WHAT'S NEXT in Exploration

ROBOTS OF THE DEEP BLUE YONDER

To the ocean's secrets we remain largely blind. But a new fleet of robot subs will soon patrol the seas and report back on life, earthquake zones and the causes of climate change.

BY CARL POSEY

ILLUSTRATIONS BY JOHN MACNEILL

NEARLY EVERY DAY,

somewhere on the crest of the 37,000 miles of mid-ocean ridges that zigzag the global seafloor, a volcanic eruption spews a stream of red-hot lava, reshaping and renewing Earth's crust. Scientists know little about these violent events, however, because by the time they realize one is under way and steer a research vessel there to investigate, the most dramatic moments have passed. Sensors, dropped into the water on tethers, pick up only incomplete data. But a new breed of robots known as autonomous underwater vehicles (AUVs) may soon fill this critical knowledge gap.

Imagine this: Volcanic activity is detected by seismic sensors secured to the seabed; the sensors send out an alert, and triangulate the site of the blast to within 3 kilometers. That "wakes up" a nearby AUV, which immediately starts searching for the volcanic plume by seeking water that's warmer or more opaque, then follows it to the source. Once there, the sub begins gathering water samples to create a second-by-second record of the changes caused by the eruption. The vehicle also instructs other AUVs to descend and take photos of the ocean floor, capturing images of Earth's crust as it is in the process of being reformed. Observing an undersea volcanic eruption this way, in real time, "would be a tremendously exciting thing," says Jim Bellingham, director of engineering at the Monterey Bay Aquarium Research Institute in Moss Landing, California.

The sea holds clues to many key questions—not only about underwater volcanoes but about the future of our planet's climate and perhaps even the very origins of life—but it is opaque to most of our instruments. Light penetrates only a few feet, radio waves drown or ricochet, sonar-burst echoes provide only approximate information about depths, objects and underwater creatures. Scientists, for their part, mostly remain on the surface, hoping for lucky glimpses of the phenomena they intend to explore. "We go out on ships to study dynamic ocean processes, but we can never be sure we will be in the right place at the right time," says Bellingham, an AUV pioneer. "How much better if we have the tools in place and are ready whenever a key event happens."

Science geeks aren't the only ones hyped up about AUVs; the U.S. military has recognized the key roles such unmanned craft could play in coastal and deep-sea warfare. The Pentagon is developing a concept for a combat AUV called Manta that will carry a cluster of smaller AUVs in its hull to launch during a battle. Naval researchers also intend to create autonomous subs that will destroy submerged minefields and conduct surveillance operations in enemy territory.

AUVs first swam close to a decade ago. The Autonomous Benthic Explorer (ABE), a deep-diving craft created at the Woods Hole Oceanographic Institution in Massachusetts, is a pro at conducting geophysical surveys, and the torpedo-shaped Hugin 3000, made by Norway's Kongsberg-Simrad, routinely monitors oil rigs, pipelines and transoceanic cables up to 2 miles deep. But as oceanographers tackle ambitious plans to build the first undersea observatories—permanent unmanned lookout stations on the ocean floor outfitted with moored sensors and buoys—a new generation of AUV is counted on to act as the key moving parts, roaming and monitoring the deep and sending real-time data to shore.

Just as the invention of the telescope made it possible for astronomers to see into the nighttime sky, underwater research stations—their first full-scale field test is scheduled for 2005—will reveal the workings of the oceans. "AUVs linked to observatories are going to be the 24-by-7 presence in the ocean that we have never had," says Alexandra Isern, program director for ocean technology at the National Science Foundation, which is funding one of the observatories. "They'll provide continuous monitoring of even the most deeply hidden ocean processes, the way satellite systems already do on land." Underwater docking stations at the observatories will enable AUVs to stay out for months at a time—the equivalent of a gas station, they'll be a place for AUVs to recharge their batteries, dump their data and await their next instructions.

Underwater observatories will make it possible for the ocean to be seen whole, its complicated physical and biological interconnections unraveled. This has become a matter of some urgency, for somewhere in the sea's wheels within wheels, the planet's climate—its fate—is shaped. "You can't make any predictions about the health of the planet without understanding the oceans," says Bellingham.

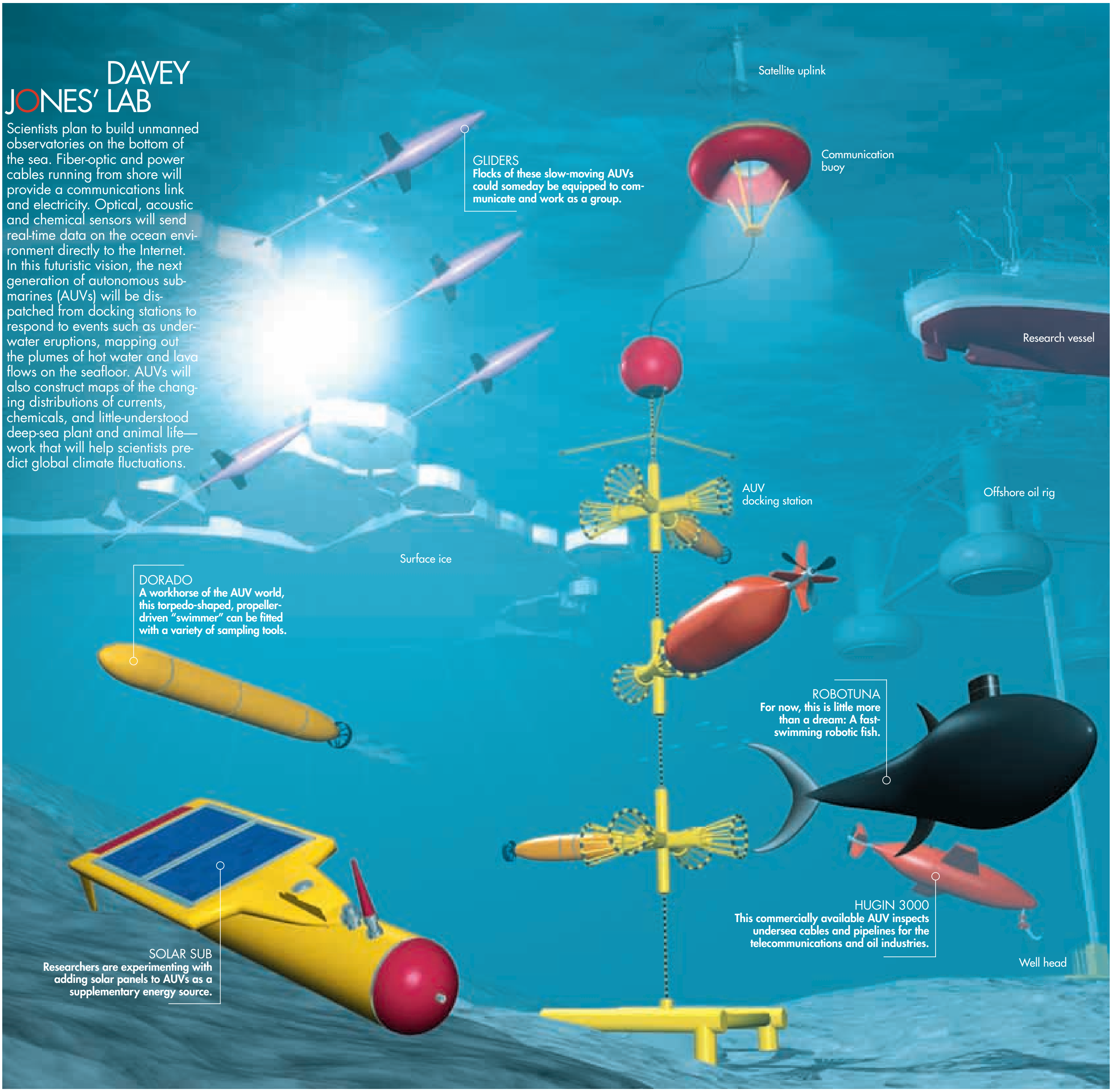
BELLINGHAM'S OFFICE, IN A SPRAWLING WARREN OF SEA-gray frame structures almost hidden by the masts of fishing vessels, offers a panoramic view of Monterey Bay, one of the planet's great natural oceanographic laboratories. Here the relative shallows of the continental shelf are cut by a gorge deeper than the Grand Canyon; the shelf drops sharply toward the abyss a few kilometers offshore, where upwelling bottom waters create a cold, food-rich incubator for organisms at the base of the food chain. Almost everything that happens in the global sea can be observed an hour's sail from here.

A 41-year-old physicist and engineer who seems constantly in motion, a refilled coffee cup always in hand, Bellingham had his first experience with seagoing robots when he took over the fledgling AUV Laboratory at the Massachusetts Institute of Technology's Sea Grant Program in 1989. Since then he's designed, built and tested a half dozen or so AUVs that have carried out hundreds of dives in every type of environment. Whether deployed under Arctic ice or in the heady currents of the Magellan Straits, whether diving to 100 feet or 500 fathoms, his robotic subs have always found their way home.

The first unmanned subs were tethered vehicles—attached to a research ship like a dog on a leash, they were operated by human handlers. By 1993, engineers had built AUVs such as ABE that were free swimming, but that still needed human intervention and could only remain underwater for a few hours. Within the past two years has come true autonomy: vehicles that execute specific programmed tasks and then return. Missions have lasted as long as a

DEEP THINKER Jim Bellingham has been fascinated by the ocean since his undergrad days, when inventor and stop-action photographer "Doc" Edgerton, an MIT prof, took him along on sonar experiments in Boston Harbor. He's standing a few hundred paces from his office at the Monterey Bay Aquarium Research Institute in Moss Landing, California.

PHOTOGRAPH BY BRYCE DUFFY



DAVEY JONES' LAB

Scientists plan to build unmanned observatories on the bottom of the sea. Fiber-optic and power cables running from shore will provide a communications link and electricity. Optical, acoustic and chemical sensors will send real-time data on the ocean environment directly to the Internet. In this futuristic vision, the next generation of autonomous submarines (AUVs) will be dispatched from docking stations to respond to events such as underwater eruptions, mapping out the plumes of hot water and lava flows on the seafloor. AUVs will also construct maps of the changing distributions of currents, chemicals, and little-understood deep-sea plant and animal life—work that will help scientists predict global climate fluctuations.

GLIDERS
Flocks of these slow-moving AUVs could someday be equipped to communicate and work as a group.

DORADO
A workhorse of the AUV world, this torpedo-shaped, propeller-driven "swimmer" can be fitted with a variety of sampling tools.

ROBOTUNA
For now, this is little more than a dream: A fast-swimming robotic fish.

HUGIN 3000
This commercially available AUV inspects undersea cables and pipelines for the telecommunications and oil industries.

SOLAR SUB
Researchers are experimenting with adding solar panels to AUVs as a supplementary energy source.

month. But the capabilities of today's AUVs are nothing compared to what Bellingham and other sub designers expect to create in the next few years. The AUVs that will be the vital eyes and ears of underwater observatories will be able to deviate from their instructions to react to ambient conditions and communicate with one another.

On this day, Bellingham's latest AUV, named Dorado—a torpedo-shaped 17-foot by 21-inch vehicle—is sprawled in the lab, its upper panels removed to reveal computers and sensors in pressure-proof aluminum, glass and titanium housings. Should it go astray, it bears a painted notice: "Unarmed oceanographic equipment. Reward. If found call . . ." It possesses 10 to 15 pounds of positive buoyancy; if disabled underwater, it will rise to the surface.

Dorado's science payload includes sonar to measure Arctic ice depths and sensors that, by detecting nitrates, oxygen, the amount of suspended matter and other parameters, identify how the properties of ocean water vary depending on the location, time of year and other factors. A conductivity-temperature-depth (CTD) instrument provides data necessary to calculate salinity and density, currents and sound velocity. Not

Eavesdrop on a conversation with one of the most visionary developers of autonomous subs at **www.popsci.com/exclusive**

long ago, CTDs came in packages that were about as big as an oceanographer and were lowered on cables from ships. Now they fit inside a small compartment inside Dorado.

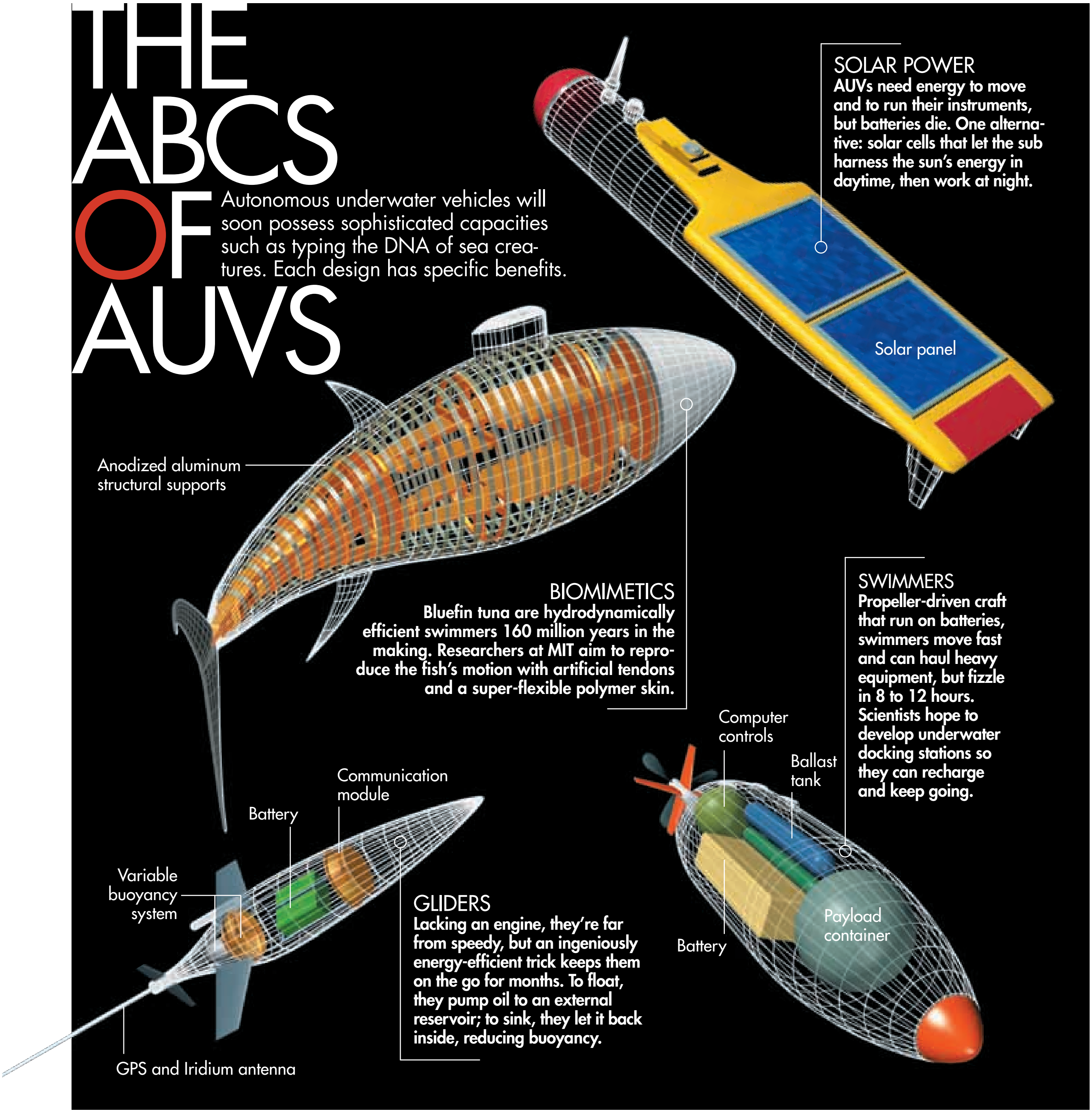
Shrinking instrumentation is one of the advances that's shaping the future of AUVs. In another lab downstairs is a device that can trap, pulverize and perform on-the-spot DNA analysis on selected microorganisms, separating the toxic creatures from their harmless look-alike companions. Nicknamed Darlene, the prototype resembles a life-size Picasso sculpture of metal framing, carousels, wires, vials, pulleys and belts. Within the next few years, Darlene will be downsized to fit into an AUV and conduct complicated biological sampling as the sub cuts through a plankton cloud or toxic algae bloom.

The Dorado—which on a future mission will fire sonobuoy probes into the underside of the Arctic ice sheet, leaving what Bellingham calls a bread-crumb trail—can swim at 3 knots for 12 hours and dive almost 3 miles down. For now, Bellingham and his crew hope to expand the amount of time their AUVs can remain at sea to about 20 hours by improving battery efficiency, but they are also testing a fuel-cell-driven version that could embark on a 260-hour jaunt.

THE DORADO IS ONE OF A CLASS OF AUVS KNOWN AS SWIMMERS because they are fitted with huge batteries that power propellers. Swimmers can travel moderate distances and carry sizeable payloads. Another more recently introduced type of

THE ABCS OF AUVS

Autonomous underwater vehicles will soon possess sophisticated capacities such as typing the DNA of sea creatures. Each design has specific benefits.



SOLAR POWER

AUVs need energy to move and to run their instruments, but batteries die. One alternative: solar cells that let the sub harness the sun's energy in daytime, then work at night.

BIOMIMETICS

Bluefin tuna are hydrodynamically efficient swimmers 160 million years in the making. Researchers at MIT aim to reproduce the fish's motion with artificial tendons and a super-flexible polymer skin.

GLIDERS

Lacking an engine, they're far from speedy, but an ingeniously energy-efficient trick keeps them on the go for months. To float, they pump oil to an external reservoir; to sink, they let it back inside, reducing buoyancy.

SWIMMERS

Propeller-driven craft that run on batteries, swimmers move fast and can haul heavy equipment, but fizzle in 8 to 12 hours. Scientists hope to develop underwater docking stations so they can recharge and keep going.

JOHN MACNEILL

AUV, the glider, uses shifts in its buoyancy and center of gravity to dive and rise. Gliders tend to be smaller than swimmers and be focused on specific, limited tasks. They move slowly—about 0.5 mph—but they have great endurance.

A typical glider is the University of Washington's Seaglider, a needle-nosed vehicle about 6 feet long and 114 pounds, with stumpy fixed wings and a fixed tail. An electric motor moves the battery pack—and the Seaglider's center of gravity—fore and aft, to control the pitch of the nose. Roll control, which allows the Seaglider to bank like an airplane, comes from shifting the batteries from side to side. To move up and down through the water column, Seaglider adjusts how much oil it holds in an internal reservoir. To rise, the glider pumps oil into an external repository, increasing its buoyancy; when Seaglider is ready to sink, it lets the oil back in again.

THE MOST HAZARDOUS ASPECT OF AN AUV MISSION: RECOVERY.

After each dive, the Seaglider comes to the surface, then dips its nose underwater, raising its trailing antenna into the air to determine its GPS location, upload its data and download any new instructions via the Iridium satellite network. The Seaglider can plumb to depths of more than 3,000 feet and is designed to stay out for months at a time, repeating its pattern of dive, stop, ascend, surface, dive, stop, ascend, surface in a ceaseless slow-motion ballet. Meanwhile, AUV researchers are experimenting with other methods to power gliders. Engineers at the Autonomous Undersea Systems Institute in Lee, New Hampshire, for example, are developing AUV-appropriate solar panels; by periodically rising to the surface to bask in the sun while uploading their data, solar-powered gliders would be able to stay out on an environmental reconnaissance mission for a year or more.

TO PROGRAM AN AUV'S ASSIGNMENTS, OPERATORS WRITE A mission script, which is a computer program. Its list of tasks is precise: "Profile the water column. Don't run shallower than 10 feet. Cycle between 15°C and 7°C seawater. If you detect a cloud of plankton, sample it. Then go down to the seafloor, follow it for 45 minutes, look for biological life. Travel upward 500 feet, search for canyons and crevasses." After that initial script is programmed in, the AUV is lowered into the water from a ship's crane, usually pushed by workers in a tender, and then sets off to run through its tasks. Once in the water, the AUV is mostly on its own and has scant contact with the scientists onboard the ship. To return, it homes in on the ship's beacon; the crew retrieves it and downloads the data it has collected. (The AUVs also have beacons, so that if they poop out, workers can find them bobbing on the surface.)

The most hazardous aspect of the AUV mission is recovery, especially in rough seas. The ambient pressure at 2 miles' depth can produce a loss of buoyancy that makes a return to the surface impossible. And then there's the chance the vehicle will hit bottom, lose its bearings and have difficulty reorienting itself. "Underwater navigation techniques require working on the hairy edge," says Bellingham. "Occasionally a vehicle thinks it knows where it is but doesn't."

Unmanned aircraft, which have been so much in the news of late, have a much easier time staying on target than AUVs do. When running near the water's surface, an AUV can use its antenna to get a continuous position-fix from GPS satellites, the way its airborne counterparts do. But because GPS signals don't penetrate the sea, on deep-water missions navigation must be performed by the sub itself. In those instances, most AUVs use GPS to get their starting point. Then, when submerged, some plot a course with dead reckoning, a system in which position is determined by keeping track of how long and how fast the vehicle travels in a given direction. Others, like the Dorado, use an inertial navigation system, in which laser-ring gyroscopes orient the vehicle spatially and accelerometers sense changes in speed and direction. A computer integrates that data to determine the vehicle's position, which is then compared against the programmed directions; if necessary, the computer resets the AUV to travel in the correct course.

EARLY FIELD STUDIES OF THE COMPONENTS THAT WILL BE used in underwater observatories have already been completed, but the big test of these permanent oceanic lookouts will be in early 2005 when researchers lay 40 miles of fiber-optic and power cable in the Pacific Ocean and flip the switch on the Monterey Accelerated Research System (MARS). MARS developers—Bellingham and his colleagues as well as scientists from institutions such as NASA's Jet Propulsion Laboratory and Canada's Dominion Astrophysical Observatory—plan to tackle some of the most complex scientific puzzles buried in California's waters. Using AUVs, imaging systems and sensors, and communicating to shore stations and research vessels via satellite and fiber-optic cables, they'll document animal behavior in relatively unexplored undersea habitats. Peering into the abyss of Monterey Canyon they'll study the movement of sediments to better understand how violent underwater landslides occur. They'll study how excess carbon dioxide—which some experts advocate dumping in the ocean to counteract global warming—would affect the health of various sea creatures. They'll examine the chemical makeup of rare plankton.

Oceanographers hope to follow MARS with a much more ambitious underwater observatory called Neptune, which will be situated in the Juan de Fuca Ridge (located near the western U.S.-Canadian border). The project's developers—NASA, the University of Washington and Woods Hole, among others—chose Juan de Fuca because it's a highly active underwater geological site where a suite of tectonic activities are constantly in motion—and earthquakes frequently threaten. Scientists hope Neptune will enable them to learn enough to ultimately predict earthquakes.

They also intend to use Neptune to study colonies of microbes that have been discovered in recent years living in roiling ocean-bed fissures known as deep-sea vents, despite the unthinkably high temperatures there. Called extremophiles because they thrive in harsh environments, such creatures, while interesting in their own right, are especially intriguing because scientists believe that microorganisms much like them may have been the first to populate our planet, and also that they are a likely template for possible extraterrestrial life-forms.

If Neptune is a success, researchers hope to build other observatories, situated in key locations such as the Arctic, that will tell them even more. For example, scientists hope underwater observatories will help them learn more about the migratory movements of key marine species: Shrimp, great white sharks and whales, among others, disappear from human view for years of their life cycles; if we knew where they went we might be able to develop sustainable fishing strategies that do less harm to their populations.

Most of all, though, scientists want to use AUVs and ocean observatories to explore how the ocean regulates Earth's climate. They particularly want to study deep-ocean convection, the cycle by which ocean currents such as the Gulf Stream transport warm water into colder regions. As the warm water travels north, it cools off, becoming saltier and denser; when this heavier water gets to the Arctic, it sinks. Scientists have observed, however, that the convection cycle has become less regular in recent years. Why? Some believe it's being disrupted by global warming: Glaciers are melting, flushing the system with extra freshwater, which dilutes the salty, dense water and prevents it from sinking. Ominously, in past millennia, disruptions in the mixing of ocean water have been associated with the rapid onset of an ice age. Some scientists hypothesize that we may be causing one now—that, in short, we face a potentially calamitous future unless we can learn enough about deep-ocean convection to get it back on track.

For oceanographers this is heady stuff, uncharted territory. Underwater observatories, boosted by the watchful prowling of AUVs, hold out the first real hope that the opaque fluid universe, the most essential physical body on Earth, may someday become as transparent as air. ■

Carl Posey is a freelance writer based in Alexandria, Virginia.

© 2003 Times Mirror Magazines, Inc., posted from Popular Science Magazine.
#444113 Managed by Reprint Management Services, (717) 399-1900. To purchase reprints online, visit www.reprintbuyer.com.