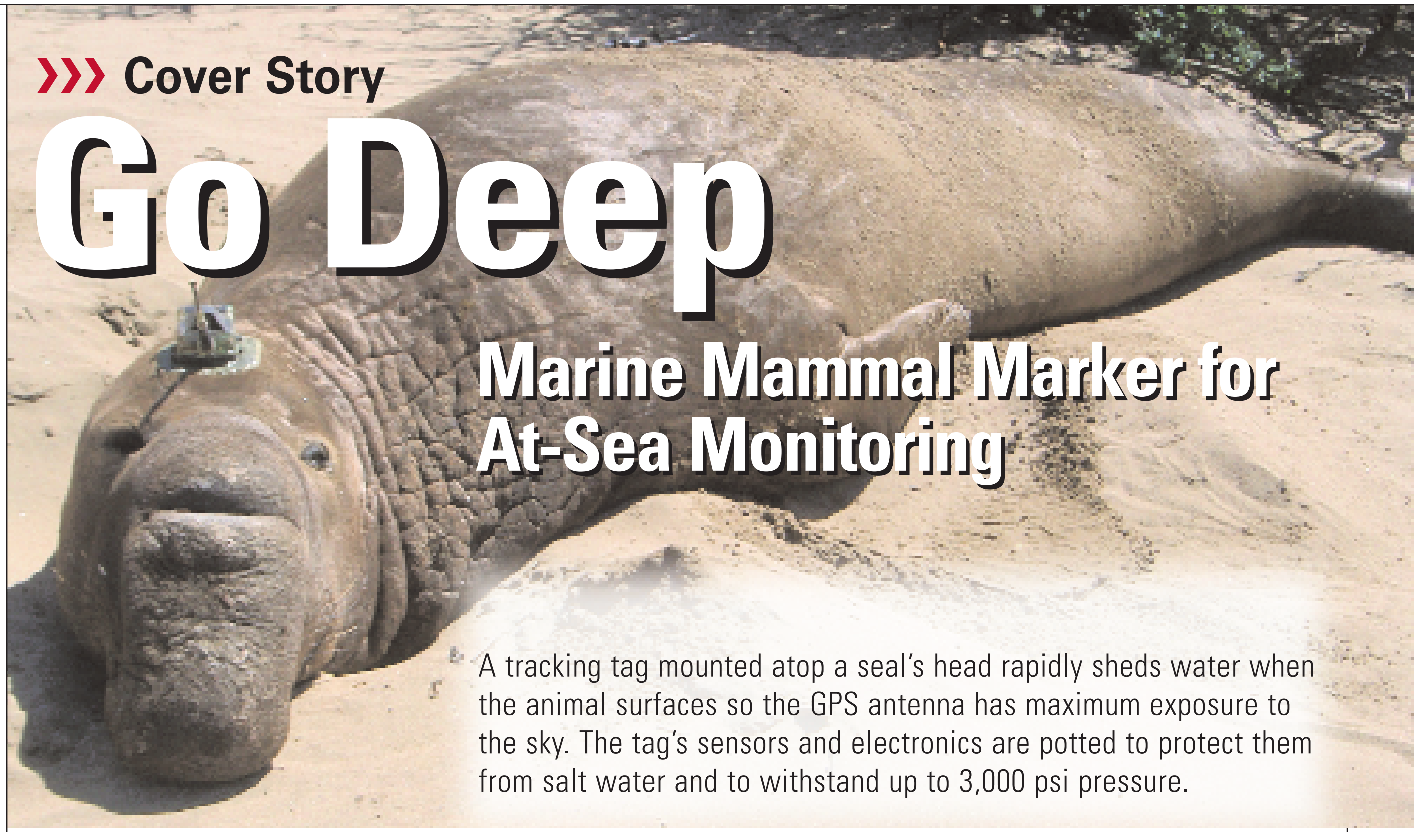

››› Cover Story

Go Deep

Marine Mammal Marker for At-Sea Monitoring

A tracking tag mounted atop a seal’s head rapidly sheds water when the animal surfaces so the GPS antenna has maximum exposure to the sky. The tag’s sensors and electronics are potted to protect them from salt water and to withstand up to 3,000 psi pressure.

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The observation technology used by wildlife researchers can limit their understanding of the behavior of marine mammals. Surface tracking using geolocation and Service Argos tags have shown that these mammals range much farther than previously thought. Relatively simple time/depth recorders (TDRs) show that they dive more than 1,000 meters deep and for longer than one hour. To further the understanding of these aquatic creatures, we developed a smaller and more capable tag with more sensing capabilities that can be deployed for longer durations. The MAMMARK tag, measuring 2.5 × 4 centimeters, carries a low-power microprocessor and a set of sensors that can be multiplexed through a high-resolution analog-to-digital converter (ADC).

The sensing suite consists of temperature, depth, speed, salinity, three axes of magnetic field, three axes of acceleration, and GPS. GPS measurements are, of course, only available at the surface. The receiver is kept in a hot-start mode so that it can reacquire the satellite signals in less than 10 seconds after returning to the surface.

▲ **PHOTOS ABOVE** and on the cover show a previous-generation tag not incorporating GPS. The photo on page 32 shows the current GPS-equipped prototype to be deployed in the wild in summer 2007.

The three-axis magnetometer and three-axis accelerometer are used to construct the animal’s three-dimensional orientation. Integrating this attitude with water speed and an initial estimate of position from GPS, a full underwater trajectory can be reconstructed, using error correction from the return surface position and depth measurement to improve the accuracy and estimate the ocean currents. The tag dumps its data to a high capacity external flash card. As currently configured, it can withstand extreme pressures and record data for up to one year; it carries an RF beeper for ease of recovery.

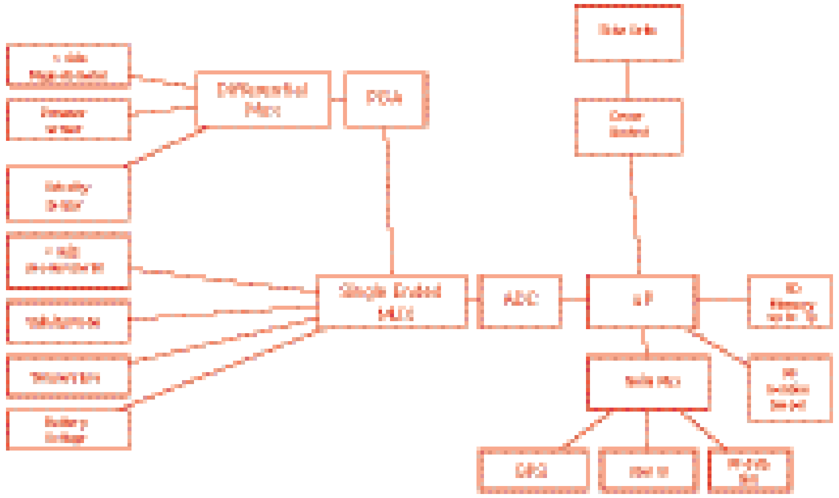
Wildlife Study

Amphibious pinnipeds — seals and sea lions — spend most of their lives at sea. Biologists can only glimpse them as they surface and so have turned to technological research methods at sea. The most extensively studied pinniped is the northern elephant seal, with much of the work performed at Año Nuevo State Reserve’s rookery in California.

In the early 1980s, TDRs to record changes in water pressure over time were first attached to elephant seals. Initial results revealed dives that were incredibly long, phenomenally deep and continuous 24 hours a day, day after day, week after week. Mean dive duration of adult females was 22.1 minutes followed by a surface interval of 2.3 minutes. One female in a 10 hour period made 10 dives, seven of which exceeded an hour, with the longest lasting 97 minutes, and each of these dives was followed by a surface interval of 3 minutes or less.

By adding a photocell to the TDRs, locations could be calculated by determining the day length, which revealed latitude, and the offset of the times of sunrise and sunset from the place where they were originally tagged, which revealed longitude. This method is accurate to within approximately 100 kilometers, and showed that elephant seals undertake two complete foraging migrations each year.

In the mid 1990s, researchers added transmitters detectable by the polar orbiting Service Argos/NOAA satellites. When a satellite was above the horizon and a seal equipped with an Argos transmitter surfaced, an uplink occurred and location could be calculated. Because elephant seals are underwater about 90 percent of the time they are at sea, most seals only had one to four “good” locations a day, ranging from an accuracy of 9 ± 16 kilometers to 48 ± 71 kilometers.



▲ **FIGURE 1** Block diagram of tag hardware, designed to be small and very low-power to record data in-situ for long duration on limited battery power.

Sensors added to TDRs in the 1990s included thermisters, velocity meters, hydrophones, video cameras, and heart-rate monitors. Suddenly biologists were data-rich, as the number of instrumented elephant seals soared past 200. The data revealed that the seals, while diving, employ behavioral and physiological tricks to achieve a lower metabolic rate than when sleeping on the beach!

Researchers sought improvements in the accuracy and frequency of surface locations and the ability to record 3-D movements of the seal between surfacing locations. Several MAP tags that married a GPS receiver to a TDR, a velocity meter, and a 3-dimensional digital compass were constructed. One succeded conceptually, but the 14-pound behemoth required 12 D-cell batteries and was only deployed on one translocated seal, who never returned to Año Nuevo.

Tags increased in size and cost. Only the best-funded researchers could afford to deploy the newer tags and even they were limited in how many they could afford to deploy because of costs ranging from several thousands to tens of thousands of dollars. Clearly, there was a need for a newly designed tag with the capabilities of the MAP tag while shrinking its size and cost.

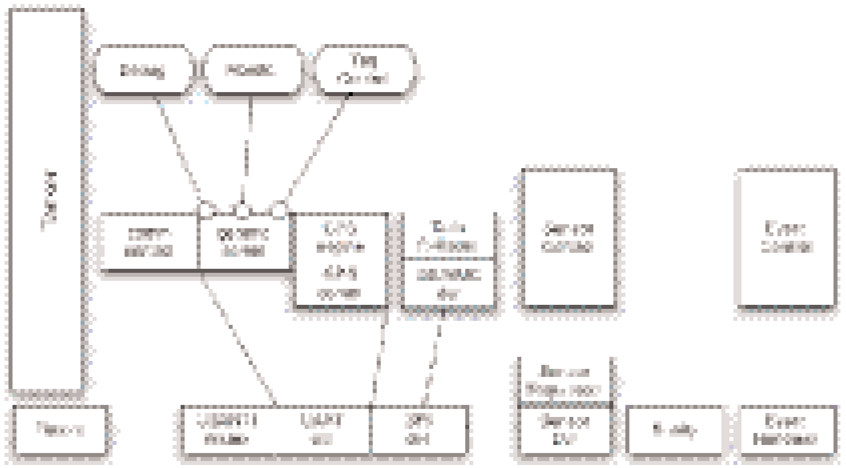
MAMMARK Hardware

The physical prototype MAMMARK tag shown in the photo carries the major hardware subsystems shown in **FIGURE 1**. The core of the hardware is an ultra-low power microcontroller that includes several on-chip peripherals: serial peripheral interface (SPI) controllers, serial communication, clock control, watchdog mechanisms, direct memory access (DMA) controllers, timers, and a small amount of program flash memory and several kilobytes of random-access memory space. As all sensors are analog in nature, the main interface between the microcontroller and the sensors is the ADC subsystem.

There are two different kinds of sensors attached to the central microcontroller: differential and single-ended. Each sensor requires a different amplification to maximize the sensitivity of the sensor. Thus, two different operational amplifiers (op-amps) are used, one differential and one single-ended. Each sensor can be optimized separately for maximum dynamic range to get the best reading from the signal of interest.

The differential sensors include the magnetometers (three axes), depth (pressure) transducer, and water velocity (measured using a two-axis strain gauge). The single-ended sensors include the accelerometers (three axes), salinity, temperature (both of the water and of the microcontroller), and battery voltage. These sensors’ data reconstruct the three dimensional trajectory (both in position and velocity domains), as well as salinity and temperature profiles.

Other subsystems include external communications, a GPS module, RF beeper, and mass storage module. Each module has provisions to be individually powered to mini-

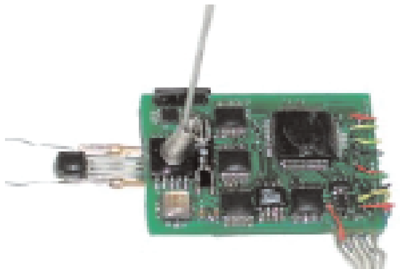


▲ **FIGURE 2** System software, divided into several subsystems and implemented as a hierarchical state machine to produce robust performance over long duration

mize overall consumption. The hardware also includes provisions for recharging the battery via an external solar cell, which would of course only be active when the animal is at the surface, most likely on the beach.

Collecting sufficient data for useful analysis requires periodic sensor sampling, filtering, correction for calibration parameters, and data storage for post-processing. Depending on the rate at which we sample each sensor, the amount of data collected can become very large; currently, the prototype limits the maximum sampling rate to 20Hz for all sensors. This is, however, an arbitrary limit imposed by the software. If we find that higher data rates are required, we can change this without modifying the hardware.

The most important aspect of the MAMMARK tag is the low-power nature of the system. To be useful in the field, the tag must collect and store sensor data until the animal returns to a place where the tag can be recovered (provisions are in place for remote data retrieval, however, the limited bandwidth of the RF link would make this a very slow process). Thus, the main function of the software is to manage the power consumption of the hardware such that data can be collected for very long duration. We expect that data collection for over a year will be accomplished with a single lithium-ion cell.



▲ **PROTOTYPE PINNIPED** sensor tag (shown without cover) attaches to skin of marine mammals and records velocity, orientation, and depth, along with the environmental salinity and temperature.

Main storage is provided by flash memory, either a secure digital or multi-media eard, connected to the SPI bus. This subsystem provides secure longterm storage of up to four gigabytes at current capacities, which are expanding and falling in price.

Most sub-systems are kept in a low or powered-off state whenever possible. The power draw of each subsystem is balanced against the required time for power-up and stabilization for high quality sensor readings. The hardware includes circuits to power or de-power each individual sensor as overall system requirements necessitate.

Software

To make MAMMARK useful, the software running on the microprocessor must carefully manage the sequencing and power consumption. **FIGURE 2** shows a simplified block diagram of the software system.

The system is broken into two main parts, Events and Tasks. Events are handled by event handlers; these are essentially messages passed between the handlers and can result in a task being awoken. Tasks themselves are implemented as simple one-shot, run-to-completion threads.

The software performs several tasks: scheduling, sequencing, reading, and so on. Lists of sensors are maintained which determine the rate that each sensor should be sampled. These lists are analyzed by the sensor control task and a current operating sensor sequence is determined. The sensor sequencer in combination with the sensor driver implements data collection. New sensors can be added as they become available.

The lowest level of hardware implementing the data path to the SD card is shared with the serial communications hardware. This complicates the software as several hardware subsystems communicate through the same bus.

The GPS subsystem is one such serial user. When the GPS subsystem is active, the GPS communication module collects data packets from the GPS and hands these to the GPS engine. The GPS engine implements the actual state machine that generates appropriate GPS events for use by the rest of the system. This includes an "ignore GPS" state while the tag is submerged.

Navigation Filtering

The tag measures several parameters common to other TDRs, however its ability to reconstruct the three-dimensional trajectory of the animal through the water is quite unique. Given the attitude of the tagged animal, and an initial starting location (from GPS), the three-dimensional trajectory is reconstructed using a dead reckoning filter that uses the magnetometer and accelerometer triads to solve for attitude, and then integrates the water speed to reconstruct position. GPS position is used to initialize the filter, and as a terminal condition once the animal reaches the surface again. The two endpoints will be used as the end conditions for a Kalman smoother that runs forward and backwards through the data to provide the optimal estimate of animal position and attitude. In the simplest case, the accumulated error is simply redistributed equally along the trajectory to force endpoints to match.

The actual dead-reckoning is based on a water-speed measurement device, a short whip attached to a two-axis strain gauge. Given the attitude of the animal from the magnetometers and accelerometers, the velocity components (measured in the plane of the animal body) can be projected into the navigation frame. The sensor is calibrated in a flume, using a simple three- or five-point calibration on each axis to generate a scale factor and bias error. More sophisticated calibration can be achieved, and will be the subject of future work.

Attributes

The tag's main features are low cost, long life, and large storage capability. MAMMARK can operate at depths of 2,000 meters and survive a two-ton seal smashing it upon the rocks. Low cost is achieved with commercial off-the-shelf technology, utilizing low-cost MEMs sensors developed for the automotive market. Low power is achieved by a low-power microcontroller to power-cycle most sensor and communication subsystems, lasting more than a year on a small battery pack.

This ruthless power management, however, complicates the software and hardware structure as several sensors must stabilize before the ADC can convert the values. Some sensors also require pre-sampling conditioning to eradicate permanent bias errors (for the magnetometers, a set/reset pulse must be performed to demagnetize the sensing element). We designed a simple, robust, software structure to maximize sensor longevity while giving good sensing performance.

While we developed the MAMMARK tag for elephant seal observation, it could be used for other marine animals such as sharks, terrestrial animals such as coyotes or elephants, and migratory avians. The tag design is optimized for marine deployment, but the modular nature of the design (in both hardware and software) allows for a relatively short development and deployment cycle as sensors are added or dropped.

We are currently testing and calibrating the prototype MAMMARK tag. Once deployed, it will represent a significant step forward for marine biologists conducting in-situ monitoring. In addition to large storage capacity, high precision sensing, and long-life, the tag will have a lower cost — we target $500–700 per unit in large numbers — than traditional TDRs enabling large-scale deployments.

Future Work

This work in progress represents a collaboration between biologists, engineers, and computer scientists. The major blocks of work for the future are: finish and test tag software; calibrate sensors; simulate trajectory reconstruction; develop trajectory Kalman filter; lab testing of finished tag; field deployment in controlled environment; field deployment for returning pinniped pups; full deployment. In summer 2007 we will deploy MAMMARK tags on juvenile elephant seals translocated from Año Nuevo to Monterey and Santa Cruz.

Early field trials will be with a human diver. Then we will perform a short term deployment on elephant seal juveniles, trucked to a location 100 miles away, and are released into the wild. These juveniles have been trained to return to the same location, and typically will show up a few days later. At this point, the MAMMARK will be recovered and the data processed. We expect this to provide a much better understanding of deployment challenges in an actual environment. ⊕

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Manufacturers

The MAMMARK tag uses a **Trimble** *Lassen iQ* GPS receiver and antenna (*www.trimble.com*), a **Texas Instruments (TI)** *MSP430* microcontroller (*www.ti.com*), **Analog Devices** ADC chip (*www.analog.com*), **Freescale** 3-axis accelerometer (*www.freescale.com*), Honeywell 3-axis magnetometer (*www.ssec.honeywell.com*), and a **Radiotronix** RF module (*www.radiotronix.com*).