TRACKING OCEAN MIGRATORS

Bodega Marine Laboratory researcher A. Peter Klimley pulled on his face mask, gulped a breath of air, and dived into a school of sharks. He jabbed one with a pole spear, then quickly bobbed to the surface and scrambled back into his boat.

That's when the real excitement began.

Aboard a small motor boat, Klimley began tracking a shark he couldn't see as it navigated an underwater realm he could hardly imagine. Following the signals of an ultrasonic telemetry transmitter he had applied to the five-foot scalloped hammerhead with his spear, he raced after the unseen animal into the night.

The shark left the shallow waters near the ridge of the seamount known as El Baho Espiritu Santo off Mexico's Gulf of California and headed for deep water. Sensors on the transmitter measuring depth and direction showed the shark was clearly not meandering. It swam purposefully for 11 miles. But its path was not a simple arc, like the path of a large airplane. It followed a more convoluted course—more like the way a helicopter flies. A helicopter pilot navigates by dead reckoning, following topographic features below, like roads or mountain ridges or rivers. But unlike a helicopter pilot, this shark could have seen no such landmarks: it was swimming at night, making vertical excursions ranging from 328 to 1,476 feet, out of view of either the sea surface or the seafloor. The signposts for its route were scriven in a language Klimley could not read.

After 12 and a half miles, the shark abruptly turned—and precisely retraced its previous route. "It had the directionality of someone driving on the Jersey turnpike," Klimley said. "And it was an utter mystery to me how it could do it."

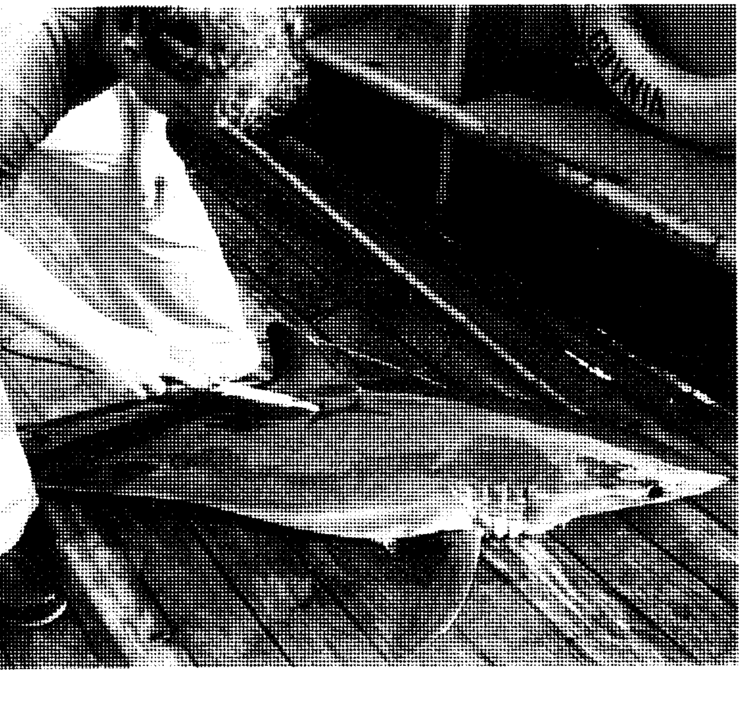
"That night, we were all stunned by what that shark had done," Klimley said. "These sharks are capable of doing something that is incredible."

But what Klimley and investigators like him are doing is perhaps equally incredible. Following sea animals in boats, tracking them on computer screens, and watching them in laboratories, researchers are catching the first glimpses into a realm humans have longed for centuries to penetrate—the unknown routes and mysterious compasses by which migrating sea creatures navigate the oceans.

Although people have wondered about these questions for centuries, never has answering them been more important. As fish

Tagging has helped to answer some old questions about where sea animals go but has raised some more difficult ones—such as how do they find their way and why do they go.

H. WES PRATT, NOAA



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A SHARK'S SENSE OF DIRECTION STUNS RESEARCHERS

BY SY MONTGOMERY

stocks crash, as driftnets and longliners drown endangered turtles, dolphins, and seals by the thousands, knowing the routes migrating creatures take could offer new ways to protect and manage dwindling marine resources. What are their signposts? In a seemingly boundless ocean, why *this* route, and not another?

"These are environments we can't really imagine. They may be following pathways we can't now imagine," says Jack Casey, who headed three decades of studies on shark movements before his retirement from the Northeast Fisheries Center in Narragansett, Rhode Island, earlier this year. "Only now we have the technology to start answering these questions."

That technology ranges from pole-orbiting satellites to transmitters and recorders that can withstand the punishing pressures of turtles' and whales' 4,200-foot dives. It includes microprocessors that scientists surgically implant inside the bodies of tuna and tags that recreational anglers attach to fighting billfish and snapping sharks. To track ocean migrants, researchers are gluing transmitters onto the heads of seals, fitting leatherback turtles into nylon suspenders, and designing instruments so "smart" that the instruments themselves figure out where they are.

And while none of their methods is foolproof, already they are sparking tantalizing new ideas about where these creatures go, how they find their way, and why.

Among the most important revelations of the past three decades of marine biology are the great distances ocean migrators swim—data gathered largely thanks to the Cooperative Game Fish Tagging Program and the Cooperative Shark Tagging Program, funded and administered by the National Marine Fisheries Service. Under these programs, scientists and recreational and commercial fishermen have outfitted more than than 160,000 individual game fish and 114,000 individual sharks with stainless steel darts and identifying streamers. The ID number of the tag links the individual with a brief but important biography: the date and place the animal was tagged, an estimate of its size at the time of that encounter, and the name of the angler who implanted the tag and released the fish.

Begun in 1954, the tag-and-release effort brought breathtaking results by 1959. That year, a bluefin tuna tagged off Massachusetts was recaptured only a few months later in the Bay of Biscay off the coast of France. Subsequent recaptures confirmed the unsuspected magnitude of these fishes' migrations: bluefin tuna have been recaptured more than 6,214 miles from their tagging site; blue marlin, 5,592 miles; white marlin, 3,107 miles; sailfish, 2,113 miles; and blue sharks, 1,243 miles. "To some of these fish, the Atlantic Ocean is just a small pond," says Eric Prince, chief of the migratory fishery biology division at the National Marine Fisheries Service's Southeast Fisheries Center in Miami.

These studies have also revealed that many migratory fishes are long-lived. Bluefin tuna have been captured 18 years after release; sandbar sharks, 21 years later. Tags led researchers to discover that female blue sharks, for instance, are, even if sexually immature, capable of storing sperm in their bodies for later use.

The females are able to delay fertilization so they have time to mature and to commute to Spain, Portugal, and the Canary Islands. There they give live birth to pups nine months to a year after their summer assignations with males off the east coast of the United States.

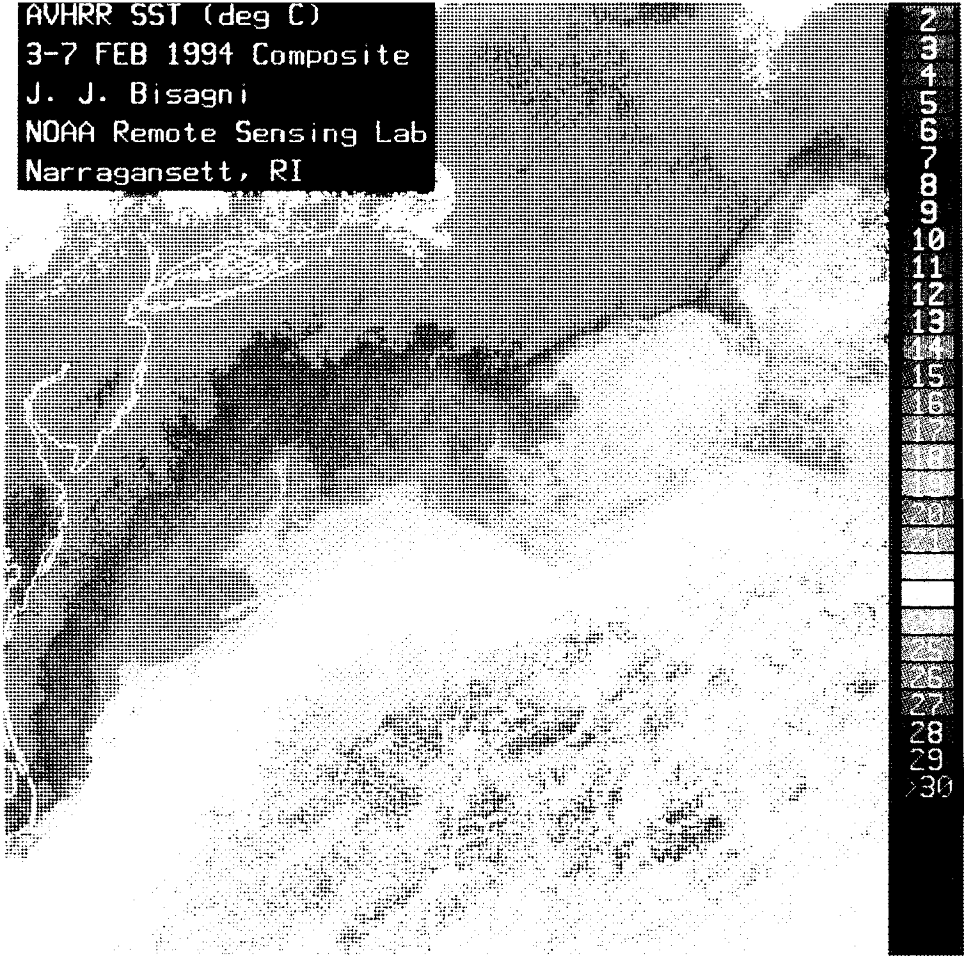
The tagging results continue to surprise and enlighten. But the picture tags provide is sketchy. Retrieving any data at all depends on the unlikely chance that a tagged fish will ever be caught again—odds against which hover near 100 to 1. Although bluefin tuna boast recapture rates of 12 to 15 percent, only 1.4 percent of tagged sailfish are ever recaptured and only 1.7 percent of white marlin. Blue marlin are the rarest recaptures of all—of the 6,962 tagged between 1954 and 1987, only 29 were ever seen again.

There are other problems as well. About one-third of the time, recaptured billfish are recorded weighing less than their original estimate at tagging—sometimes many years later. It's an understandable error: not only does refraction of light by water make the fish appear larger but so does the excitement of fighting a monster marlin slashing with a razor-sharp upper bill.

But the greatest limitation, says Prince, is this: "Tags show the fish went from point A to point B"—but not what points in the journey point A and B represent. "With highly migratory species, it's crucial to know what goes on in between."

For what "goes on in between" comprises routes that are possibly not only longer, but almost certainly far more complex and sophisticated than the straight lines between release and recapture suggest.

Consider, for instance, Scott Eckert's studies of leatherbacks. In 1993, the senior research biologist at Hubbs-Sea World Research



The satellite image above shows the separate tracks of two tagged blue sharks over a three-week period in early 1993.

JAMES BISAGNI/NOAA, NMFS

Institute specially fitted two Mexican leatherbacks with nylon suspenders to hold on their transmitters (unlike the case with other sea turtles, the telemeters can't be glued to leatherbacks' leathery shells) and tracked them as they left their nesting beaches off Mexico's Pacific coast and headed for their famous migration—in the "wrong" direction.

"We know from tag returns from the North Atlantic and North Pacific that these turtles nest in the tropics and forage in the north," he explains. "So one would think they would have headed north. But they headed south."

One of these turtles died after a month. Because of her telemetry, Eckert knows she was killed aboard the deck of a fishing vessel. Although the satellite located her bearings far offshore, her depth recorder relayed she was on the surface for more than six hours—obviously, on the deck of a boat. The other south-pointing turtle was turning west when her battery pack failed after 120 days at sea—a record for leatherbacks.

Eckert's data so far suggests that rather than a simple north-south route, leatherbacks may undertake a clockwise, circum-Pacific pathway. Three leatherbacks he's been tracking from Trinidad since they left those nesting beaches in May have, as this article goes to press, covered more than 1,000 nautical miles and are headed northwest.

Eckert is among the hundreds of researchers worldwide now tracking about 800 individual animals on both land and sea with the Argos location and data collection system. Argos instruments are flown on board the National Oceanic and Atmospheric Administration's polar-orbiting satellites. The animals' transmitters, whether fastened to a collar on the neck of a bear, glued to the head of a seal (whose yearly molt will remove it), or attached to a backpack on a penguin, operate on the same principle. Sensors on the transmitter collect data—typically depth, temperature, direction—which is then transmitted to the satellite. The Argos system calculates the latitude and longitude of the transmitter by measuring the change in the frequency of the message as it is received aboard the moving satellite (the change is due to a phenomenon known as Doppler shift, which accounts for the change in the sound of the whistle of an approaching and departing train).

Service Argos provides data daily about more than 2,200 transmitters deployed on land and water. It delivers Eckert's turtle data to his e-mail account. Says Eckert, "What a great way to be doing science!"

But for ocean-going animals, satellite telemetry has a serious limitation: to transmit to the satellite, the animal bearing the transmitter must come close enough to the surface that its antenna reaches above water—and it must do so during the time that a satellite is overhead. This is something that many sea animals don't do and that even air-breathing turtles, whales, and dolphins may not perform to schedule.

The number of times an Argos satellite passes over any transmitter increases with latitude. At the poles, each satellite passes about 14 times a day, at the equator, 3.5 on average. Each satellite pass offers an 8 to 15 minute "window" during which the satellite can receive messages. No data can be transmitted if the animal doesn't surface during that time. If it sur-

faces but remains above water too briefly for the satellite to register its Doppler shift, the animal's position cannot be calculated. The longer the data gaps, the sketchier the map of travel.

At present, the only reliable way to track individual animals that don't regularly surface is to personally follow them. This is what Klimley did in his boat, racing after hammerhead pathways traced by ultrasonic pings.

In all, Klimley and his colleagues followed 14 trips to and from the seamount involving three different sharks. The results were all the same: the sharks followed remarkably constant bearings, choosing a few clear, well-defined paths. But what did the sharks "see" in these pathways?

Klimley followed the sharks as they telemetered depth, temperature, light levels, and direction of travel. A second small boat followed his, periodically sampling temperature, light levels, and water current to a depth of 650 feet. And the large support vessel measured topographic features of the seafloor with sonar. Finally, the magnetic field intensity of the seamount was mapped with a towed magnetometer.

Klimley reasoned the sharks might be following isobaths—depth contours, swimming up and down specific gradients of depth. Or they might be picking a fixed direction in relation to currents. They could be following a highway of temperature or a path signposted with chemical cues.

For scientists exploring the sensory realms of animals have documented that animals possess whole worlds of sensation that humans never experience: the sonar imagery of bats and dolphins, the infrasonic sounds of calling elephants and whales. Birds can see polarized light invisible to our eyes. Sharks and their flattened relatives, rays and skates, can detect weak electric fields with pit-like organs known as the ampullae of Lorenzini, which may help them capture prey. These same organs can detect the electric fields induced by the fish's own displacement as it swims across the lines of force of the earth's magnetic field.

Klimley's results strongly suggest that his hammerheads may use local features of the geomagnetic field to help them navigate. Plotted on a map of geomagnetic features, the sharks' pathways followed a change in steadily increasing or decreasing magnetic fields—the magnetic equivalent of topographic slopes or valleys.

Klimley's findings were so astonishing that seven scientific journals refused to publish them. But after his first reports appeared in *Marine Biology* in 1993, they were hailed as landmarks—with one caveat. They suffered not from lack of rigor, wrote University of Washington researcher Thomas Quinn in a review of the data, but from "the common limitation of telemetry studies." Without tracking more animals, it's impossible to tell whether the conclusions were valid. With costs of running one research vessel between $4,000 to $7,000 a day, that can be very expensive.

But soon it may be possible to compile extremely detailed information without directly following an animal or without regular contact with a satellite. In theory, at least, a fish need only be seen twice—just like with conventional streamer tags—in order to learn the complete history of its every move.

The odds are against retrieving a tagged fish, but when it happens the results can be startling.

L. J. NATASON, NOAA

On first encounter, the fish is surgically implanted (all it takes is a single slit and suture) with an experimental new device called an archival tag. It is actually a miniature computer, capable of storing megabytes of information for years—which it downloads if the fish is caught again.

"This is really the emerging technology that before long will revolutionize fisheries research," Klimley believes.

Advances in miniaturization and microchip technology keep the tag's size small: today's prototypes may be two inches long and half an inch thick and weigh just under two ounces. Not only can these tags store an undreamed of wealth of sensor measurements—they can also use the measurements to obtain a record of the daily geographic locations of each tagged fish.

Wide use of the tags could mean an explosion of extremely detailed data on species about which almost nothing is presently known. "Satellites used by marine mammals have a limited ability to carry data—512 bytes of data per day, if you have huge batteries," explains Roger Hill, founder and president of Wildlife Computers Inc., an eight-year-old company that manufactures telemetry for use with both satellites and handheld receivers as well as archival tags. "Those data are a trickle. But the archival tags can store up to megabytes per day—more than two million readings. Now we can record in fine detail what these animals do."

Maybe not quite now, but soon. Prince points out "some very basic problems still need to be worked out," among them, the fact that latitude readings may be off by as many as 240 nautical miles.

The tags currently measure latitude by sensing day length (even in deep water, sensors can detect the rapid light changes of dawn and dusk). Day length changes with distance along a meridian on the earth's surface, from which latitude can be calculated.

But day length varies with season and changes so little at the equator that the method is almost useless in the tropics.

Australian researcher John Gunn, who has deployed more than 180 geolocating archival tags on southern bluefin tuna, compared tag-determined positions of tunas enclosed in a cage towed through the water at the sea surface with the actual position. Although the latitudes were sometimes seriously off, he found the tags accurately reported longitude—that measurement is determined by a method similar to that used by ancient sailors, by calculations comparing the time of high noon with that at a reference location.

And there remains the problem of recovering the tagged fish. The chances of recovering an archival tag are no better than recovering a conventional streamer tag. The archival tag's loss is more disheartening—each costs between $1,000 and $2,500.

Still, the phenomenal amount of data a single tag could record would reward the rare recovery. Of the 90 tags deployed by English fisheries researcher Geoff Arnold since December 1993, only 11 have been recovered. But those 11 tags produced 462 days of detailed data, including long-term records of the fishes' vertical excursions during migratory movements in the North Sea. "One return of an archival tag from a prized species such as black marlin might actually be worth the $100,000 cost of a hundred tags," said Gunn.

Developers of archival tags are confident of their future. Klimley is working on a way to improve latitude accuracy by adding a new sensor. The intensity of the earth's magnetic field changes with latitude, decreasing in the northeast Pacific to the equator along a gradient that can be used to measure degrees latitude. Researchers are also investigating ways to boost recovery rates. Klimley and colleague Will Mangan envision "listening stations" that would regularly pick up data from passing fish, without requiring anglers to land them. Automatic monitors could be moored at submerged locations to which fish often return, like seamounts and reefs. The listening stations could "interrogate" the tags with an ultrasonic modem. At the signal, the tags would download their data to the station, which would then transmit the information by VHF radio to shorebased stations.

Others propose "pop up" archival tags. The tag could be equipped with a radio transmitter that would release from the fish after a time, float to the surface, and uplink its data to a satellite.

"The ability to track any one of the highly migratory species—to follow that animal for days, weeks, and months—is the answer to any biologist's dream," says David Potter of Woods Hole Oceanographic Institution.

Now, at this crucial crossroads in marine conservation history, that dream is about to come true.

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