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Modern Mermaids: New Floats Image the Deep Earth

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Scientists get a window into deep Earth structures by using a method called seismic tomography. Similar to computed tomography (CT) scans of the brain, seismic tomography uses delays in the arrival times of seismic P waves to make scans and three-dimensional images of the variations in seismic wave speed in the Earth's interior. Patterns in the delays indicate thermal or compositional anomalies in the Earth's mantle and core, such as those caused by sinking cold oceanic lithosphere or rising hot thermal plumes. A large number of observations of such delays are available for continental regions; the number of observations for the United States is especially high due to a dense deployment of stations currently being installed temporarily and moved across a large area as part of the USArray project, a branch of the U.S. National Science Foundation's EarthScope program. In contrast, no comparable sensor density has been available in the oceans.

Robots equipped with hydrophones, floating freely 1–2 kilometers below the ocean's surface, can potentially bring moving seismic networks of USArray type to the oceans. This concept was first tested and shown to be feasible by Frederik Simons of Princeton University, who used an improvised mounting of a hydrophone on a Sounding Oceanographic Lagrangian Observer (SOLO) float built by the Scripps Institution of Oceanography [Simons *et al.*, 2006, 2009]. Simons called his instrument Mobile Earthquake Recorder in Marine Areas by Independent Divers (MERMAID).

Scientists and engineers at Géoazur in Villefranche-sur-Mer, France, developed and tested a more definite prototype of a MERMAID module using an Apex float from Teledyne Webb Research, a RAFOS hydrophone, and electronics developed in collaboration with OSEAN, a small engineering firm in France. These floats are approaching their final design and should become available for use in research projects in 2012. Multichannel acquisition hardware, which allows MERMAIDs to serve multiple observing missions simultaneously, has also been developed. Although their battery life

expectancy is shorter than that of floats in the large international Argo project (the 3000 Argo floats, scattered throughout the world's oceans, monitor conductivity and temperature for climate and ocean models) because of increased activity in their central processing units, the new MERMAID systems can also serve the oceanographic community by recording temperature, conductivity (a proxy for salinity), and the strengths of currents in the deep ocean.

Testing the New MERMAID System

Figure 1 (left) shows one of the prototypes for the new MERMAID system (MERMAID I). The hydrophone that records seismic energy as it travels through water is mounted on top of the float and protected by a red cover. The yellow antenna serves to provide its location at the time of surfacing using GPS and enables two-way communication with the Iridium satellite system. During the initial testing phase, currently under way, data from instruments are continuously recorded for a short time, after which the instrument

surfaces and is recovered. In a future operational phase the floats will remain at large, surfacing only when a strong P wave is recorded. The command to surface is triggered by a discrimination algorithm developed by *Sukhovich et al.* [2011]; once surfaced, the instrument transmits the stored seismograms via satellite before returning to its floating depth.

Two of the new prototypes (MERMAID I and III) have just completed their longest autonomous trips so far. They were launched early in the morning, local time, on 15 June 2011 in the Ligurian Sea just south of Nice, France (43.45°N, 7.83°E); after initial test dives to calibrate the depth sensor, the floats were programmed to dive to a series of cruising depths for the purpose of noise analysis; surfacing after each new depth was maintained for 3 or 4 days. MERMAID I, built with a carbon hull, typically descended from the surface to parking depth at an average speed of 5 centimeters per second and surfaced at 19 centimeters per second. For MERMAID III, which sports an aluminum hull, the diving and surfacing speeds were 7 and 14 centimeters per second, respectively.

Although the depth of the float is continuously recorded, it is important to have an idea of the horizontal drift, because the float's location needs to be interpolated unless it comes

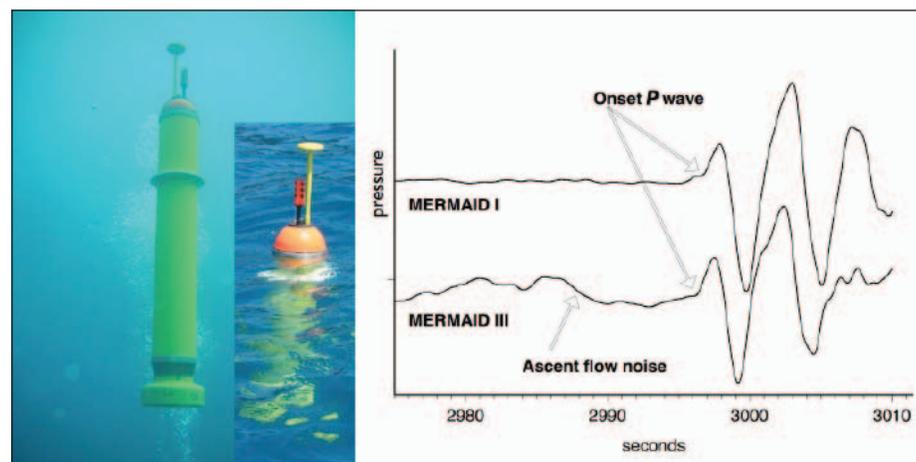


Fig. 1. (left) A photo, taken by A. Anglade, shows Mobile Earthquake Recorder in Marine Areas by Independent Divers (MERMAID) I ascending to the surface; the inset (photo by Y. Hello) shows the float at the surface with hydrophone (red) and a GPS/Iridium antenna (yellow). (right) The seismograms show acoustic pressure variations referenced to a mean of arbitrary magnitude, with arbitrary units offset vertically to ease visibility and low-passed at 0.2 hertz. The time origin has no special significance, but the arrival time of the two pulses identifies them unambiguously as P waves from the event near Fox Island (Aleutians). The two pulses arrive at almost exactly the time expected for the arrival of the P wave from the Fox Island event.

to the surface immediately after recording an event (to conserve energy, it surfaces and records its position only when it is absolutely sure it has recorded a *P* wave). The horizontal drift of the MERMAIDs is a function of location and cruising depth. During this experiment, average lateral drifts of up to 6.4 kilometers per day (about 7 centimeters per second), but more generally 1–3 kilometers per day (1–3 centimeters per second), have been observed while floats cruised at depths between two surfacings, comparable to the “daily drift” of USArray of about 1.3 kilometers. When at the surface, the drift is dominated by wind and varied between 10 and 20 centimeters per second, with one observation as high as 40 centimeters per second. The latter figure would imply a drift of about 1 kilometer during the time needed for signal transmission. The total drift over 13 days was 28 kilometers for MERMAID I (drifting between 1050 and 1500 meters) but only 3.5 kilometers for MERMAID III, floating 1540–1937 meters below the sea surface.

P waves can be recorded from earthquakes that occur as far away as about 12,000 kilometers from MERMAID instruments; *P* waves from earthquakes farther away than 12,000 kilometers would disappear into the shadow created by the Earth’s core. Within this range, one strong earthquake (magnitude 7.4) occurred during the experiment on 24 June at 03:09:39.6 near Fox Islands (Aleutians). The preliminary hypocenter was 52.04°N, 171.84°W at a depth of 47 kilometers, 9450 kilometers from the floats. Figure 1 (right) shows the recording of this event in the two floats. The noise level in MERMAID III was

high for this event because it had just operated its pump and begun its ascent for one of its preprogrammed surfacings, but the noise level in MERMAID I was low, yielding a signal-to-noise ratio of 53. This confirms the estimate of *Simons et al.* [2009] that earthquakes of magnitude 6 and higher have a good chance of being recorded above noise at long (teleaseismic) distance.

The Benefits of MERMAID

To obtain information over different wave trajectories inside the Earth, even when earthquakes repeat themselves often at the same location, seismograph arrays need to be redeployed at different locations as time progresses. Because MERMAIDs drift at an almost optimal speed to provide such new trajectories, they do not require frequent recovery and redeployment to record *P* waves over large areas in the oceanic domain. They are thus able to provide crucial information over the ocean that global seismic tomography so far desperately lacks.

The first fleet of a half dozen MERMAIDs will be launched in the Indian Ocean in the second half of 2012. The multichannel hardware developed allows for oceanographic, meteorological (rainfall or ice formation), biological (ZooScans), and seismological observations from the same float. Further, the technology of the floats themselves is still improving; in particular, scientists and engineers are hoping to develop somewhat larger and more lightweight floats with battery capacities that allow them to survive for up to 5 years while serving multiple missions. In the

future, combined experiments at the scale of the current ARGO project will enable seismic tomographers to fill the major gap posed by the absence of seismometers in the oceans, which is currently hampering scientific ability to better image convective processes—in particular, how the Earth recycles oceanic lithosphere—with high precision.

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