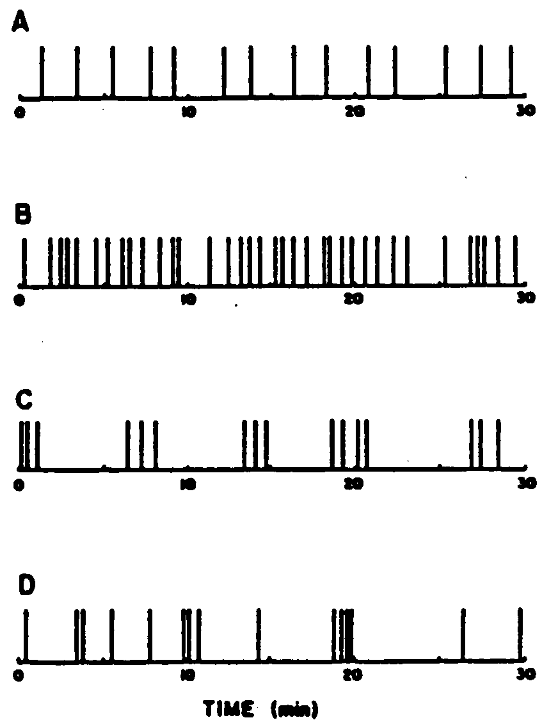


Fig. 6. Examples of three dive patterns (from Whale 100R) which are typical of gray whales in San Ignacio Lagoon. (A) Regular-long, (B) regular-short, (C) clumped. The irregular or unpatterned dive series is shown in (D). Each vertical line represents a series of signals received when a whale surfaced

The results of an analysis of surfacing patterns for 2 whales (100R and 120R) is shown in Table 2. A 30.07 hour subset of data for whale 100R revealed that the whale surfaced 1108 times; 45% of the time (42% of the surfacings) the surfacings were irregular. The "clumped" pattern was most frequently observed for whale 100R and represented 29% (321) of the surfacings and 29% (8.72 hours) of the total time. The "regular-long" pattern was the second most common pattern occurring 22% (6.62 hours) of the time in representing 19% (211) of the surfacings. The "regular-short" pattern occurred only 4% of the time (1.20 hours) or 111 dives.

Table 2. Amount of time and number of surfacings for specific surfacing patterns from two radio-tagged gray whales in San Ignacio Lagoon.

	Surfacing patterns				
	Clumped	Regular–Long	Regular–Short	Unpatterned	Total
Whale 100R					
Time in hr*	8.72	6.62	1.20	13.53	30.07*
Surfacings**	321	211	111	465	1108**
Whale 120R					
Time in hr*	7.94	8.34	1.59	21.85	39.72*
Surfacings**	368	284	134	869	1655**

*The total time and number of surfacings for each whale is in parentheses.
*Significant difference ($\chi^2 = 31.43$, $p < .05$).
**Not significant ($p > .05$).

Whale 120R surfaced 1655 times during the 39.72 hours of analyzed surface patterns; 46% of these surfacings were in the irregular pattern. The "regular-long" pattern of surfacings was recorded 21% (8.34 hours) of the time and the "clump" pattern occurred 20% of the time (7.94 hours). As with whale 100R, "regular-short" surfacing patterns were only observed 4% of the time (1.59 hours). There was a significant difference between whales for the amount of time spent in each pattern ($x^2 = 31.43$, $P < .05$), but no significant difference was found for the number of surfacings in each pattern ($P > .05$).

Movements

In and Out of San Ignacio Lagoon:

All whales remained in the lagoon for at least one day. The single animals (those without calves) were all tagged in early February and stayed in the lagoon 2 days or less each. However, signals were heard from each of those animals along the Pacific Coast for 7, 40 and 50 days after tagging.

It is not remarkable that single whales stayed in the lagoon shorter periods of time than many females with calves, because the single whales were tagged late in their lagoon season and most single animals had already left the lagoon. Single whales start migrating north before females with calves. Many of the females with calves were tagged late in the cow/calf season (early to mid-April) and also stayed short periods of time. Of the 7 females with calves, only 3 were monitored inside the lagoon longer than 2 days (4, 5 and 11 days). The female with calf which was monitored for 11 days was an animal that was first seen within the lagoon one month prior to tagging and was last seen in the lagoon 19 days after tagging. Movements in and out of the lagoon by females with calves were reasonably common, such as whale 100R which in 11 days moved out of the lagoon and returned on 7 different occasions. With only one exception, movement out of the lagoon was during twilight or at night while movement into the lagoon, with only one exception, was done during full daylight. Two females with calves which were monitored for 2 and 5 days also left the lagoon and returned on 2 separate occasions each. While it is not known why females with calves leave the lagoon during the night and return, it is known that a modest shrimp fishery was conducted offshore from San Ignacio as a night fishery up until 1975 when the shrimp population was too small for harvest. Whales did not merely drift in and out of the lagoon with tidal movements: 40% of all movements were against the tide.

Outside Lagoon:

The longest movement recorded was over a period of 94 days by a single adult (100W) tagged on 27 February 1979 (Figure 7). Signals from this animal were subsequently received at the La Jolla receiver site 43 days after tagging, off Oregon by either aircraft or land-based receivers 61, 62 and 63 days after tagging, and at Unimak Pass, Alaska, 94 days after tagging (Table 3). This animal had traveled at least 6680 km from the tagging site. The transmitter and colored streamer of this animal was resighted by five researchers aboard a University of California research vessel 27 months after tagging (Mate and Harvey, 1984).

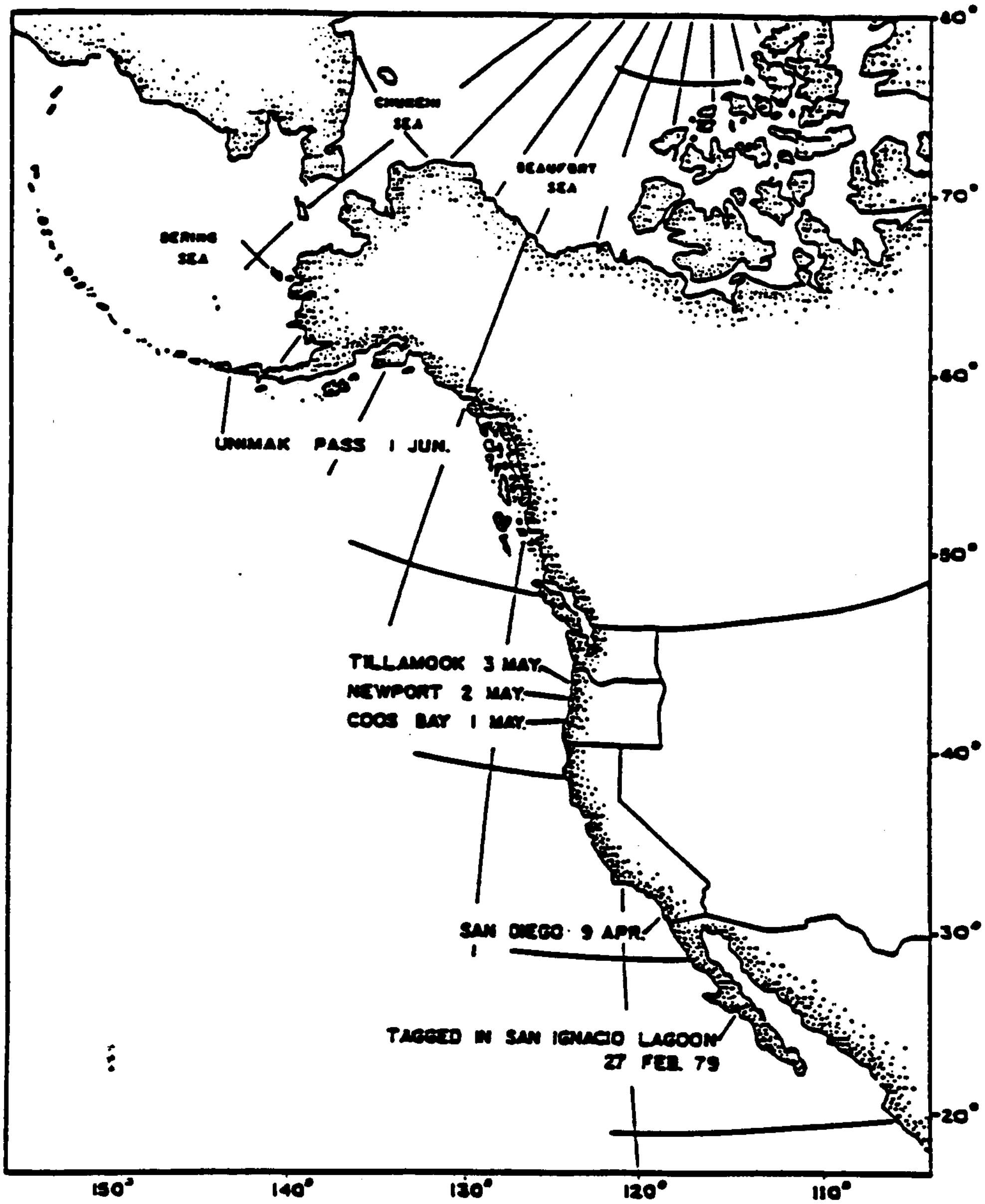


Fig. 7. Locations and dates of signal receptions from a radio tag attached to an adult gray whale (100W) during the northward migration of 1979.

Table 3. Date, location, minimum distance traveled from previous location, time from previous reception, calculated average speed between locations and number of days after tagging for Whale 100W.

Date	Location	Minimum distance (km)	Time (days)	Average speed between locations (km/day)	Number of days after tagging
February 27	San Ignacio Lagoon (26.8°N)	—	Date of tagging	—	—
March 14	San Ignacio Lagoon (26.8°N)	—	Last signals received in the lagoon	—	15
April 9	San Diego, California (32.5°N)[a]	880	Departure date from lagoon unknown	>33	41
May 1	Coos Bay, Oregon (43.2°N)	1870	22	85	63
May 2	Newport, Oregon (44.4°N)	130	1.3	100	64
May 3	Tillamook, Oregon (45.3°N)	100	1	100	65
June 6	Unimak Pass, Alaska (54.3°N)	3700	29	127.6	94
	Total distance traveled	6680			

[a]Data from 1979.

In 1980, four female gray whales with calves (50F, 80R, 160R, 50B) and 3 single adults (50Y, 80Y, 160Y) were located a total of 16 times after they had left San Ignacio Lagoon (Figure 8). One single female (80Y) was located 24 days after tagging near Magdalena Bay (192 km south of the lagoon). Ten days later the same animal was located more than 500 km to the north of San Ignacio Lagoon. Two tagged females with calves were located in the vicinity of Ojo de Liebre Lagoon, one on 2 consecutive days. The observations of whales moving both north and south to adjacent breeding and calving areas suggest that movement among lagoons may be common and challenge the hypothesis that each lagoon may represent a reproductively isolated stock.

The longest radio tracks of whale movements in 1980 were for whales without calves (Table 4). Tags may stay attached longer on single whales than on females with calves. For example, females with calves may have a higher risk of tag loss as a result of less complete initial attachment and the large amount of physical contact between mother and young. However, as single whales were tagged earlier in the season and aerial surveys terminated before most females with calves had moved north of San Francisco, the shorter tracks of females with calves may merely reflect a bias in efforts to locate tagged whales.

Table 4. The dates of ocean relocations, minimum distances between locations and minimum average daily swimming speed for radio-tagged whales.

Whale I.D.	Dates observed in 1980	Distance (km) from prior sighting	Days between sightings	Minimum speed (km/day)
80Y (single)	Feb. 11	Tagged		
	Mar. 6	192 south	24	
	Mar. 16	706	10	70.6
	Mar. 22	176	6	29.3
		1074	40	$\bar{X}$ = 26.9
50Y (single)	Feb. 8	Tagged		
	Feb. 14	208	6	34.7
		208	6	
160Y (single)	Feb. 11	Tagged		
	Feb. 14	208	3	69.3
	Apr. 1	1342	47	28.6
		1550	50	$\bar{X}$ = 31.0
50R (female/calf)	Mar. 18	Tagged		
	Apr. 5	310	18	17.2
		310	18	
160R (female/calf)	Apr. 11	Tagged		
	Apr. 23	395	12	32.9
	Apr. 27	272	4	68
	Mar. 1	383	4	95.8
		1050	20	$\bar{X}$ = 52.5
80R (female/calf)	Apr. 14	Tagged		
	Apr. 23	144	8	18
	Apr. 24	0	1	0
	Apr. 27	226	3	75.3
		370	13	$\bar{X}$ = 28.5
50B (female/calf)	Apr. 11	Tagged		
	Apr. 14	184	3	61.3
	Apr. 23	128	9	9.0
	Apr. 24	0	1	0
	Apr. 27	280	3	93.3
		592	16	$\bar{X}$ = 37.0

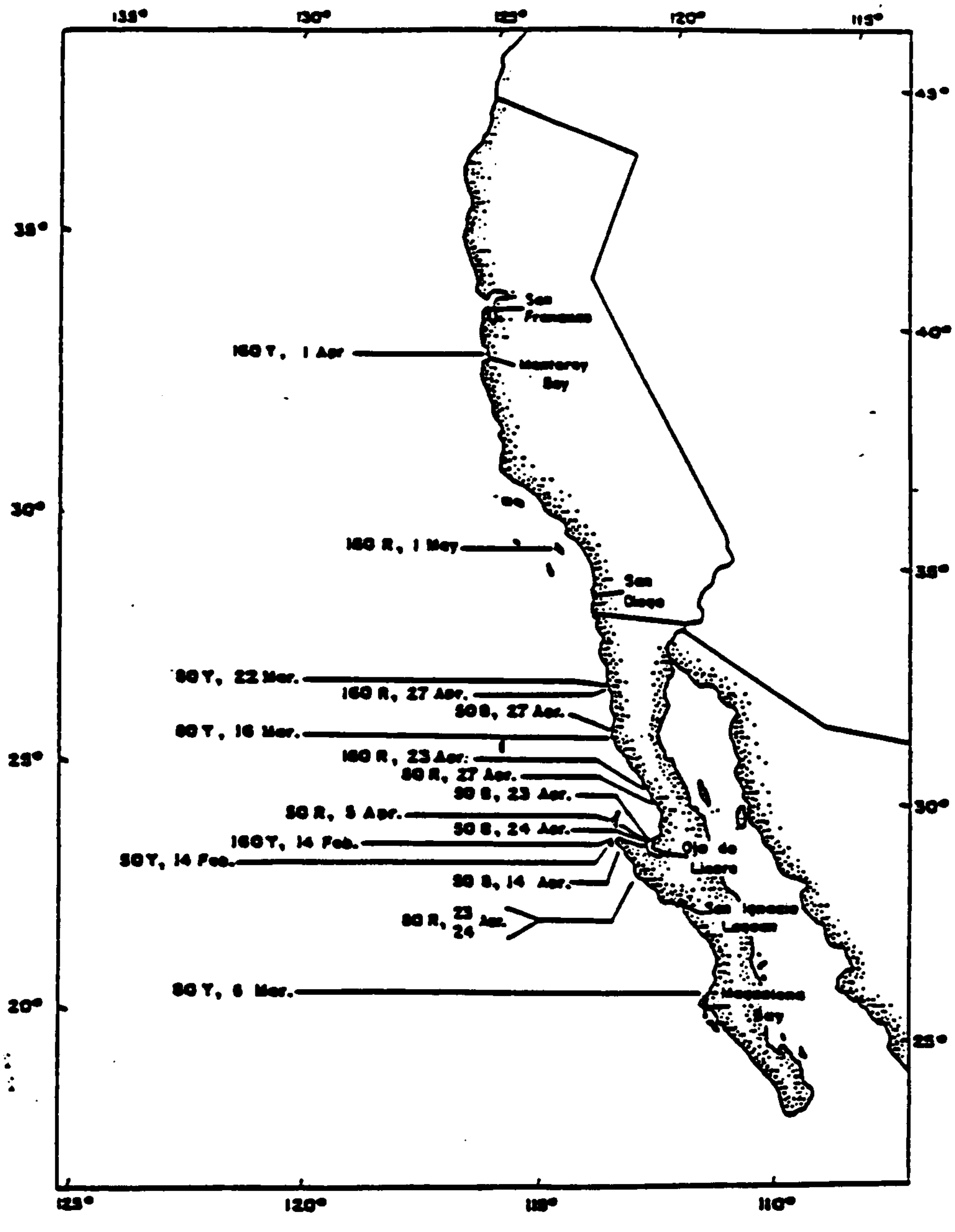


Fig. 8. Ocean locations of gray whales tagged in San Ignacio Lagoon in 1980. The whale identification is followed by the date of signal reception.

During an aerial survey in late April 1980, one radio-tagged whale was relocated near El Rosario along the northern Baja coast, where 60 other adults (most with calves) were found. These animals were consistently surfacing with mud streaming from their mouths, apparently feeding 0.2 - 1.2 km offshore.

Swimming Speeds

Whales tagged in 1980 traveled 208 - 1550 km in 6 - 50 days (Figure 8). Minimum average swimming speeds, calculated for the shortest route between sightings, revealed considerable variability (Table 4). Estimated speeds were generally higher for animals relocated after shorter periods of time. Longer intervals may include periods of wandering, resting, and feeding as well as directed travel, resulting in lower estimated swimming rates. Three of 4 females with calves had higher rates of travel (up to 96 km/day) than did single adult whales. Pike (1962) estimated an average northward speed of 91 km/day for gray whales, in northern waters, whereas Leatherwood (1974) estimated average speeds of 67 km/day off southern California. The single adult whale (100W) from this study, which was relocated 5 times in 1979, averaged at least 33 km/day between San Ignacio Lagoon and San Diego; 81 km/day from San Diego, California to Coos Bay, Oregon (close to Leatherwood's estimated speed off San Diego); 100 km/day on 2 consecutive days of travel along the Oregon coast (close to Pike's estimated speed off British Columbia); and 127 km/day for the subsequent 29 days of transit between Oregon and Unimak Pass, Alaska (Table 3). Although several days of high average daily speed were observed in Baja during 1980, the overall average was 31.4 km/whale-day. Slower speeds in Mexico and southern California may be due to activities such as mating and suckling, more common to the southern portion of the gray whale's range. Single whales appear to increase their rate of travel when they are north of these areas, and they perhaps swim at a more consistent rate as well.

These estimated rates of travel for individual whales can be compared to estimates for the bulk of the population by comparing the time at which maximum numbers of whales pass various locations in California, Oregon, and Alaska (Figure 9). If the maximum passage rate occurring at each location is the result of a migratory "wave" of animals, then the estimated speed of the group is also an estimate of individual swimming speeds (Herzing and Mate, 1984). The "wave" averaged 65 km/day between the central California and central Oregon coasts and 92 km/day from Oregon to Unimak Pass, Alaska (Mate and Harvey, 1984). These figures compare favorably to the swimming speed estimates for the single radio-tagged whale tracked northward in 1979, supporting the idea that there is a somewhat cohesive migratory wave. Note that the 1979 animal was among the last single animals to leave San Ignacio Lagoon (still there March 14) and continued to be later than most other single whales in migrating north. The timing of peak numbers of whales passing study sites during the southbound migration is included in Figure 9, and supports Pike's (1962) contention that gray whales move faster during the southbound migration (approximately 125 km/day from Unimak Pass, Alaska to Monterey, California) than when they migrate north (approximately 88 km/day from Piedras Blancas to Unimak Pass in 1981).

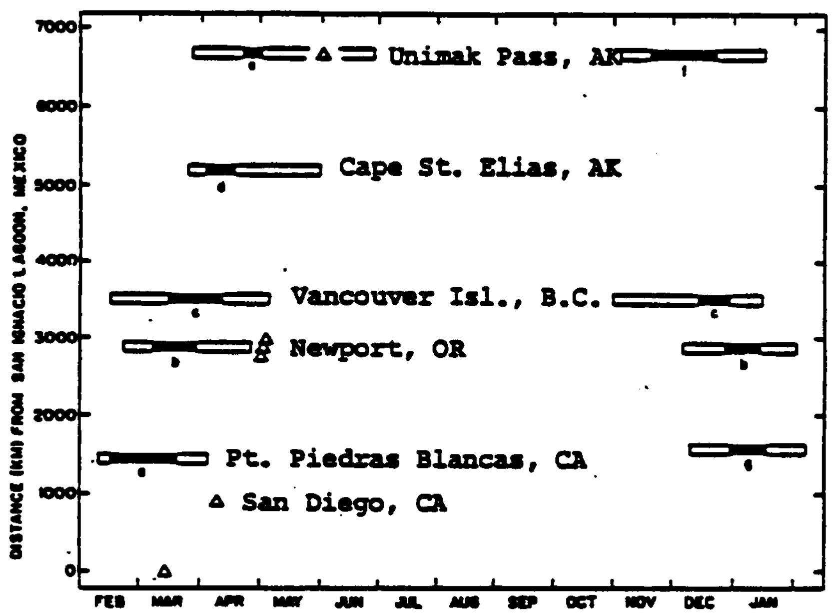


Fig. 9. Times of northward and southward migrations of gray whales along western North America (open rectangle) with solid rectangle indicating period of peak passage rates: (A and G) Poole, 1984: (B) Herzing and Mate, 1984: (C) Darling, 1984: (D) Cunningham, unpub. m.s. (E) P. Hessing, pers. comm.: (F) Reilly, 1984; Rugh, 1984: and northward movements of one whale radio tagged in 1974 (triangle).

Discussion of Shore-based and Aerial Survey Strategies for Radio-tagged Whales

Broad-spectrum RF emissions created by relay closures and large electric motors provided sufficient signal strength to occasionally turn on the automated shore-based recorders. While it was possible to sort false signals from real whale transmissions, it was time consuming.

Monitoring in the lagoon was quite effective. Data were acquired on 303.7 hours of the 520 hours monitored. However, shore-based monitoring stations along the migration route were not as successful. Figure 10 illustrates some of the difficulties associated with shore-based reception. Whales must be moving close enough to shore to be within reception range as they pass the receiver in order to be heard. Whales closer to shore have a high probability of surfacing while they're within receiver range. Animals moving offshore, beyond receiver range, are obviously missed. There is now good documentation that gray whales move through the Channel Islands and even farther offshore, so the receiver north of San Diego did not have sufficient range to monitor all whales passing north.

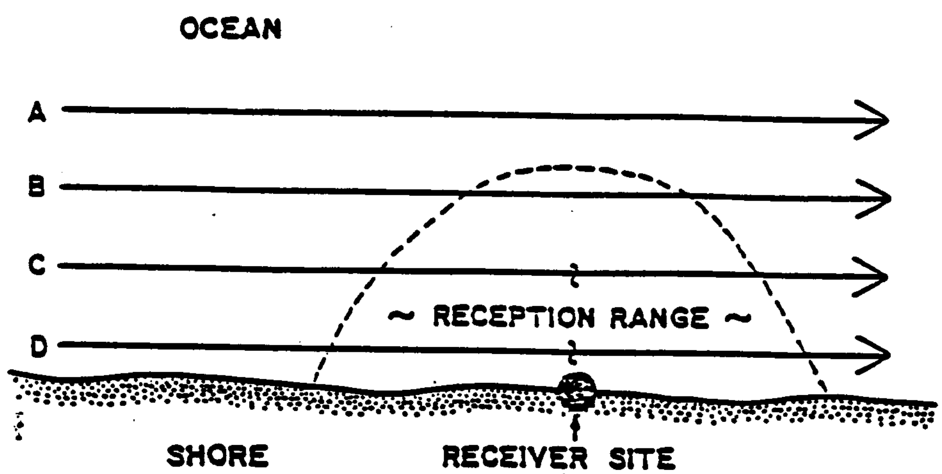
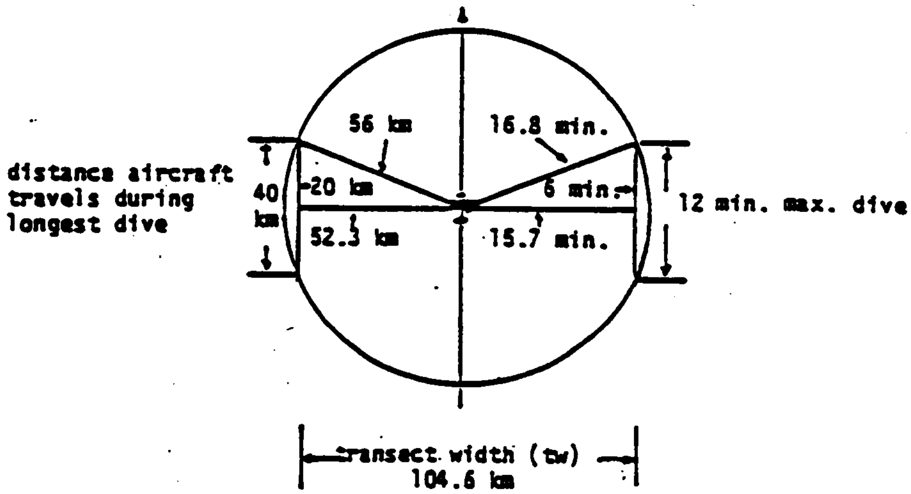


Fig. 10. An example of a land-based recovery with a fixed reception range, and tagged whales (A, B, C and D) traveling at various distances parallel to shore.

Even the most simplistic view of aerial surveying greatly complicates the issue of receiving signals from radio-tagged whales along the aircraft's trackline. The probability of receiving signals from a whale varies with the height of the aircraft, effective range of the antennas, duration of whale dives, speed of the aircraft and distance of the whale from the aircraft trackline (Mate and Harvey, 1981). Figure 11 depicts an aircraft traveling 200 km per hour searching for tagged whales which might dive for a maximum time of 12 min. With an idealized circular reception range of 56 km (a height-dependent variable), the effective transect width of the aircraft can be calculated. During a 12 minute whale dive the aircraft will travel 40 km, so a whale in the portion of the reception range which does not stay in view for at least 40 min (>52.3 km from the aircraft's ground track) may be missed. Merely changing the duration of the maximum dive to 24 min reduces the effective track width from 104.6 km to 78.2 km. A formula for the generalized example is shown at the bottom of Figure 11. In reality, of course, reception ranges are rarely circular. Reception range depends upon the antenna's sensitivity pattern and the height of the aircraft. Measuring the directional sensitivity of an antenna is rarely done well enough to accurately predict an effective track width. In practice, aircraft usually perform aerial surveys to locate radio tags at high altitudes to maximize the reception range, making it difficult to combine this mission with visual survey activities.

It became apparent during the course of the lagoon field season that scanning was not a satisfactory method of monitoring multiple whale transmitters when each was at the surface an average of only 4.5% of the time. Scanning multiple frequencies reduces the probability of receiving a signal even when a whale is within range. Even if the time spent monitoring each frequency is short, whale surfacings are so brief that there is a great chance of missing signals from radio tags if each frequency is not monitored full time. When scanning, the proportion of time spent on each frequency also describes the probability of hearing a transmission on that frequency (i.e. if 20% of listening time is spent on one frequency, the chance of hearing all signals on that frequency is only 20%). These problems are further compounded by the fact that VHF transmissions are pulsed and at least 2 pulses must be heard to confirm the source is a radio tag and get directional information. It is recommended that multiple transmitter frequencies not be used unless there are independent receivers for each frequency. It would be preferable to have all transmitters on the same frequency and discern different transmitters from each other with either frequency modulation or differences in the pulse rates.



$$tw = \left(\sqrt{(\text{reception range})^2 - [(\frac{\text{max. dive time}}{2})(\text{airspeed})]^2}\right)(2)$$

Fig. 11. Calculation of aerial transect width for a hypothetical circular reception range of 56 km radius and airspeed of 200 km/hr for whales with a maximum dive time of 12 minutes.

In most cases, it is more time and cost efficient to intensively collect data on a single whale than to keep track of several whales. Once contact with a whale has been broken, it gets increasingly difficult to relocate it. It can be particularly difficult to relocate whales in pelagic circumstances. The product of the whale's swimming speed and the amount of time since it was last located describe the radius (r) of a circular search area which gets dramatically larger (πr^2) as time goes by. For example, after one day a whale traveling at 100 km/day might be anywhere within a 31,400 km^2 circle if its direction of travel is unknown. After 4 days the same whale might be located anywhere within a 502,400 km^2 circle. An aircraft flying at an altitude necessary for a reception range of 50 km, searching for a whale with a 12 minute maximum dive and traveling at a speed of 200 km/hr can cover 10,000 km^2 per hour and would take 3.1 hr and 50.2 hr to fly the respective search areas.

HUMPBACK WHALES: 1981 AND 1982

During 1981 and 1982 this project's principal goal was to find another situation and species where the subdermal attachments and VHF radio tag could be tested before making commitments to tag bowhead whales and develop satellite-monitored radio tags. The interest in collecting diving and surfacing data from other species was primarily to assess the feasibility of locating whales by satellite.

Humpback whales in Newfoundland were chosen because : 1) the species inhabit and pass through offshore oil and gas lease areas; 2) they routinely become entangled in Newfoundland fishermen's nets, making close access for pole-deployment possible; and 3) Newfoundland experts in the release of entrapped whales (Jon Lien and Peter Beamish) were willing to assist the project.

Materials and Methods

The radio tags and techniques for tagging were identical to those used for gray whales.

Results

Although most entrapments usually occur in June and July, a trip was made to Newfoundland in September 1981 to reconnoiter the area and VHF tag whales if opportunities arose. No entrapments occurred, but for 10 days typical humpback feeding areas were observed and approximately 50 close approaches to free-swimming whales were made. Humpbacks often surfaced 6 to 10 times to breathe before diving for 4 to 5 min. Often whales were approached quickly to within 15 to 20 m before they dove for a long dive. Whales which were preoccupied with feeding were easier to approach as were larger groups of whales. Whales not preoccupied were approached as close as 4 m.

In 1982, while working with Memorial University of Newfoundland (MUN) professor Jon Lien, an entrapped humpback was tagged with an umbrella-type VHF tag. The animal showed no overt reaction to tagging and when released swam away from shore quickly. Both Lien and Beamish felt this was a typical reaction for released whales. The tag deployed properly and appeared well attached, but there was no capability to monitor it offshore so its longevity is unknown. However, the main purpose for attaching a VHF tag was to assure that the entrapment release process was compatible with tagging efforts.

PART II:

SATELLITE-LINKED WHALE TELEMETRY & TRACKING

Introduction to the Argos Satellite System

The Argos system is capable of locating specialized transmitters anywhere in the world. The system is composed of three basic units: transmitters, satellite-based receivers and ground processing services.

A transmitter for the Argos system is called a platform transmitter terminal (PTT). A PTT transmits on an ultra-high frequency (UHF) of 401.650 MHz. The transmitters are required to emit one watt of radiated power and be frequency stable. This stability is necessary because PTT locations are calculated from Doppler shifts (the change in apparent frequency as a result of movement of the satellite receiver past the stationary transmitter) and instability would result in location errors. Each PTT transmits a discrete identification code followed by up to 256 bits of data. Transmissions can vary from 320 to 980 msec duration according to how much encoded data are sent. Transmissions must be spaced at least 40 s apart to prevent system saturation.

Four Argos receivers are onboard each NOAA, TIROS-N series weather satellite. These are principally weather satellites in sun synchronous, polar orbits at elevations of 830 to 870 km above the earth. A complete orbit lasts 101 min. Two satellites are kept active and have orbital planes 75° from one another to assure coverage at different times of the day (Figure 12). Coverage of a specific geographic area on earth is accomplished at the same local solar time daily. The satellites cross over both poles on every orbit and change their equator crossing by 25°W (approximately 2800 km) on each successive orbit. Argos receivers receive PTT messages within a range of 2,500 km of the satellite's ground path. Thus, the full width of a satellite's coverage is 5,000 km (note the circles along the ground path in Figure 12) and there is approximately a 40% overlap in reception range of orbits even at the equator with much greater overlap at higher latitudes and complete coverage of areas above 75° latitude on every orbit. From a fixed point on the earth, satellites go from horizon to horizon and are available to receive signals for 8 to 15 min. PTT information received by the satellites is returned to earth two ways: 1) data are stored and then retransmitted when the satellite passes over one of three ground telemetry stations (Lannion, France; Wallops Island, Virginia; or Gilmore Creek, Alaska. See Figure 13); and 2) the satellite immediately retransmits received data along with the reception time and Doppler data on a VHF frequency, which can be monitored by a local user terminal (LUT). A LUT is a specialized receiver for Argos down-link data which can be located virtually anywhere and is capable of calculating locations of PTT's from 3 or more messages. Greater accuracy is achieved with more messages. The information received from the ground stations in the U.S. was sent to the NASA "concentrator" facility at Suitland, Maryland, then transmitted via satellite to the Service Argos Center in Toulouse, France until 1987. Since 1987, the data from North America have gone to the new Argos Data Processing Center in Suitland. Locations were calculated at Service Argos when 5 or more messages were received during a single orbit prior to 1987. Since then, special processing from as few as 3 messages has been possible and will soon be available as a standard product. Location and encoded sensor data are made available to investigators with approximately a 3-6 hour delay by Service Argos via computer modem links, telex, or mailed computer tapes and printouts. Most of the delay is due to the satellite storing data until it passes over a down-link ground station.

Feasibility Assessment of Locating Whales Through Argos

The Argos criteria of 5 messages/orbit for location determinations was more stringent than LUT requirements and stipulated that the first and last messages had to be at least 420 s apart. These criteria were changed to 3 messages in 1987 (with reduced accuracy) and will be offered on an experimental basis with 2 messages in 1988 at additional cost. An analysis of the diving and surfacing patterns of whales was necessary to determine if Argos locations could be achieved. Analyses were made of data collected during this study from radio-tagged gray whales (Mate et al., 1983), radio-tagged humpback whales (Goodyear, unpublished data) and bowhead whales observed from shore or aircraft (unpublished data from D. Rugh, B. Krogman, B. Wursig, M. Fraker, J. Richardson & D. Ljungblad). The results (Mate and Harvey, 1982) have influenced changes in Argos procedures and criteria.

Fig. 12. A map of the earth showing the separation of 75 degrees between orbital planes (dashed lines) of two NOAA TIROS-N satellites. Overlapping circles show the satellite reception range for ARGOS PTT's at 5 minute intervals.

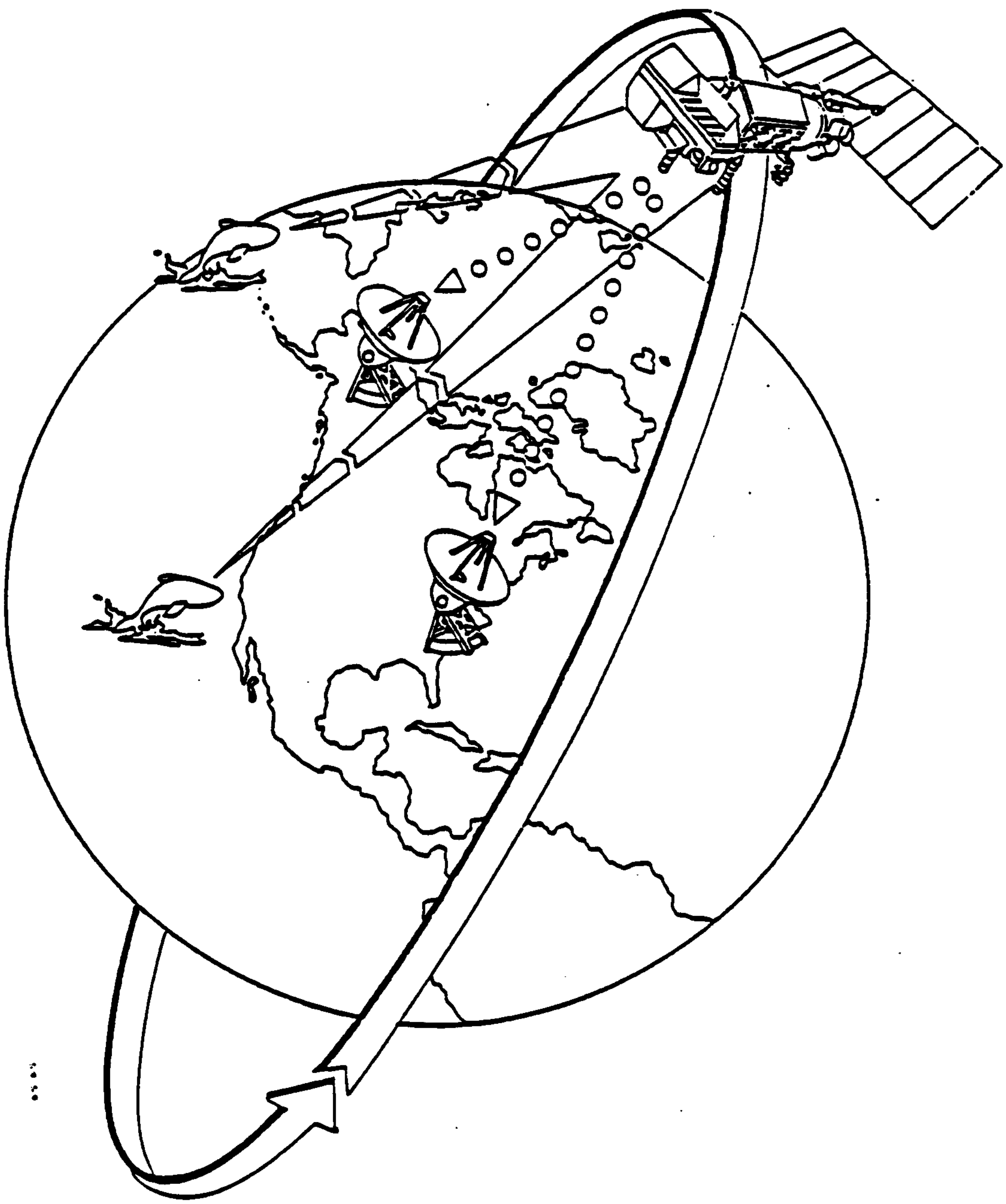


Fig. 13. Representation of a NOAA TIROS-N satellite in polar orbit receiving transmissions from two different whale PTT's and relaying the information to ground stations at Wallops Island, Virginia and Gilmore Creek, Alaska.

Gray whale and humpback whale dive data were analyzed on an individual whale basis because there was enough individual information available. In contrast, Krogman (pers. comm.) analyzed over 16,000 bowhead whale dive segments available over multiple years of NMFS and North Slope Borough shore-based observations at Pt. Barrow and found only 47 dives which could be used with confidence. One of these dives lasted 76 min. Because of the difficulty in collecting bowhead whale data, due to the whale's ability to remain underwater for long periods and travel great distances undetected, the bowhead information was pooled.

The probability of each whale species surfacing sufficiently to result in 5 or more (suitably separated) messages was calculated (Figure 14). These probabilities were applied to the predicted number of daily orbits and their durations at various latitudes to estimate the likely number of whale locations daily over the species' migratory range (Table 5). These analyses predicted that location by satellite was feasible for all three species, but would be most successful with humpback whales. Gray whales would likely be located from 2 times daily in Mexico to 5 times daily in the central Bering Sea. Humpbacks varied from 6 to 9 times daily in their range, while bowheads were estimated at 2 to 3 times each day.

Development of an Argos-linked Transmitter

The Argos system was an outgrowth of the earlier NIMBUS-RAMS system. Both systems were basically developed for telemetry of oceanographic buoys and meteorological balloons. Early attempts were made to use the NIMBUS system to track wildlife, including free-ranging elk (Craighead et al., 1972), polar bear (Kolz et al., 1978), and porpoise (Jennings & Gandy, 1980). Each of these programs was handicapped by transmitters which were large and bulky due primarily to battery requirements. The lack of a temperature-stable oscillator required battery power to heat the transmitter and create a temperature-stable environment. The only tracking success of a fully aquatic marine animal during the NIMBUS-RAMS program was that of Priede (1983) who re-acquired signals intermittently from a basking shark for 17 days. The experiments described in this report include the first and most successful examples of tracking fully aquatic marine mammals by satellite to date.

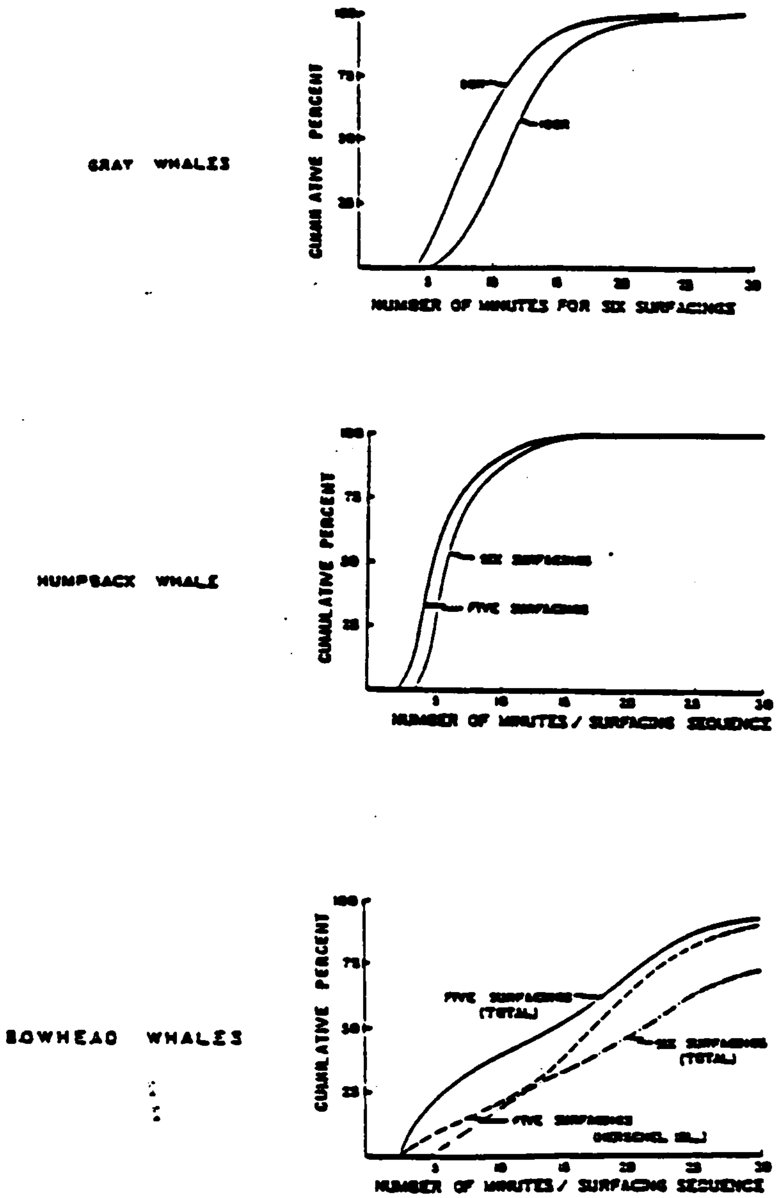


Fig. 14. The probability of five and/or six sequential surfacings separated by at least 45 seconds from one another for gray whales, humpback whales and bowhead whales as calculated from data from Mate and Harvey (unpub. data), Goodyear (unpub. data), Rugh, Fraker and Wursig, Richardson, and Krogman (unpub. data).

Table 5. A three day sampling of satellite passes achieving azimuths of > 2.5° and > 5.0° for various locations (° latitude), summarizing their average duration and the expected number of location fixes for various species of whale likely per day.

Location	Date	Total Passes >2.5°	>5.0°	Avg. Duration(min.) >2.5°	>5.0°	Expected No. Position Fixes: Gray >2.5°	Gray >5.0°	Humpback >2.5°	Humpback >5.0°	Bowhead >2.5°	Bowhead >5.0°
Baja Calif.	7-8-82	8	8	11.4	10.8	3.65	3.24	7.14	6.96		
Sur--26.83°N	7-9-82	9	8	10.3	10.2	3.83	2.81	7.17	6.69		
113.17°W	7-10-82	10	10	10.0	7.7	3.31	2.25	7.64	5.80		
Newport, OR	7-8-82	12	10	10.3	9.9	4.84	3.23	9.13	8.21		
44.62°N	7-9-82	12	11	10.4	9.3	4.62	3.17	9.45	8.02		
124.04°W	7-10-82	12	11	10.6	9.4	4.88	3.41	9.39	8.30		
Newfoundland	7-8-82	15	15	9.8	9.3			11.10	9.54		
47.00°N	7-9-82	14	14	9.6	7.8			9.91	8.94		
53.00° W	7-10-82	13	13	9.8	8.7			9.98	8.94		
St. Matthews	7-8-82	20	19	10.4	9.0	7.73	4.99	16.35	13.07	3.46	2.30
Isl. 60°N	7-9-82	21	21	10.7	8.8	8.13	5.38	17.51	14.05	3.65	2.06
173°W	7-10-82	20	20	10.4	8.7	7.27	5.18	16.3	12.85	3.35	2.14
Tuktoyaktuk	7-8-82	23	21	11.2	10.5					4.54	3.20
70°N	7-9-82	24	23	11.2	9.9					4.82	3.35
133°W	7-10-82	23	22	11.3	10.2					4.68	3.39

During 1980 and 1981 a BLM-funded effort by the Marine Mammal Tagging Office of the National Marine Mammal Laboratory attempted to develop a PTT for large whales but concluded it was not feasible at the time (Hobbs & Goebel, 1982). A contract to develop a temperature-stable oscillator was initiated but was discontinued due to difficulties in the production of a critical microchip. In a January 1981 meeting (Botkiin et al., 1981), Charles Cote (NASA) suggested obtaining an experimental waiver from Argos frequency stability requirements to experiment with the system. This was arranged through Vincent Lally at the National Center for Atmospheric Research (NCAR), one of the developers of the NIMBUS system.

Further discussions with Gerald Soffen, (director of the NASA Life Sciences Program) and Larry Heacock (NASA Goddard Space Flight Center) revealed that the creation of small Argos transmitters was totally dependent upon development of a temperature-stable oscillator.

In October 1981 O.S.U., NCAR and Telonics personnel met and identified the technological difficulties and potential remedies to create: 1) a small Argos PTT without a temperature-stable oscillator; and 2) modify PTT's to monitor, record and relay information on dive depth and temperature profiles (important oceanographic descriptors of water masses to help identify how whales migrate and find prey). Funding for the PTT development was not available until Spring 1982 when Telonics modified a NCAR PTT with experimental identification codes and calibrated the temperature-induced frequency drift so corrections to the Doppler shift data could be made after satellite reception. Telonics also developed "saltwater switch" circuitry, a truncated-helix antenna and micro-miniaturized some of the existing components to repackage the PTT in a smaller housing.

Argos calculated good locations on a routine basis when the PTT was spread out on a laboratory bench; but when it was repackaged into a small housing, it did not work well. Unfortunately, there were inherent design problems in the NCAR unit which allowed radio frequency (RF) energy from the final power amplifier to disrupt the controlling microprocessor. Despite two additional versions of the original pressure housing and attempts to isolate the power amplifier from other critical components by shielding, the problem persisted. The experience Telonics gained in modifying the NCAR PTT made it possible to consider building a complete PTT where small packaging was an initial design priority. Much of the miniaturization work had already been done for components of the NCAR PTT and design ideas had already been developed to replace many of the larger NCAR-based components. By July the major electronic design work had been accomplished.

OSU undertook the design, construction and testing of the PTT pressure housing, attachments, applicator, antenna feed-through connections and saltwater switch contact points. Romaine Maiefski, the project's engineer and design consultant, finalized the pressure housing and feed-through designs after Telonics developed the transmitter and power supply. Ultimately, the PTT was housed in an aluminum cylinder 14 cm in diameter, 7.6 cm long and weighing 3.52 kg. One end of the cylinder was attached to a flat 30 mm thick stainless steel base plate 29 cm long and 14.5 cm wide, which tapered at each end (Figure 15). The other end of the PTT's cylindrical housing was capped with a lid using an O-ring seal. A truncated helix antenna (8.9 cm in height and 63 mm in diameter) was mounted on the lid, as was a saltwater switch contact electrically isolated from the lid by an O-ring sealed electrical feed-through and stiffened by a machined Delrin cone which also promoted water drainage. The top of the entire lid was cast in high density orange polyurethane at an angle to facilitate water runoff and provide mechanical rigidity to the base of the otherwise flexible antenna.

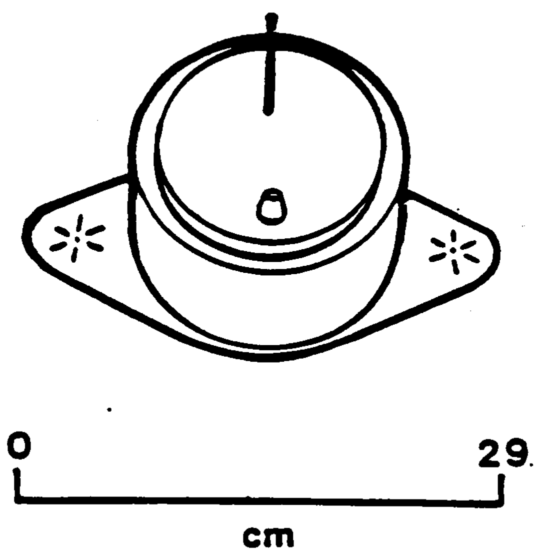


Fig. 15. A first generation housing for a Telonics PTT deployed on a humpback whale in 1983.

A 4.5 m Zodiac inflatable boat, equipped with a special mast and boom to counterbalance the application equipment, was used to approach whales. The tag in its applicator was suspended at the end of a 4.8 m fiberglass pole supported at its center by a rope from the boom of the boat. A counterbalancing weight moved up and down inside the mast.

Six slots in a circular pattern were cut into each end of the base plate (Figure 15) through which umbrella anchors fastened the tag to the whale's back (Mate and Harvey, 1982b). The umbrella anchors and electrically actuated pressure cartridges were identical to those used with VHF tags.

While Telonics was preparing its PTT, TOYOCOM was also preparing a PTT for tracking dolphins. The project's chief engineer, Mr. Tsuitsuimi, showed their engineering prototype (Figure 16) at a Service Argos Users' Conference. It was later purchased as a backup to the Telonics hardware.

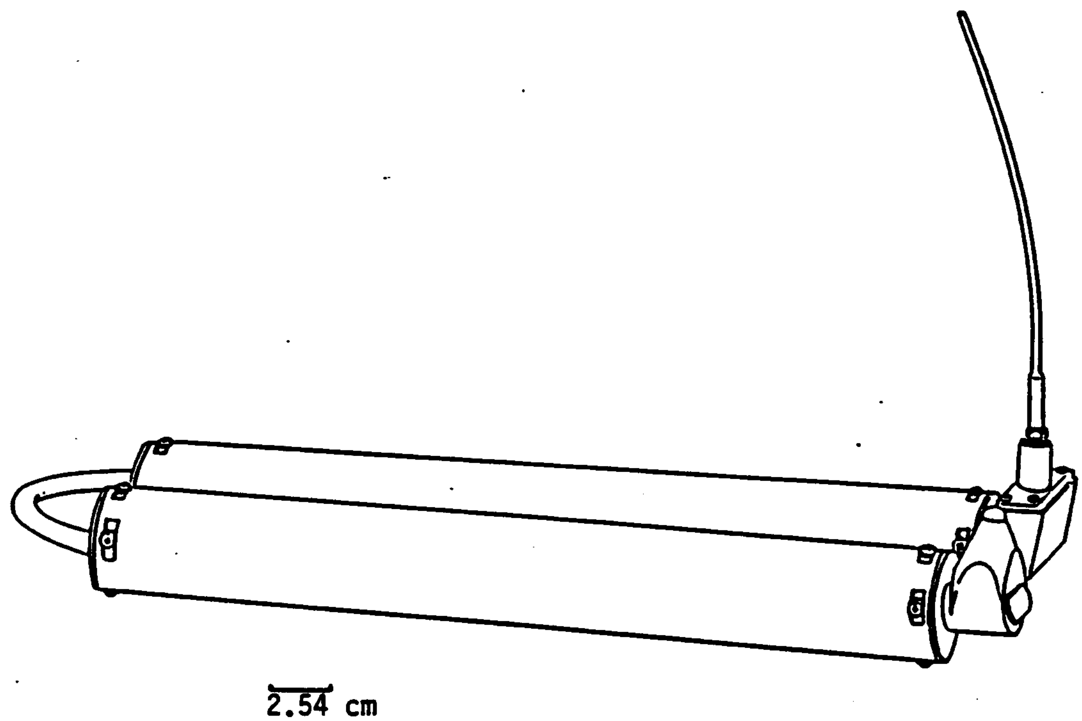


Fig. 16. A Toyocom PTT prototype designed for porpoises.

The TOYOCOM PTT consisted of two tubes 30 cm long and 4 cm in diameter. One tube housed the PTT electronics and was fitted with a whip antenna at one end. The other tube contained the batteries and was linked to the electronics tube by an U-shaped conduit. Maiefski designed and fabricated a saltwater switch and circuit for one end of the battery tube. A separate attachment system was built for the TOYOCOM unit based on the umbrella design. The resultant unit was fairly large but, nonetheless, provided the only available alternative to the Telonics PTT.

The TOYOCOM PTT stopped transmitting after a test firing of the applicator. Inspection of the electronics revealed a broken fuse. The fuse was replaced with no signs of an overload, so it was concluded that the fuse had been damaged physically by the shock of the applicator firing. The fuse was eliminated from the circuitry as there would be no way to replace the fuse once the PTT was on a whale. The PTT continued to operate after two additional applicator tests. The tag was taken to Mexico during the 1983 winter field season as a back-up to the Telonics PTT.

Gray Whales: 1983

The Telonics tag was delivered immediately before field operations began without extensive marine testing. Nonetheless, its operation was deemed adequate during saltwater tests in Phoenix at Telonics. Seawater tests conducted in San Diego Bay prior to crossing into Mexico for the 1983 tagging season resulted in good locations. A Telonics PTT was applied to a gray whale using the umbrella attachment system, but failed to communicate with the Argos system. At the time there were no receivers commercially available to confirm the PTT's operation in the field. While Telonics tried to diagnose the problem by testing additional PTT's in Phoenix, efforts to tag a gray whale with the TOYOCOM PTT began. Twelve hours before a tagging attempt, the TOYOCOM PTT was activated to run all night to confirm its operation. The next morning, however, the tag was hot and inoperative. Burned electronic components and dead batteries were found inside the protective housing. The PTT was damaged beyond any field repair and was later returned to the manufacturer.

The Telonics PTT failure was traced to a flaw in the microprocessor's programming (software) which under certain circumstances prevented the PTT from recognizing it had surfaced (and thus, from transmitting). A later evaluation of the TOYOCOM PTT failure revealed that two "back to back" electronic boards had been separated from each other by a thin mylar sheet and the shock of applicator trials had allowed the soldered tips of the boards to penetrate the mylar sheet and short out against one another. This did not occur when the tag was sitting quietly but did occur during handling after the PTT had been turned on. With no fuse in the circuit any longer, there was no protection to the transmitter when the circuits began to short out. The transmitter was repaired and employed as a "ground truth" transmitter to confirm location operations and improve the location accuracy of calculated whale positions. The gray whale PTT was not successful although the process of attachment went well.

Humpback Whales: 1983

Methods

The Telonics PTT was reprogrammed, tested and available in May 1983 for testing on humpback whales off Newfoundland. Cooperative arrangements were made with the Canadian Department of Fisheries & Oceans through Jon Lien (Memorial University of Newfoundland) and with Peter Beamish. Both Lien and Beamish operate programs to help fishermen release entrapped whales. The entrapment season is usually June, July and early August.

Since whales surface irregularly and at least 5 transmissions were required by Service Argos to calculate locations, the PTT was programmed to transmit twice during a single surfacing but with 2 different ID codes, one for each of the two transmissions. The transmission sequence was initiated when the saltwater-switch transmitters surfaced. The transmission sequence included the first identification code, the temperature of the transmitter, the duration of the next to the last dive, a 500 msec pause, a second ID code, the temperature of the transmitter and duration of the most recent dive. The two ID codes later helped determine the optimal time after surfacing for transmission. Part of the reasoning for two transmissions was an uncertainty about how fast water would drain from the antenna for a good first transmission and concern that a short surfacing might result in the antenna being underwater before completion of the second transmission. If both ID codes were received by the satellite during a single surfacing, data from two dives were received. A comparison of data from both ID codes was used to determine the frequency of undetected surfacings. PTT temperatures were measured to the nearest .03°C and were used to determine the temperature induced frequency drift, which could then be corrected in our Doppler calculations. Time was measured to the nearest 80 msec. The experimental status of this project allowed a real time analysis of Service Argos to supply Doppler data (with a 6 week delay) so additional locations could be calculated from as few as 3 messages. A local user terminal (LUT) at NASA's Goddard Space Flight Center in Maryland monitored part-time during the field trials in Newfoundland. The NASA facility also monitored PTT tests in both Oregon and Arizona during certain times of the day. Tests of the PTT's locational accuracy were made during trips ranging from San Ignacio Lagoon, Baja Mexico (27°N) where temperatures reached 35°C, to Point Barrow, Alaska (72°N) where temperatures were below 0°C. Simulated diving and surfacing sequences were carried out in seawater at the OSU Marine Science Center in Newport, Oregon (44°N) in water temperatures of 10°C to 16°C. All tests were successful before attempts were made to tag humpback whales.

Field studies were conducted in Newfoundland during June and July 1983. During 5 weeks only one opportunity developed to tag a humpback. A young whale, approximately 9.7 m long, became entangled in a gillnet 1.1 km northwest of Cape Bonavista (48.707°N, 52.059°W) in water 12 m deep and was reported by Peter Beamish. A rope from a gillnet bridled the whale and limited its movements to a circle of 15 m radius. The tagging boat tied onto the rope approximately 10 m from the whale and attempted to tag it when the whale surfaced. A second boat was tied to the tagging boat 5 m further from the whale as a safety backup. A Beaufort-four seastate and swells up to 1.5 m made it difficult to anticipate the whale's surfacing, properly position the boat and handle the tagging pole. As a result, it took nearly 3 hours to apply the PTT. Hydrophone recordings of the entrapped humpback whale were made before, during and after tagging. Vocalizations were heard during all 3 periods and no startle vocalization or changes were noted (Beamish, pers. comm.). The PTT was applied 1.5 m behind the whale's blowhole along the mid-dorsal line (Figure 17). One of the Holex pressure cartridges did not fire with sufficient force to break one of the two nylon bolts holding the PTT to the applicator. Fortunately, the whale did not visually react to the tagging and stayed at the surface where the nylon screw was cut with a knife. The attachments were not completely deployed.

Approximately 70% of the umbrella attachment's holding power was generated in the last 30% of its deployment, when the tynes spread out laterally and bend at their insertion into the piston body (Mate and Harvey, 1981). In this case, the attachment probably only developed 30% of its potential attachment strength. The loose attachment allowed the transmitter to visibly wobble upon surfacing, subjecting the PTT to more hydrodynamic drag than a fully deployed tag. It was not possible to remove the tag.

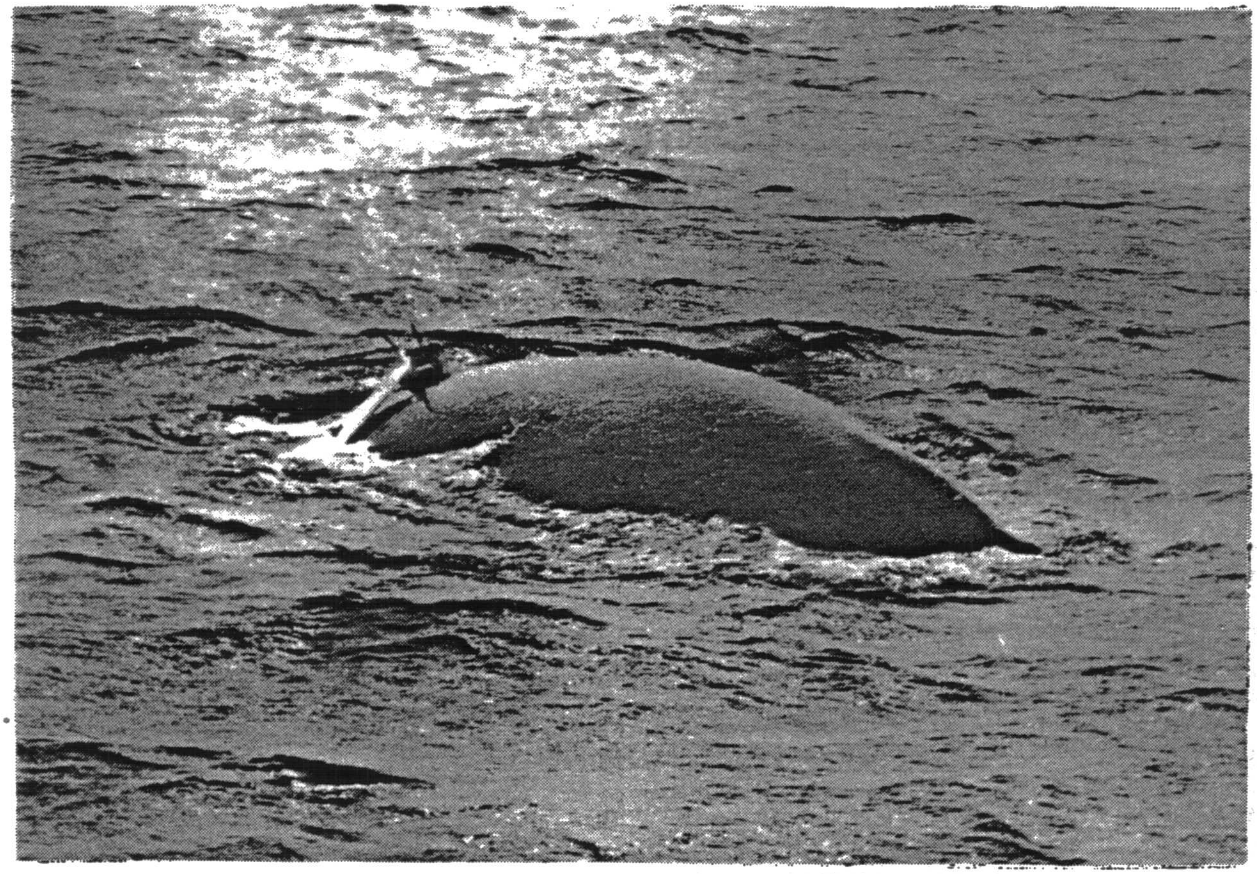


Fig. 17. A humpback whale fitted with a Telonics satellite-monitored radio tag and a VHF umbrella tag off Newfoundland in July 1983.

A VHF radio tag with a 1 m long white streamer was also applied with no visible reaction and deployed properly. The tag was applied at 1230 GMT (10:00 Newfoundland Daylight Savings Time) on 15 June. Underwater photographs of the entrapped whale were taken prior to cutting the animal loose from its bridle. The PTT's function was confirmed and the VHF transmitter was monitored from a headland using a Telonics TR2 receiver and a two-element hand held Yagi antenna until 1645 when only weak signals could still be heard.

The first Argos messages were collected at 1721 GMT. Data were acquired over a 144 hour period until the tag fell off, most likely due to the loose tag attachment. During the PTT transmission period, 72 orbits occurred over the tagging area.

New data were obtained from 121 complete messages on 59 orbits (82%) (Mate, 1983a). Fifty-four messages from 40 orbits were documented during 8 interrogations of the Suitland concentrator. Data from each orbit were obtained from the concentrator by routine interrogation. The concentrator only maintained a record of the most recent message and location. Thus, if data were not collected by interrogating the concentrator before new information replaced it, there would be no record of the older data until the complete data printout came from Service Argos. The concentrator showed no new data for a 33 hour period due to technical problems at Service Argos but began again on the afternoon of 20 July. Orbits acquiring new data varied in elevation above the horizon from 4° to 87°. A complete transmission sequence in this experiment included 2 ID codes and information for 2 dives (duration of dive and PTT temperature). An example of this was the surfacing at 196/1758 (the 196th Julian day of the year at 1758 GMT). The first transmission (ID #842) indicated that the next to last dive was 2.83 min in duration and the transmitter temperature was then 10.84°C. The second transmission (ID #843) indicated that the most recent dive was 2.22 min in duration and that the temperature had risen to 10.98°C. The sequence of received data also allowed some intervening dives to be inferred such as from the surfacings at 197/0618 and 197/0622. In this instance the dive associated with ID #843 during the first surfacing was for the most recent dive and the dive associated with ID #842 during the second surfacing was a repeat of that dive, assuring that there were no intervening surfacings and that the time in between these transmissions represented a dive for which there were no recorded data. Thus, 8 interpreted dives (6% of total dives) could be added to the 121 transmitted dives.

As a result of overlapping signals and inferred dives, dive sequences as long as 21.6 min could be created (Figure 18). The first 6 messages were received by NOAA-7 and the last two were received by NOAA-8. The 8 messages represent 8 separate surfacings which define at least 7 dives. Two additional dives prior to the first surfacing were identified by the first transmission of the first and second surfacings in the sequence. Although a dive sequence (of at least 10 dives) covering in excess of 21 min could be reconstructed, satellites were only overhead for 15.3 min. Two different values for the duration of the third dive were encoded in transmissions from the two different ID codes on subsequent surfacings. However, because the surfacings were sequential it was possible to confirm which was the correct value. When using a full 256 bits of data,

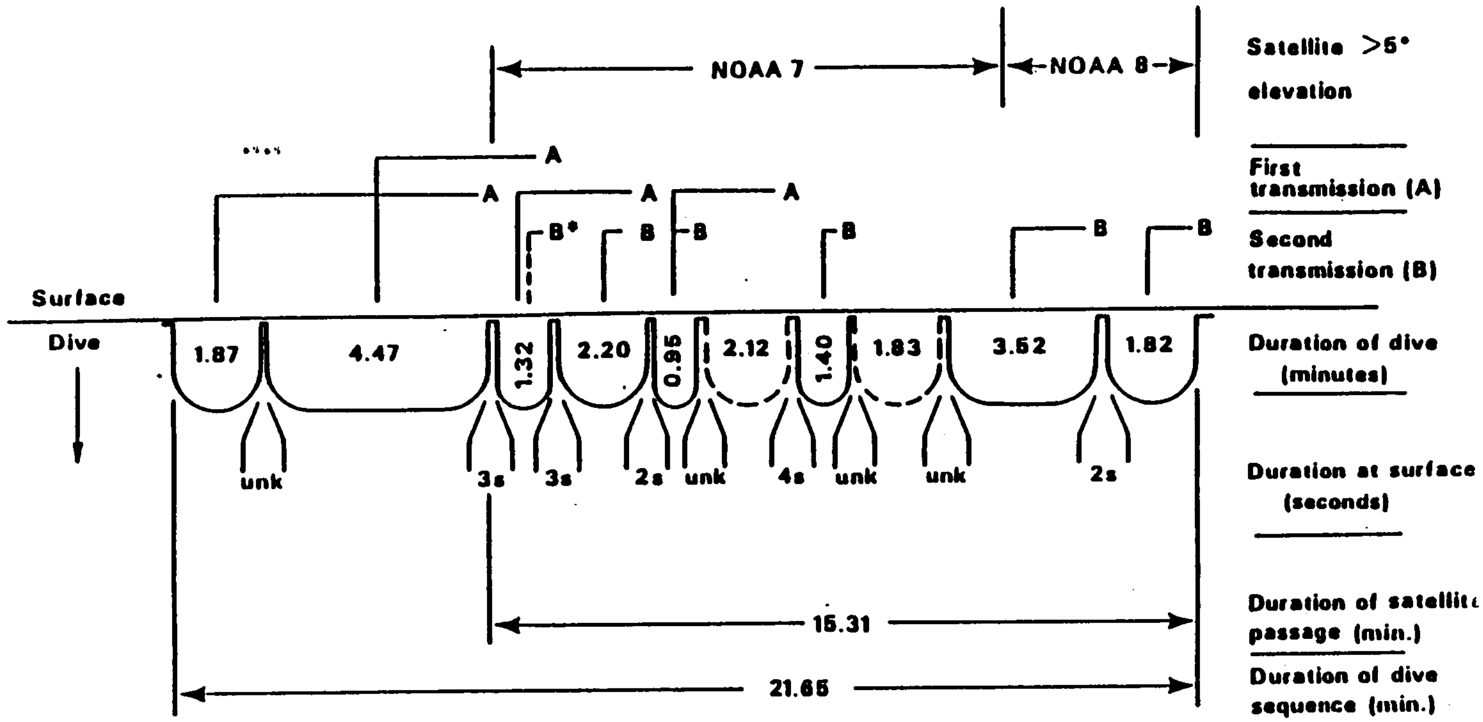


Fig. 18. An example of humpback whale diving and surfacing deduced from ARGOS satellite data. Data from two ID codes are shown. Some dives are inferred. Periods of unknown time are abbreviated "unk".

Service Argos estimates that bit synchrony errors may account for error rates of up to 15% and encourages either multiple transmissions of the same data or methods of evaluating such errors.

Two locations were determined by the NASA LUT. Locations were never determined by Service Argos because: 1) in most cases an insufficient number of messages were received during a single orbit; and 2) when a sufficient number of messages were received, they were not sufficiently spread out by at least 420 s as required. However, subsequent analysis of the Doppler data supplied by Service Argos allowed the calculation of 8 additional locations. The location algorithm used for these determinations is detailed in Hoissinston and Gilbert (1984). Figure 19 shows the tagging location and 10 subsequent locations of the tagged humpback whale as it moved east offshore through the Labrador Current to its convergence with the Gulf Stream, which the whale followed south. Sea surface temperatures in the figure are 3 day averages (Canadian Forces METOC Centre) and show the cold Labrador Current moving southward waters and splitting the warmer Gulf Stream into 2 branches which is common (Petrie & Anderson, 1983).

Movements of humpback whales between inshore and offshore locations have been documented between years from fluke photographs (Whitehead and Lien, 1983). The tagged whale moved at least 693 km in 119.45 hours, for an average speed of 5.8 km per hour. Table 6 shows the distance traveled between locations (8 to 140 km) and average segment swimming speeds. Short distances and time intervals are more subject to errors and likely to reflect unreasonably high swimming speeds. These speeds in general are conservative estimates as the whale may have wandered from the straight line path between successive locations. Humpbacks spend most of their summer feeding or in search of food (Whitehead et al., 1982). One of the PTT-tagged whale's locations was along the southeast edge of the Grand Banks, close to where a concentration of humpback whales had been seen one week earlier (Whitehead, pers. comm.). The Labrador Current moves south at a maximum speed of 2.8 km along the eastern edge of the Grand Banks with a mean velocity of 0.54 km nearshore and 1.3 km 300 km from shore (Petrie & Anderson, op. cit.).

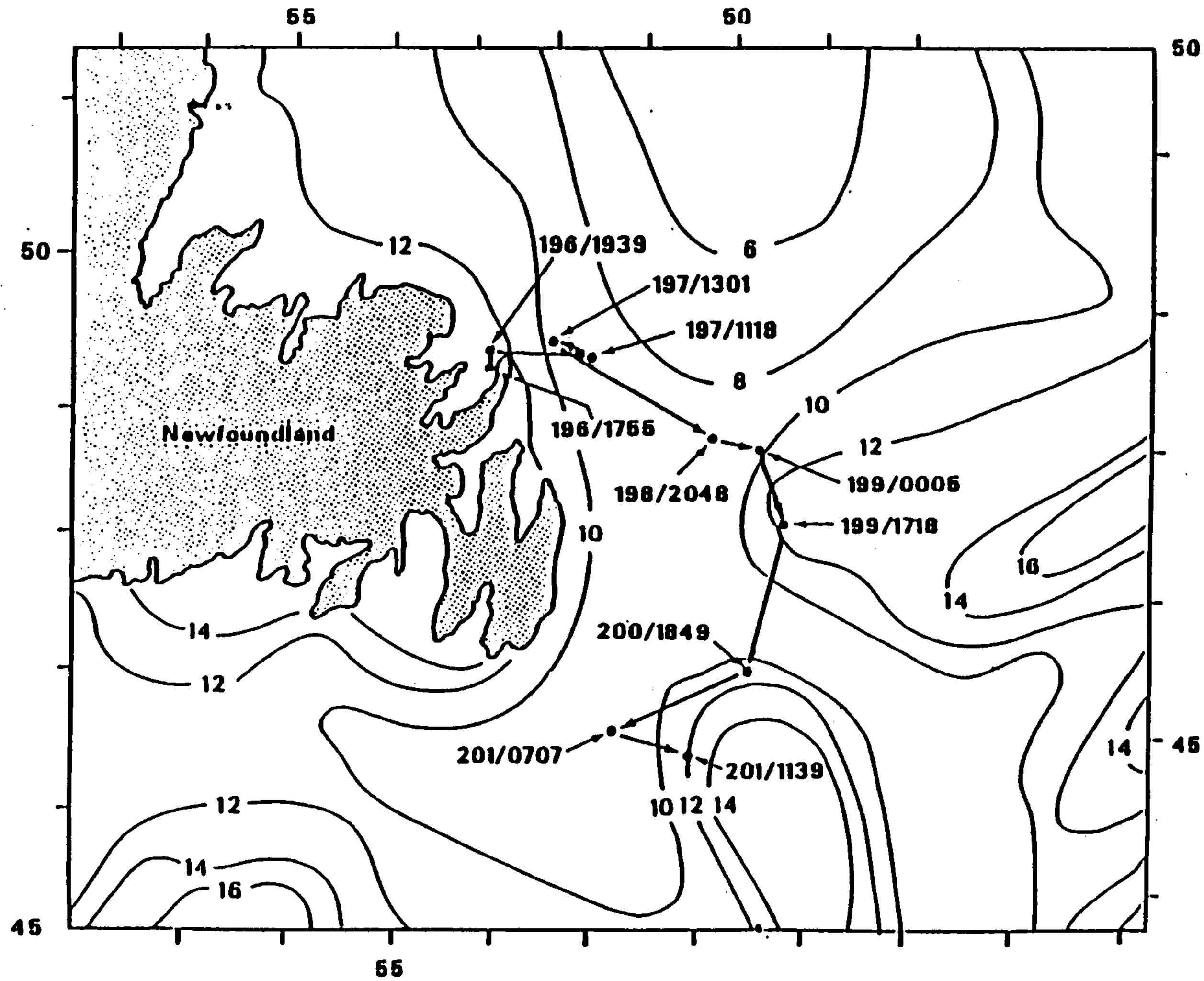


Fig. 19. Locations of tagging and subsequent location determinations calculated from ARGOS satellite data for a free-ranging humpback whale. Surface temperatures are for 18 to 20 July 1983 (Canadian METOC Centre).

Table 6. Distance and speed of travel for a SWT-tagged humpback whale, 15-20 July 1983.

		TIME (HR)		DISTANCE (KM)		SPEED (KM/HR)	
DATE	TIME	ABS*	SUM**	ABS	SUM	ABS	SUM
196	1230						
		5.42	5.42	8.25	8.25	1.52	1.52
196	1755						
		1.73	7.15	13.57	21.82	7.84	3.05
196	1939						
		15.95	23.10	96.40	118.22	6.05	5.12
197	1118						
		1.72	24.82	45.41	163.63	26.40	6.59
197	1301						
		31.78	56.60	140.73	304.36	4.43	5.38
198	2048						
		3.28	59.88	44.43	348.79	13.55	5.83
199	0005						
		17.22	77.10	68.31	417.10	3.97	5.41
199	1718						
		25.52	102.62	126.46	543.56	4.96	5.30
200	1849						
		12.30	114.92	94.04	637.60	7.65	5.55
201	0707						
		4.53	119.45	55.91	693.51	12.34	5.81
201	1139						

*ABS = Absolute (Time or distance between locations).
**SUM = Summary (Total time or distance since tagging).

The water off Newfoundland generally gets colder with depth and has one or more distinct thermoclines in some areas (Lynch, 1983). Subsurface water temperatures as low as -1.50°C were measured in early July (Whitehead, pers. comm.). Thus, transmitter temperatures can infer the depths of dives. The temperature sensor was located inside the transmitter. The PTT's internal temperature changed slowly due to the thermal mass of the housing so the transmitter temperature represented an amorphous average of the "recent" water temperatures encountered by the whale. Therefore, reported temperatures more accurately reflect the whale's dive depth profile rather than surface water temperatures. Following long dives into cool (deep) water the depressed temperature of the transmitter was observed to warm during several short dives near the surface. Temperature trends for consecutive dives were, therefore, of value in further evaluating a whale's diving behavior. For example, a dive sequence on Julian day 196 between 1940 and 1955 GMT showed a general trend toward lower temperatures, starting at 10.29°C and ending at 8.93°C, which may indicate a period of diving to deeper (colder) waters than before the sequence began (especially as the transmitter's starting temperature was close to the infra-red sea surface temperatures reported for the area). Thus, it is not surprising that reported dive duration does not correlate well with lagging temperature data (Figure 20). Duration of dive may also have little effect on temperature, if whales select temperature strata. Bredin (1983) has reported that feeding humpback whales concentrate their activities in waters bounded by one or more thermoclines which contain capelin but this activity shows considerable variability relative to surface temperatures (Whitehead et al. 1982). Fish exhibit temperature preferences off Newfoundland; cod prefer 0 to 4°C, capelin prefer 6 to 12°C, and basking sharks prefer 8 to 12°C. As Newfoundland humpbacks feed primarily on capelin, it is not surprising that PTT temperatures greater than 6°C comprised 92% of all reported temperatures. There is generally good correspondence between the maximum PTT temperature associated with an Argos location and the METOC-derived temperatures. The PTT reported temperatures higher than immediately adjacent waters only once. The temperature contours supplied by the METOC Centre are 3 day averages and do not take into consideration the dynamic temperature gradients which change constantly with small scale localized eddies. Lower PTT temperatures likely reflect subsurface temperature measurements and do not help corroborate location determinations. The METOC data were taken from sea surface infra-red (IR) scanners on board the same NOAA satellites carrying the Argos receivers. Although IR sensitivity allows differentiation of as little as .5°C, there is often inadequate ground truth measurement for good calibration during much of the year.

Figure 21 depicts the frequency distribution of 114 dives in 15 s increments. Because Service Argos prohibits PTTs from transmitting more than once every 40 s, a built in delay of 45 s was incorporated so that no dives from 0 to 45 s in duration were recorded. However, short dives of less than 1 min are likely to be more frequent than any other category. The number of surfacings resulting in a transmission during a single orbit is a reflection of: 1) the amount of time the satellite spends passing over the area for that time of day, 2) the duration of the dives themselves (i.e. more short dives are possible than long dives in a given amount of time), and 3) the seastate conditions which might tend to reduce the number of transmissions reaching the satellite. The dive duration distribution for the PTT-tagged

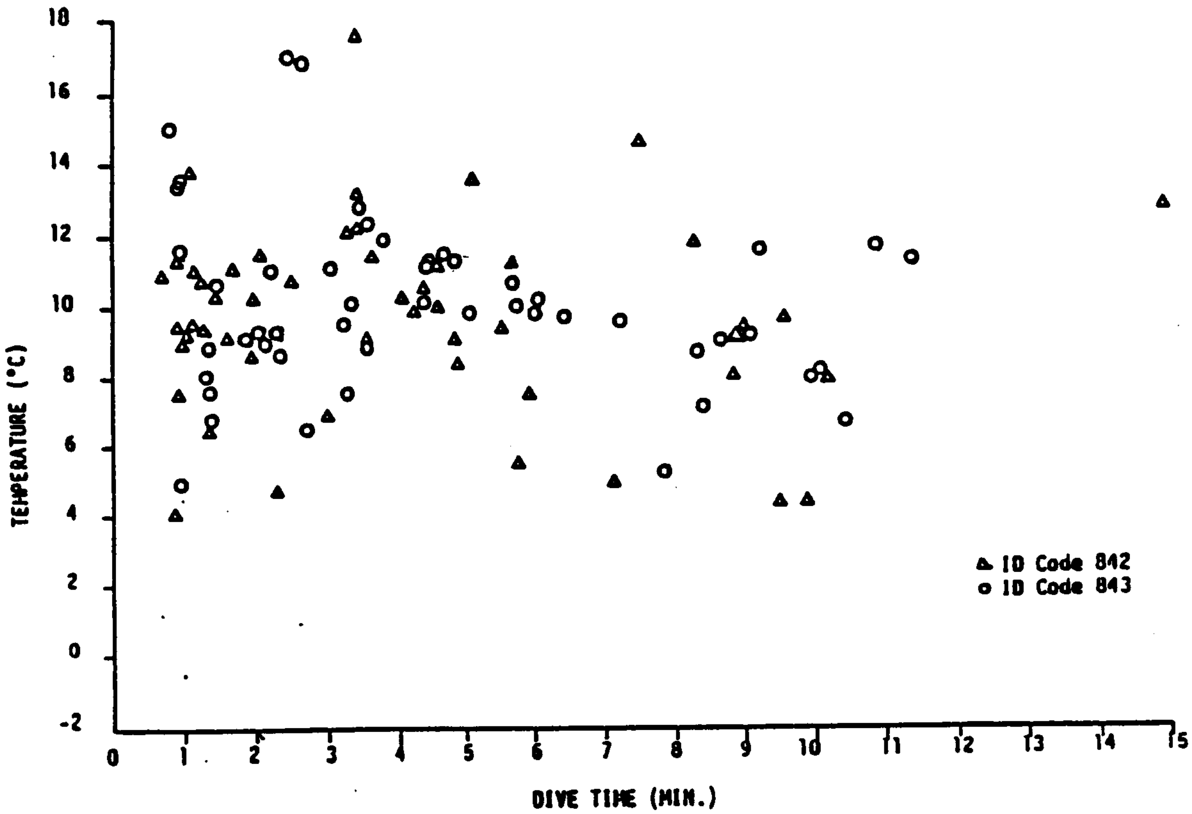


Fig. 20. Temperatures and related dive times from a SWT-tagged humpback whale off the Newfoundland Atlantic coast (15-21 July 1983).

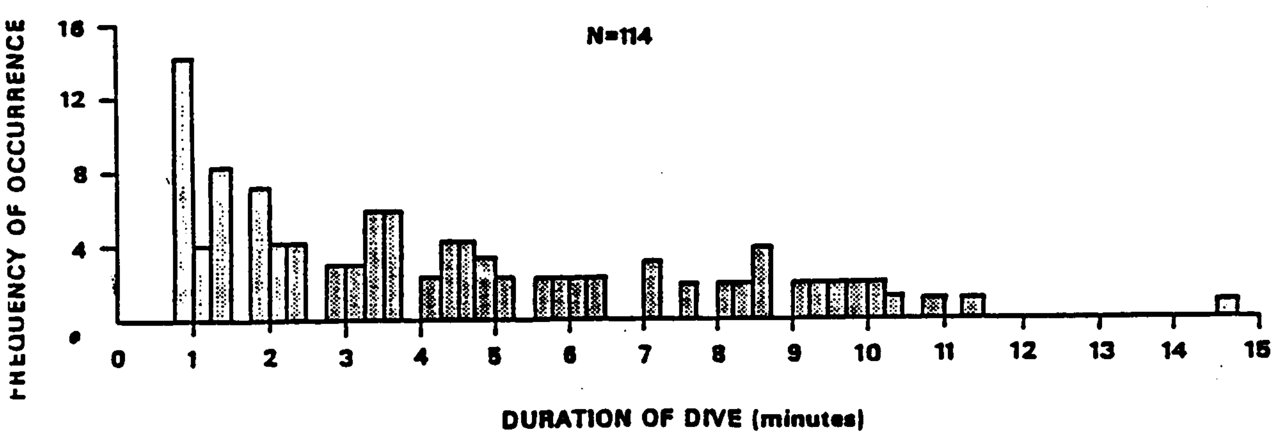


Fig. 21. The frequency of 114 dives of varying duration in 15 s increments from a satellite-monitored humpback whale.

humpback whale was less exponential than the data obtained by VHF radio tagging gray whales (Figure 5) suggesting that there were either basic differences in the diving patterns of humpback and gray whales or that the specific behaviors of the two whales during the data collection period may have been quite different.

Dives over 20 min would be considered rare for humpback whales. Two very long dives (53.68 and 74.49 min) were transmitted, but by cross-checking between ID codes and satellite recorded reception times both were confirmed bit-synchrony errors. Figure 22 summarizes the duration of whale dives over the 6 day monitoring period by time of day. Lack of data between 1130 and 1230 and between 2230 and 0230 reflects a lack of satellite passes rather than an absence of surfacing activity. Although the sample size is limited, there appear to be times of the day when longer and shorter dives were more prevalent.

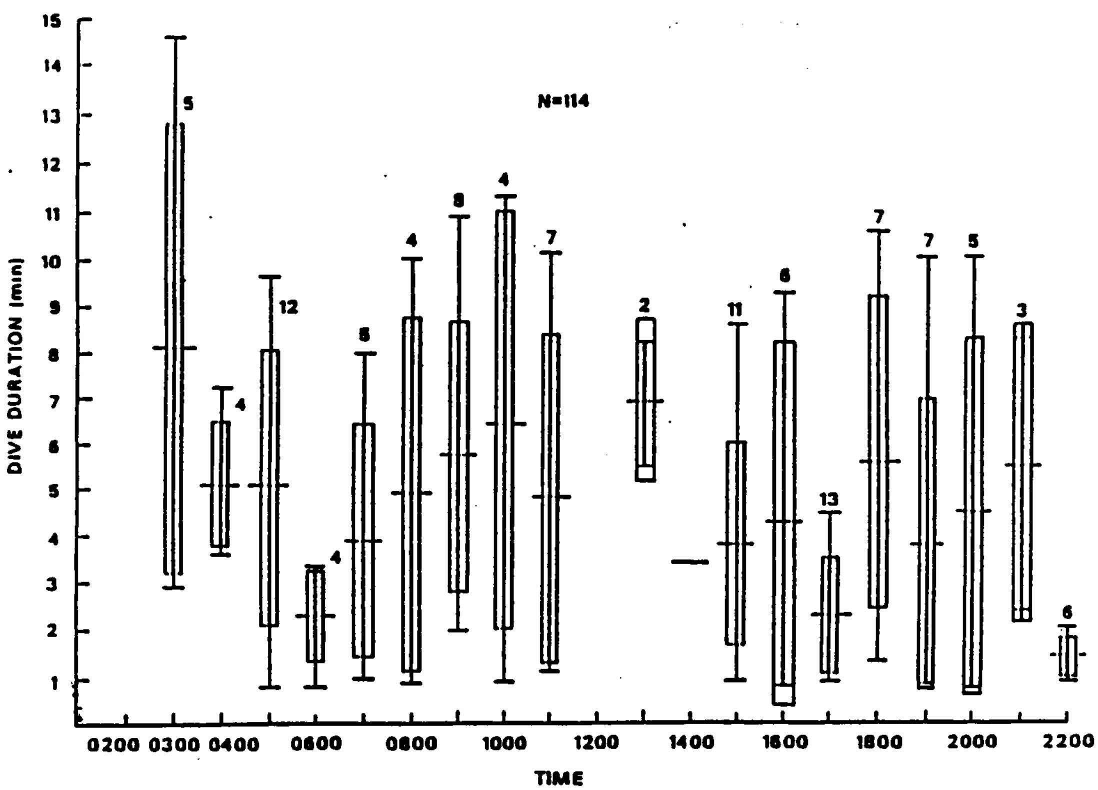


Fig. 22. The mean, standard deviation and range of dive durations by time of day for an ARGOS-monitored humpback whale.

Douglas and Green (1980) observed that the inshore activity of humpback whales in St. Vincent's, Hollyrood Bay, Newfoundland decreased during the midday. At night capelin rose to the surface and scattered, perhaps to feed on vertically migrating prey species. In morning, schools of capelin were found in shallow waters, so shallow dives were sufficient for whales to feed. The short dives at 0600 likely result from surface skim feeding which was commonly observed at sunrise. Douglas and Green also observed that later in the day humpbacks needed deeper dives (to cooler temperatures) to catch capelin which had migrated to deeper waters. This pattern of activity was substantiated by the PTT temperatures reported throughout the day. For example, on Julian day 201, the 10 morning dives between 0533 and 0913 GMT were all at least 11.8°C ($\bar{x}$ = 13.6°C), while the 13 dives from 1048 to 2030 GMT averaged only 9.51°C. This may also represent animals foraging along the convergence of the Labrador and Gulf Stream currents where there is a steep temperature gradient.

Discussion

This experiment was the first successful demonstration of satellite-tracking whales (Mate et al. 1983)! The electronics worked perfectly for 6 days. The terrestrial trials and the dive simulations confirmed an excellent location capability and the accurate transmission of dive and temperature data. Without being able to re-sight the PTT-tagged whale offshore, we were unable to confirm the location accuracy of the PTT at sea. However, the first Argos location was only 5 hours after the release and only 8.5 km from the tagging site, requiring only 1.5 km/hour traveling speed. The whale was last observed moving slowly and was within 20 km of the tagging site during the locating orbit as judged by audible VHF signals. Only 7 erroneous dive times and 2 erroneous temperatures were reported in 121 occurrences of each. The reason for these aberrations falls into the general category of bit-synchrony error which may occur either from encoding in the transmitter, reception at the satellite or re-transmission from the satellite to ground stations. It is impossible to tell which of these circumstances occurred. However, laboratory measurements of the temperatures reported by the transmitter showed perfect encoding at the transmitter and the errors tended to occur during low elevation passes (average 16.8°) suggesting satellite reception or retransmission as the most likely cause.

Signal strength of messages at the satellite was good to excellent during terrestrial trials and fair to good while the PTT was on the whale. The position of the antenna, perpendicular to the major axis of the whale and adjacent to the shorter saltwater switch on top of the PTT, assured that the antenna was clear of the water before the saltwater switch activated the transmitter. The saltwater switch functioned well, both in laboratory experiments and in field trials prior to deployment.

The use of two ID codes allowed the PTT to act essentially like two separate transmitters. Each ID code accounted for 50% of the total data received. Only 18 surfacings (15%) resulted in data from both ID codes. Thus, it was an important strategy to have 2 ID codes because it resulted in much more data than 1 ID code, and has now narrowed the time of maximum antenna exposure following saltwater switch opening. Further experiments would profit by having a single transmission placed intermittently between the timing of the first and second transmission in this experiment. This experiment also suggests maximal length transmissions (transmitting 256 bits of data in 960 ms) may have trouble relaying their full message to the satellite without having portions obliterated by the antenna being submerged prior to complete transmission.

The transmitter was programmed to transmit at every surfacing of the whale and the oscillator ran continuously. This was an energy consumptive strategy but one which was important to evaluate how frequently locations might be obtainable. Thirteen of the 52 orbits obtaining data contained 3 or more messages which might have been useful in calculating locations. The frequency with which orbits containing 3 or more messages occurred suggested a strategy of transmitting only during certain portions of the day to extend the functional life of the PTT. This PTT had a designed operational life of 35 days. The operational life was calculated from the battery capacity and energy demands. Transmissions accounted for 50% of the power used while maintenance functions (microprocessor, continuous oscillator, interrogation of sensors, quartz clock) used the rest, but at a lower current. As satellites were only available during certain portions of the day, limiting transmissions to those times of the day would have greatly extended the PTT's operational life. In later experiments this was done and the power consumption of the oscillator was reduced by turning it on and off prior to each transmission period resulting in an operational transmitter life of 10 months.

More locations might have been achieved through the Argos system if Service Argos would have allowed transmission at each whale surfacing rather than waiting a mandatory 40 s interval. (Attempts to change the rate of transmission policy met with some success at the International Service Argos User's Meeting in Washington, D.C. in September 1987.) Use of local user terminals (LUTs) will be the most timely means of obtaining accurate whale location and sensor data in the field but Service Argos has recently become more flexible in its location criteria (see 1987 experiment on pilot whale).

Obtaining real-time information is important to make follow-up observations of the tag's attachment and whale behavior associated with certain dive patterns. Despite alerting other investigators studying humpbacks in the North Atlantic, no observations of the VHF tag/streamer were made during the 1983 feeding season or in the winter breeding areas (Whitehead et al. 1982; Katona et al. 1980) of Silver and Navidad Banks (20.5°N).

DIVE PROFILING PTT -- GRAY WHALES 1984

During January 1984 two gray whales were tagged with Telonics satellite-monitored radio tags. One of these tags was modified from a design used on a humpback whale in 1983 by incorporating a pressure transducer in the lid of the PTT. New software was written for the onboard microprocessor which collected, recorded and encoded pressure readings every 15 s during a dive. The PTT's message length changed according to the duration of the dive (the amount of pressure data) to conserve energy. When the PTT surfaced, the microprocessor sent the PTT identification code and a preamble code to indicate how many bytes of information would follow. The tag was applied to a female gray whale (Figure 23) which was active with two male gray whales within 10 min after tagging. Three such bouts, lasting from 10 to 17 min, occurred during the first 45 min after tagging. During each encounter, the massive whale bodies were seen rubbing against each other and flippers stroked over the PTT without dislodging it.

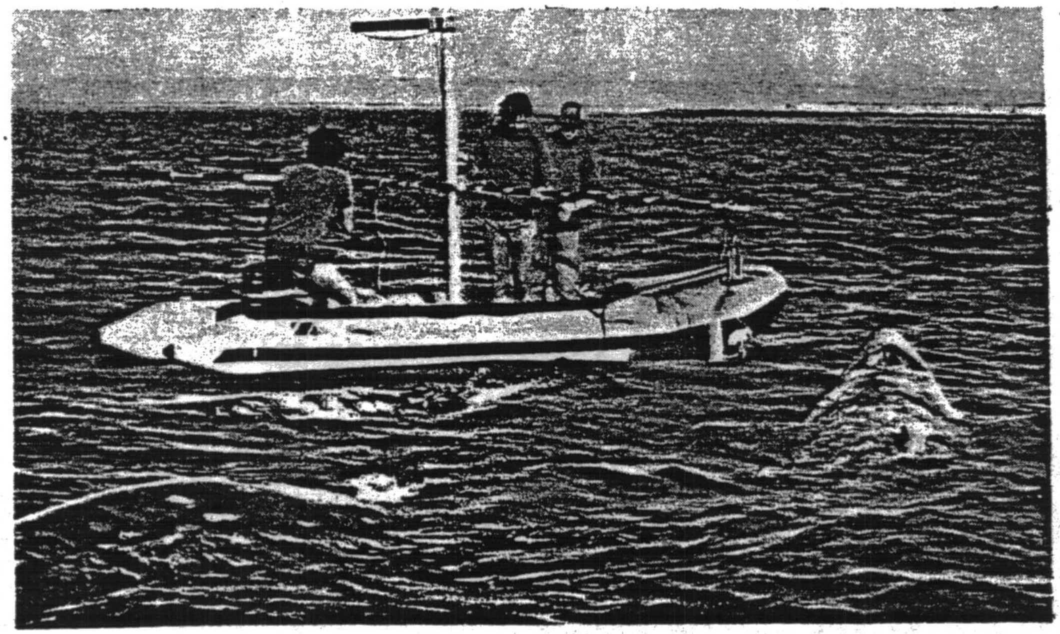


Fig. 23. A female gray whale (forward of boat) with a dive-profiling satellite-monitored radio tag (right of mid-dorsal) in San Ignacio Lagoon in February 1984. The 2 male whales to the left attempted mating within 10 min. of tagging.

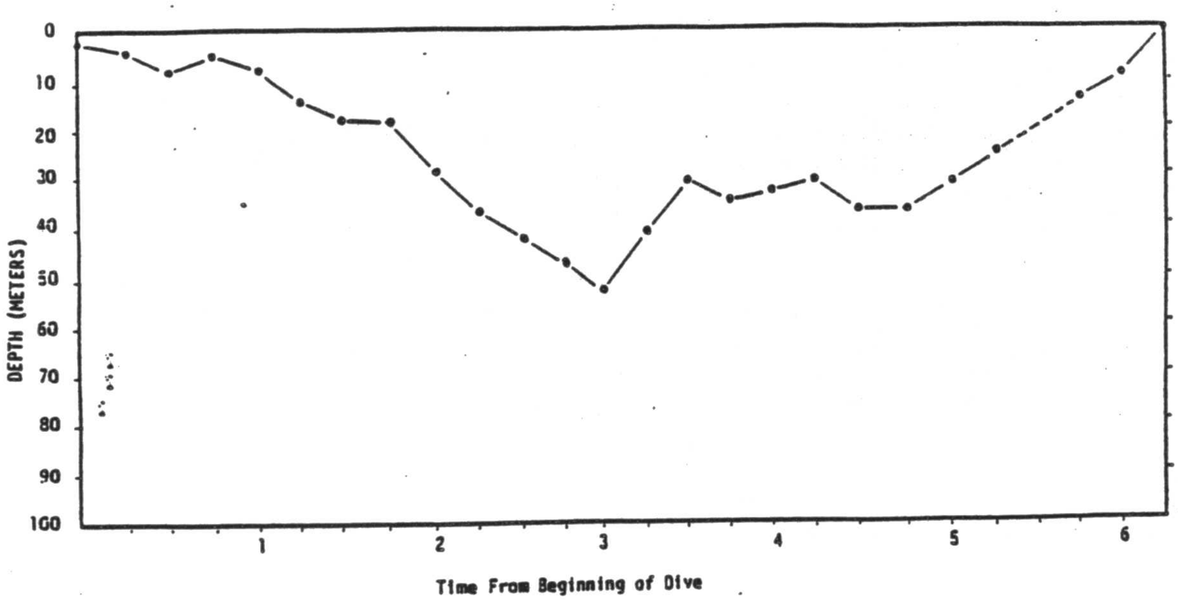


Fig. 24. Dive profile for an unrestrained radio-tagged gray whale monitored by satellite.

Good dive profiling messages were received for 28 hours after tagging. The longest dive recorded (6.5 min) was also the deepest dive reaching a depth of 56 m (Figure 24). The dive took place at least 4 km from the entrance to San Ignacio Lagoon.

It is likely that the tag came off as a result of direct contact with other whales during courtship encounters. Every "friendly" gray whale whose sex was determined over four field seasons in San Ignacio Lagoon was a female. Often when females approached the boat they rolled over on their backs and swollen genital areas were visible. It is possible that friendly behavior by single whales is associated with an estrous or pre-estrous condition. Perhaps it has been more than coincidence that VHF tags on animals without calves have lasted longer and traveled further than on females with calves. The attachment on animals without calves may be superior to females with calves because they have less physical interaction with other whales and perhaps because of differences in the consistency of their blubber. Breeding/calving seasons can present special difficulties: most female whales will either be calving or mating and males will be vying for access to breeding females. These highly tactile behaviors jeopardize the tag and antenna which protrude above the skin surface and emphasize the need for low profile housings. The best opportunity for tagging gray whales appears to be in the lagoons, but whales on the northbound migration or on the feeding grounds have much less physical contact with other whales.

The technical achievement of creating a dive profiling PTT was significant and the resultant data were extremely worthwhile (Mate, 1984). This was the first device of its sort to telemeter the three dimensional movements of a marine animal by satellite. Although time-depth recorders (TDR's) also record details of diving depth and duration, they must be recovered and do not give location information about where the diving occurred. The significance of a dive profiling PTT can be seen when examining foraging behavior. Gray whales, for instance, are bottom feeders. By knowing the location of a gray whale, it is possible to determine the approximate water depth from bathymetric charts. Dives to such depths could be considered foraging dives and an estimate of foraging effort throughout the day and night could be determined. Similarly, humpback whales are thought to press prey species, such as capelin, against thermoclines as though they were physical barriers to concentrate the prey and thus increase their foraging efficiency (Lien, pers. comm.). As whales spend approximately 95% of their time below water, their depth of dive tells a great deal about how they go about feeding, migrating and even resting.

Although the two PTTs deployed on gray whales in 1984 appeared to be well attached, neither apparently survived breeding encounters for very long. This led to a substantial re-evaluation of the attachments themselves and the size of the PTT. The pistons which held the two rosettes of subdermal inconel wires could each be pulled from whale flesh by hand with vice grip pliers. Having attachments at the ends of the long axis of the attachment plate possibly made the tag vulnerable to lateral impacts. The tag stood so high it also provided substantial hydrodynamic drag and the possibility of being caught on ropes, kelp, bottom substrates or other whales. It was not worth deploying more PTTs without improvement of the attachments, reducing the size of the PTT and changing the shape of its housing. To some extent this required waiting 1.5 years for further micro-miniaturization of the electronics and a more energy efficient design to increase the operational life of the PTT.

It should be noted that Service Argos was not only unsuccessful in acquiring positions of the dive profiling PTT but did not even acquire the telemetered dive data. Service Argos had assured us that their software could handle a PTT with a continuously changing message length and preamble, which was not true. The only data recovered was from a local user terminal (LUT) at Telonics in Mesa, Arizona. Service Argos has since developed software flexible enough for preamble changes and varying message lengths.

SATELLITE WHALE TAG ANALYSIS PACKAGE (SOFTWARE)

While expenditures for hardware and field work went on an indefinite hold awaiting the technical developments described above, software was developed for: acquiring PTT data from Service Argos; translating encoded data into meaningful numbers; creating statistical summaries; and producing graphics to portray the results. Software was not available previously for this processing. The necessary programs were developed at OSU and a user documentation manual for IBM-PC use entitled, "The Satellite Whale Tag Analysis Package (SWTPAK)" (Merrick and Mate, 1985) was supplied to MMS on an IBM-compatible floppy disk. The SWTPAK evolved out of a single program for reformatting data retrieved from Service Argos and was later expanded with programs for the presentation of data and the calculation of locations from

Doppler data supplied by Service Argos. The SWTPAK software provided a bridge between the PTT transmission and available commercial software. It also provided capabilities tailored to the specific application of this research: location fixes, two dimensional plots of dive profiles and three dimensional plots of a series of dives. Capable of using either Service Argos or LUT data, it was designed to interface with off the shelf communication data base and graphic software. During the software development, data from a U. S. Fish & Wildlife Service-funded Argos experiment on manatees were retrieved and analyzed in order to work out any operational problems in the package. The SWTPAK was used to monitor the movements of a PTT tagged manatee in 1985 over a 114 day period (Mate and Rathbun, 1985; Mate et al., 1985), and more recently three manatees in 1986 along the west coast of Florida for periods up to 300 days (Mate and Reid, 1988).

The SWTPAK is a collection of 7 programs designed to 1) edit, print and reformat data received from tag transmissions communicated from the NOAA satellites via the Service Argos data dissemination center at Toulouse, France, or from a local user terminal (LUT); 2) prepare graphical displays of dive data; and 3) calculate the location of PTTs at the time of transmission, if the location is not included in the transmitted record.

The 7 specific programs include (Figure 25):

1. CONTROL - Package menu
2. DISPOSE - Dispose file analysis
3. LINEPLOT - 2D plot of time vs depth for a single dive
4. DIVEPLOT - 3D plot of a group of dives. Requires a plotting package and a printer capable of printing graphics, such as an Epson FX80.
5. HISTGRAM - Histogram and related statistics of the time or depth frequency for a group of dives
6. LOCFIX1 - Location fixes without reference station
7. LOCFIX2 - Location fixes with reference station.

All programs were written in Microsoft Basic, implemented under PC-DOS Version 2.0, using an IBM-PC (tm) with 256K of RAM, and 2 single sided disk drives, or one disk and a fixed disk. A color monitor or a monochrome monitor with a graphics adapter is optional for the graphics software. Full implementation of the package requires communications software, such as PC-TALK (tm), database management software, such as PC-FILE (tm), and graphics software, such as the Golden Software (tm) package.

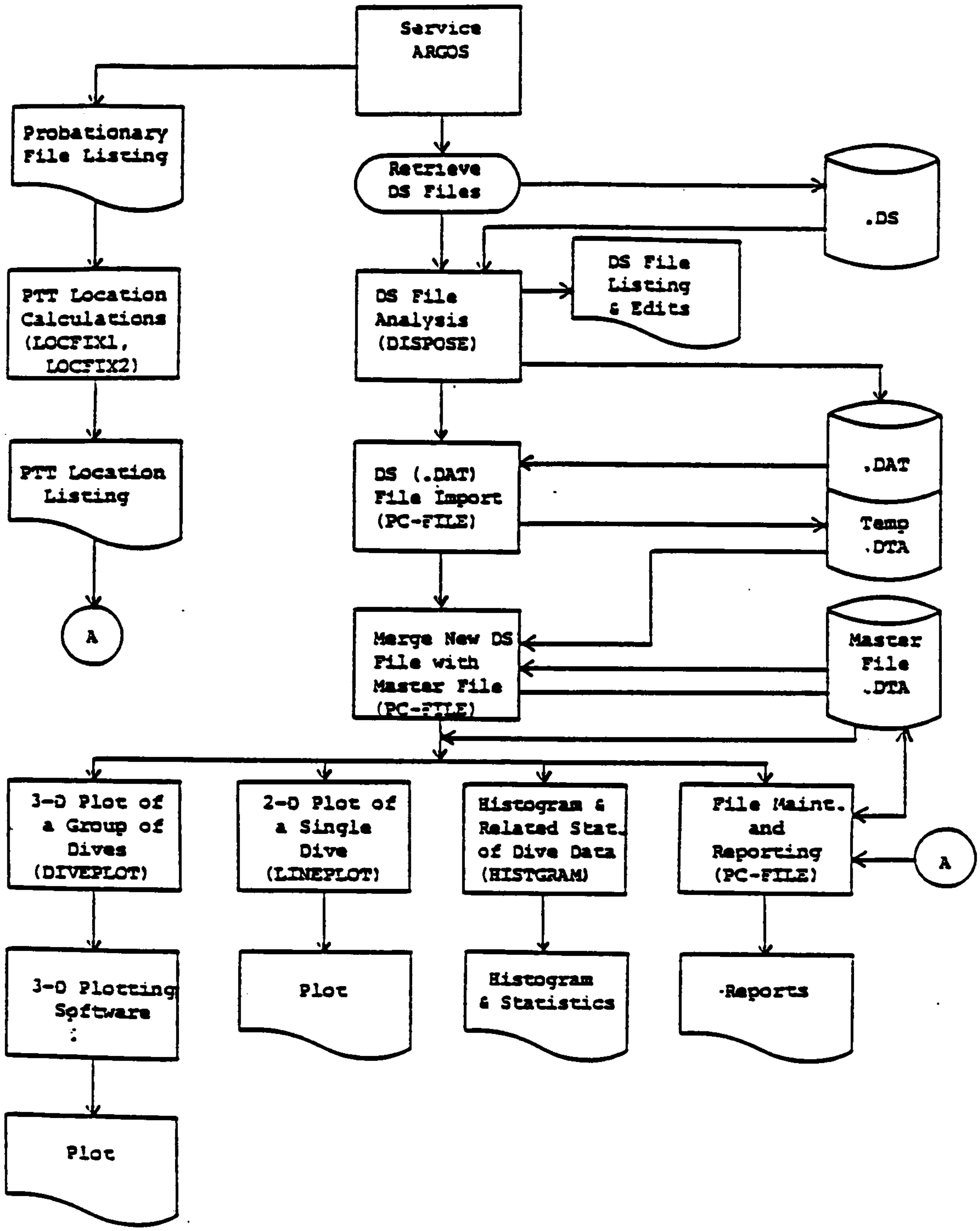


Fig. 25. SWTPAK Processing Flowchart.

Two types of data are recovered by the SWTPAK from Service Argos: probationary file listings and dispose files. Probationary files are obtainable only with special experimental user arrangements and come in a printed format which can be run through the location determination programs called LOCFIX1 or LOCFIX2 and result in the PTT locations being listed. Probationary files are not a common Service Argos product and were available only after a delay of several weeks during the 1983 and 1984 experiments. The programs LOCFIX1 and LOCFIX2 are used to calculate the PTT's location. They are the only programs that require data to be entered from the keyboard.

Both require at least three transmissions of data during a single orbit and an approximate location. LOCFIX1 operates solely on data about the PTT while LOCFIX2 provides a more precise location but requires precise satellite location and timing data from one or more earth reference stations. The output of both programs includes an error index, transmission bias and the PTT's latitude and longitude. The algorithm used for the calculations in both programs is detailed in Merrick and Mate (1985). Dispose files are available to all Argos users and contain detailed data for all transmissions which meet Service Argos standards. Initially, these data were only held for 12 hours, but are now available for 72 hours making weekend coverage more convenient. Dispose files are usually recovered with a communications program such as PC-TALK (tm) or SMARTCOM II (tm), a modem and a long distance telephone connection to Service Argos via TYMNET and TRANSPAC. Dispose files disappeared from the Service Argos computer after a single interrogation, making multiple user access impossible. Recently this has been changed at the urging of users and with the addition of new equipment at Service Argos. Service Argos also provides an "Adjour" (day) file which gives the most recent time and date of location and transmission for each PTT. All of the SWTPAK programs, with the exception of the probationary file data, use dispose file data or some re-formatted version of it. The detailed procedures for data retrieval are presented in the User's Manual (Merrick and Mate, op. cit.). SWTPAK is presented in a "menu" mode providing the user with questions and choices to guide the user through normal operation. Once dispose files are re-formatted, the data are available for graphic display. Three programs are used for analysis and display: 1) LINEPLOT, creates a two dimensional plot of a single dive; 2) DIVEPLOT, creates a three dimensional plot of a group of dives; and 3) HISTGRAM gives a histogram and statistical summaries for a group of dive durations or depths. All three programs can be used to create presentation quality displays on a dot matrix printer with graphics capabilities.

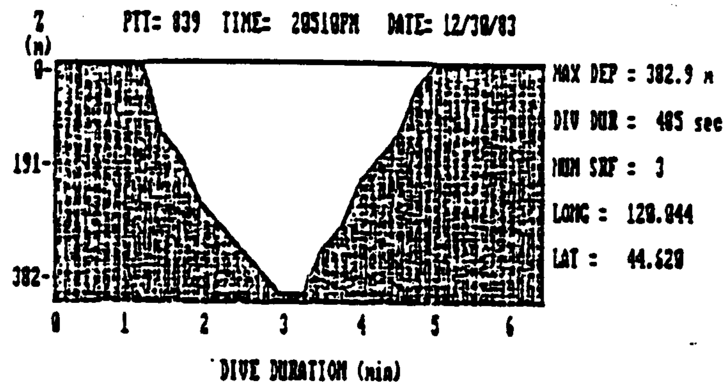
From time to time the procedures for accessing Service Argos data change. Thus, persons interested in using the SWTPAK software should consult with Service Argos or a user familiar with the system before attempting access. A sample of a typical interrogation of the Argos computer is shown in Figure 26. Two versions of LINEPLOT graphics can be seen in Figure 27 depicting a hypothetical whale dive of 485 s duration, reaching a maximum depth of 382.9 m. Figure 28 depicts an example of DIVEPLOT's ability to illustrate data using three dimensional graphics. An example of this might be the duration of dives by time of day and calendar day of the month where peaks would show when (time of day and year) the longest dives occurred. The vertical axis may also be used for dive frequency on a per hour basis throughout the year to show when diving was most frequent, and might be expected to show a significant difference between calving periods, migrations and the feeding season. Figure 29 demonstrates the HISTGRAM program output, looking at the temperatures reported from a PTT-equipped manatee after its release in the Homosassa River during January 1985. Manatees prefer warm water. The cold temperature readings were recorded when the animal moved out into the cooler ocean waters to move between the Homosassa River and Suwannee River Sound. During this open water movement the animal traveled at least 72 km in 36 hours. This was somewhat startling to knowledgeable biologists and the fastest documented movement of a manatee over this distance.

MANATEE MOVEMENTS -- 1985

Although manatee work was not funded directly by MMS, a discussion of these experiments is appropriate because the same PTT electronics developed under MMS funding for whales were used and functioned for such a long period that utility of the SWTPAK could be demonstrated on a large data set. A contract to OSU from the U.S. Fish & Wildlife Service (and supplemented by Florida Power & Light) had been developing a subdermal attachment for a manatee VHF radio tag for tracking in nearshore ocean waters. A parallel development (Rathbun, et al., unpublished data) used a strap around the animal's caudal peduncle and a swivel to attach a 2 m nylon rod to a floating VHF transmitter. This technique proved so successful that the OSU funds were reallocated to design and build a floating PTT for satellite tracking. The design work was carried out during 1984 and a unit was field tested in January, 1985.

```
please type your terminal identifier
-2240-010-
please log in: CNESERVICE

password: 120803101023
itt/remote network:  call connected  via  itt:

*** ARGOS SYSTEM READY  PLEASE LOGIN
LOGIN.0040.PIERRE


LOGIN  AT 065/1826

*
*WELCOME TO THE ARGOS PROCESSING CENTER.
*FUNCTIONING OF THE CENTER IS NOMINAL
*ORBITAL ELEMENTS
*SAT1 064/22222 229.4-22.2 102.0
*SAT2 064/10222 122.2-22.2 101.1

ARGOS READY
*STAT


*
      **STATUS LABEL USER 0040  **

**N.EX**FILES  **SIZE**REC.TIME**STAT**

**0263**086602**0004**065/0620** AVA**

**0263**086001**0002**065/1221** AVA**

**0263**086C01**0003**065/1241** AVA**

PUBLIC FILE LAST UPDATE : 065/1822

ARGOS READY
*srv.0263.ds6602


*
  263  11    847  4 12348 85  65  0 28 57 3  -1 2           0 401650245          001
  263         3       29.317  276.885   27.882  269.944       0 401650203          002
  263 12348   0 22 57   1  202               138        000           000          003
  263 12348   0 24 57   1  202               143        000           000          004
  263 12348   0 25 57   1  203               148        000           000          005
  263 12348   0 26 57   1  203               154        000           000          006
  263 12348   0 27 57   1  203               161        000           000          007
  263 12348   0 28 57   1  203               186        000           000          008
  263 12348   0 30 57   1  202               185        000           000          009
  263 12348   0 32 57   2  203               200        000           000          00A
  263 12348   0 33 57   1  203               198        000           000          00B

ARGOS READY
*COM.0263.DIDK.00847


*
EXP 0263

00847  29.276N  82.104W OR 22.928N 112.624W  065/0920Z-
  ( 1)  199           246         .  009           000

ARGOS READY
*LOGOUT


LOGOUT AT 065/1827
```

Fig. 26. Sample Service ARGOS Session.



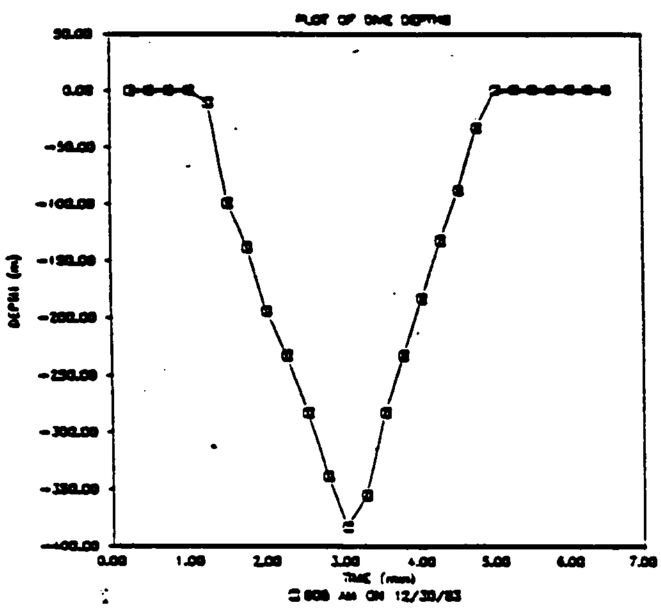


Fig. 27. LINEPLOT dive profile in full graphics mode (above) and Golden Graphics (tm) software (below).

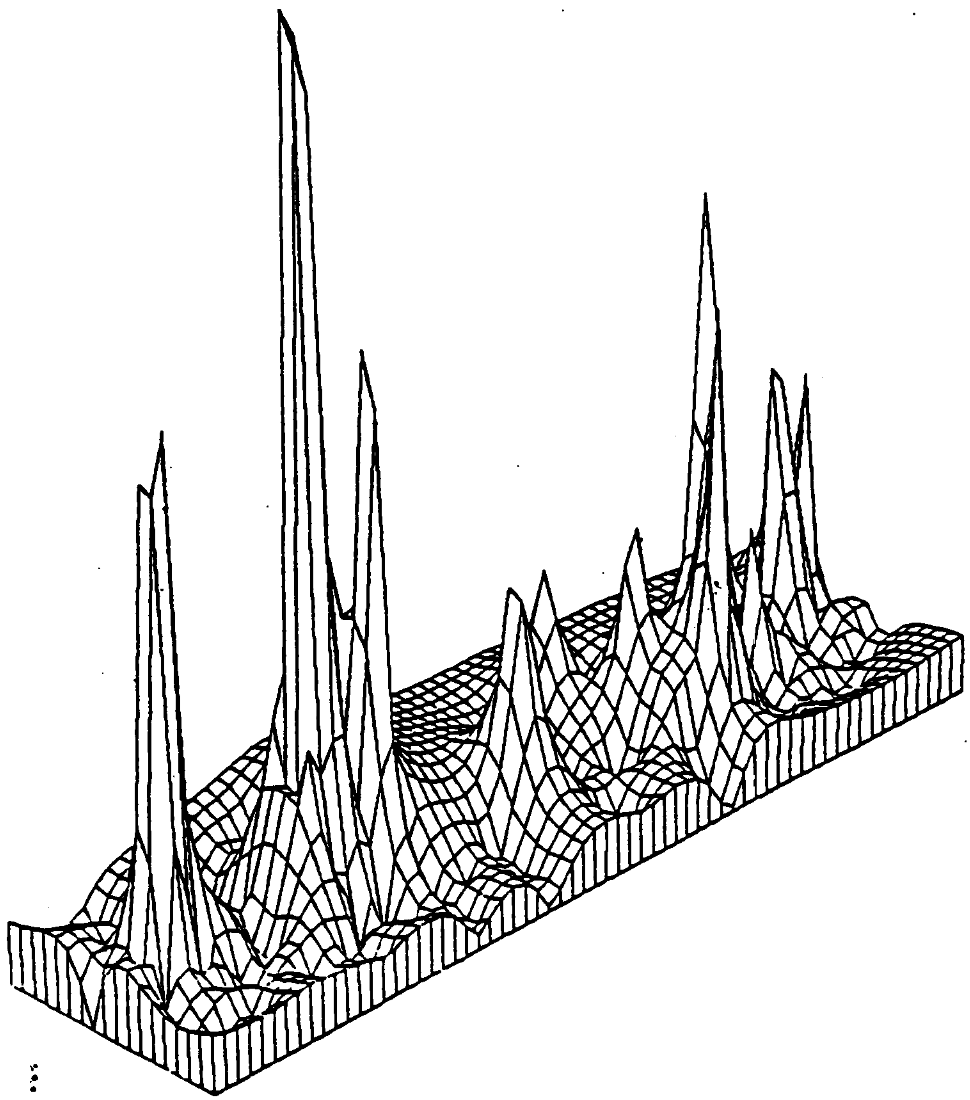


Fig. 28. DIVEPLOT 3-D plot using Golden Graphics (tm) software.

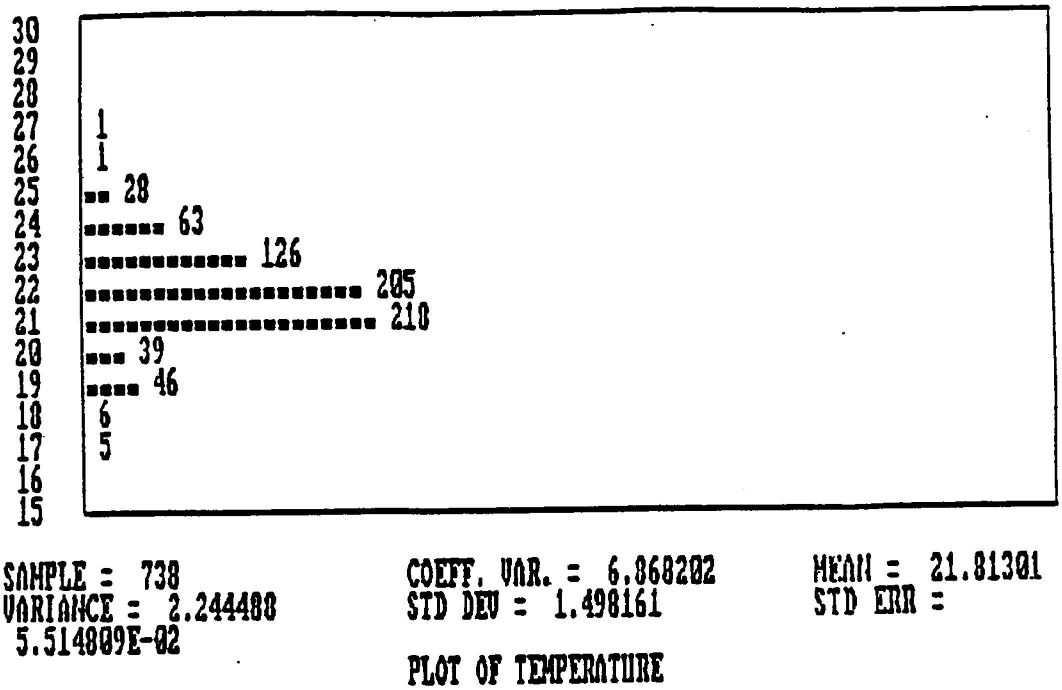


Fig. 29. Frequency histogram of temperatures (degrees Centigrade) for a satellite-monitored manatee in 1985.

The initial manatee experiment in 1985 and a more extensive 1986 experiment are reported here only to show the PTT and SWTPAK capabilities. Each PTT was housed in a watertight PVC plastic pipe, 35 cm long and 4.5 cm in diameter. It floated vertically with about 4 cm of freeboard, exposing a 12 cm stainless steel whip antenna covered with shrink tubing (Figure 30). The submerged end was tapered to shed aquatic vegetation and reduce hydrodynamic drag. The normally slow movements and shallow water nature of manatees caused the antenna to remain above the water and transmit for long periods of time.

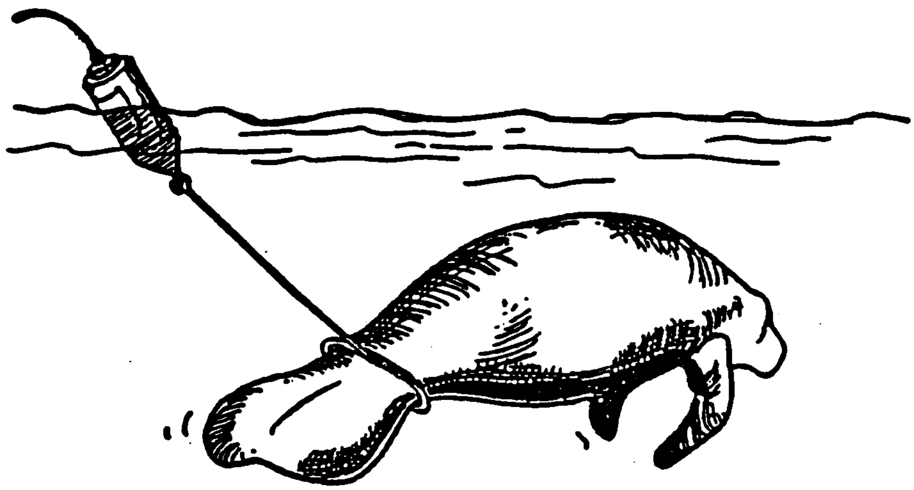


Figure 30. Drawing of the PTT and method of attachment to a manatee.

This was the first PTT to use programmable duty cycling to reduce its power consumption. In 1985 the PTT transmitted on 1 min intervals during two 8 hour periods each day (960 transmissions/day). The PTT sent information from motion sensors and about the internal temperature of the transmitter. An adult male manatee, which had been held in captivity for several years following its rehabilitation, was fitted with the PTT and released in an enclosed area approximately 500 m x 50 m at the headwaters of the Homosassa River on 5 February 1985. During the next 8 days, 443 messages were received during 80 orbits and 46 locations were calculated ($\bar{x}$ = 3.3 locations/day). The mean distance of these locations was 313 m from the center of the impoundment which compared favorably with the maximum radius to the area. Ninety-six percent of the locations were within 600 m of the center of the impoundment and the other 4% (2 locations) were within 2 km. The water temperature in the spring fed area was between 21°C and 25°C. The mean PTT temperature was 23°C. The manatee was released with the PTT attached on 19 February into the Homosassa River. During the next 36 days of free-ranging activity, 91 locations were determined by Service Argos ($\bar{x}$ = 2.5 per day). Warm springs and rivers flowing from warm springs are common habitat for manatees during winter months when ocean waters are colder than their apparent preferred temperatures.

The manatee stayed in the Homosassa River for 3 days and then swam approximately 72 km north in 36 hours to the mouth of the Suwannee River for a minimum average speed of 2 km/hr. On 18 March the manatee swam approximately 55 km south in one day to the mouth of the Withlacoochee River. On 26 March 1985 the functioning PTT was removed from the manatee for replacement of its batteries and a VHF transmitter was attached to the original tether. The manatee was relocated on 15 April at the mouth of the Suwannee River and retagged with the original PTT which functioned for an additional 64 days before the batteries were exhausted, as expected. During the second tagging period 117 PTT locations were determined ($\overline{x}$ = 1.83 per day).

The mean PTT temperature, from 738 messages following the release, was 21.8°C. Temperatures as low as 17°C were recorded during the animal's movements between rivers, and temperatures as high as 27°C were recorded while the animal was at the mouth of the Suwannee.

This experiment demonstrated 100 days (36 and 64 continuous days) of free-ranging activity and was the first experiment with such long term success in satellite tracking a marine (or terrestrial) animal. The U.S. Fish & Wildlife Service considered the satellite-collected information extremely cost effective as daily free-ranging movement data would have been much more difficult and expensive to obtain by monitoring VHF tags, despite the manatee's inland and nearshore preferences (O'Shea, pers. comm.). During its free-ranging period of 100 days, the manatee was located 261 times and covered a total distance of at least 1141 km for an average movement of 11 km/day.

The manatee has a reputation as a slow and sluggish animal. This experiment proved that manatees can move reasonably fast, navigate to offshore areas aperiodically (such as Suwannee River Reef 4 km offshore) and are extremely mobile, using even tributaries (Figure 31). The mobility and variety of habitats for a single animal may partially explain why estimates of the population have been consistently lower than might be expected (from annual mortalities). These "Generation 1" model PTTs had a limited operational life of 65 days because the oscillator had to run continuously.

Fig. 31. The locations of a satellite-monitored manatee in the Suwannee Sound region of western Florida.

Table 7. Monthly message statistics for a satellite-monitored manatee in 1986.

	#Messages	#Messages/Day	#Days W/O Messages	#Mess/Day W/Messages	#Orbits W/Messages
Jan 5 - 31	698	25.85	1*	26.85	106
Feb 1 - 28	853	30.46	0	30.46	122
Mar 1 - 31	869	28.03	2*	28.97	122
Apr 1 - 30	1020	34.00	0	34.00	137
May 1 - 31	951	30.67	0	30.67	113
Jun 1 - 30	882	29.4	0	29.4	128
Jul 1 - 31	911	29.58	0	29.58	129
Aug 1 - 31	765	24.68	0	24.68	123
Sep 1 - 30	746	24.87	0	24.87	123
Oct 1 - 31	515	16.62	4	19.07	100
300 days TOTALS:	8216	27.39	7	28.04	1203

*Service Argos not in operation

MANATEE TRACKING -- 1986

Three additional manatees were tagged with Telonics (Generation 2) PTTs in the Fort Myers region on the west coast of Florida during January 1986. One tag was removed by an alligator after 143 days and another by a fisherman after 58 days. The third tag remained active for 302 days after tagging (approximately 290,000 transmissions) before the batteries were exhausted. The messages received during the last 2 days were garbled and not useful. During the first 300 days of operation, however, 8,216 messages were received on 1,203 orbits ($\bar{x}$ = 27.4 messages/day, Table 7). A total of 693 locations were determined during 287 days from the day of tagging through 18 October ($\bar{x}$ = 2.4 locations/day, Table 8). The deterioration of the PTT batteries during the last month was apparent from the monthly statistical summaries showing fewer messages/orbit, fewer days with messages and fewer locations/month. No locations were determined during the last 15 days of operation and messages were garbled during the last 2 days. Over the operational life of the PTT, an average of 4 orbits/day acquired new data with an average of 6.83 messages/orbit.

The manatee basically stayed within a 150 km^2 area in the general Fort Myers region during the entire 10 months of monitoring. Figure 32 shows the 693 locations of the animal from 5 January through 18 October and shows the relative importance of some areas to the manatee. However, it does not show the animal's dynamic movements and the importance of specific locations at certain times of the year. For instance, Figure 33 shows the importance the southern end of Pine Island during the month of May. Lines connecting chronological locations show that the animal moved exclusively within this region, frequently moving from one side of the island to the other and exploring a channel in the upper portion of the map on 3 separate occasions over a 28 day period. In contrast, the manatee's movements during the months of July and August were wide ranging along the barrier islands and both the northern and southern ends of Pine Island. The manatee avoided the highly developed man-made waterways virtually throughout the year. The manatee usually moved slowly between locations (Table 9) with the longest ranging movements and highest speed (2.2km/hr) in June.

Table 8. Monthly position (location) statistics for a satellite-monitored manatee in 1986.

	#Pos.	AV #POS DAY	# DAYS WITH NO Pos.	AV # POS DAY WITH POS.
Jan 5 - 31	58	2.15	4*	2.52
Feb 1 - 28	71	2.54	3	2.84
Mar 1 - 31	71	2.29	5**	2.73
Apr 1 - 30	84	2.80	0	2.80
May 1 - 31	86	2.77	3	3.07
Jun 1 - 30	74	2.47	1	2.55
Jul 1 - 31	77	2.48	0	2.48
Aug 1 - 31	60	1.94	2	2.07
Sep 1 - 30	68	2.27	2	2.45
Oct 1 - 18	44	2.44	0	2.44
TOTAL	693	2.41	20	2.59

*Service Argos not in operation for 1 day.
**Service Argos not in operation for 2 days.

Table 9. The monthly mean and standard deviation of speed between locations by a satellite-monitored manatee #10023 during 1986. Only distances greater than 3 km were used to calculate speeds.

Month	Occurrences	Speed	
		Mean	Sd
Jan	11	.457	.439
Feb	18	.429	.202
Mar	16	.539	.340
Apr	26	.443	.237
May	27	.398	.190
Jun	26	.645	.516
Jul	16	.540	.278
Aug	24	.499	.282
Sep	11	.445	.205
Oct	08	.640	.647

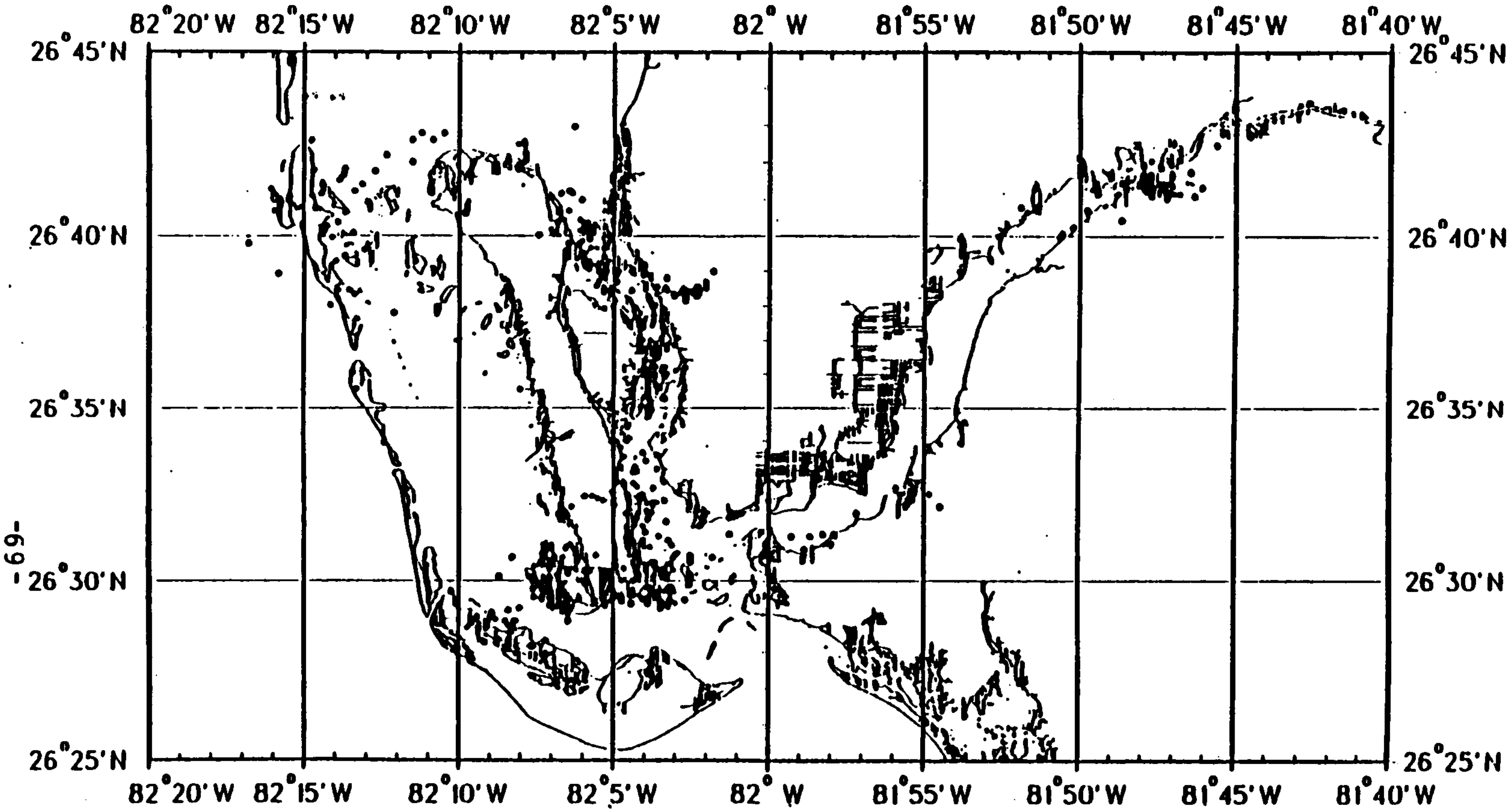


Fig. 32. Satellite-monitored manatee movements: 1986 - Tag #1002

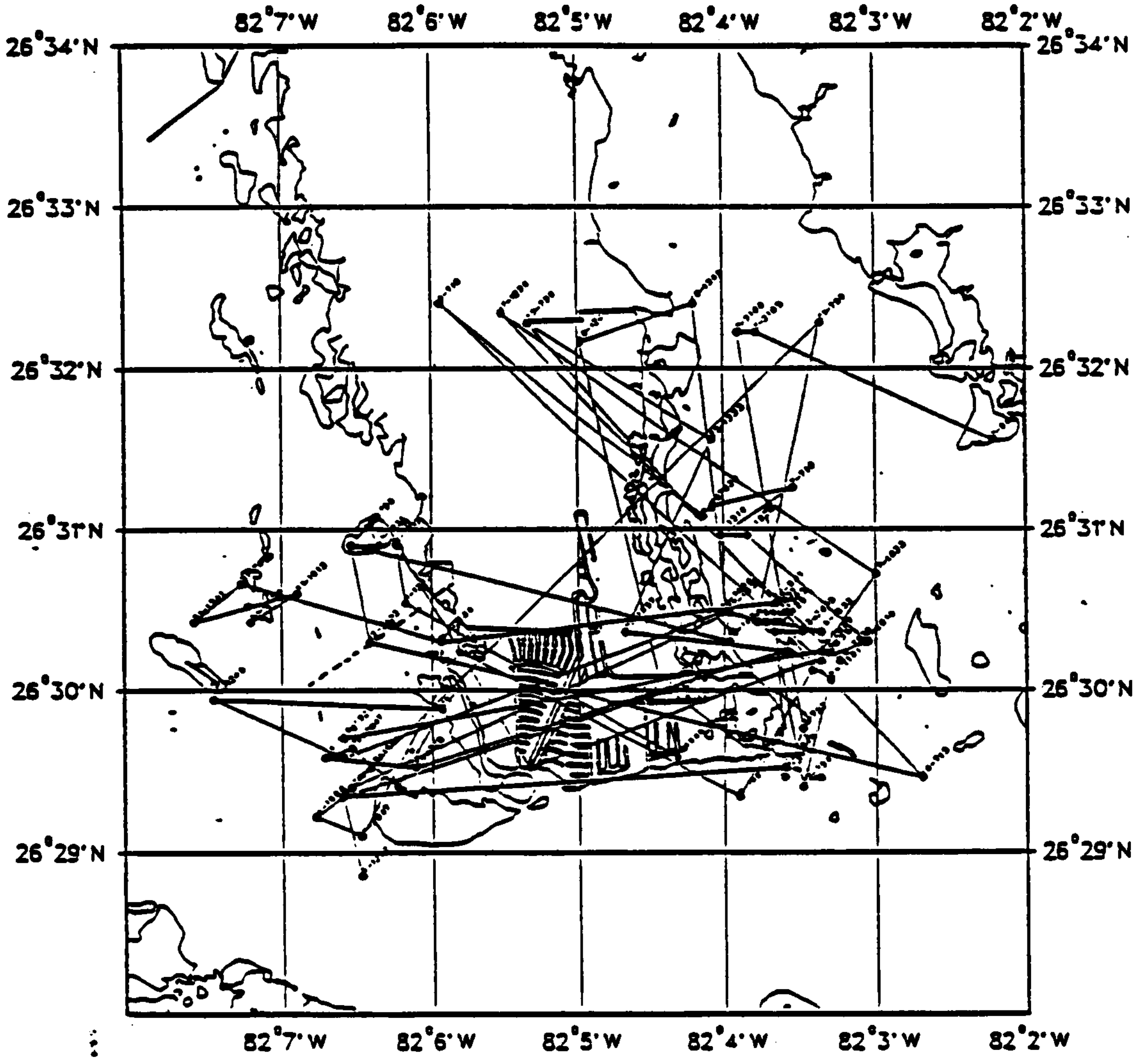


Fig. 33. Manatee movements: May 1986 - Tag #10023

The transmitters used during the 1986 field season were second generation Telonics PTTs incorporating the more energy efficient oscillator and microprocessor controlled duty cycling. The PTT transmitted on 1 min intervals during 2 periods of 8 and 7 hours when satellites would be orbiting the area. The number of orbits acquiring new data each month was relatively consistent and had the same proportion between night, morning and afternoon (Figure 34). The different number of orbits (night, morning and afternoon) reflects the differences in the actual number of orbits during those time periods and not differences related to the animal's behavior.

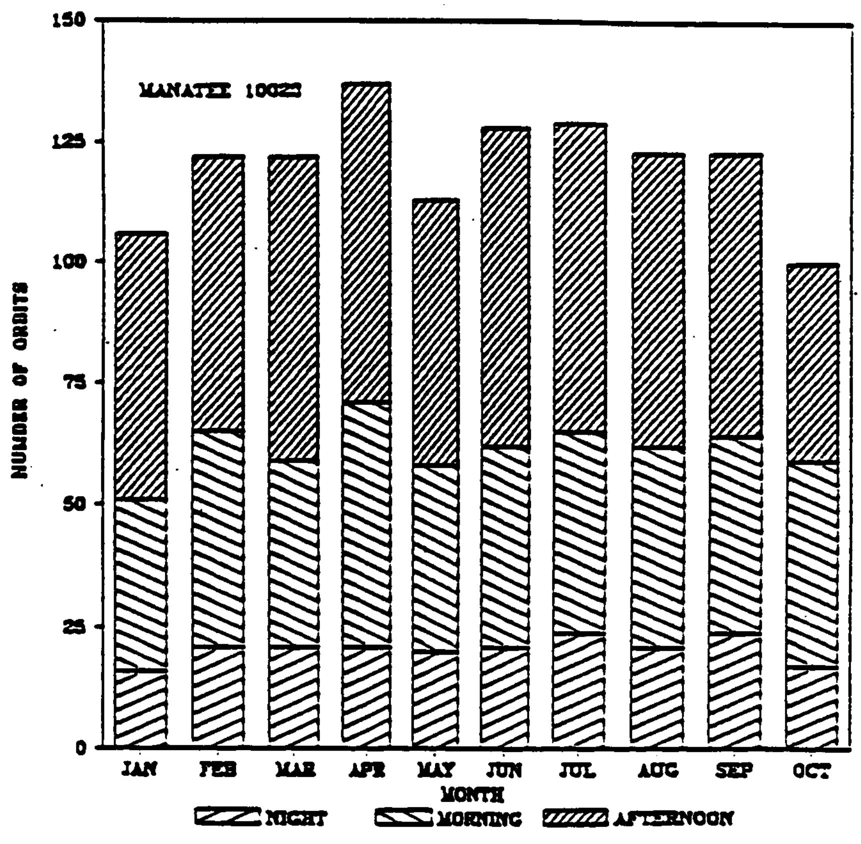


Fig. 34. A frequency histogram of the number of satellite orbits during which transmissions from manatee #10023 were received. The data are partitioned into time segments of NIGHT (07:00-09:00 GMT), MORNING (12:00-16:00 GMT) and AFTERNOON (18:00-22:00 GMT) during January to October 1986.

Early in the year, the water temperature appeared to be a primary factor in keeping the manatee within a single 5 min grid (Table 10). A general warming trend in the minimum, maximum and mean temperatures continued throughout the tracking period with only minor fluctuation until October when a definite dip in the minimum temperature was observed. Although the mean temperature was nearly the average of the minimum and maximum for most months, the first and last month represented the best evidence of the animal seeking warmer temperatures. The relatively low standard deviation of PTT reported temperatures also indicates that the animal did not often venture into colder waters.

Table 10. Monthly temperature statistics for a satellite-monitored manatee in 1986.

	MONTHLY TEMPERATURE (CENTIGRADE)			
	Mean	Min	Max	Sd
Jan	23.44	12	29	2.23
Feb	23.40	18	29	2.41
Mar	24.53	18	30	2.37
Apr	25.68	22	29	1.59
May	29.68	25	34	1.76
Jun	32.18	30	34	1.11
Jul	32.76	29	36	1.54
Aug	32.30	28	35	1.44
Sep	32.71	30	36	1.38
Oct	32.42	24	36	2.16

DEVELOPMENT OF A REMOTE DELIVERY SYSTEM

Remote Delivery System

Because satellite-monitored tags, in suitable pressure housings, weigh AT LEAST 1.5 kg, it has been difficult to consider fully projectile tags (see bowhead section), yet getting close enough for pole deployment has required specialized circumstances. It is generally difficult to approach most whales to within the 3 m distance necessary for pole deployment. The possibility of using a small radio-controlled (R/C) helicopter to deliver the tag and applicator to a whale at distances up to 50 m was explored in 1985 and 1986. The long distance flying capacity of R/C helicopters had already been demonstrated by flying one across the English Channel. In January 1985 Len Mount, then British National Champion of R/C model helicopters, demonstrated the feasibility of carrying a payload of 18 kg. Domestic animals (cattle, goats and sheep) did not react to slow flight maneuvers within 10 feet. This was particularly encouraging in light of the known sensitivity of whales to aircraft and helicopter sounds. Whales probably react primarily to low frequency sounds generated by helicopters, especially the low frequency beating, known as rotor slap, associated with pitch changes and heavy payloads during flight. R/C helicopters do not generate much low frequency noise even after 10,000+ rpm engine speed. Geared down, their rotor blades have tip velocities of 150 mph, producing a high frequency noise. Higher frequency sounds are more quickly attenuated in saltwater. With conventional mufflers, the noise level of the R/C helicopter was only 86 decibels. During September 1985, Mount was hired under Alaska Oil and Gas Association (AOGA) funding to conduct tests on the North Slope to demonstrate the feasibility of flying R/C helicopters in the Arctic and around bowhead whales. The 140 cm long helicopter with a 122 cm rotor span was demonstrated to MMS personnel and interested AOGA members in Anchorage enroute to the North Slope. The work was conducted under the auspices of a permit granted by National Marine Fisheries Service (NMFS) to MMS to determine the reactions and effects of aircraft noise on bowhead whales.

Special arrangements were made to conduct the research in Canadian waters, since it was anticipated that whales would still be in ice-free waters around Komakuk where they had been seen within the previous week. Bad weather precluded observations in the Komakuk area for several days and ice formed over such a large area that while waiting for the weather trend to reverse and generate open water, the R/C helicopter was tested in the Prudhoe Bay area. Fitted with a 16 ounce gas tank (approximately 40 min of flying) the helicopter's maneuverability and speed proved to be excellent in tests at $0^{o}C$. Recognizing that offshore operations might be necessary, a large helicopter Messeerschmidt Bullcow was used to take the R/C helicopter operation to an ice floe edge (Figure 35). A portable remote starting system proved practical for cold weather starts. Because whales might be found too far from shore or ice leads for a R/C pilot to work his

Fig. 35. A radio-controlled helicopter flown from a full-sized helicopter in flight carried an 18 kg payload at 70 km/h in temperatures below freezing.

machine, Mount demonstrated his ability to fly the R/C helicopter while he was a passenger inside the full-scale helicopter in flight. It worked well the very first time. The R/C helicopter carried an 18 kg weight to simulate the radio tag/applicator and flew at 70 km/hr at an elevation of 130 m for 25 km. A gas line, which was not properly secured, came loose in flight and resulted in an emergency auto-rotation of the R/C helicopter onto a gravel bar. The damage was minor and the R/C helicopter was ready for additional test flights after only 1.5 hours of repair.

As the noise of a large-scale helicopter is directed mostly at right angles to the rotor blades, it was hoped that a large helicopter might be able to hover over an ice floe quietly enough not to disturb whales but close enough for a R/C pilot to operate his helicopter. The large helicopter had four rotor blades and has had some success in approaching large whales without frightening them, which may be attributable to less of the low frequency rotor slap commonly associated with two-bladed helicopters.

As a result of the R/C test flights, recommendations were developed to improve the helicopter's lift, noise suppression and long duration flight capability. Because MMS funds were not available for the development of the R/C helicopter, AOGA funds were used to pursue its further development for field testing in the 1986summer humpback whale tagging season. This was done with the hope that further tagging during the fall of 1986 on bowhead whales would be possible (see the assessment of the R/C helicopter under 1986 humpback field studies).

HUMPBACK WHALES - 1986

BACKGROUND

MMS directed that the latest PTT technology be tested on humpback whales before application to bowhead whales. Cape Cod was chosen as the study area for tagging humpback whales because: 1) whales were historically abundant in this area; 2) investigators had catalogued 286 identifiable whales in the area with long histories, including reproductive data, for many individuals; 3) extensive ongoing studies by investigators in the area assured follow-up observations of behavior, location accuracy and tag condition; 4) other studies in the breeding area

(Silver and Navidad Banks) were planned which might relocate tagged animals and examine the condition of the tag/attachment; and 5) identifiable whales might be relocated in subsequent years so the long term visible effects of tagging (such as discoloration, scarring or tissue erosion) could be examined.

In preparation for this field effort, modifications of attachments, housings, PTT programming and an alternate delivery system were developed.

Housing Design

The MMS criterion for a successful PTT was 2 months of operation. This could be accomplished with the use of 3 organic lithium "C" cell batteries. The lowest possible profile was dictated by the size of the batteries and resulted in a housing design which was nearly square with low hydrodynamic drag . It appeared that the pressure housing could be made with molded, light weight, high-density urethane plastic. With a bulkhead running through the center of the housing, the unit withstood pressures up to 21.5 atmospheres (300 psi) simulating a depth of 215 m. The housing was low profile and light weight, but it failed long-term moisture penetration tests in November and December of 1985 (Figure 36).

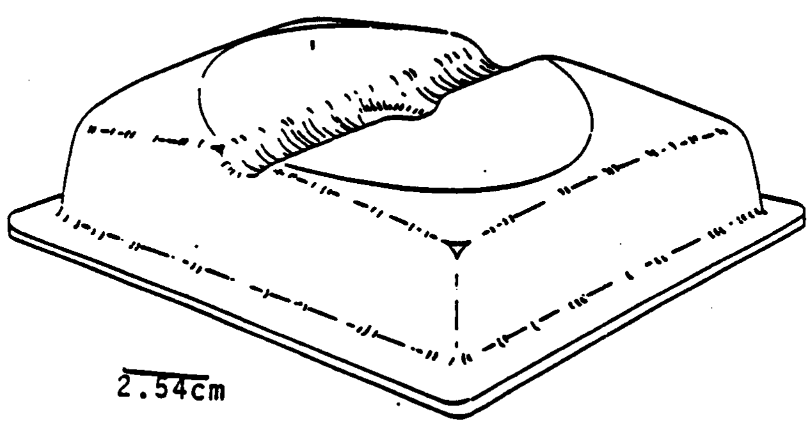


Fig. 36. A prototype PTT housing of thermal molded plastic.

During January and February of 1986 an alternative housing design was developed. Although somewhat larger and heavier than the initial design, it provided for twice as much space for batteries. An O-ring sealed the hydrodynamically shaped circular cover over a lip in the PTT base (inset approximately 1.2 cm from its outer perimeter, Figure 37). This was a vast improvement in size, weight and shape over the previously deployed whale PTTs. The quarter-wave, flexible whip antenna and antenna feed-through designs from the successful manatee PTT were used. The base and housing were constructed of stainless steel. The 40 mm thick base was 14.5 cm in diameter. The housing cover was 13.5 cm in diameter at its base and tapered to 11 cm in diameter at its apex. Twelve "forming" fixtures were evenly spaced around the perimeter of the base. An electrically isolated saltwater switch was located along the sloping side of the housing and stood off on a machined mound of insulative delrin. The latter was sealed with two O-rings to prevent water penetration into the PTT housing. The entire housing was covered with teflon to promote rapid wicking of saltwater and to discourage the growth of algae. A flexible stainless steel antenna (16.5 cm long) was located in a 2.5 cm depression in the top which was filled with high density polyurethane.

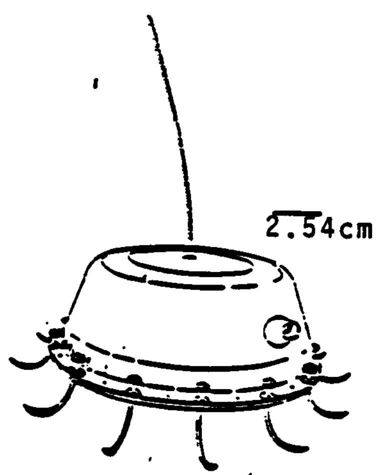


Fig. 37. A PTT with a teflon-coated spun-cast housing, deployed sutures, saltwater switch and stainless steel antenna as applied to a humpback whale in 1986.

The original umbrella tag had one serious flaw. The precurved wires bent at their insertion into the piston as part of the deployment process and were easily bent straight again. A system of forming hollow subdermal sutures was developed during the manatee work. Stainless steel 16-gauge hypodermic needles were used instead of wires. A separate forming "fixture" was used to bend each needle precisely, controlling the depth of penetration and lateral deployment. Each subdermal suture was filled with an antibiotic to medicate disturbed tissues immediately, reduce infection and promote healing. The early manatee prototype used four sutures and was powered by a CO_2 cartridge. The activation of the applicator was initiated by only one pound of pressure. The pressure required to form 10 to 12 sutures around the perimeter of a whale PTT could not be generated by reasonable volumes of CO_2 so a specialized applicator was developed.

The applicator (Figure 38) consisted of a hydraulic master cylinder driving 12 slave cylinders. Each slave cylinder was responsible for forming a single suture. The master cylinder was driven by a Holex 6502 (400 mg) pressure cartridge which was

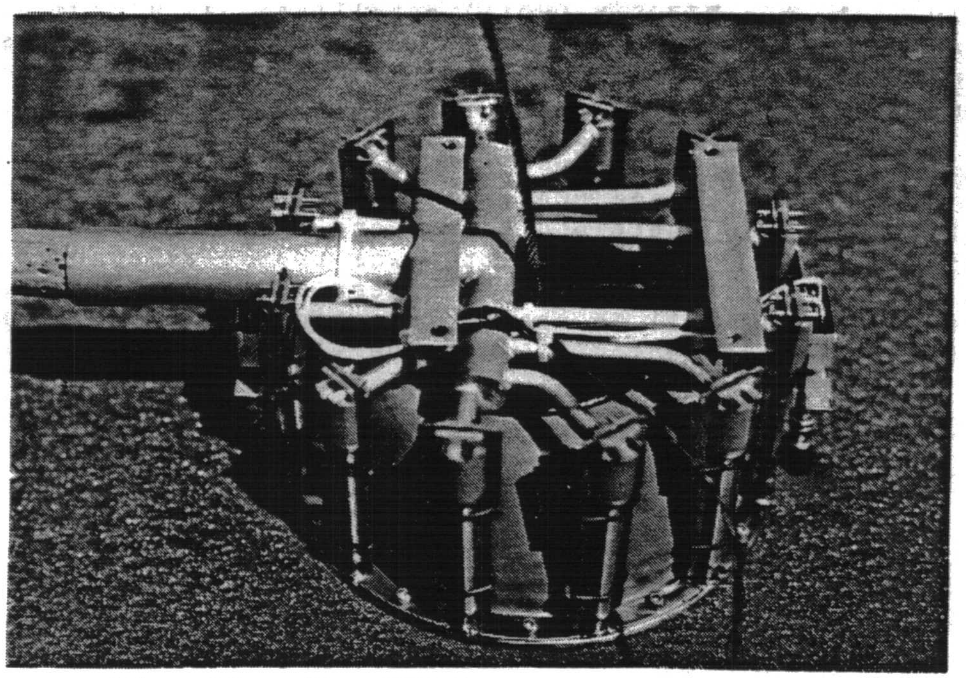


Fig. 38. The PTT loaded in its applicator.

electrically activated by 2 pressure sensitive switches in series at opposite sides of the applicator's base. The tag had to be flat on a surface (whale's back) to have both switches close and initiate attachment. Pressure tests to 300 m resulted in deflections beyond acceptable limits although the housing did not fail mechanically and remained watertight. An internal reinforcement (which could be accommodated within the existing space) was developed and tested at the sacrifice of internal shock absorbing materials. The final housing accommodated 6 C-cell organic lithium batteries providing 12 ampere hours of power. In calculating the useful life of these batteries with high current loads, they were de-rated to 10 ampere hours.

Transmitter Duty Cycles

The energy savings accomplished in the second generation manatee tag by using the oscillator intermittently proved its value by increasing the operational life of the PTT by 500%. the same technology was incorporated into the 1986 whale PTT.

Normally, only two TIROS-N (NOAA) satellites carrying Argos receivers are operational at the same time. Each satellite has a different orbit and is usually replaced before its orbit deteriorates or equipment wears out. However, NOAA-8, the replacement for NOAA-6, failed after launch, so NOAA-6 was reactivated despite a badly decayed orbit. Two anticipated launches of NOAA-10 to replace NOAA-6 had to be rescheduled following the Challenger shuttle disaster and two other NASA rocket launch failures. The transmitter was thus programmed to accommodate the calculated orbital parameters of NOAA-6 and NOAA-9 which were in use, as well as the anticipated orbital elements of NOAA-10 (finally launched on 17 September 1986). These parameters collectively established the overall transmission duty cycle. These data were provided to Telonics to program the transmitters during their construction. The timing of satellite passes varies from one location to another and is sensitive to latitudinal and longitudinal change. Thus, transmission times were optimized for several latitudes because humpback whales tagged off Cape Cod might continue to move north to Newfoundland or migrate south in winter to Silver Banks in the Caribbean. The calculation of orbital passes has since been greatly simplified by the development of a satellite predictor program by Telonics in 1986. There is no comparable product available on the market. In addition, predictions can be displayed on a monitor or a dot matrix printer (Figures 39 and 40).

Because it was not known when the transition between NOAA-6 and NOAA-10 would occur, it was necessary to accommodate all three satellites and allow the transmitter to function for 20 hours each day. An estimated operational life of 9.5 months would have been possible if humpback whales surfaced on the average of once every 90 s (as in 1983 tagging) and the transmitter had been limited to operating 8 hr/day to cover 2 dependable satellites. However, with 20 hr/day of operation, the operational life was reduced to 4.5 months.

Permit

Operational and logistics planning for humpback whale operations in Cape Cod took place during the Society for Marine Mammalogy meeting in December 1985 and were confirmed by early 1986. Permits for humpback whale tagging operations were initiated in December 1985 and generated two rounds of questions from the Marine Mammal Commission and the National Marine Fisheries Service. The permit was issued in late May for operations which began in June. The permit allowed both R/C helicopter tagging and pole-type tagging in the region of Cape Cod.

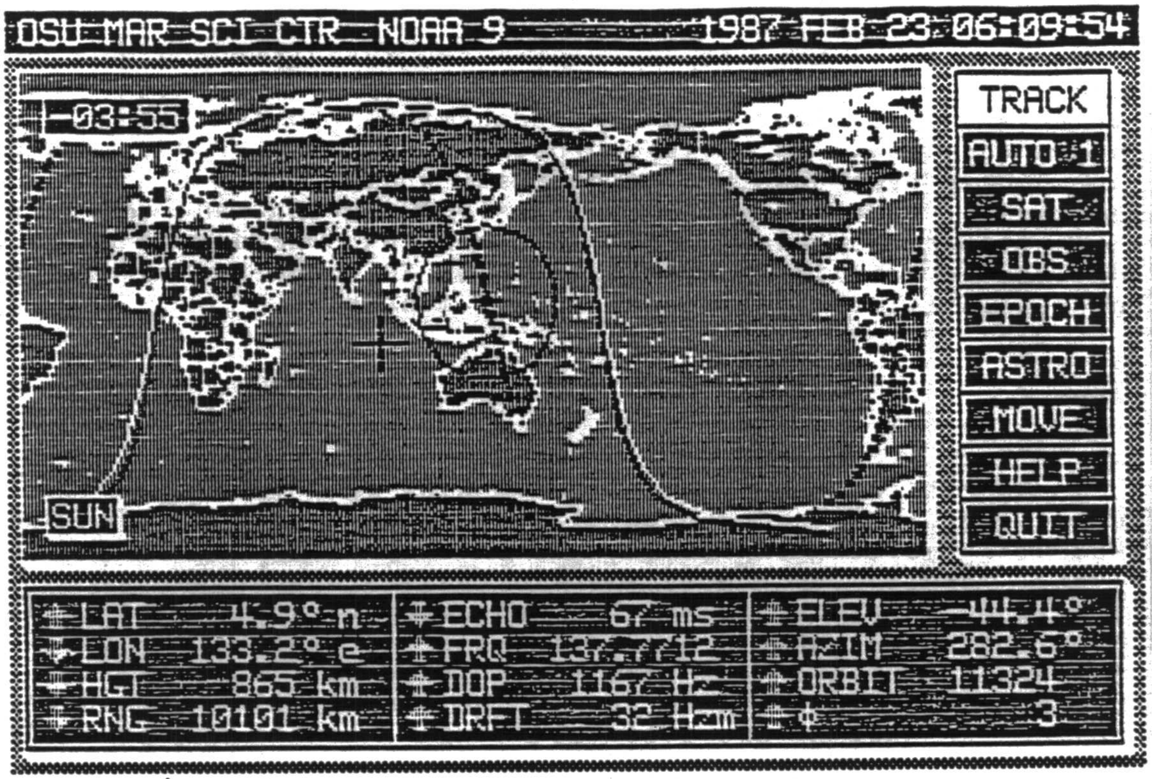


Fig. 39. A transverse mercator projection of the world showing the present position of the sun as a large cross, the NOAA-9 satellite as a cross inside a circle indicating the range within which it can receive signals from Argos PTT's, and the ascending orbital path of the NOAA-9 satellite.

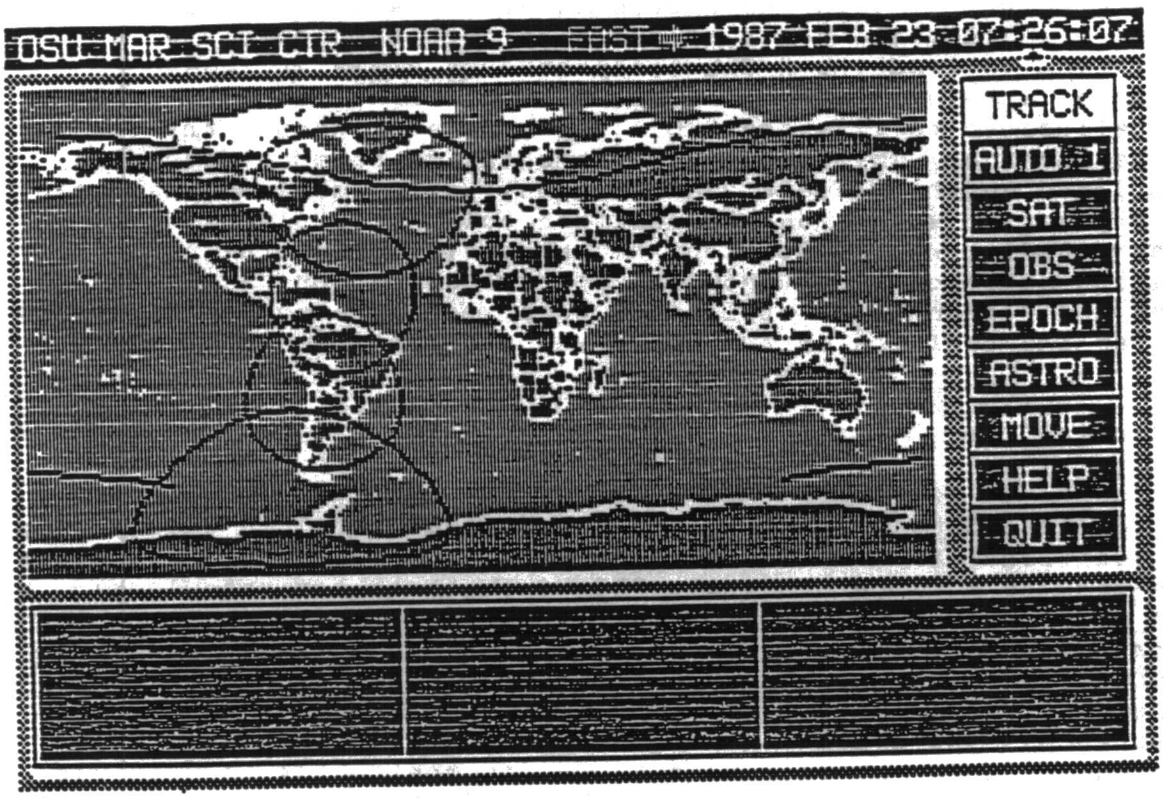


Fig. 40. Five ranges of Argos reception shown along the orbital path of the NOAA-9 satellite at 10 minute intervals. Note: the upper "line" indicates simultaneous reception for the entire arctic 75° N latitude.

Delivery System

Changes in Mr. Mount's available time necessitated a change in pilots and the construction of R/C helicopters for use in the summer humpback season. John Gorham, owner of the largest R/C helicopter supply business in the United States, recommended that OSU contract John Smith, an internationally ranked R/C helicopter competitor. Mr. Smith constructed three helicopters similar to those used by Mount in the Arctic but with larger capacity and power. To alleviate depth of field perception problems when attempting to land the R/C helicopter on a whale at some distance, a television camera and transmitter were built for the R/C helicopter to give the R/C pilot a "view" through the bottom of the machine. This would allow the tag to be more accurately positioned on the whale's back. A Sony Watchcam camera was used in conjunction with a UHF transmitter built from plans (North Country Radio, Wykagl Station, NY) to achieve a useful range. A separate radio control (from the pilot's operation) was used to "arm" and "disarm" the applicator so a second person could decide whether the position on the whale was appropriate for tagging.

Monitoring

Because Service Argos had not been successful in calculating the locations of whale PTTs in previous experiments, arrangements were made to monitor the whale PTTs from three separate local user terminals (LUTs) in different locations. Canadian Atmospheric & Environmental Services (Toronto, Canada) and MICROLOG (Washington, D. C.) were willing to monitor continuously while NASA Goddard (Bethesda, M.D.) was in a tenuous state of preparedness but could be brought on line in the event of an emergency. In an attempt to arrange for monitoring from an old Coast Guard LUT in Florida, the LUT was decommissioned and given to the project through the Office of Naval Research. The LUT was not operational and requires refurbishment (which may not be cost effective) to make it operational.

Field Operations: Cape Cod

Field work began in early June. Unfortunately, 1986 represented the lowest abundance of humpback whales off Cape Cod in living memory (Mayo, pers. comm.). Humpback whales left the Stellwagen Bank area off Cape Cod in late May and did not return in significant numbers until November. Nonetheless, we attempted without success until late June to find humpback whales on Stellwagen Bank. Contact was maintained with 4 tour boat operations which searched large areas but were unsuccessful in finding any whales within our boat's operational range. The Center for Coastal Studies (CCS) provided: space to the project, additional people, logistics, and contacts with fishermen and other whale researchers in an attempt to locate animals for our tagging effort. The CCS vessel, SIRRUS had spotted humpbacks in the Great South Channel (GSC) in mid-May and early June. Some of the photos from the the June cruise identified whales previously seen on Stellwagen Bank in April and May. The availability of whales in the GSC was confirmed from fishermen in that area. The fishing vessel JOANNA, a 65 foot trawl fishing boat, was chartered to extend operations to the GSC but summer storms and high seas resulted in only 2 trips in late June. During both trips humpback whales were observed feeding on sand lance at the surface in the early morning or late afternoon. Sand lance has been the primary food of humpback whales in the Cape Cod region, but according to National Marine Fisheries Service scientists, sand lance virtually disappeared from Stellwagen Bank during the summer of 1986 (Smith, pers. comm.). This was confirmed during research submarine observations by Winn (pers. comm.).

A selection of candidate whales for tagging was made from the fluke catalog of local whales (Mayo et al. 1985) emphasizing animals of a suitable size with a history of repeat sightings within a single summer and which had returned to the region on multiple years.

Results

During the first charter trip humpback whales were found 10 hours from port in 1.3 m swells. The running R/C helicopter was held by a special release cable to a bow platform on the front of a 4.5 m Zodiac as we attempted to approach humpback whales. Only 2 such approaches were attempted due to the swells and the fast movements of humpbacks between concentrations of sand lance "boiling" at the surface. It was not possible to safely launch the R/C helicopter from the moving Zodiac. In the late afternoon a concentration of feeding whales was located and an attempt was made to launch the R/C helicopter from the roof of the JOANNA's wheelhouse. The height of the wheelhouse roof above the center of the vessel's rotation accentuated the swell's affect. While attempting to take off, a rotor blade of the R/C helicopter struck a radar mast and "crashed" on the ship's deck. The impact closed the "arming" relay for the applicator (usually under separate radio control) and as the tag was flat on the deck, resulted in "tagging" the vessel. The tag attached itself firmly to a fiberglass covered 2 cm thick plywood deck. Although 2 of the 12 sutures collapsed without significant penetration, 10 other sutures deployed completely and had to be removed with vise-grip pliers and a claw hammer. Whales were observed feeding for an additional hour. During active feeding it was not possible to tag with a pole, but CCS personnel and fishermen described surface resting behaviors which would have been suitable for pole-deployment.

The idea of launching the R/C helicopter from the Zodiac was abandoned in view of JOANNA's ability to get close to actively feeding whales and a 2.5 m by 3.6 m plywood landing pad was built off JOANNA's stern. The second charter (28 June) arrived in the GSC early in the morning while whales were moving rapidly between patches of sand lance to feed. Other vessels were also attempting to get close to whales. A whale known to frequent Stellwagen bank was identified (Phil Clapham, CCS) and approached as it moved between feeding areas. The vessel did not appear to affect the whale's movements but its activities were erratic, making the time and location of its next surfacing unpredictable. The R/C helicopter was launched from the back deck of the JOANNA and flew at 15 m altitude waiting for the whale to surface. On 2 successive surfacing sequences the helicopter did not get to the whale fast enough to accomplish a landing (tagging). On neither occasion did the whale appear disturbed by the small helicopter although sand lance swarming at the surface reacted to the helicopter in the same way they react to birds, suggesting a "visual" reaction. During the second tagging attempt, the helicopter descended more rapidly and, in the process of slowing down its descent, turned downwind and lost much of its lift. Not pleased with the control under these circumstances, the float-equipped helicopter was landed in the water near the JOANNA's stern to make adjustments rather than risk a downwind landing on JOANNA's rear deck. The landing was without incident but the helicopter drifted with the wind under the landing platform and a rotor caught a dangling rope. The rotor strike caused minor damage, but the shock fired the applicator and the PTT was lost in 200 m of water. Operations were halted. Further funds for vessel charter were not available and GSC was too far from shore (170 km) to safely operate the project's small boats. Notorious for fog, the GSC area is also a shipping channel so experience and radar are essential. The three days left contractually for John Smith were inadequate to rework the lift problem with appropriate modifications and further tests. As the main contractual objective was to demonstrate the longevity of the suture attachments and the PTT electronics, it was decided (in consultation with the Contracting Officer's Authorized Representative) that pole deployment of the tag should be attempted on whales entrapped in fishing nets in Newfoundland. Six whales had been entrapped in Newfoundland during the last week of Cape Cod operations (John Lien, pers. comm.).

Field Operations: Newfoundland

Field operations were moved to Memorial University of Newfoundland in St. John's with the cooperation of Dr. Jon Lien. Permission was received from the Department of Fisheries & Oceans to tag whales in the course of Dr. Lien's program to help fishermen release net entrapped whales. During 6 weeks in Newfoundland 6 humpback entrapments were examined. The first entrapment (9 July) was a 8.5 m humpback whale bridled in a gillnet in deep water 6.4 km south of Fogo Island. The whale was tagged from a Zodiac using the pole deployment system and released from the net at 10:00 A.M. Newfoundland Daylight Savings Time (1230 GMT). Of the other 5 whales, 2 died before examination, 1 was badly injured (not appropriate for tagging) and 2 were healthy. Poor circumstances (a storm brewing after dark and mechanical difficulties for both Zodiacs 5 km from shore) prevented attempts to tag the 2 healthy whales.

Most of the entrapments in Newfoundland during 1986 occurred in June (before the tagging efforts) during an enormous run of capelin and in September, well after the tagging efforts had been suspended. There were no feasible live entrapments beyond 25 July as a low production cod fishing season for most the island resulted in fishermen removing their nets in late July and early August. This reduced fishing effort made the chances of further entrapments quite small. Whales were also in very low abundance and efforts to tag ended on 13 August.

RESULTS

Tagging Attachment

The tagging of the humpback whale near Fogo Island on 9 July went very smoothly with no reaction from the whale to the tagging process. All of the entangling net was removed before tagging except for a single polypropylene rope. After the whale was tagged, but before the rope could be cut, the whale turned in a direction which allowed the rope to slide up the whale's back under tension and under the tag. At the time there was concern that the tag would be ripped completely free of the animal because of the tremendous tension on the rope. However, it was impossible to remove the tag and it appeared well attached. The whale was released 5 min after tagging with only 2 m of rope trailing from the left side of its mouth. Photographs developed after the release showed that the rope had indeed gone under the tag, damaging at least 5 (of the 12) adjacent subdermal sutures at the rear of the tag (Figure 41).

PTT Performance

The PTT performed perfectly for 22.5 hours sending 56 messages (Table 11) during 11 orbits and providing 4 locations from the Toronto LUT. Service Argos received all the messages, but failed to calculate any locations. Signals were strong and the encoded data were appropriate. Up to 10 messages were received during a single orbit. The tag likely came off 22.5+ hours after tagging as a result of the damaged sutures. The tag attachment depends on the opposition of the sutures and the loss of at least 5 posterior sutures would allow the tag to back out readily from hydrodynamic drag.

The whale moved 134 km (84 miles) from the tagging site in 20 hours and 26 min (Table 12). The whale's speed varied from 3.4 to 10.1 km/hr between locations, averaging 6.6 km/hr. This average speed was faster than the 5.3 km/hr observed for a radio-tagged northbound migrant gray whale during 29 days travel between Oregon and Alaska (Mate and Harvey, 1984), and the 4.9 km/hr average over a 6 day period for a satellite-monitored humpback off Newfoundland in 1983 (Mate, in press). The relatively fast travel speed probably contributed to the premature loss of the tag by increasing hydrodynamic drag. Despite the tagged whale's speed, 4 locations in less than 1 day were determined, which exceeded the performance of the previous humpback whale PTT in 1983 ($\bar{x}$ = 1.7 locations/day) and equaled the best (manatee) of all other completely aquatic marine animal applications (sharks, turtles, porpoises and manatees) to that date.

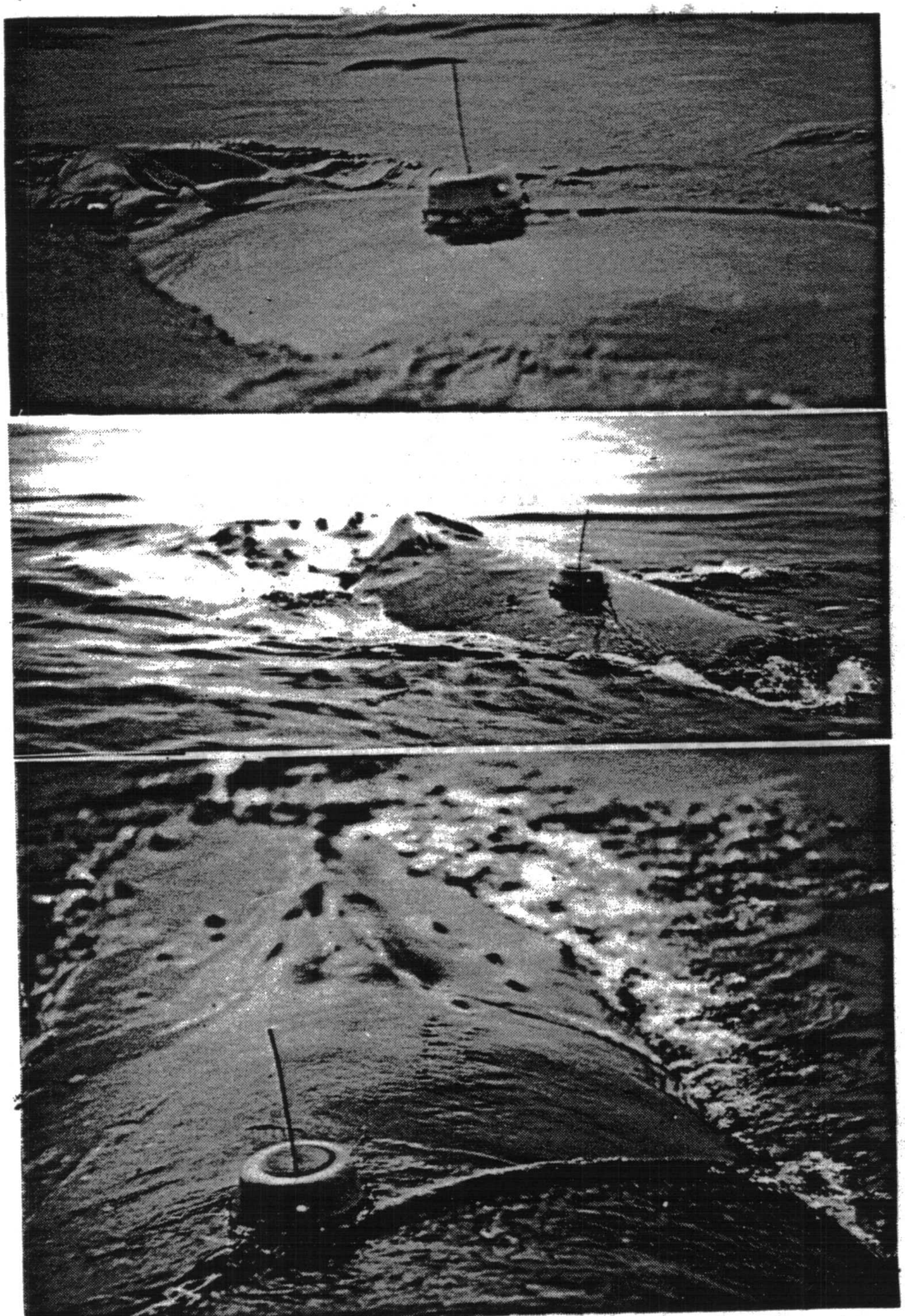


Fig. 41. Photographs of a satellite-monitoring radio tag on a humpback whale off of Newfoundland in 1986. (Note the rope under the tag in the lower frame).

Table 11. Data from whale tagged with PTT #840 off of Newfoundland in July 1986.

PTT	POSITION DATE	POSITION TIME	SAT	LAT (N)	LON (W)	TEMP	TRANSMISSION DATE	TRANSMISSION TIME	LAST DIVE TIME (SCS)	AV 12 HR DIVE TIME	# DIVES LAST 12 HR	SURFACINGS BTWN XMNS	EST DIVE TM BTWN XMNS
840	86/07/09	110903	1	49.484	-54.155	8.2	86/07/09	154440	220	2046	3	1	20.0
840	86/07/09	110903	1	49.484	-54.155	8.2	86/07/09	154520	38	2046	3	0	
840	86/07/09	171700	1	49.661	-53.650	7.9	86/07/09	171402	28	68	177	1	20.0
840	86/07/09	171700	1	49.661	-53.650	8.5	86/07/09	171645	126	68	177	1	37.0 #
840	86/07/09	171700	1	49.661	-53.650	8.8	86/07/09	171821	64	68	177	1	32.0 #
840	86/07/09	171700	1	49.661	-53.650	8.5	86/07/09	172158	194	68	177	1	23.0 #
840	86/07/09	171700	1	49.661	-53.650	8.8	86/07/09	172344	56	68	177	0	
840	86/07/09	171700	1	49.661	-53.650	9.0	86/07/09	172554	126	68	177	0	
840	86/07/09	171700	1	49.661	-53.650	9.0	86/07/09	172636	40	68	177	0	
840	86/07/09	171700	1	49.661	-53.650	9.3	86/07/09	172753	74	68	177	0	
840	86/07/09	185400	1	49.705	-53.620	8.2	86/07/09	185720	140	68	177	2	13.3
840	86/07/09	185400	1	49.705	-53.620	8.2	86/07/09	190052	178	68	177	2	17.0
840	86/07/09	185400	1	49.705	-53.620	8.2	86/07/09	190451	202	68	177	2	18.5
840	86/07/09	185400	1	49.705	-53.620	7.9	86/07/09	190904	192	68	177	1	10.0
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	191440	132	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	191744	150	68	177	2	17.0
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	191904	76	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.2	86/07/09	192332	38	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	205222	74	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	205318	54	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	205457	96	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	205727	92	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	205828	52	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	210014	110	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	210210	112	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	210323	73	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	210420	54	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	210530	66	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	223429	20	68	177	1	20.0
840	86/07/09	185400	2	49.705	-53.620	8.8	86/07/09	223553	82	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.5	86/07/09	223832	156	68	177	0	
840	86/07/09	185400	2	49.705	-53.620	8.2	86/07/09	224223	192	68	177	2	19.5
840	86/07/09	185400	2	49.705	-53.620	8.2	86/07/09	224311	12	68	177	2	18.0
840	86/07/10	71500	1	50.230	-53.072	7.6	86/07/10	71342	198	66	511	2	13.3
840	86/07/10	71500	1	50.230	-53.072	7.9	86/07/10	71715	182	66	511	2	15.5
840	86/07/10	71500	1	50.230	-53.072	7.6	86/07/10	72047	178	66	511	2	17.0
840	86/07/10	71500	1	50.230	-53.072	7.6	86/07/10	72335	158	66	511	2	15.0
840	86/07/10	71500	1	50.230	-53.072	7.6	86/07/10	72435	20	66	511	1	20.0 #
840	86/07/10	71500	1	50.230	-53.072	7.9	86/07/10	72652	134	66	511	0	
840	86/07/10	85600	1	50.281	-52.846	8.2	86/07/10	85349	72	66	511	1	20.0
840	86/07/10	85600	2	50.281	-52.846	8.2	86/07/10	90314	114	66	511	2	13.3
840	86/07/10	85600	2	50.281	-52.846	8.2	86/07/10	90411	42	66	511	1	15.0 #
840	86/07/10	85600	2	50.281	-52.846	8.2	86/07/10	90512	38	66	511	0	
840	86/07/10	85600	2	50.281	-52.846	7.9	86/07/10	90812	176	66	511	0	
840	86/07/10	85600	2	50.281	-52.846	7.9	86/07/10	90853	14	66	511	2	14.5
840	86/07/10	85600	2	50.281	-52.846	7.9	86/07/10	90949	38	66	511	1	16.0 #
840	86/07/10	85600	2	50.281	-52.846	8.2	86/07/10	91044	52	66	511	0	
840	86/07/10	85600	2	50.281	-52.846	8.2	86/07/10	91257	130	66	511	0	
840	86/07/10	85600	1	50.281	-52.846	7.4	86/07/10	103843	220	66	511	0	
840	86/07/10	85600	1	50.281	-52.846	7.4	86/07/10	103931	12	66	511	2	18.0
840	86/07/10	85600	2	50.281	-52.846	7.4	86/07/10	104238	204	66	511	0	
840	86/07/10	85600	2	50.281	-52.846	7.4	86/07/10	104340	20	66	511	1	22.0 #
840	86/07/10	85600	2	50.281	-52.846	7.6	86/07/10	104444	62	66	511	0	
840	86/07/10	85600	2	50.281	-52.846	7.6	86/07/10	104820	210	66	511	0	
840	86/07/10	85600	2	50.281	-52.846	7.6	86/07/10	104905	12	66	511	2	11.0
840	86/07/10	85600	2	50.281	-52.846	7.9	86/07/10	105215	188	66	511	0	

ALL TIMES ARE GMT

data points where exact time could be determined

Table 12. The location of tagging, locations determined by the Toronoto LUT and subsequently calculated distances, traveling speeds and mean dive durations between location.

Location	Latitude Longitude	Between Locations km	Between Locations Time(hr.)	Between Locations Speed (km/hr)	For Each Location No. Orbits	For Each Location No. Msgs	For Each Location Avg. Dive Time*
Tagging/ Release Site	49.484N 54.155W	—	—	—	1	2	A) 92.67 B) 129.0
Location 1	49.661 53.650	41.4	4.78	8.7	1	8	A) 68.33 B) 83.22
Location 2	49.705 53.620	5.4	1.61	3.4	4	23	A) 69.99 B) 110.69
Location3	50.230 53.072	70.3	12.35	5.7	1	6	A) 67.44 B) 170.0
Location 4	50.281 52.346	17.0	1.68	10.1	4	17	A) 60.72 B) 120.46
		134.1	20.42	X=6.6			

*Average Dive Time: A) All Dives
B) Dives ≥30 seconds

The PTT sent information on transmitter temperature, the duration of the last dive, the mean duration of dives > 6 s during the last 12 hour interval, the number of dives in the last 12 hour interval, and the number of surfacings between transmissions (if surfacings occurred within the first 40 s after a transmission, when the PTT could not transmit). The latter 3 measures were new innovations to interpret diurnal behavioral changes (see pilot whale data).

Temperature

Transmitter temperatures varied from 7.4°C to 9.3°C and were consistent with surface and sub-surface water temperatures in the area during the tracking period.

Dive Duration

Dive durations (n = 96) ranged from 10 s to 220 s (3.67 min.). Because Service Argos does not allow transmissions more frequently than once every 40 s, a count of surfacings between transmissions was made and reported as part of the data string during each transmission. These surfacings are meaningful in the interpretation of the whale's behavior, diving physiology and as a potential correction factor for aerial surveys of the time whales spend "visibly" at the surface (Ljungblad et al., 1987). The duration of 41 such dives were estimated. In 7 circumstances, where the time of the previous transmission was known, an exact duration could be determined (Table 11, last column). Figure 42 summarizes dive duration data. Dives of < 30 s (n = 47) were nearly as common as dives of > 30 s (n = 49). The mean dive duration for all dives was 67 s.

The number of surfacings between transmissions varied from 0 to 3 ($\bar{x}$ = .73). Twenty-six of the 56 transmissions (45%) indicated that the whale had surfaced one or more times ($\bar{x}$ = 1.6) between transmissions. Such surfacings represent dives of less than 40 s duration and were associated with all 8 reported short dives (< 30 s), emphasizing that short dives often occurred in groups of up to at least 4 consecutive dives.

The 2 longest sequences were collected during the last 3 monitored orbits (Figure 43). These records took place during the period of fastest calculated swimming speed. Having had some time to recover from the stress of entrapment, these dives may best characterize the whale's normal diving behavior during active swimming. Long dives frequently preceded or followed a series of short dives. This relationship can also be seen in Figure 44, where changes in the mean duration of dives/orbit have a similar trend to the mean number of surfacings between transmissions/orbit, suggesting that the whale was either hyperventilating to prepare for long dives or recovering from oxygen debt after long dives.

In general, there was little difference in the range and mean of dive durations between orbits (Figure 44), but 2 dive sequences deserve particular attention. Four consecutive long dives (140 s - 220 s) were recorded between 1857 and 1909 and resulted in the highest mean dive duration for any orbit. Each long dive was associated with 1 to 2 ($\bar{x}$ = 1.75) surfacings between transmissions, which would effectively reduce the mean for that orbit close to the overall mean for all dives. Interestingly, the only orbit without surfacings between

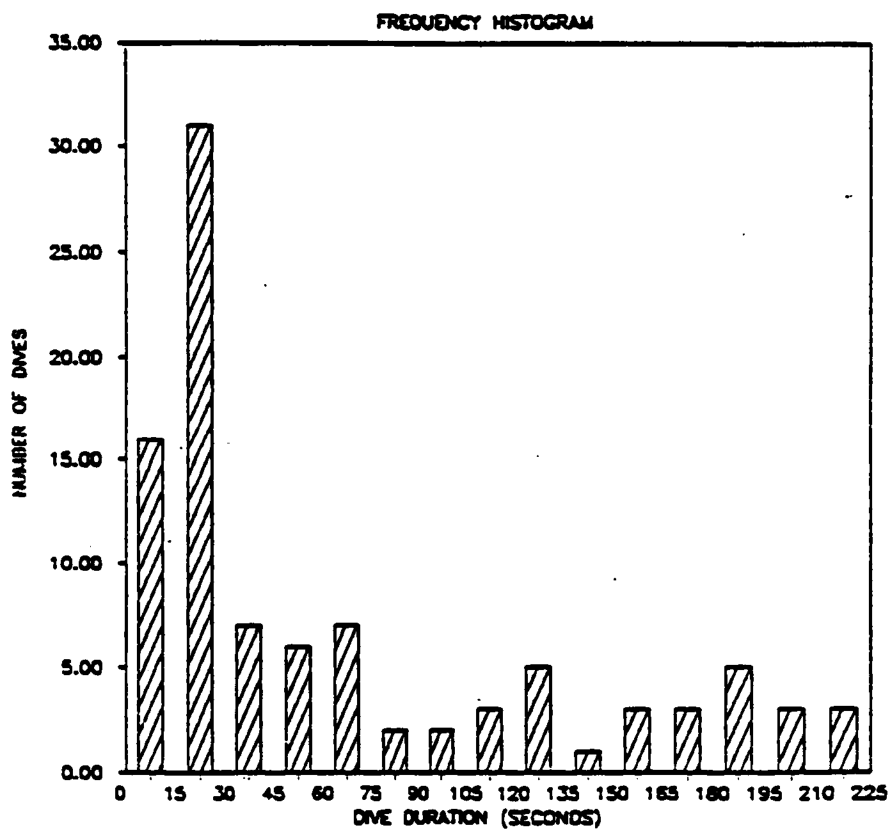


Fig. 42. A frequency histogram of dive durations of a satellite-monitored humpback whale. The dive durations are represented in 15 s intervals.

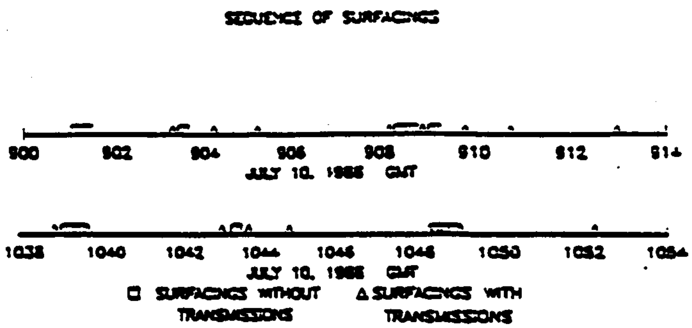


Fig. 43. Two diving sequences monitored by the ARGOS satellite system from a PTT equipped humpback whale off of Newfoundland.

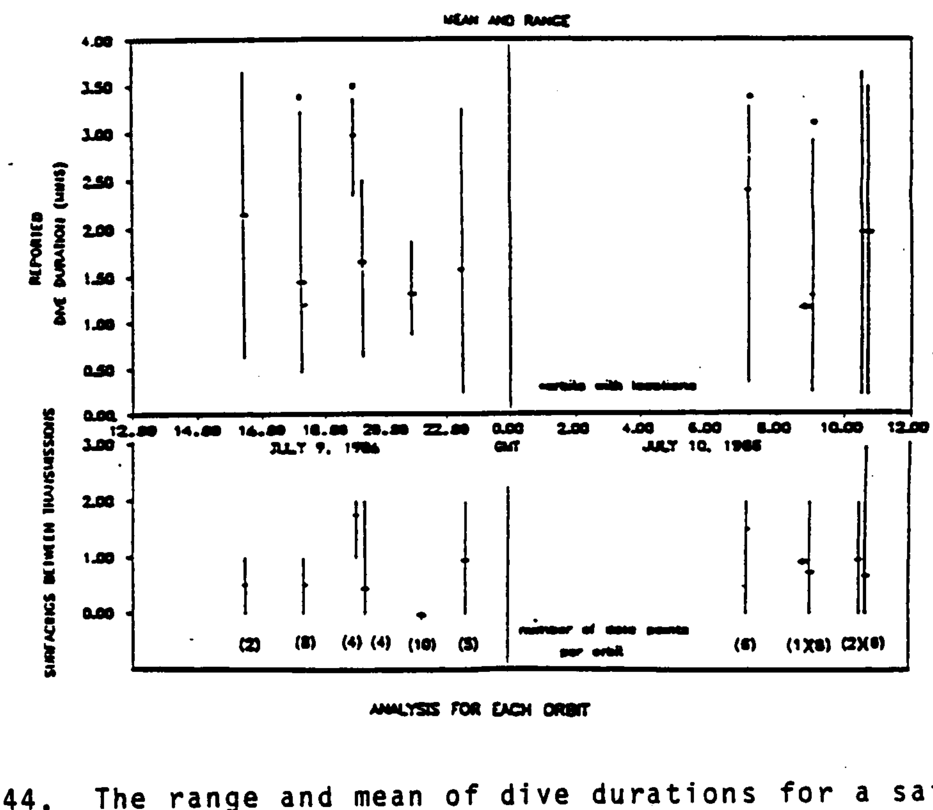


Fig. 44. The range and mean of dive durations for a satellite-monitored humpback whale on July 9 and July 10, 1986. The range and mean of surfacings between transmissions for the same whale and time.

transmissions was also the orbit with the largest number of messages (n = 10). However, the durations of all 10 dives were quite similar (52 - 112 s), resulting in the smallest range of dive durations for any orbit. This consistency may imply that the whale was performing some very routine behavior, such as resting near the surface, and that breath holds of this duration are not at all stressful as they do not require intermediate short breaths. It is hoped that in the future examples of stereotypical dive patterns will be correlated with specific behaviors by observing tagged whales to facilitate behavioral interpretations of telemetered dive data.

The number of dives (n = 511) and their average duration ($\bar{x}$ = 66 s) was only available for 1 complete 12 hour interval (7 to 19 hours after the tagging). The value of 511 represented a "full" counter and it is likely more dives were completed. However, with an average dive of 66 s, there could not have been more than 650 dives. The mean dive duration calculated from reported and estimated dives ($\bar{x}$ = 67 s) was virtually identical with the 12 hour average dive calculated for all durations ($\bar{x}$ = 66 s) by the PTT microprocessor on the whale.

CONCLUSIONS

Although 6 of 11 orbits obtained 5 to 10 messages, Service Argos failed to calculate any locations. This was important for future satellite-monitored whale experiments and was presented at the International Service Argos User's Meeting as a major problem which has since been resolved. The Toronto LUT calculated 4 locations and special processing of the Doppler data could have produced a total of 8 locations. In 1986 there were 4 LUTs operating in North America which together covered virtually all coastal U. S. waters. With proper arrangements, it would not be necessary to depend on Service Argos for future PTT locations.

The distances traveled daily by tagged humpback whales released from entanglements (1983, $\bar{x}$ = 85 km/day; 1986, $\bar{x}$ = 134+ km/day) were similar to those observed for unharassed gray whales (Mate and Harvey, 1984). This was not likely an effect of tagging as all released humpbacks nearshore off Newfoundland appeared to move offshore and none have been resighted during the same season (Lien, pers. comm.). Special circumstances or logistics would need to be instituted to resight tagged animals to view the condition of the tag's attachment. If follow-up observations were needed for impact assessment or collection of behavioral data, a seaworthy vessel would be required for most species unless special animals with histories of high site fidelity were tagged. The 1986 field experiences demonstrated the extent to which environmental variations affect the distribution of whales and the need to be flexible in operational (and monetary) protocols.

BOWHEAD WHALES

The emphasis of funding cetacean tagging out of the Anchorage office of Minerals Management Service has always been toward developing useful information on bowhead whales. As early as 1981, Hobbs and Goebel (1982) attempted to tag bowheads using barnacle VHF tags. Experience during that project demonstrated the difficulty of closely approaching bowhead whales. Observations of how bowhead whales move through different types of ice in the Bering and Chukchi Seas were made in 1983 during MMS-funded aerial surveys by Ljungblad and from ice camps where North Slope Borough personnel counted whales moving past Barrow, Alaska. The ice/whale interaction was deemed important in the development of a suitable PTT for bowheads. Discussions with numerous experienced observers confirmed that bowheads moved freely through grease ice and often broke ice with their heads. Their body often "rolled" through the open-water hole created by the head. After the initial breaking of the ice, the leading edge of the body rarely came in contact with the unbroken ice ahead of the whale. In heavier ice situations it was more common for a whale to rise slowly under the ice, break the ice into a "tent", exhale, inhale and then submerge straight down so that the ice fell back into place. Frequently it was not possible to detect where whales had surfaced in heavy ice during aerial surveys or even with closer inspection out on the ice. In heavy ice situations it is unlikely that the enormous back of the whale contacts much ice.

The difficulty of approaching bowhead whales (from discussions with many native hunters) suggested that a projectile tag might be the only possible method to tag bowhead whales and a prototype projectile housing was constructed for testing on dead bowhead whales. The projectile housing (designed by Maiefski) was similar to that used by Watkins for VHF tagging (1.9 cm diameter x 23 cm) but was larger (4.8 cm diameter x 29 cm) to accommodate 3 "half-C" cell batteries and a highly miniaturized future version of the PTT electronics (Figure 45). Such small electronic packages do not presently exist (Montgomery, 1987).

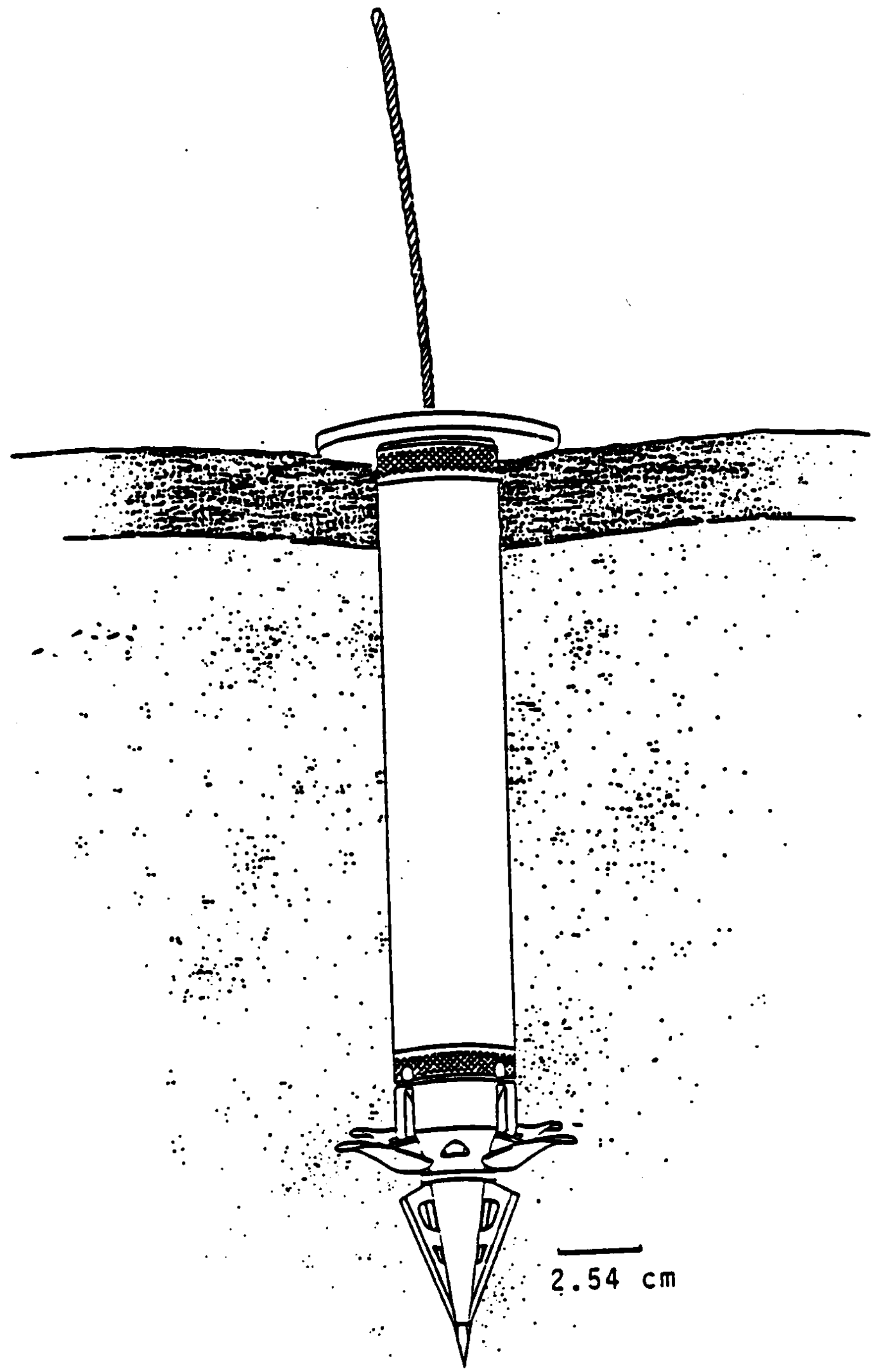


Fig. 45. A prototype projectile PTT for bowhead whales.

Use of a cylindrical housing has several engineering advantages. The circular cross-section provides great strength. Bulkheads in the cylinder's interior effectively shorten the distance of unsupported spans and allow the use of thinner wall tubing materials. Nonetheless, the weight of the electronics, batteries and housings with the most optimistic miniaturization (feasible for the next several years) would be at least 1.5 kg. A speed of at least 90 m/sec. would be needed to assure an accurate trajectory and adequate penetration. The resultant "equal and opposite" force would make it difficult to consider a hand held or shoulder-fired applicator. The freedom and mobility of a hand held applicator is desirable for proper placement of projectile tags on fast moving whales. Notwithstanding the problems of acceleration and deceleration on batteries and electronics, the result of such a heavy and fast moving object hitting a whale would, no doubt, result in some trauma and subdermal hematoma (bruising) in the area of impact.

Batteries currently comprise 60% of the tag's volume and 40% of its weight. Organic lithium batteries have the highest energy density presently available over a broad range of temperatures and amperage loads. Given the radiated power requirements of an Argos PTT and the current development of advanced battery systems, it is not likely that battery weights will be reduced in the near future. Without substantial weight savings in the near future for batteries, electronics or housings, the idea of a fully projectile PTT was shelved in favor of a design which might be deployed as a "harpoon" by native hunters or scientists. The harpoon tag was tested at Kaktovik on a fresh bowhead carcass in the fall of 1983 and penetrated to a depth of 23 cm through the skin and blubber. The tag did not penetrate its full length (29 cm) despite the use of a heavy wooden harpoon thrown by an experienced whaling captain. Some whalers were concerned about the size of the tag although it was designed on optimistic estimations of future miniaturization and power consumption which have not yet come to pass.

By April 1984 the tip of the harpoon tag was modified in the hope that a test (on an animal taken during the spring hunt) by the village of Gambell, St. Lawrence Island, might be possible. A member of the Whaling Captain's Association asked how possible future deployments might affect strike allocations. Communities were limited in how many whales may be struck in a single season during attempts to land bowhead whales. It must be made clear in all future scientific permits for tagging that they do not reduce the native strike quotas. No opportunity arose to test the tag during the spring hunt.

During 1985, attempts to approach bowhead whales with a small R/C helicopter and a full-size four-bladed helicopter (See "R/C helicopter development") were not successful due to a lack of whales and early freeze-up of the Beaufort Sea.

1986 Tagging Season

Background

In January 1986, application was made to the Canadian Department of Fisheries and Oceans (DFO) to tag bowhead whales in the Canadian Beaufort Sea. A presentation of the proposed research to the DFO and the Native Hunting & Fishing Council in Inuvik was made during April. Plans for tagging bowheads in September and October of 1986 were contingent upon the successful operation of PTTs for at least 2 months on humpback whales in the North Atlantic during June and July. MMS decided in July to cancel plans for the 1986 bowhead whale tagging and stopped funds to further modify the R/C helicopter.

The humpback whale field work ended on 22 August. On 26 August the Alaska Region MMS office requested an attempt be made to tag bowhead whales in the Canadian Beaufort Sea because: 1) the lack of a humpback whale success was in large part due to a lack of whales rather than the failure of completely deployed tags; 2) it would not be possible to modify the existing contract for a later effort; and 3) the work was part of the original statement of work for this project; 4) the weather on the North Slope was excellent; 5) large numbers of bowheads were being sighted nearshore in the western Canadian Beaufort; 6) successful satellite or VHF tagging would support the ongoing MMS-sponsored "Bowhead Feeding Study"; and, 7) the Canadian permits requested in January had been granted. Because improvement of the R/C helicopter had stopped in July, it was not ready for a tagging effort. Arrangements had been made to stay at the Defense Early Warning (DEW) site at Komakuk and 9 days of Twin Otter time was made available. Application of PTTs was the primary objective and assisting Ljungblad with shotgun-deployed VHF capsule radio tags was a secondary objective. The surface-attached PTT (as used for the 1986 humpback season) was used with a pole deployment.

Methods

The field crew and equipment were assembled between 28 and 30 August before moving to Komakuk, 15 km east of the Alaska/Northwest Territories border on the Beaufort Sea. The field season lasted 11 days with 9 days of Twin Otter aircraft support. Two of the 9 days were used to support tagging efforts by Jeff Goodyear and 1 day was too foggy to fly. The aircraft was used to find whales and deliver equipment (2 inflatable boats, 2 outboard motors, gas tanks, tagging equipment and survival gear) to beaches between Demarcation Bay and Shingle Point (Figure 46). Whales were found nearshore close to 3 suitable landing locations (Stokes Point, Kings Point and Herschel Island), where boats were assembled and launched from the beach. The plane was occasionally used to great effect in directing the boat crews to bowhead whale concentrations. Without air support, boats operated within a 19 km radius of Komakuk for 7 days. Fog or rough seas prevented efforts on 3 days. When working from the beach at Komakuk, crew members alternated standing watch to sight whales.

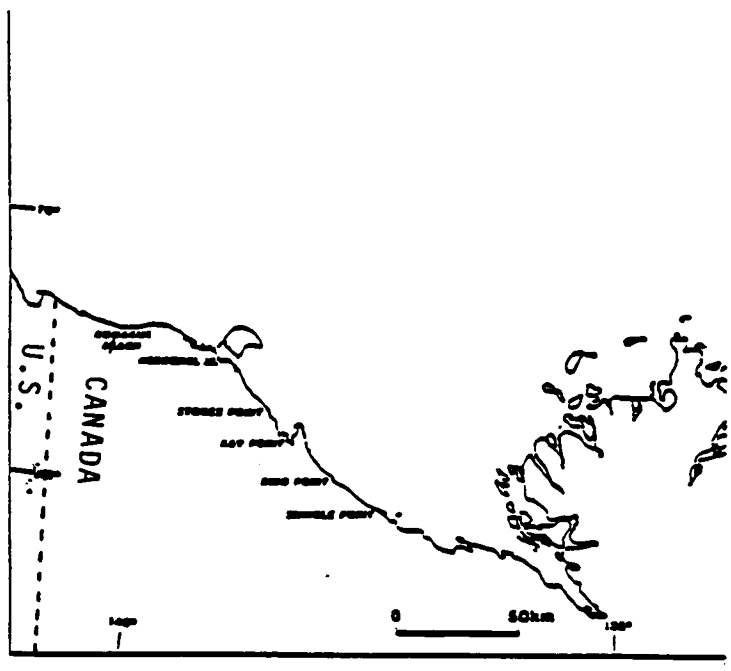


Fig. 46. A map of the Western Canadian Beaufort coast showing field operation locations.

The tagging protocol was identical to the 2 boat effort on gray and humpback whales. There were instances when the backup boat was important to safe operation (a motor failure) and helped control the movements of whales. Whales were approached between Kay Point and King Point, near Stokes Point, near Demarcation Bay and near Komakuk. Small whales tended to be nearer to shore in the mornings and move away from shore in the afternoons.

A technique was developed to successfully approach bowhead whales to within 10 m using a Zodiac on either side of the whale's course. Whales were pursued when they surfaced for a breath which limited them to just a few breaths. Often, after a short blow sequence, the whales took relatively short dives and the boat maintained some control of the whale's heading. Unharassed bowheads usually surfaced up to 6 times in a 1 to 3 min period before taking a longer dive (similar to data from Richardson et al., 1987). If approached close enough early in the surfacing sequence, whales often swam away fast and left turbulent eddies visible on the water's surface which were useful guides in following the animal's direction and most frequently were associated with short and shallow dives. Lone adults were harder to approach as they swam faster, breathed less frequently and surfaced at greater distances from the boat.

The PTT for bowheads was designed to transmit 20 h/day. The batteries had to be further de-rated to 7.5 ampere hours in low temperature applications for arctic bowhead whales. If a bowhead averaged 90 s dives in the Arctic, the PTT would last only 2.5 months due to the cold environment. Changing the duty cycle to 8 hr/day and assuming bowhead dives averaged 2 min (Wursig et al. 1985; Ljungblad et al. 1987; and Richardson et al 1987) would extend the transmitter's operational life to at least 6 months.

Bowhead whales in the Canadian Beaufort Sea would eventually travel west and south through the Beaufort, Chukchi and Bering Seas. The consideration of this movement was less limiting than for migrant whales in more temperate latitudes because satellite coverage is much more frequent at such high latitudes.

Results

Of 31 whales which were approached, the tagging boat came within 15 m of 13. Half of the approached whales were never seen after the initial approach. Only a female with a calf was close enough to have been tagged with a pole-deployed tag although the boat's speed would have made handling the pole difficult in such rough water. No attempt was made to tag the female with a PTT because her calf would have likely rubbed the tag off. Two bowhead whales were tagged with VHF projectile tags on 15 September: the previously mentioned 15 m female with a calf and a 10.6 m adult. Both whales were approximately 10 to 12 km northwest of Komakuk. The female was tagged from a distance of approximately 2.5 m after at least 5 surfacing sequences and the single adult was tagged at a distance of approximately 5 m. Neither whale reacted overtly to the tagging. Both tagged whales were reapproached soon after tagging to confirm tag placement and antenna orientation. The gun applicator worked very well.

On good weather days when whales were abundant, it may have been possible to apply as many as 5 projectile VHF tags in a single day. Tags were applied accurately, deployed completely and had good antenna orientation. Monitoring for the tags was carried out and reported by LGL (Goodyear, et al., (1987) and NOSC (Ljungblad et al., 1987). The deployment of additional VHF tags by LGL made it unnecessary to deploy further NOSC VHF tags. The tagging team left Komakuk on 17 September and returned to Prudhoe.

On 19 September, a portion of blubber and skin from a large whale taken by Kaktovik whalers was used to demonstrate the satellite tag applicator to whaling captains (Figure 47). The application of the tag went smoothly and was received favorably. Questions about the kinds of information the tag could report were answered.

Even if the R/C helicopter had been ready, there were few opportunities to tag whales with it from shore at Komakuk early in September. However, by mid-September whales were moving west slowly, very nearshore, with prolonged surfacings and good back exposure. Similar behavior had been seen earlier in September near Kay Point and King Point.

The PTTs were allowed to transmit on a daily basis during tagging attempts. These transmissions were monitored to locate the tagging efforts and ground truth the PTT locations. The tags were allowed to run in a "fail-safe" mode after the bowhead whale tagging season until the batteries were exhausted. The microprocessor in the PTT activated the fail-safe mode whenever the saltwater switch did not cycle "open" and "closed" (indicating submergence) within 24 hours. The fail-safe program was designed to respond to a saltwater switch failure (such as thick algae growth) by having the tag transmit once every 40 s

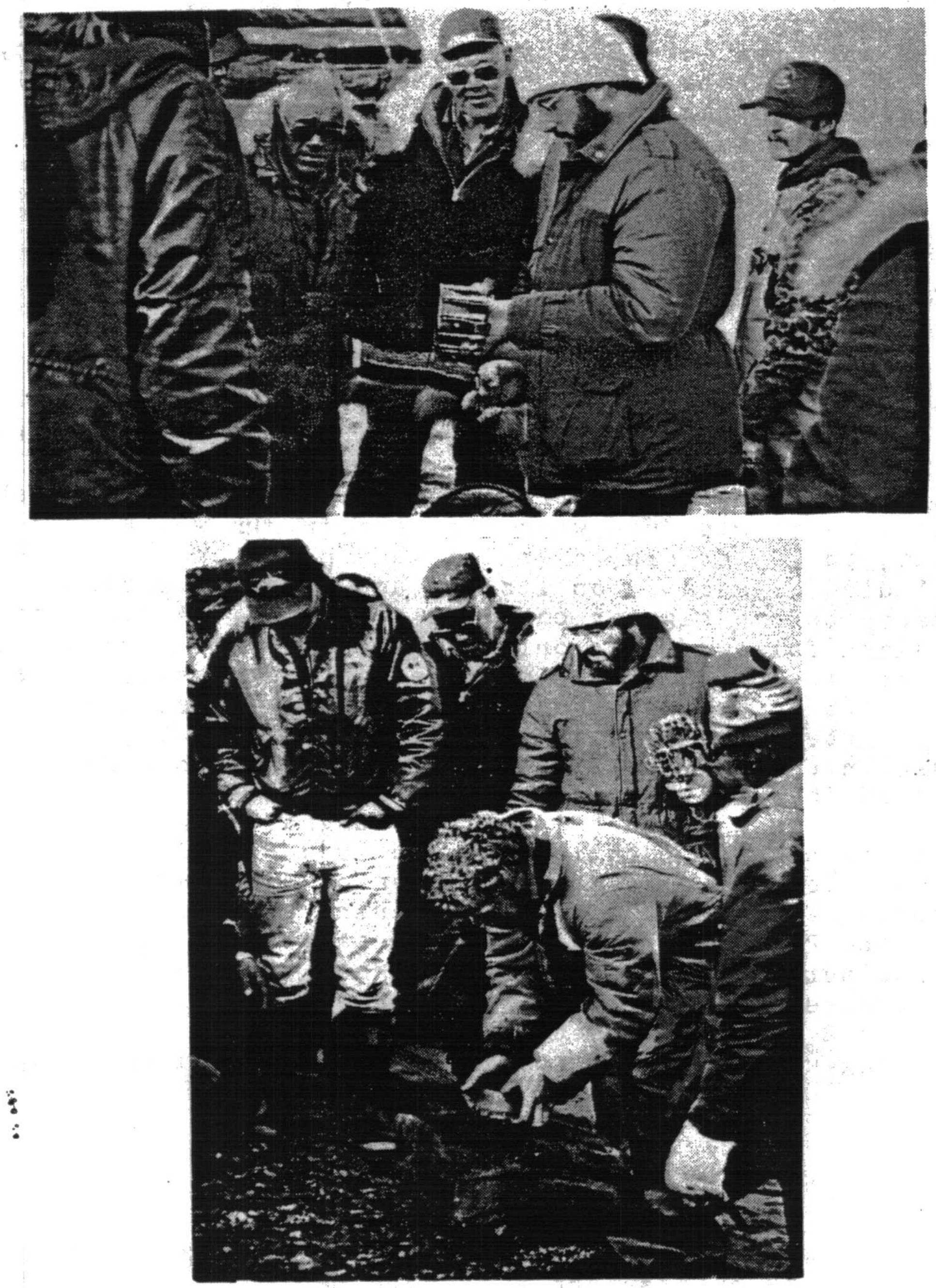


Fig. 47. Photographs of the satellite-monitored radio whale tag in its applicator (center of upper frame) and on a piece of bowhead blubber (lower frame) after a demonstration on 19 September at the village of Kaktovik.

until the saltwater switch resumed closure or until the batteries were exhausted. In fail-safe mode the tag transmitted 55% more frequently than anticipated for average humpback whale dives and 3 times the anticipated rate for bowhead whales. Without any duty cycle pattern, the tag's operational life was short. In the fail-safe mode, the tag ran as anticipated suggesting its performance on whales would have continued for its planned duration.

1987 HUMPBACK SEASON

Attempts were made during 1987 to place 4 PTT tags (remaining from the 1986 season) on entrapped humpback whales off Newfoundland. The strategy and equipment were identical to the 1986 effort. A fishermen's strike prevented the capelin fishery from opening until mid-June when the capelin run was almost over. As a result, only 3 entrapped whales were reported between 9 and 26 June: 1 died, 1 escaped on its own and 1 was released by another party before tagging could be attempted. A poor cod fishing season followed with only 5 whales entrapped from 3 to 20 July: 1 died, 1 escaped, 1 was released in rough seas, 1 was tagged and another was released. The latter release occurred immediately after tagging a whale because a second tag could not be reloaded in the only applicator and applied before dark. It took 7 hrs on 16 July to catch, free and tag a 9.5 m humpback whale entrapped in a gillnet 14 km off Musgrave Harbor. While the tag was physically identical to the 1986 PTT, its software had been modified to increase the number of dives which could be counted during a 12 hr period. A different attachment system was also used: the PTT was attached to a rectangular plate with a rosette of 6 sutures located in each corner (Figure 48). Despite numerous successful tests on sperm whale and humpback whale blubber, only 2 of the 4 rosettes (on diagonal corners) deployed before the tag was released from the applicator (Figure 49).

Results

Despite the incomplete attachment, 94 messages were received during 28 orbits over a 71 hour period. New information during every orbit the PTT transmitted. One to 6 messages per orbit were received ($\bar{x}$ = 3.4/orbit). Only 1 location was obtained through standard Service Argos processing but special

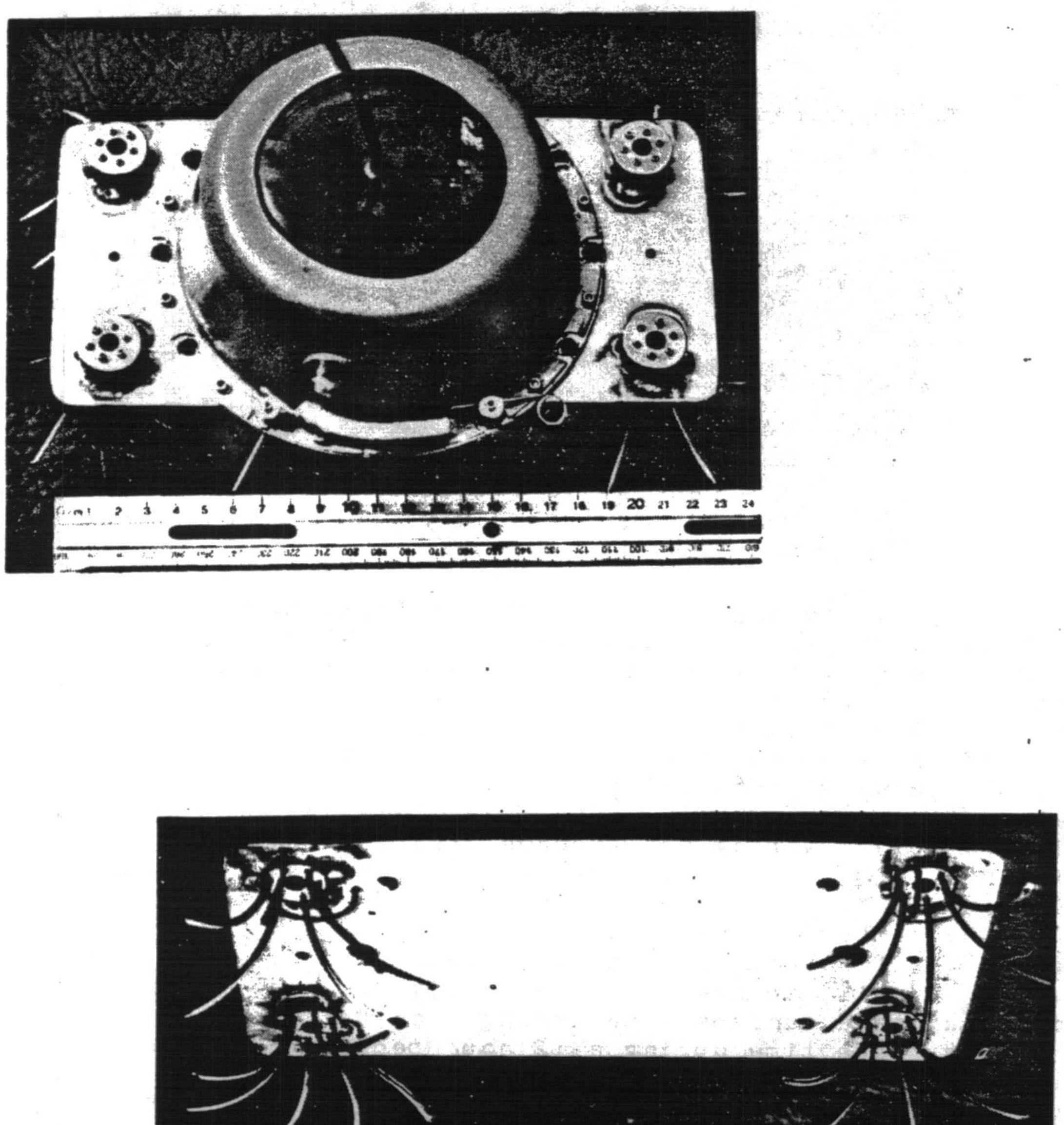


Fig. 48. The attachment system used for tagging a humpback whale on 16 July 1987 off Fogo Is., Newfoundland. Upper view shows PTT attached to a rectangular plate with 6 sutures in each corner. Lower view shows how sutures deploy into blubber.

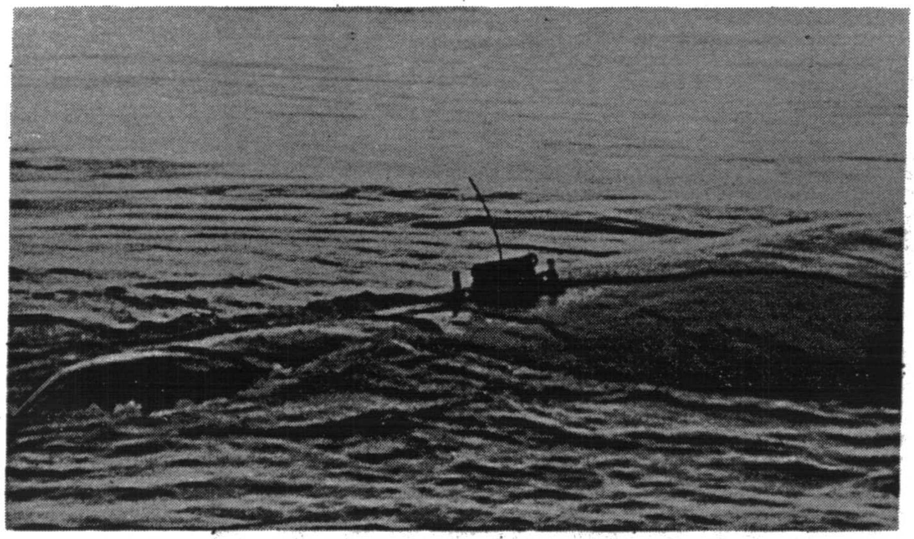


Fig. 49. A humpback whale tagged off Newfoundland on 16 July 1986, showing the incompletely deployed sutures at opposite ends of the tag (arrows).

processing by the Argos Service Center in Suitland, MD resulted in 16 locations ($\bar{x}$ = 5.3 locations/day). With only 1 bit synchrony error, the duration of 93 dives were measured ranging from 8 s to 11.25 min. ($\bar{x}$ = 179.2 s ± 202.7 s. Up to 4 short dives (< 30 s) frequently preceded or followed long dives. Measured dives of <30 s accounted for 39 of the 93 dives measured (41.9%). However, 86 additional dives took place between transmissions ($\bar{x}$ = 20 s). Thus, 125 of 179 dives were actually <30 s (69.8%) lowering the average duration of all dives to 102.7 s ± 166.1 s. This agreed very well with the six 12 hour averages calculated by the PTT (overall average was 98.6 s ± 11.6 s (Table 13). The number of dives in a 12 hour period varied from 327 (during the first 12 hours after release) to 519 ($\bar{x}$ = 405.3 ± 66.8). Overall, an average of 33.7 dives per hour were completed and the average surface time during these dives was 8.2 s. The average surface time during a 12 hour period varied from 3.2 s to 38.1 s. The latter occurred during the first 12 hour period and represented a total of 28.8% of the animal's time spent at the surface. This was 4 times higher than any other 12 hour period and 6 times higher than the average for all other 12 hour periods. The high percentage of surface activity during the first 12 hour period suggests that the whale was recovering from the trauma of entrapment. Although fewer dives were completed during the first 12 h period, the average duration of dive ($\bar{x}$ = 94 s) was very close to the overall average ($\bar{x}$ = 98 s). The consistency of the animal's performance after the first 12 hours (duration of long dives, number of dives per hour, average dive duration and time spent at the surface) suggests a resumption of normal behavior and compares favorably with data from the 1983 humpback experiment.

Table 13. Six 12-h summaries of the number of dives, average duration of dives, average surface time and percentage of time at surface for a satellite-monitored humpback whale in 1987.

	#dives	avg dive(s)	avg. surface time(s)
	327	94	38.1 (28.8%)
	442	94	3.7 (3.8%)
	392	106	4.2 (3.8%)
	371	112	4.5 (3.8%)
	381	106	7.4 (6.5%)
	519	80	3.2 (3.9%)
$\bar{x}$ =	405	98 ± 11	10.2

$\bar{x}$ = 4.6 without first 12 h period.

Long dives took place during the day and night. Long dives were frequently associated with depressed transmitter temperatures suggesting deep dives into colder water. On occasions long dives showed no temperature depression suggesting shallow dives or dives in well mixed water masses. There was a positive correlation between the duration of a long dive (> 200 s) and the number of short dives following it. However, a series of 3 dives (166 s, 162 s and 162 s) were made without any intervening short dives suggesting that dives of this duration were not stressful to the animal and may approximate the animal's dive capability on a single breath.

Some problems were identified during the course of this experiment with high latitude locations. Satellite-determined locations always have a mirror "possible location" perpendicular to the satellite's ground track. A computer usually makes the decision about which location more closely approximates the animal's last location. When satellites pass over a PTT at a high elevation angle ($>70^{\circ}$), the mirror image locations are closer to the satellite's ground path making correct choices more difficult. This is a particular problem at higher latitudes because the polar-orbiting nature of the satellite results in more passes with high elevation angles.

PILOT WHALES - 1987

The analyses reported here are preliminary and should not be considered final until they have been further evaluated and published in a journal. They are presented here for illustrative purposes to show the real potential of satellite tracking cetaceans.

Methods

Three pilot whales brought to the New England Aquarium from a stranding on Cape Cod in December 1986 were rehabilitated and released 100 km southeast of Cape Cod on 29 June 1987. One whale was equipped with a Telonics PTT in a 11.5 cm x 6.6 cm x 6 cm metal housing divided into two compartments. One compartment contained the batteries and was filled with a high density polyurethane to eliminate compressible air space and the other housed the PTT electronics. A 16.5 cm flexible quarter-wave whip antenna rose from the front of the tag which was attached to a dorsal "saddle pack" made of heat-moldable PVC and lined with closed-cell neoprene (Figure 50). The front of the tag was shielded by a wedge of heat-moldable PVC to reduce hydrodynamic drag. The tag and saddle were attached to the dorsal fin with 6 mm Delrin pins threaded at each end and secured with stainless steel nuts. The immediate objectives of tracking the released whale were to determine if the animal: 1) survived; 2) stayed in the company of the 2 whales released with it; and 3) joined up with others of its own kind? To answer the second of these questions, both the other animals were tagged with VHF radio tags. One VHF tag was lost in the release process; the other, however, provided information (up to 3 weeks after release) that it was still in the company of the satellite-tagged whale. It was also heard when the PTT-equipped whale was spotted in a pod of at least 100 pilot whales.

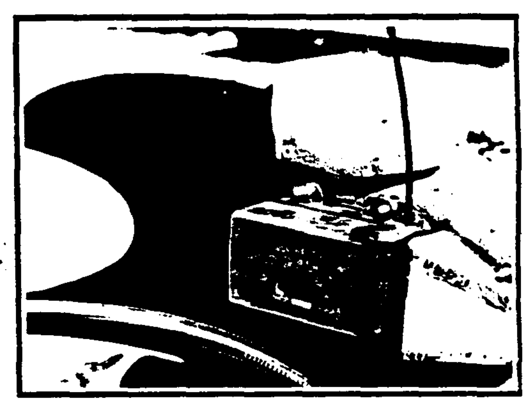


Fig. 50. A Telonics satellite-monitored radio tag attached to the dorsal fin of a pilot whale.

Results

The satellite-monitored whale was tracked for 95 days and covered a distance of at least 7,588 km between 479 satellite-determined locations (Figure 51). This was an average of 5 locations per day. More than one-half the locations were determined by processing orbits with only 2 - 5 messages at the Argos Service Center. The average daily movement was 80 km/day and was reasonably consistent throughout the entire experiment. A maximum movement of 234 km in a single 24 hour period demonstrated how fast and far small cetaceans can move in short periods. The 12 hour dive counter made it possible to count every dive the animal took from the time it left the ship until the transmitter batteries were exhausted. Except for 2 days of data which were lost during a power outage at a NOAA computer facility, all dives were measured and counted. During 93 days the animal dove 187,866 times ($\bar{X}$ = 2,020 dives/day) for an average dive duration of 40 s. The number of dives in a 12 hour period ranged from 636 to 1625 reflecting changes in the animal's activity patterns and metabolic rate. Swimming speeds averaged 3.3 km/hr over the 95 day period. Speeds in excess of 16 km/hr were maintained for periods in excess of 3 hours. During the day of longest travel (24 hours), the animal averaged 9.75 km/hr.

The maximum dive duration was > 7 min. Dives typically averaged between 24 s and 62 s during 12 hour summaries reflecting from 53 to 119 dives/hr. The dive durations by time of day for dives < 7 min. are shown in Figure 52. There were important correlations in the animal's movements and dive patterns with sea surface temperature measurements which varied between 14°C and 30°C. The whale spent most of the month of July in the Gulf Stream where the water was warm and well mixed. The animal spent time inside a warm core ring. The rest of the animal's movements seemed to correlate with escarpments near the 200 m isobath and temperature convergence areas. The whale encountered temperatures down to 6°C during dives which occurred primarily at night and secondarily just before sunset. These temperatures reflected deep dives and coincided with the nocturnal rise of the deep scattering layer, including the pilot

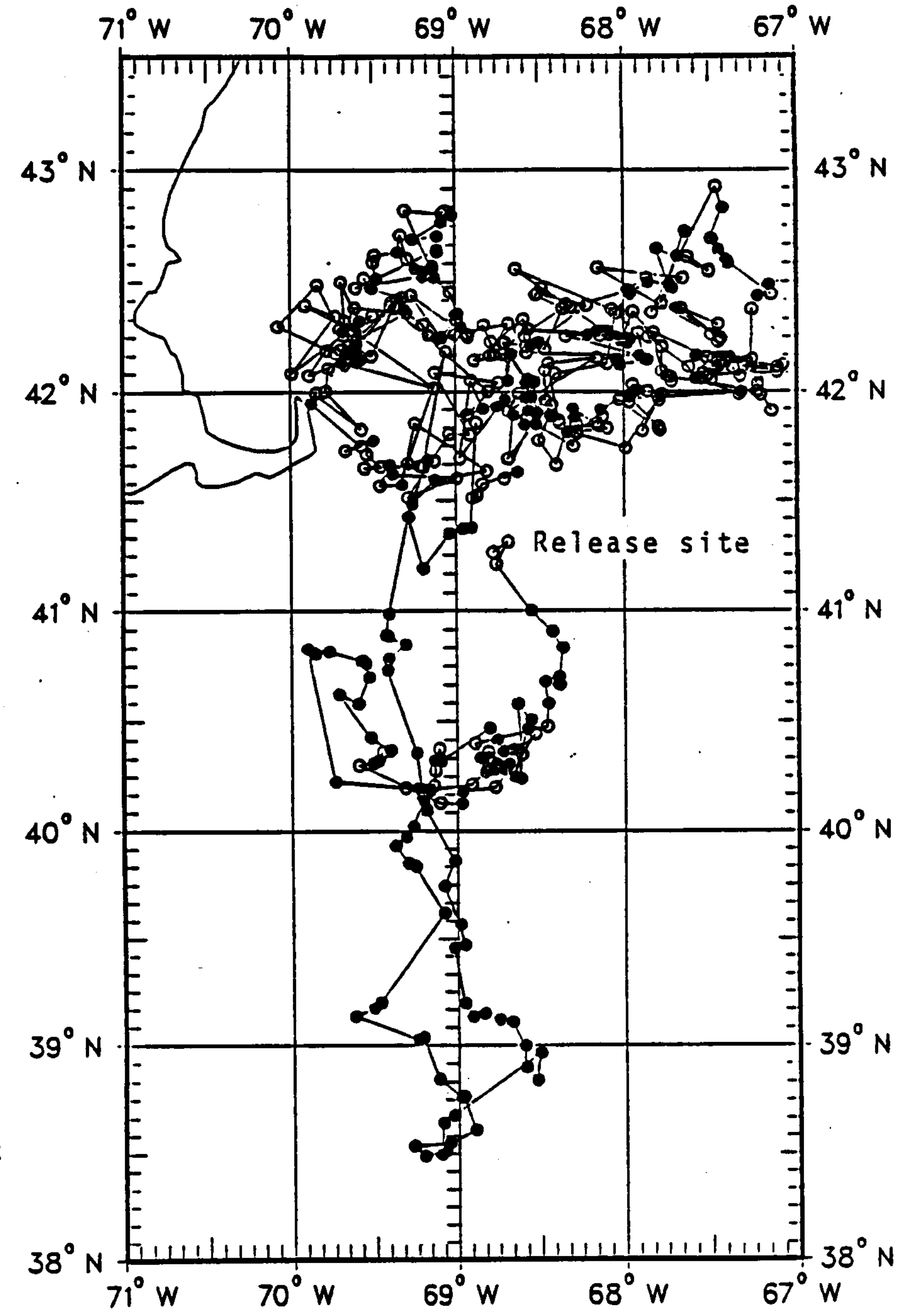


Fig. 51. The 479 Argos-determined locations of a pilot whale over a 95 day period. Solid circles are standard Argos processing, open circles are degraded locations from special processing. Total distance is at least 7,588 km.

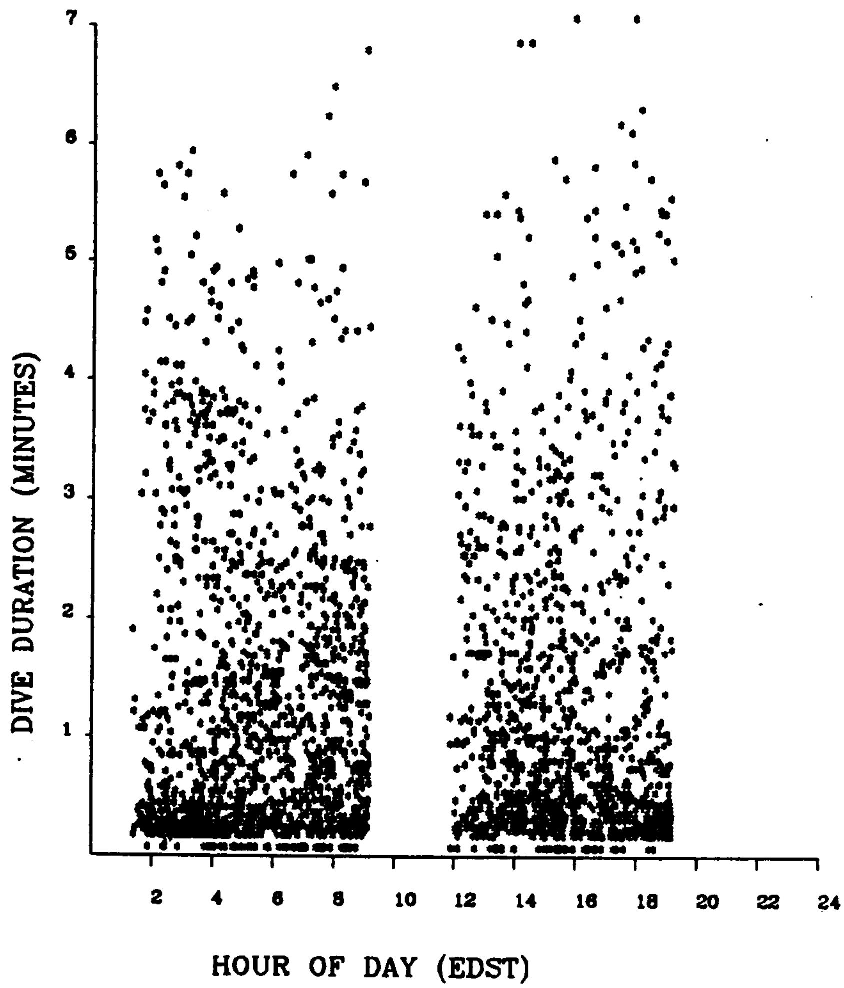


Fig. 52. The duration of 3,109 pilot whale dives 7 min long by time of day for 95 days (beginning 29 June 1987).

whale's favorite food, squid. Few deep dives were reported during daylight hours when pilot whales have been observed surface feeding on mackerel (Waring and Payne, pers. comm.). If feeding occurred during daylight hours, it was a completely different strategy than at night and was limited to surface waters. This is the first direct documentation of the importance of night feeding in this species and of foraging behavior determined by satellite. The highest swimming speeds were also observed at night and just before sunset suggesting that the pilot whale either had to travel fast in pursuit of prey or moved quickly in search of prey patches.

The time spent at the surface varied between 12 hour periods. There were messages received from the PTT with 0 dive duration indicating a 40 s period spent at the surface. Sequences of such messages indicated the whale spent up to 15 min. (the full passage of time of the satellite overhead) resting at the surface without a single submergence. Surface resting was most common in the 3 hours immediately after sunrise. Significant periods of surface resting occurred on a 4 - 7 day cycle (Figure 53). These are the first long-term data on surface resting patterns for a free-ranging cetacean.

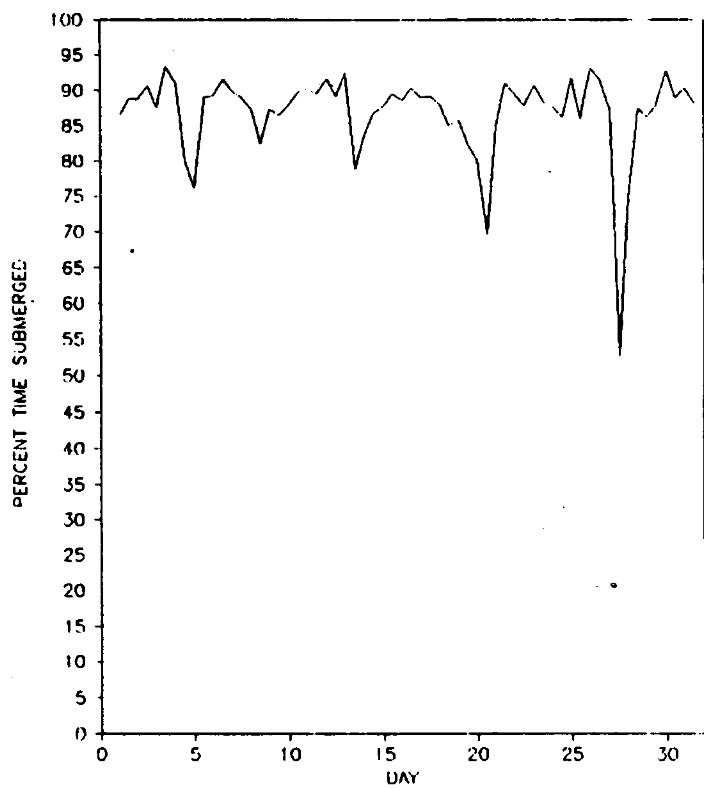


Fig. 53. The percentage of 12 hour periods spent submerged by a satellite-monitored pilot whale in August 1987. A pattern of cyclic surface resting is evident.

Discussion

Future work on these data will include analysis of movement patterns during travel and foraging, whether rest cycles coincide with periods of good weather and how bathymetric and sea surface temperature data relate to the movements of the animals. Pilot whale movements probably relate primarily to the abundance of squid. The increase in the number of locations (from as few as 2 messages) is the result of special Argos processing with new computer equipment, the creation of an Argos Service Center in North America and comments from this and other projects at past Argos users' meetings. A move by the French to privatize aspects of Argos has created more flexibility in their operations and a greater ability to service customers.

The transmitter sent the same information as that provided for the 1987 humpback whale experiment during two 8 hour periods daily. It was impossible to predict exactly how long the transmitter would last without knowing something of the dive characteristics of pilot whales. After the first several weeks of dive data, it was predicted that the tag would last 75 days. Movements into warm Gulf Stream waters helped extend the battery life. A deterioration in the quality of the messages and the number of messages per orbit during the last few days of operation confirmed that the PTT's batteries were near exhaustion (similar to the manatee studies).

Assessment of Satellite Technology

Two broad objectives of this contract were to: 1) assess the utility of using satellite technology to monitor and track large whales; and 2) make recommendations as to how this technology might be applied to bowhead whales. The project has covered a variety of developments from attachments, housing, electronic technologies, data recovery systems and field techniques. The development in satellite tracking animals during this project is comparable to the evolution in transportation from the horse and buggy to the automobile. In the 1979 VHF gray whale study, 6 locations along the migration route during 94 days was considered an enormous success and the large amounts of labor and logistics to collect 11,000 dives in 1980 were considered well spent. Now, with very little labor, a pilot whale can be tracked for 95 days with up to 6 daily locations and the duration of every dive monitored so that interpretations of behavior and metabolic rate are now feasible. This section will review: 1) improvements in the Argos capability including possible future developments; 2) the evolution of transmitter technology; 3) attachment experiences related to future development; 4) the evolution of deployment methods; 5) alternative satellite systems; and 6) recommendations specific to bowhead studies.

Argos System Capability

Because the Argos system was designed for tracking high altitude metrological balloons and oceanographic buoys, there was little concern at its inception for size and weight constraints, or determining locations from intermittent transmitters. When use of the Argos system was investigated early in this project (Mate and Harvey, 1982a), it was necessary to send 5 messages to the satellite over a period of at least 720 seconds. Message length was a fixed format at the initiation of the experiment and transmissions could not be more frequent than once every 40 seconds. Argos encouraged the development of wildlife applications but did not cater to the market. Over time, Argos has grown and developed. An Argos center has been established in North America to share the acquisition and distribution of data and a more user-oriented service concept has been implemented. Newer, more capable equipment has also been brought on line.

Locations can now routinely be determined from as few as 3 messages (and 2 with special added cost) with a modest loss in location accuracy. Location quality criteria have also been established. The 1987 International Argos Users' Conference included a user discussion with Service Argos personnel in which Service Argos agreed to consider allowing the use of repetition rates which merely averaged no more than 1 transmission every 40 s. This paves the way to allowing whale transmitters to transmit at every surfacing when dives average at least 40 s so that more messages might be available for the calculation of locations. There was also a genuine consideration of reducing the Argos power requirements of transmitters on an experimental basis to determine whether some users might be able to extend the life of their PTTs successfully with less batteries (reduce the size of transmitters).

Service Argos has also upgraded its software for better user access. It is now possible for multiple users to access current data files. Earlier, each user's access deleted the examined file so that it was difficult to allow more than one user without risking the loss of data. Large data storage capabilities have also been added which allow users longer access to larger bodies of original information. The 1983 system was so limited in storage space that users had to recover data within 12-24 hours or lose it until monthly tapes or printed summaries became available. In 1987, users have 72 hour data storage.

Initially it was thought that local user terminals (LUT) would be a necessity for any whale program because of the rigid criteria for location and a lack of success in locating whale PTTs through the Argos system. Service Argos has become more responsive to users' needs (and perhaps the availability of competitive LUTs) and is willing to provide services that were previously only available with LUTs. During the 1987 Service Argos Users' Meeting, a report by NASA (Turkiewicz et al. 1988) suggested the use of a dual beam interferometer to determine the location of Argos PTTs from a single message. Such locations would only be accurate to within 10km. The lower power requirement and subsequent small size advantages are obvious. Equally important is an increase in the probability of locating whales which dive for long periods and result in few messages/orbit. This system has a conceptual basis and has been looked at from an engineering feasibility standpoint but is not currently programmed for implementation. With pressure from agencies and users, this capability could be mobilized in as short as 7-8 years at a cost of perhaps $10 million. It is likely NASA would bear the cost if a constituency asked for the product.

Transmitter Technology

Several commercial businesses are now producing PTTs for wildlife applications: TOYOCOM working with Tokai University on porpoises (Tanaka, 1987), Mariner Radar working with the Sea Mammals Research Unit in Great Britain on seals and whales, the John Hopkins APL development under license to Polar Research Laboratories which has concentrated on large bird work, Wood Ivy which did some of the early turtle work and Telonics which has built the equipment used in this project and instrumented manatees, polar bears, caribou, walrus and terrestrial animals in more temperate environments. This widespread interest and competition will, no doubt, reduce the size, weight and energy requirements of PTTs in the future. Already there have been tremendous improvements in these areas. The longevity of the Telonics PTT has increased by an order of magnitude with an actual decrease in size. The Telonics PTTs used in these studies have pioneered the use of seasonally programmable duty cycles and saltwater switches to extend the useful life of PTTs in marine applications. Where early units were genuine developmental prototypes, the electronics today can be considered highly reliable and have now been tested over long periods in the marine environment (300 days on manatees and 95 days on pilot whales). This is a big accomplishment in such a short period of time. The pilot whale experiment was the first long term test of the saltwater switch capability on a free-ranging animal and worked flawlessly.

Transmitters will, no doubt, become less expensive as the volume of transmitter production increases. Like most electronics, it may be one of the few items in today's society that gets better and less expensive in the future. Because of the reasonably complex nature of PTTs, they will probably never get down to the same price as low power VHF transmitters. However, considering the expense and logistics required to apply either type of tag and the the additional cost to monitor VHF tags at close range, satellite-monitored tags start to become cost effective for experiments lasting more than just a few weeks. The expense of recovering Argos data presently is less than $12/day. If and when a dual beam interferometer is available in space, it will likely be feasible to make small, projectile transmitters by reducing the battery requirements. Even before that occurs, it is likely that power requirements may be met by smaller batteries, trickle-charging a capacitive discharge system like a strobe flash. Work is currently underway to incorporate an Argos receiver into a PTT so transmissions only occur when the satellite is overhead. Presently, it takes too long for an Argos receiver to determine if the satellite is present and initiate a signal to be useful during a short whale surfacing.

Attachments

The central theme of the attachment philosophy explored during this project appears to be a good one: a surface-mounted tag, using subdermal hold-downs. Tags cannot be fully implanted due to the absorption of radio frequency energy at ultra-high frequencies. Fully projectile tags which implant themselves with an external antenna may be possible when smaller PTTs become available. Size is also a consideration for surface mounted tags. The tags create drag. This pull on the attachments can lead to pressure necrosis causing the thin tines to act like blunt knives moving slowly through tissue. Future emphasis must be on the reduction of hydrodynamic drag and/or increasing the surface area of subdermal attachments to more evenly spread the lifting forces produced by drag.

The success of the pilot whale attachment was important because the tag was located in an area of high velocity flow and presumed high importance to the stability of the animal. The consistently high number of messages per orbit maintained over the entire experiment suggests that the animal did not compensate behaviorally to the unbalanced hydrodynamic load by rolling over to one side. With the saltwater switch 6 inches below the tip of the antenna, it would not have taken much "listing" to the "tag-side" of the dorsal fin before the saltwater switch would remain closed. The number of dives per 12 hour period, the average duration of dives, the maximum dive durations and the speed of movements, were as consistent for the pilot whale in the last 2 weeks of the experiment as they were during the first 2 weeks. This level of activity suggests that the animal stayed healthy over the entire experiment. Using similar tags on large whales ought to have even less effect in terms of drag and impact to the animal. There is no doubt that attaching the tag on a captive animal was easier than on a free-ranging animal. Also, using the leading edge of the dorsal fin to distribute some of the hydrodynamic drag was a great advantage. For some large whales, dorsal fin attachment may be a practical future consideration. The dorsal ridge of many medium sized whales may also prove suitable.

It is doubtful that the caudal peduncle attachment used for manatees would be suitable for long term attachment to whales. The relatively slow nature of manatees is quite different from most whale species and it is likely that even a padded attachment would create enough surface friction to wear through the skin of most whales after a prolonged period. Tethered tags are also subjected to high acceleration and deceleration moments.

No matter what the attachment, the question of tissue reaction is paramount. As long as there is even an antenna coming through the skin to the outside of the animal, there will be irrigation of the initial "wound." The tag must be stabilized as quickly as possible so that healing of the entry wound can take place before the tag loosens sufficiently to cause additional drag and irritation. For most species, the effectiveness of a tag attachment technique will have to be judged empirically. Gray whales may be better adapted to foreign objects in their skin and blubber than any other cetacean. Even some of the less barnacle infested species, however, have demonstrated a tolerance of foreign objects in their skin and blubber. Sperm whales have trailed rope from tethered harpoons more than a year. Bowhead whales have carried unexploded bombs in their blubber and recovered from explosive harpoons. Right whales have demonstrated an ability to heal, even enormous open wounds caused by large ships (Kraus, pers. comm.). The use of bio-compatible materials has been examined recently by Geraci (1986) and suggests that the application of porous or textured materials may facilitate tissue adhesion. Future attachments may also have larger open spaces through which tissue can reconnect. Until that time, it appears that a key to success will be providing sufficient surface area to the attachments to distribute the pressure and lift from hydrodynamic drag and to reduce the size and shape of tags to minimize drag. It may also be appropriate to involve as much healthy tissue and create as little injury in the attachment process as possible. From a practical standpoint it is likely that any tag will eventually migrate out. Thus, it is reasonable to consider that if future tags last for periods less than one years, it may be necessary to tag whales in different geographic areas and seasons to piece together their annual cycle.

Deployment Strategies

While a fully projectile tag is desirable, the present size, weight and speed for successful deployment may injure the tissue in the area of impact and thus compromise the goal of long term attachment. However, if methods can be developed to use the momentum of a projectile tag to deploy attachments and slow the tag down, the method may even be suitable for surface-mounted tags. The biggest problem is getting the tag to the whale accurately and without undue injury. Accuracy of tagging is important because the PTT's antenna must surface each time the whale does in order to contact the satellite and collect reliable dive data. The consequence of a misplaced tag is a poor return of information and even misleading misinformation. Pole deployment was used during this project and may still have considerable utility for those species which can be approached while resting at the surface. While many investigators have related this form of behavior, several have emphasized that the opportunity to take advantage of such behaviors varies considerably and, in some cases, a dedicated effort may be required to achieve even moderate success. In other circumstances, this behavior is routine enough or the animal is immobilized sufficiently (net entanglements, strandings and, in some case, captures) to consider continued use of pole deployments. Goodyear (pers. comm.) has been successful in approaching bowhead and right whales close enough with small boats without motors to have used pole-deployed tags. Use of a pole technique from a bow sprint or swordfish plank may also make it possible to tag animals which allow a reasonably close approach while free-ranging.

A surface-mounted subdermal attachment which deploys on contact can be attached many ways. One explored during this project was the use of a small radio-controlled (R/C) helicopter. While this still has considerable potential for use in tagging whales, it must be emphasized that it is a job that requires considerable skill and dexterity and is not a skill that biologists are likely to pick up in their "leisure" time.

Another "R/C" technique worthy of consideration is a small R/C boat similar to that used by Jorge Reynolds (pers. comm.) to tag humpback and right whales with short-term electrocardiogram recording equipment.

Two methods have been considered during the development of this project that have not been actively pursued. These combine the merits of a projectile tag and a surface-mounted tag with subdermal attachments: a sea lion system and a "wire-guided" system. The sea lion system would use trained animals in a manner similar to those used by the U.S. Navy's project "Quickfind" in recovering drones, missiles and torpedoes. A small pinger would be shot onto a whale with a visual marker. If the location were deemed appropriate for a tag, a sea lion would be put into the water with the tag applicator in a bite plate. The sea lion would home in on the acoustic signal and press the tag applicator against the whale in the vicinity of the visual mark. The tag would attach itself when pressed firmly against the whale. The "wire-guided" deployment would use a small projectile dart with a trailing wire and a deployment vehicle. The latter would either reel itself to the dart on the whale or be pulled toward the dart by manually retrieving the other end of the line through an eyelet at the dart. The wire-guided system could even work with a sea anchor at one end of the wire pulling the tag (at the other end) to the dart. Assurance that the tag would not attach itself before reaching the dart could be achieved by activating the applicator only when it had reached the dart. The obvious advantage to both the last two techniques is that neither commits expensive radio tags irreversibly until the position of the dart is deemed satisfactory. Precision placement of PTT would be assured.

Some of the earliest VHF tagging work with gray whales used transmitters dropped on surfacing whales from a helicopter at low elevation. It is unlikely that such crude dropping "techniques" will be effective from helicopters, , hang gliders, or radio-controlled fixed-wing aircraft. Nonetheless, recently developed small radio-controlled dirigibles may warrant further consideration despite the obvious physical constraints (winds and quickly changing temperatures) of their deployment.

Alternate Locating Systems

A number of satellite systems have evolved to locate earth-bound receivers, principally used for ocean-going vessels (LORAN, NAVSAT, GEOSTAR). It has been suggested that tags combining receivers for these systems might determine and transmit their own location. The principal difficulty with these systems is that the determination of location requires time. The extra complexity of a receiver, and the additional energy to run the receiver are also problems. The technique has been used with some success in STARFIND. Receiver/transmitters produced by Telonics have determined locations by LORAN and then relayed the information through the Argos system, which has also provided a backup location capability. In the future, STARFIND anticipates having satellites of its own in geo-stationary orbit and determining locations totally independently. The utility of this technology remains to be seen but appears to be at least 10 years away from feasible application to marine wildlife.

The development of a dual beam interferometer is essentially a large antenna associated with the current Argos receiving strategy. While this would make modest resolution locations available from single messages, there are currently no funded plans to put this equipment in space. At a minimum, the time schedule would be 1995 if efforts were initiated soon to see such a system activated.

Application of Satellite-Tag Technology to Bowhead Whales

Seasons

As mentioned in the section on attachments, it may be appropriate to consider the attachment of tags to whales as short term (2 - 4 months) and expect incremental information from multiple animals being tagged in different geographic areas. The concept of tracking animals for periods of 6-12 months may be highly desirable but not a practicable expectation at the present time. By lowering the expected duration of tracking, smaller equipment can be produced with a better chance of staying attached. In that respect it is important to consider the reasons why tagging might be desirable and where these information needs are most needed. The affinity bowhead whales have for ice may or may not make long term tag attachment more difficult than other species. The short, open water summer season in the Canadian and U.S. Beaufort Sea appears to be the time and place where ice is the least significant factor. Information from whales in these areas will be important in understanding its feeding habits and foraging range during the summer. It might also be successful in tracking the westward migration through Canadian and U.S. waters out of the Beaufort Sea and into the Chukchi Sea (areas of importance ot OCS development. With success in open water situations, it might be appropriate to consider testing in a the less reliable environment of the spring ice leads along the northwest Alaskan coast. This is an area with good access to whales and an exposure to ice which will lessen with time as the animals move into their summer range. In some years, animals also come nearshore in September prior to the fall migration. A fourth setting which may be appropriate for seasonal tagging is the animal's winter range in the Bering Sea. Numerous sightings of bowheads in polynyas during the spring before leads develop suggest that polynyas may be important to bowheads for prolonged periods. Recent evidence of high productivity in these areas (Stringer, unpub. data) and isotopic studies by Schell (unpub. data) and Saupe (unpub. data) suggest an even stronger emphasis on the importance of the Chukchi and Bering Seas to the nutrition of bowhead whales. This area includes some planned OCS development and is likely the site of some breeding and calving activities.

In any future study, it will be important to consider oceanographic variables which can be measured by a PTTs (Mate, 1985). Successful tracking of bowheads will help define what elements jointly constitute critical habitat (Mate 1986). These will likely include water temperatures which have been correlated with high production areas (Richardson et al., 1987) and a consideration of how whales use the water column through dive profiling. The segregation of zooplankton with physical oceanographic factors such as temperature, salinity and water mass movements has been well demonstrated in the Beaufort Sea (Richardson et al., op. cit.) and in the movement of water from the Gulf of Anadyr into the Bering and Chukchi Seas.

Bowhead transmitters should be as small as practical and low profile to reduce drag and lower the risk of the transmitter being caught by the ice edge. It would be desirable to coat metal surfaces of the transmitter and antenna with materials which would shed ice.

The primary season for testing purposes would be the open water feeding season to reduce ice interaction and maximize the opportunity to resight the whale's behavior and tag attachment. For the longest open-water period, tagging should occur in the Canadian Beaufort. Adequate ship support for tagging and follow-up observations will be important. The duty cycle should provide for frequent transmissions (perhaps four 2 h periods daily) during the open-water season (10 weeks) for locations and then greatly reduce transmission frequency (to perhaps 1 h twice each week) to determine the longevity of the attachment. The latter strategy may produce some locations but has an emphasis on determining tag retention to facilitate future plans for tagging. A Marine Mammal Commission sponsored workshop has recommended 10 tags as a sample size (Montgomery 1987).

It would be inappropriate to complicate the first application of tags to bowheads with experiments. Tagged animals during the first year should be considered "controls." Their movements and dive patterns should be analyzed for individual variability and the variability between individuals. The results of such analyses could greatly affect future experimental designs. To the extent feasible, other environmental variables (currents, ice edge, sea surface temperature, winds, cloud cover, etc.) should be brought into such an analyses. Many of these factors can be monitored at reasonable cost with adequate planning.

Given the special cultural nature of the bowhead, it is important to keep the North Slope Borough, the Alaska Eskimo Whaling Commission and the National Marine Fisheries Service appraised of research plans as they develop. The Canadian Department of Fisheries and Oceans and the Department of Indian and Northern Affairs should possibly be directly involved in planning and could be approached as co-sponsors of bowhead research. Practical aspects of Canadian participation could be participation of arctic-knowledgeable personnel, increased logistic support and permit facilitation.

RECOMMENDATIONS

Conventional (VHF) Radio Tags for Tagged Whales

1. Scanning multiple frequencies should be avoided. If multiple frequencies must be used, a separate receiver should be committed to each frequency.

2. Transmitters should pulse at rates of at least 2 s to: assure multiple signals during a brief surfacing, help verify the source, facilitate locating efforts and allow accurate measurement of inter-pulse intervals.

3. Transmitter size should be as small as possible for the task and duration of the experiment to reduce weight and hydrodynamic drag.

4. For detailed data from individual whales, it is generally better to concentrate monitoring efforts on a single animal and monitor it thoroughly, than try to "sample" data from multiple whales simultaneously.

5. Development of sensors for maximum dive depth, temperature, acoustic parameters and physiological monitoring would facilitate the utility of this type of tag.

6. Because searching for tags with a limited range can be expensive, it is generally preferable to stay within reception range at all times and this may require a vessel large enough to take open ocean weather and enough crew quarters for rotating shifts to maintain continuous monitoring effort.

7. Aerial surveys are generally <u>not</u> a very good strategy for animals tagged with low power VHF tags. If planes must be used, considerable planning should precede any budgeting or field effort (see: Mate & Harvey, 1981).

8. An automatic direction finder (ADF) in VHF frequencies would be desirable, but reliable units are not presently available.

9. Automated data collection (ADC) stations sometimes collect false signals and should not rely on simple frequency scanning. ADC systems should be designed to confirm tag signals from multiple sources of information (pulse width, pulse intervals, FM codas, etc.) Ideally, such systems would have a flexible program to allow for changing priorities (especially if it is designed to monitor or scan multiple frequencies simultaneously).

10. Behavioral data should be collected simultaneously with dive duration data when possible so correlations will help interpret later studies without observations.

11. Tag attachments should be tested for reliability under application conditions on real whale flesh. Frozen tissue is usually much tougher than fresh material and flesh density may vary between animals of different age and sex classes.

Satellite-monitored Radio Tags for Whales

1. Form follows function: it is important to have the desired experimental results (temperature, depth, dive durations, etc.) and operational criteria (number locations/day, duration of study, etc.) clearly defined and practiced so that specific configurations can be designed to meet the need (minimize size, weight, housing design and attachments).

2. Keep it simple: short messages conserve battery power and are less frequently interrupted by a wave or dive. When part of a message is lost, it cannot be used in calculating a location. If locations are the most important aspect of a tagging experiment, ancillary data should be kept close to the minimum message length (32 bits, 360ms).

3. Sensors should be internalized as much as possible to reduce the number of "feed throughs" in the housing which might develop leaks. Where possible, internal space in PTT's should be filled with solid material to provide additional strength and avoid air spaces which might collapse under pressure.

4. Batteries must be chosen with care. Organic lithium batteries (there are many types) have the best energy density but some will not take heavy amperage loads and blow internal (and not replaceable) fuses or vent corrosive fumes which will attack electronic components. Obviously, a whale PTT can expect some rough treatment so internal mechanical considerations are also important. Some batteries are more delicate than others and may not be suitable even with protective shock mountings. At the present time, C-cells are the smallest batteries capable of sustaining the amperage necessary for a one watt transmission.

5. Mechanical strength, stability and adequate cushioning are important in construction and mounting of the PTT electronics. Nothing should be left "unsecured." All connections should be hard-wired to avoid vibrating loose.

6. Determining how frequently, how long and how accurately location data are needed will largely determine the size of the PTT. The maximum pressure exposure will dictate much of the housing design. With significant pressure, small and cylindrical housings will be favored. While there are advantages to tags which can be opened (turn batteries on when needed and change batteries) each closure must be tested to assure a good seal. O-rings are effective seals and are most easily fitted to cylindrical containers, but must be free of grit when installed.

7. A reliable saltwater switch is essential for any whale application and must be placed where it will work reliably. Pressure switches have not been demonstrated sensitive enough to control the transmitter's function.

8. Because bit-synchrony errors are predicted to affect 15% of all telemetered data, it is recommended to either repeat data on multiple transmissions or repeat an early element of the data stream at the end of the transmission.

9. Attachments should be limited to the skin and blubber, which have little blood and nerve supply. Attachments should avoid involvement of muscle tissue where movement may cause tearing, internal bleeding and possible pain.

10. Within the blubber layer, deeper attachments may have advantages by allowing more tissue to be involved in the attachment process, spreading the pressure of hydrodynamic drag and reducing potential movement of the tag.

11. It might be desirable in shorter-term experiments with large amounts of data, to use multiple Argos identification codes so several messages can be sent at each surfacing rather than at 40 second minimum intervals.

12. The use of duty-cycles is highly recommended to extend the operational life of PTT's. It is now possible to program PTT's to only transmit at certain times (up to 4 cycles/day) and change these cycles 4 times (periods or seasons) during the life of the PTT. This could be used to provide intense follow-up for several weeks immediately after tagging when resighting might be desirable and then reduce the number of transmissions/day or transmission-days/week to extend the longevity of the tag to identify a migration route.

13. Capacitive discharge systems may reduce the size of batteries currently needed for a PTT.

14. Ideally, monitoring should be done in the field with a local user terminal (LUT)(which currently cost approximately $35,000). LUT's are becoming more common and cooperation with existing LUT owners could cover most areas where whales might be tagged for a reasonable added expense. The most efficient way to collect data from a LUT (with storage capacity) is with a computer and modem.

15. Near real-time location data are essential in relocating tagged whales for behavioral observations or evaluation of the tag attachment.

16. It is important that field activities be adequately funded sufficiently far in advance to account for the design, construction and testing of housings, attachments, electronics, programming of duty cycles and data processing of sensor data. It also takes time to acquire or train new personnel for more complex developments (sensor, data acquisition and data reduction) and bureaucratic processes (permits, Service Argos, Global Agreements). Program continuity would greatly reduce the expense of tagging programs compared with multiple single-year efforts (contracts).

17. The experience of tagging gray whales on their breeding and calving grounds suggests that females will either be breeding or giving birth to a calf and that males and juveniles will either be breeding or "playing" with each other so physically that tags must be low-profile to stay attached. If low profile tags are not used, tagging efforts might better be directed at whales on their feeding grounds or along migration routes where less physical contact between one another is expected.

18. Changes in hybridization technology and simplified circuitry are likely to make PTT electronics shrink in size by 40% over the next few years and should increase the chances of long-term attachment and tracking success.

19. Further development of deployment methods is needed to increase future success in tagging free-ranging whales. Several ideas should be developed in parallel by cooperating engineers, field oriented biologists and electronics personnel. The up-front costs of this coordinated effort will pay off by increasing the success of tagging programs.

20. While there may be advantages in considering double tagging with PTT's to assess the duration of attachments, failure of a tag cannot be judged without close range viewing and this is often quite difficult. Geraci (pers. comm.) has indicated that whale radio tagging techniques currently in use pose no serious harm to large whales and certainly do not jeopardize their lives. As the PTT electronics have become quite reliable, it is likely that a loss of PTT signals indicates loss of the PTT. The expense of determining this by observation will be great (ship time, data from fewer whales and man-power). It would be more cost and data effective to use a single PTT for each whale. If different types of PTTs were used and one irritated the whale, both might be damaged by the whale.

21. Support should be given to NASA to develop the dual beam interferometer for Argos so future locations can be determined from fewer messages.

22. Attention should be maintained to alternate systems which may provide location and data recovery services from smaller or more energy-efficient transmitters.

23. On-board recharging systems would be an obvious benefit. Systems examined so far with little encouragement have included: temperature flux, pressure, photocell, propeller, aluminum/saltwater and galvanic action (sacrificial metal). The propeller driven system would be the most dependable if it would not foul but necessitates a certain amount of added drag to produce power.

24. The compaction of analyzed sensor data at the PTT into as few bytes as needed keeps transmissions short, reduces onshore analysis time and focuses the experimental design.

25. Development of acoustic sensors for physiological and sociological studies should be given some attention (funding) if they are to become realities. They will require some time to develop but should not be incorporated into PTT design until the basic PTT has been proven effective.

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