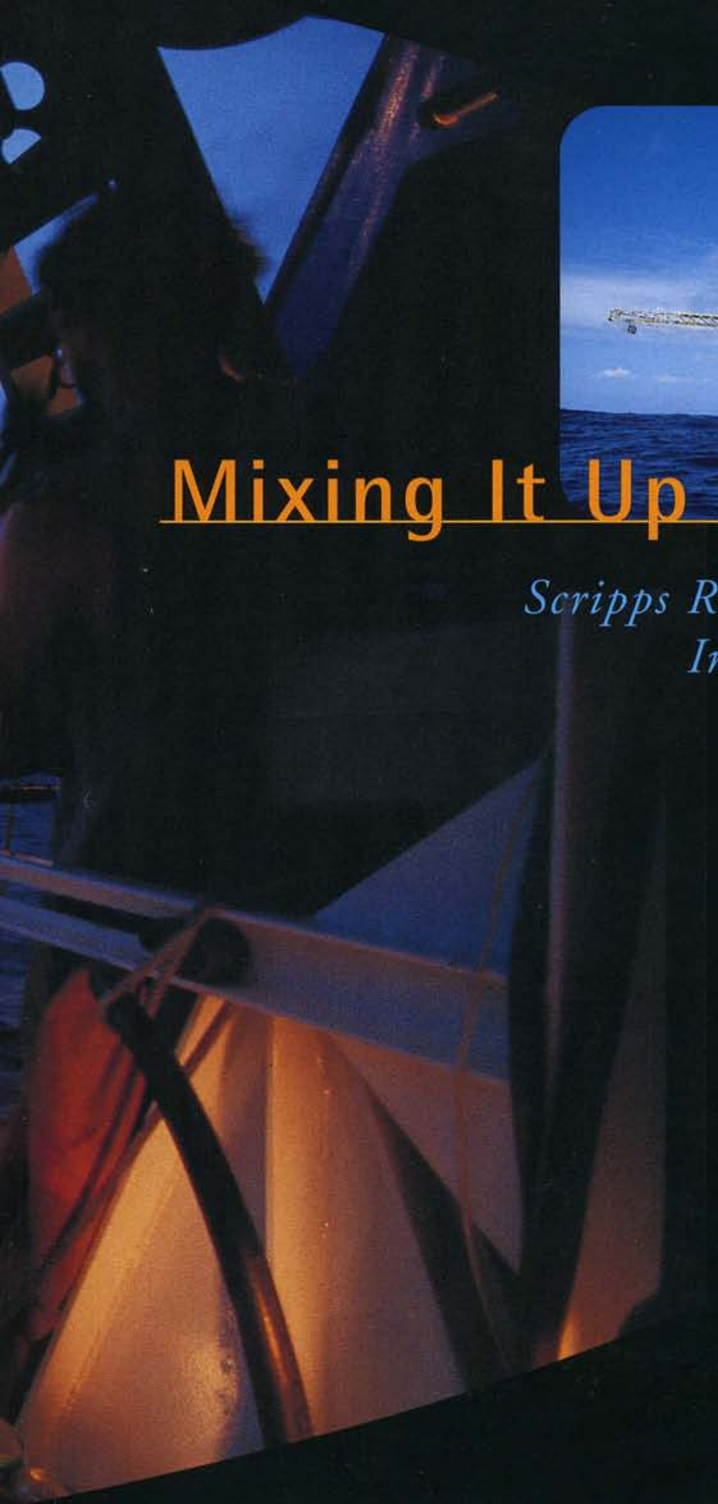
Graduate student Luc Rainville takes in a Pacific Ocean sunset aboard the research platform FLIP. FLIP **(above inset)** *carries a suite of instruments that monitored the Pacific Ocean's tidal energy as part of the Hawaii Ocean-Mixing Experiment.*



Mixing It Up in Hawaiian Waters

Scripps Researchers Lead Multi-Institutional Experiment

BY ROBERT MONROE

THE FAINT LIGHT PULSE from a lighthouse helped the science party aboard R/P FLIP keep its bearings in the darkness of night. Against the hull of the research platform, an unlikely metal island in the middle of the Pacific, lashed a steady current out of the northeast.

The scientists and crew braced like subway riders with each lurch. Deep tidal currents tugged at the mile-long anchor lines that held the platform, flipped to its vertical position, on the edge of a five-kilometer- (three-mile-) deep undersea precipice.

This was four weeks into one of the final field surveys in the Hawaii Ocean-Mixing Experiment, better known as HOME, a scientific program to observe the interaction of the energetic Pacific Ocean tide and the steep topography of the Hawaiian Ridge, a 2,575-kilometer (1,600-mile) long backbone of islands and submerged seamounts that includes America's fiftieth state. Broadsided by a high tide every 12 hours, the ridge is thought to be home to several "hot spots" of concentrated tidal interactions including one directly below FLIP.

Just as relentless as the regular roar of the passing swells pushed on by trade winds toward Asia was the steady drone of the winches on deck lowering and raising sensors off the starboard and aft decks.

Two sensor packages, named Fish 1 and Fish 2, dangled like bait at the ends of 3/16-inch-gauge steel

cables. They were repeatedly lowered and then raised toward the surface by the winches, making a round-trip every four minutes. Fish 1 measured the temperature, conductivity, and pressure of the ocean from the surface to 400 meters (1,312 feet) deep. Fish 2 did the same from 400 to 800 meters (1,312–2,624 feet).

Nearly 12,000 such profiles were taken over the course of five weeks, 12,000 trips orchestrated automatically by the computers in FLIP's lab. The end product was a continuous depth–time image of oceanic motions in unprecedented detail.

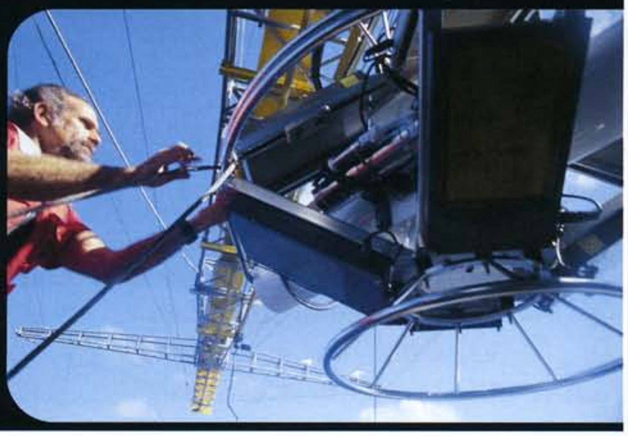
Over the years, Scripps Institution of Oceanography physical oceanographers and engineers taking part in HOME have developed instruments that have become standard tools of marine exploration. The science team designed and built most of the equipment for this experiment from scratch and spent months planning its deployment. Physical oceanographer Rob Pinkel has been waiting 15 years to see the data that the equipment will produce.

Above, *Scripps engineer Lloyd Green guides the sonar unit Deep-8 in for inspection.* **Left,** *Leaving Honolulu, R/V Revelle heads out on the 2001 HOME cruise led by Peter Worcester.*

The reward for the team's meticulous preparation was routine data collection. To fill in lulls in the action, team members brought homework, computer games, and DVDs to watch, along with the five tons of gear they brought to support the scientific instruments.

"There's not much to experience between boredom and panic," Pinkel said. Around 11 p.m. on October 6, right in the middle of watching the movie *Silverado*, what sounded like a fire alarm blared from one of the computers. Fish 2 had stopped communicating.

This was the panic part.



MISSING MAJORITY

HOME is a grassroots effort of nearly 20 scientists from eight major institutions to track the cascade of energy from the surface tide to various smaller scales of motion, and eventually to viscous dissipation, following the interaction between the tide and the topography of the Hawaiian Ridge. Planning for the experiment began in 1996, with support obtained from the National Science Foundation in 1998 for a six-year $16-million effort.

Pinkel, who has spent 29 years as a Scripps reseacher, is HOME's chief scientist. Other researchers are from the University of Washington, Oregon State University, University of Hawaii, Woods Hole Oceanographic Institution, and the National Oceanic and Atmospheric Administration. Each researcher is studying a different aspect of the immense activity taking place around the Hawaiian Ridge. During the field-survey portion of HOME, the scientists logged more than a year's ship time on four research vessels including FLIP.

After data are processed and analyzed, the resulting computer models and theories will have far-reaching implications on oceanographic research.

The world's ocean surface is heated at low latitudes and cooled near the poles. The cooled water sinks at high latitudes, spreading slowly toward the equator in the deep sea. If this process were to proceed uninterrupted, the ocean basins would simply fill with cold water over a period of several thousand years. They don't because of the presence of a variety of small-scale processes that mix the heat from the surface downward to maintain the thermal and salinity structures that are seen in the ocean today.

HOME PROFILE

MURRAY LEVINE AND TIM BOYD

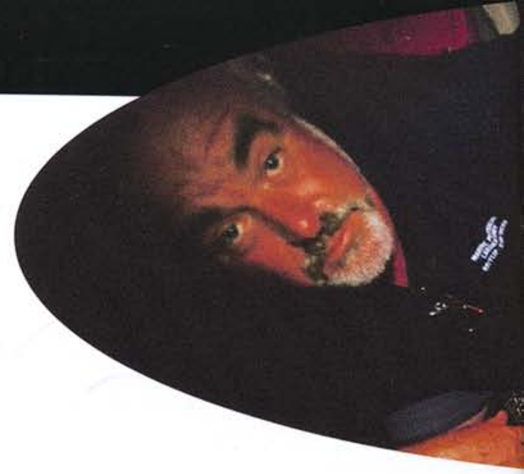
Oregon State University

Murray Levine

To complement the ocean measurements taken by moving research vessels, Murray Levine and Tim Boyd deployed a pair of moorings at fixed locations off the steep undersea slopes of the Kaena Ridge.

The moorings bore instruments that measured water temperature, conductivity, and current velocity. Over a three-month period in 2002, the measurements were recorded in intervals ranging from one to eight minutes to show the dynamics of the tidal cycle and internal waves over time. The spectacular results, said Levine, included witnessing the ocean's waters literally flipped upside down.

"We've seen density inversions that are due to the breaking of giant internal waves that ultimately result in mixing the water," Levine said. "There are some amazingly large overturning events."



Scripps physicist Walter Munk first posed the question in 1966 of how and where this mixing occurs. He arrived at an estimate of how

much mixing must be taking place in the oceans. In the decades since, however, oceanographers have found only about 10 percent of what Munk predicted they should find.

"The idea that tides are doing the mixing at certain places is very attractive," said Dan Rudnick, a physical oceanographer at Scripps and coinvestigator for HOME. "There are a lot of reasons to believe that might be the case, and I think to a large extent, we've shown that is what's happening."

The geography and efficiency of vertical mixing are key components in the large computer models that are now being developed to aid climate prediction. More fundamentally, mixing is necessary for the life of the ocean. The distribution of mixing plays a key role in resupplying nutrients to the upper ocean and oxygen to the deep sea. For example, during El Niño conditions, vertical mixing processes shut down in the eastern equatorial Pacific, resulting in a massive die-off of the fish population. Understanding ocean mixing will help researchers assess the impact that naturally occurring events such as El Niño have on the oceans and their inhabitants.

HOME IN THE FIELD

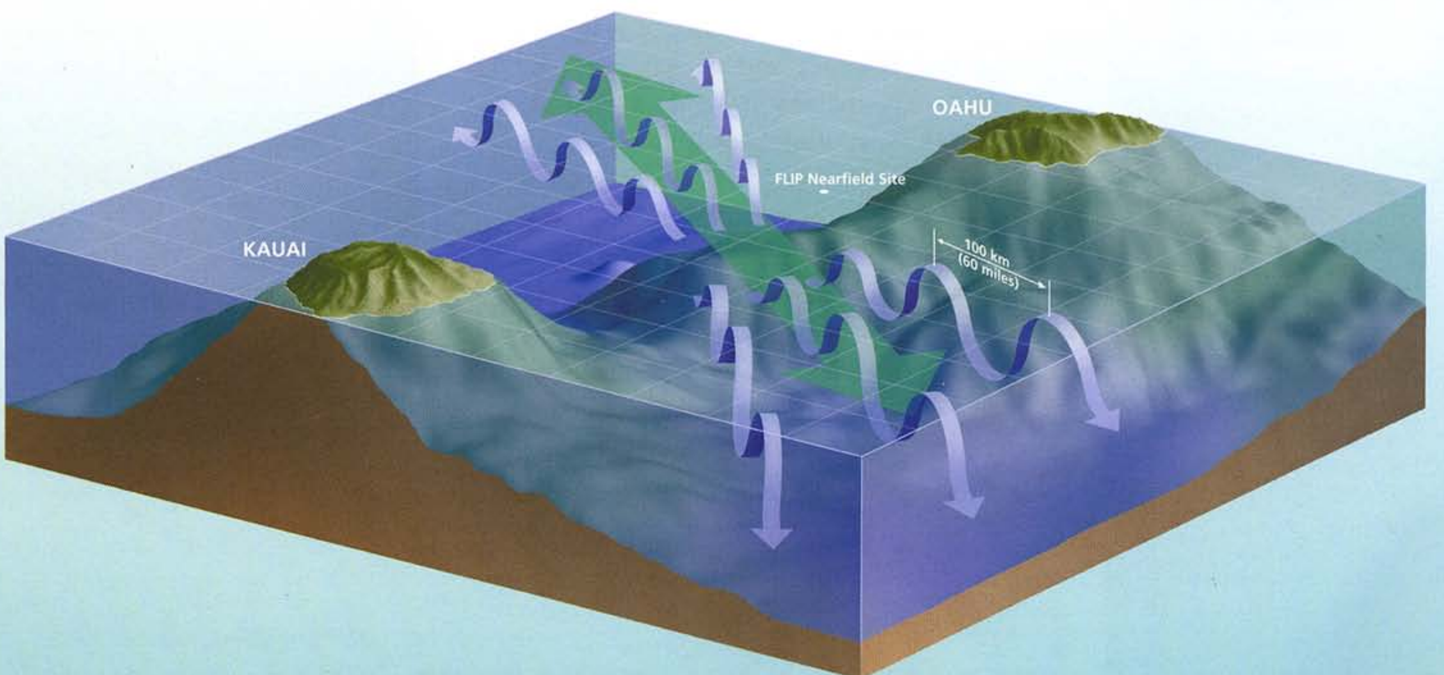
HOME investigators chose to focus on mixing caused by tides, in part, because tidal energy could be quantified with satellite measurements of sea-surface elevation. In recent years, satellite technology has revolutionized scientists' ability to understand surface tides. Using a combination of satellite observations and computer modeling, they can now draw global maps of tides and regions of high tidal energy loss.

By the late 1990s, researchers had determined that the tide along the Hawaiian Ridge was emitting 20 gigawatts (20 billion watts) of energy each day, enough to power 20 million typical homes.

HOME researchers hope to learn what happens to the lost tidal energy: Does it radiate into the deep sea as a large-scale internal tide, drive local currents around the topography of the ridge, or mix the local ocean?

If answers can be distilled into general principles, they will be used in conjunction with global maps to infer how the deep ocean responds to tidal dissipation around the planet.

At the same time, researchers at the University of Hawaii and Australia National University began a parallel effort, making computer models of tidal interactions with the ridge. Their initial results



were surprising. The ridge, rather than appearing as a monolithic wall, features a number of precisely tuned hot spots where the tidal interaction was much stronger than normal. The regions around French Frigate Shoals and Necker Island—two very small islands northwest of Kauai in the Hawaiian chain—and the Kaena Ridge—west of Oahu—were centers of intense activity.

In August 2000, the first of HOME's field experiments, a survey of the ridge led by Rudnick, confirmed the computer predictions. The following spring, the second phase, the HOME Farfield Experiment, began. Led by Scripps physical oceanographer Peter Worcester, Farfield gathered data to verify the estimates of tidal-energy loss and quantify the fraction of this energy that radiated from the ridge as internal waves into the deep Pacific.

Below, *HOME graduate student Luc Rainville and Principal Investigator Rob Pinkel at the controls of a winch driving CTD sensors.*

Meeting in Honolulu in February 2002, HOME investigators laid plans for their third field effort, the Nearfield Experiment. Examining the Rudnick survey and Farfield results, they decided to focus on the Kaena Ridge, just off Oahu's western point, to look at tidal conversion and mixing processes in detail. Here, the various aspects of the tidal conversion process were all active in a small region. Kaena Ridge offered researchers the best chance of unraveling the complex chain of events that leads from tides to turbulence.

SETTING UP SHOP ON KAENA RIDGE

In September and October 2002, Scripps's R/V *Roger Revelle* and Oregon State University's R/V *Wecoma* cruised through Kauai Channel, each taking very detailed measurements of conditions such as temperature and salinity.

Above left, *Scripps technician Matthew Norenberg and research specialist Lisa Day install a radio beacon that will be used to recover instrument moorings during the 2001 Revelle cruise.* **Top,** *FLIP Captain Tom Golfinos below deck.* **Left,** *Twice daily, the northern Pacific Ocean tide broadsides the Hawaiian Ridge as it flows back and forth between northeast and southwest. The collision sets in motion a cascade of internal waves that propagate in ripple fashion away from the islands with wavelengths up to about 100 kilometers (60 miles). Associated fine-scale turbulent activity accounts for a disproportionate share of the mixing of warm and cold water that takes place in the Pacific and is especially strong at "hot spots" like the Kaena Ridge, an undersea finger extending from Oahu into the Kauai Channel.*

HOME PROFILE
MICHAEL GREGG
University of Washington

Shear-measuring SWIMS2

Large-scale releases of energy from the ocean's internal waves are the sum of their parts, and Michael Gregg observed some of the smallest scale elements of the process during HOME.

Using instruments ranging from a hydrographic Doppler sonar system developed at Scripps to advanced microstructure profilers called Deep AMPs, Gregg measured velocity, shear, and temperature exchanges down to the scale of centimeters in the Kauai Channel.

When it becomes strong enough, shear overturns stratified water and creates turbulence that mixes the water on small scales. Aboard Scripps's R/V *Roger Revelle*, Gregg recorded shear to produce three-dimensional views of the flow going over the Hawaiian Ridge.

While he is still analyzing his data, Gregg said one success of HOME is that it bore out the predictions of computer models.

"In the past we were flying more on intuition than on modeling results," Gregg said. "It's much more satisfying to get that interchange between theory and observation."

PETER WORCESTER

Scripps Institution of Oceanography

Peter Worcester

When Pacific Ocean tidal currents run into the undersea slopes surrounding the Hawaiian Islands, they have nowhere to go but up. The up-and-down motions that result partly radiate away from the islands as internal tides and are partly transformed into turbulence, helping to mix the ocean near the islands.

Peter Worcester and colleagues deployed an array of instruments in March 2001 to observe both the incoming tidal currents and the internal tides radiating away from the islands.

They made very precise measurements of the amount of time it took pulses of sound to travel through the ocean between the instruments. Sound travels faster in warm water than in cold water and faster with a current than against it. From the measurements of the speed at which the sound traveled, they could determine the temperature changes caused by the internal tides and the velocity of the tidal currents between the moorings.

The research could help computer modelers understand how ocean mixing affects climate.

"The data are still being analyzed, but at the moment it looks as though only a small fraction of the incoming tidal energy is radiated away as internal tides, leaving a relatively large amount of energy to generate turbulence and mixing near the islands," Worcester said.

Nearly every day, the two vessels would pass FLIP, which was towed in early September to 158°37.819 min W, 21°40.752 min N over the undersea feature Kaena Ridge. There the water was slightly more than 1,000 meters (3,280 feet) deep, the ideal depth for Conductivity-Temperature-Depth (CTD) sensors to get a surface-to-near-seafloor profile.

Another instrument on board was a one-of-a-kind sonar unit called Deep-8. Unlike the CTDs, which were in constant motion, the Scripps-designed Deep-8 was in a steady position at 400 meters (1,312 feet). It viewed both upward and downward from its midwater position, profiling horizontal ocean currents from the sea surface to a depth of 900 meters (2,953 feet). Able to measure spatial distances as small as four meters (13 feet), Deep-8 provided a graphic view of horizontal flows, complementing the pictures of vertical motion provided by Fish 1 and Fish 2.

Above, *Provisions, like potatoes being culled for freshness and mangoes, were supplied every few weeks.*

As a vessel without the power to move on its own, FLIP—a floating instrument platform—requires more seamanship of its crew than most ships. Captain Tom Golfinos, only the fourth captain FLIP has had in its 41-year history, is a former Greek Merchant Marine and tuna boat chief engineer. He is in his ninth year as officer in charge. FLIP requires the traditional duties of a contemporary sea captain as well as the specialized skills to operate FLIP's unique machinery to anchor the vessel in the deep ocean.

SCRIPPS'S R/P FLIP ROUTINELY DROPS SOME OF THE LONGEST ANCHOR LINES OF ANY VESSEL IN THE WORLD. IN A FALL 2001 RESEARCH CRUISE 450 KILOMETERS (280 MILES) SOUTH OF HAWAII, FLIP'S ANCHOR LINE WAS 10,576 METERS (34,700 FEET) LONG, A LENGTH EQUIVALENT TO THE ALTITUDE AT WHICH MANY COMMERCIAL AIRCRAFT FLY. THE 13,063—KILOGRAM (35,000-POUND) ANCHOR AT THE END OF THE LINE NEEDED 78 MINUTES TO REACH BOTTOM.

For the Nearfield Experiment, Pinkel's choice of locations presented a challenge. The Kaena Ridge includes a south-facing cliff with a 1,500-meter (4,900-foot) drop—and Pinkel wanted to set up shop right on the lip.

Pinkel wanted a three-point mooring so FLIP wouldn't twist and turn in the current. Compounding things, just to the northeast of

JIM MOUM

Oregon State University

Above, *Luc Rainville and Rob Pinkel in the FLIP laboratory.*

R/V Wecoma

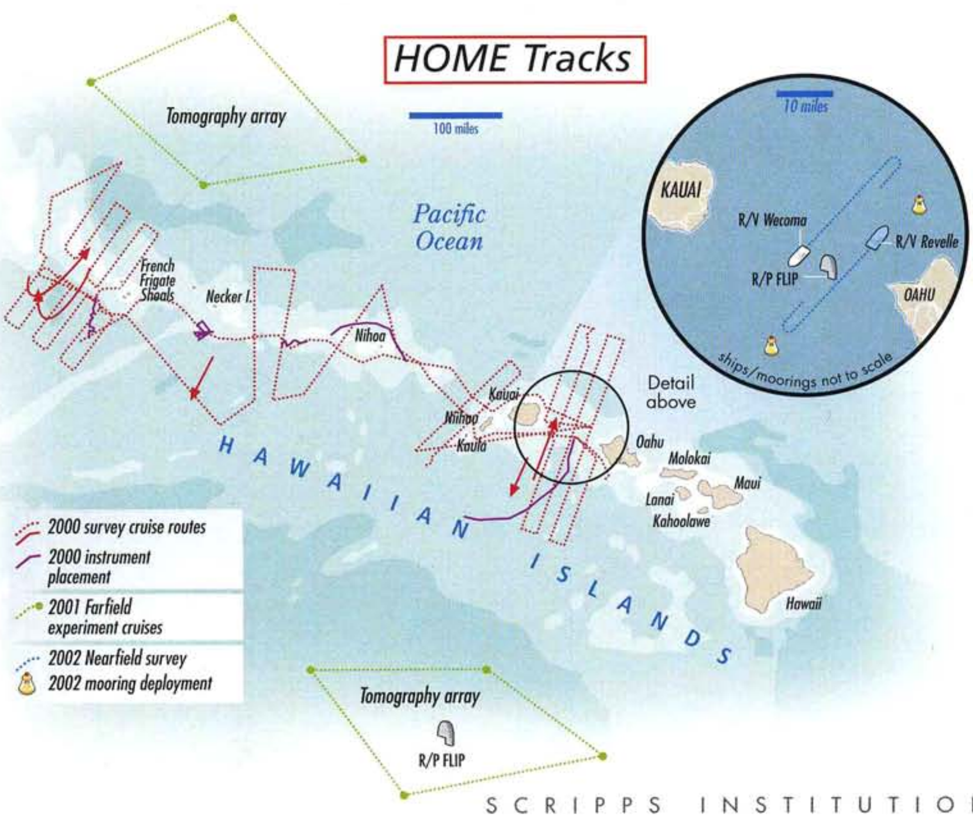
the cliff is a field of submarine telecommunications cables that keeps Hawaii in contact with the rest of the world. Seafloor maps of cable locations depict what looks like mounds of spaghetti dumped on the ridge.

On arrival at the site, Golfinos had to flip FLIP to vertical and anchor it very quickly, before it drifted northward over the field of communication cables or southward over the cliff.

THE HOME STRETCH

Once the instruments were operational, information from Fish 1 and Fish 2 revealed phenomena never seen before. On monitors, water that seemed homogenous stratified into jagged bands of coded colors, revealing enormous tidal elevations. As the crew and scientists leaned on the deck railings outside and mused over the steady ripples passing FLIP, the water beneath the surface writhed with violent energy.

At the greatest depth observable, just as the biggest internal tides crest near the sea floor, huge bursts called internal solitary waves recurred over periods as short as twenty minutes. Development engineer Lloyd Green, on board to maintain the equipment he helped build, quipped that they should be called Pinkel Peaks after the chief scientist on board. The



When the ocean mixes, it causes a chain of events that can range from massive tidal motions over many miles to the formation of internal waves to fine-scale turbulence. As part of HOME, Jim Moum measured activity unfolding on a scale of centimeters.

Moum, who led two HOME research cruises on Oregon State University's R/V *Wecoma*, recorded turbulence by measuring very slight changes in velocity and temperature in ocean water. Such energy dissipation is a key part of ocean mixing and is an important factor in determining an overall estimate of tidal energy pathways.

Observing such quiet activity required sensitive sensors and equipment that do not generate much noise of their own. Marlin, the specialized platform that carried the sensors, helped make the 2002 survey a success.

"Our biggest operational challenge was in achieving low-noise measurements," Moum said. "Because signal levels are low and the scales are very small, Marlin needed to be quiet both electrically and mechanically."

Scripps Institution of Oceanography

SeaSoar

Some HOME researchers observed ocean mixing at fixed locations. Dan Rudnick watched the cascade of tidal energy unfold during a research cruise in October 2002.

Outrunning the Pacific tide just slightly, Rudnick zigzagged through the Kauai Channel aboard R/V *Roger Revelle*, making a complete 580-kilometer (360-mile) circuit every 22 hours. With equipment such as the glider SeaSoar (above), he measured current, temperature, and conductivity of the ocean behind him, getting a look at a different phase of the spring tide with every pass.

Rudnick found evidence that the tide does generate internal waves as scientists had predicted and affirmation of the hypothesis that more activity takes place during the spring tide.

The activity observed by Rudnick and other HOME researchers also appears to answer a larger, more fundamental question: Whether all of the mixing of cold and warm water that takes place in the ocean can be extrapolated from "hot spots" like the Kauai Channel.

"The open question for us is to understand how big is the mixing, whether it's big enough to account for all that we think is going on," Rudnick said.

waves were several hundred feet tall and would be catastrophic tsunamis if they were at the surface. Here they formed undersea without fanfare every morning around dawn.

"We're seeing those for the first time," Pinkel said one morning on the FLIP bridge, with Coast Guard advisories for Oahu waters blasting out of a nearby radio. "For the moment, there's no clear theory of how you could have such a thing."

Between 2000 and 2002, a total of 16 HOME research cruises tried to capture as much of the mixing picture as possible.

With so many ambitiously diverse projects, angst over equipment failures is inevitable.

"You don't sleep well during these cruises," said Eric Slater, a principal designer of Deep-8 who oversees much of the equipment deployment. "You're always on edge. The cruise is like the test, the big game."

But equipment problems such as those with Fish 2 happen anyway. Its sudden malfunction sent nearly the entire

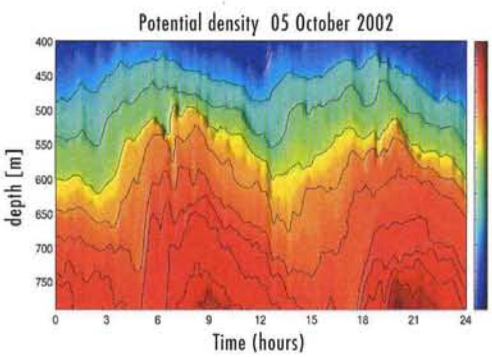
HOME researchers bring a CTD unit aboard for repair. ***Top,*** *Scripps physical oceanographer Dan Rudnick.*



Above, *(left to right), Suspended in the water column with subsurface floats, tomography arrays deployed by Peter Worcestar determined velocity of tidal currents.*

science party into the tiny lab. Graduate students were crawling under the computer bank, disassembling computers and checking hardware. The scientists shut down Fish 1 as a precaution. Hours were going by and the data gap was getting bigger.

If there really is any panic, Pinkel didn't show it. He remembers when he was a Scripps graduate student in 1969 on another FLIP cruise, having problems like this every night with a rudimentary CTD. It turned out that the mahi mahi attracted to FLIP were



Above, *Contrasts in water density come to life through CTD readings. The rapid vertical motion of density layers between the sixth and ninth hours indicates the presence of internal solitary waves.*

using the plastic housing around its electric wires as chew toys, shorting out the entire system.

Fish 2 was repaired in the early hours of October 7. An underwater connector, fatigued after 8,000 trips, had failed. Like members of a pit crew, Green and electronics technician Tony Aja installed a replacement connector and the instrument was redeployed. The profiling winch was carefully brought back online and the experiment was once again turned over to the computers for routine operation.

Two days after Fish 2 was repaired, trouble struck again. The strong currents of the spring tide caused a collision between the 150-pound Fish 2, which moves at seven knots, and Deep-8. The two instruments were entangled, hanging 400 meters (1,312 feet) beneath the surface.

It took 18 hours to resolve the problem and get the experiment back online.

Overall, Pinkel rates HOME a success thus far. The limited downtime, less than five percent, scarcely diminishes the major discoveries made. In a project like this, failure means not seeing anything new.

"What we're finding in HOME is a whole new menagerie of physical phenomena coming into view. We'll be able to incorporate them in computer models and predict how the whole Pacific basin responds," Pinkel said. "Hawaii is kind of a very large-scale fluid mechanics laboratory. The good news is that we're seeing things that haven't been seen before but they make sense. They're the sorts of things we hoped we'd find."

CRAIG LEE, AND
ERIC KUNZE
University of Washington

Tom Sanford

As the Pacific Ocean surface tide impinges on the Hawaiian Ridge, it generates internal waves that propagate away from the ridge and patches of turbulence that linger and mix the water. Participating in HOME, Tom Sanford, Craig Lee, and Eric Kunze measured the intensity of the internal waves and turbulence generated by the tides.

During the 2000 survey, they took dozens of velocity profiles through the entire depth of the water column to measure the energy flux of the internal waves escaping into deep water and the dissipation rate of kinetic energy remaining in the form of turbulence.

In places, "we were getting energy fluxes in the survey on the order of 10 to 15 kilowatts per meter of ridge," Sanford said.

The survey helped confirm where the energy flux was most intense along the Hawaiian Ridge in anticipation of the 2002 Nearfield surveys. In September 2002, the researchers took further velocity measurements by using a combination of highly accurate recoverable profilers and expendable profilers that record data with the ship under way.

"We addressed the questions of how much energy is being dissipated locally and how much is going out into deep water," Sanford said. "It will take more time to know what the answers are."