

# **Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis - II**

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## **LONG-TERM GOALS**

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at the scales that control how they live, reproduce, and die.

## **OBJECTIVES**

Working with researchers from several institutions, we have been studying layered organization in the coastal ocean (LOCO) with an emphasis on describing thin layers of zooplankton in relation to their small-scale vertical environments. We have two major near-term objectives. First, we are comparing our data from two experiments in Monterey Bay with those of our colleagues in the LOCO program and preparing several publications. During the last half of FY 2007 we focused on the analysis of data collected during FY 2005 and 2006. Additional data from a brief occupation of the same coastal site during 2002 are also being used to support our analysis effort. Our second objective supports the first, and involves making several major upgrades to our custom data analysis software. One of these upgrades has been to add a capability to extract information from our acoustical measurements about the distribution and sizes of very small gas bubbles (1 to 50 microns radius) in the water column.

## **APPROACH**

Both of the investigators listed above retired from BAE Systems during the first half of FY 2007. They have been active in the LOCO program since its inception. Under a grant to the University of Rhode Island (URI) they are continuing to work up the LOCO data that they have collected. The data acquisition for LOCO was carried out during the period from October 2006 through February 2007 and is summarized in a companion report. Progress on the analysis of the LOCO data during the period from April 2007 through the end of FY 2007 is the subject of this report.

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During the late summer and early fall of 2005 and 2006, very thin layers of phytoplankton, zooplankton, nutrients, and water column physical structure were studied by a part of the LOCO research team at several closely spaced shallow, near-shore stations in northeastern Monterey Bay. Other team members examined larger scale horizontal distributions and temporal thin layer patterns in deeper water nearby, while still others collected plankton and made measurements of turbulence and various optical properties of the water column. Our part of this research involved the deployment of several acoustic and ancillary sensors on the seabed. The acoustic sensors were used to describe the distributions of small zooplankton, micronekton and small gas bubbles.

The data acquisition phase of LOCO was successfully completed on 31 July 2006. We are now approximately at the 20% point in the two-year analysis and synthesis phase. We are organizing specific data sets to support papers that we, and our colleagues, are preparing, adding new capabilities to some of the software we use to process and display our acoustical volume scattering data, and examining data sets from several ancillary sensors that we used during the 2006 field-work.

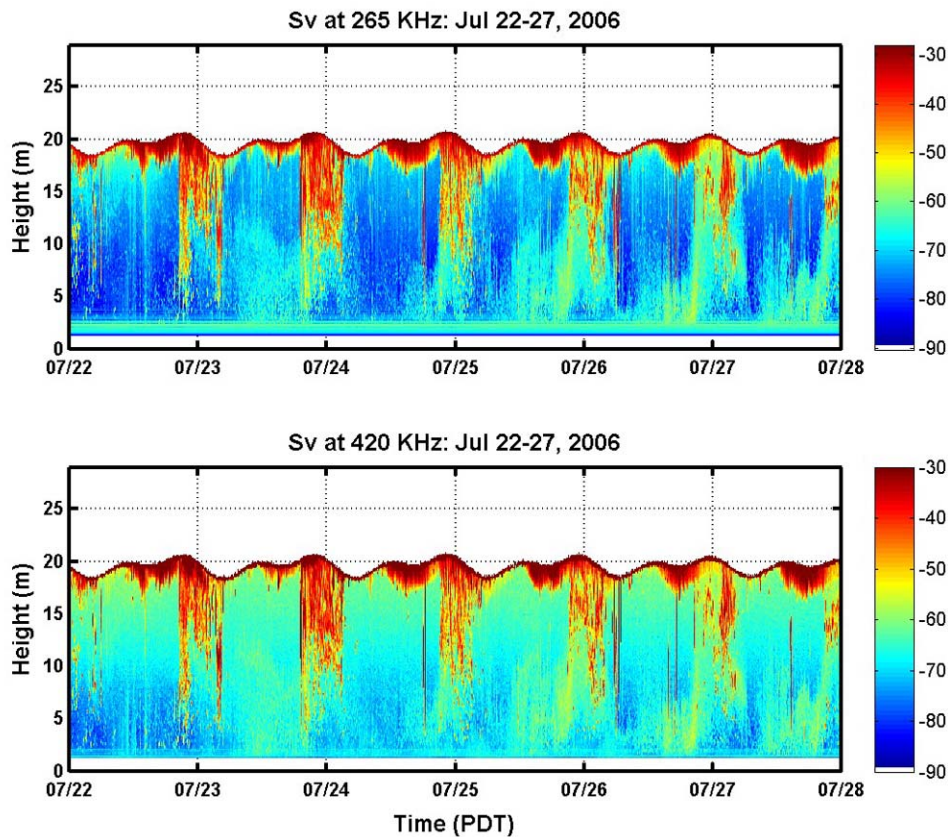
## **WORK COMPLETED**

To date, we have plotted and examined all of the acoustical volume scattering strength profiles from the field work in Monterey Bay from both 2005 and 2006. These data are available to any LOCO principal investigator and their team members. Preliminary results can be accessed by team members at the U of HI's LOCO project web site. An ongoing part of our analysis work also involves responding to specific requests for data or information by any of our LOCO co-PIs. We have answered several of these requests, and anticipate many more as the analysis proceeds.

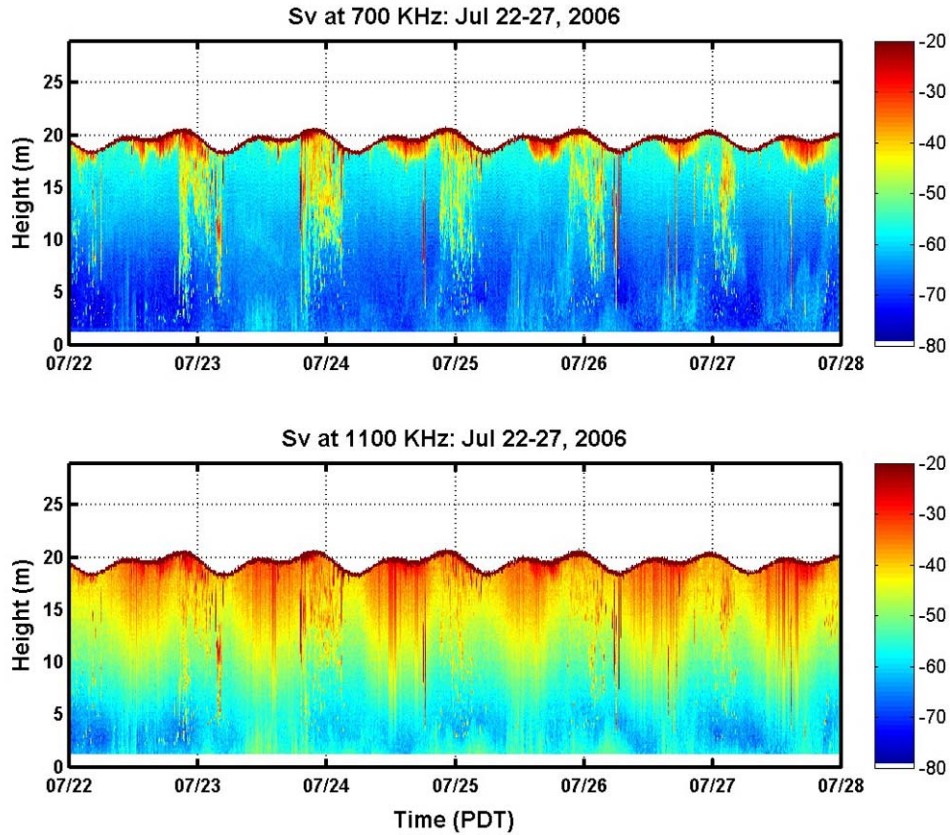
We have been upgrading several of our custom software analysis packages. One improvement involved adding new capabilities to our inverse code. The basic principles behind these calculations can be found in Holliday (1977) and in Holliday *et al.* (2003a). We use these programs to process volume scattering strength (Sv) measurements collected with our acoustical sensors. The acoustical spectra are used to make estimates of the size-abundance spectra at different depths and times. In the past these data processing codes were limited to making estimates for organisms with any two of three basic scattering types. One of these is an acoustically penetrable fluid sphere. It is used to model acoustic scattering from small zooplankton. Many common small copepods, their eggs, and fish eggs approximate this shape and scatterer type. Another scattering model we use is the rigid sphere. It has been used to approximate scattering from organisms such as shelled pteropods and has also been used when sand was in the water column, although better approximations may now be available and are being considered for inclusion in our analysis code. The third model we have used is for elongate micronekton, such as krill or mysids. Given a scaled outline, scattering from organisms with elongate shapes can be modeled in 2-D by using a distorted wave Born approximation. We have models for several species of elongate copepods, krill, and mysids. We have recently added the capability of modeling very small gas bubbles. Our inverse code now simultaneously calculates size-abundance spectra for particles represented by any two of these types of scatterers, plus small bubbles.

## RESULTS

Multiple frequency TAPS zooplankton acoustics sensors were deployed at the LOCO site K1 on the shelf just SW of Aptos, CA (see Fig. 1 in the companion report). These sensors “look” upward into the water column much like an inverted echo sounder. Described in detail elsewhere (Holliday 2003a), narrow beams at frequencies of 265, 420, 700, 1100, 1850 and 3000 kHz are used to measure volume scattering strengths throughout the water column. The vertical resolution is 12.5 cm. Sixteen echo ranging cycles are collected at programmable intervals of as short as 30 sec. An interval of 1 min was used for the data in this report. Two way telemetry between the TAPS and a shore station in Aptos, CA allowed us to display and distribute data from these sensors quickly. The systems were also controlled from shore in an adaptive manner during the LOCO research field period. In order to minimize aliasing, faster sampling was used when the observed scattering was changing rapidly. We also used this capability to slow the sampling and save battery power when fast sampling was deemed less critical. A representative multi-day sample of data from our TAPS-6 sensors illustrates the variability in acoustical scattering (Figs. 1 and 2).



**Figure 1:** Volume scattering strength profiles from a TAPS-6 acoustical zooplankton sensor at a location on the shelf near Aptos, CA revealed the presence of variability of ca. 60 dB, or a difference of one million in sound scattering intensity from depth-to-depth and time-to-time in the 20 m water column. The 6 day record reveals strong diel variability at 265 kHz (top panel) and 420 kHz (bottom panel), with the night-time scattering generally being higher in the top half of the water column.

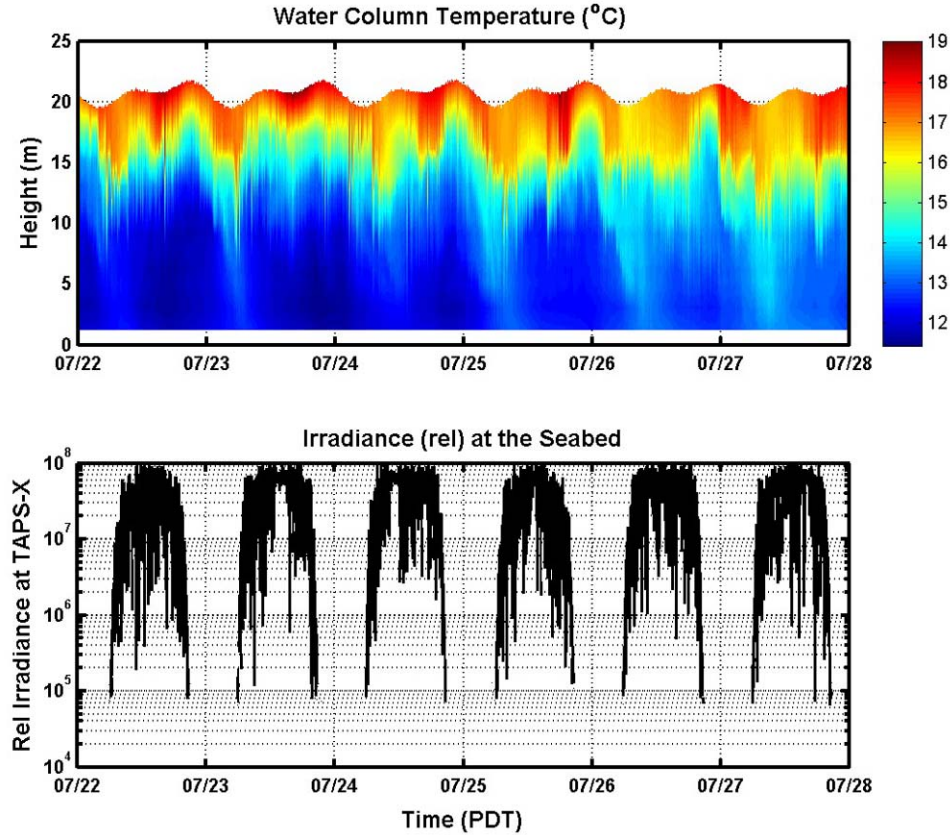


***Figure 2: The volume scattering strength profiles at 700 and 1100 kHz (top and bottom panels respectively) also reveals the presence of variability of ca. 60 dB during the same period displayed in Fig. 1. (Note the change in the color scale). The day-time scattering was also generally higher at 1100 kHz and at higher frequencies (not shown here), with “plumes” of high scattering extending from the surface well into the water column (bottom panel) . Episodic “emergence” events can also be seen originating near, in or on the sea floor.***

Water temperature was measured with internally recording thermisters at 1 m depth intervals on the vertical mooring cable below the nearby spar buoy used to support the TAPS telemetry. The water temperature was also measured by the TAPS at ca. 30 cm above the seabed. These measurements were combined to reveal variability in the water temperature through the entire water column at the site (Fig. 3). The downwelling light at a sensor on the TAPS, ca. 1 m above the seabed also provided information regarding variations in downwelling irradiance.

Focusing on the 265 kHz record (Fig.1, top panel), we can see evidence of the vertical movement of sound scattering organisms over relatively short periods. Some traces appear to indicate that the organisms are swimming down (negative slope in time-depth) , while at other times, there is an upward trending trace with advancing time. Examples of the former include six downward migration events between noon and 18:00 PDT on 7/21 and strong downward morning migrations from the water column to a location near the seabed. Upward migrations can be seen at each sunset , starting near the seabed and often appearing to reach the surface. When plotting these scattering data in a space of 1.4” x 1.375” independent pixels overlap, sometimes suppressing critical evidence of fine structure.

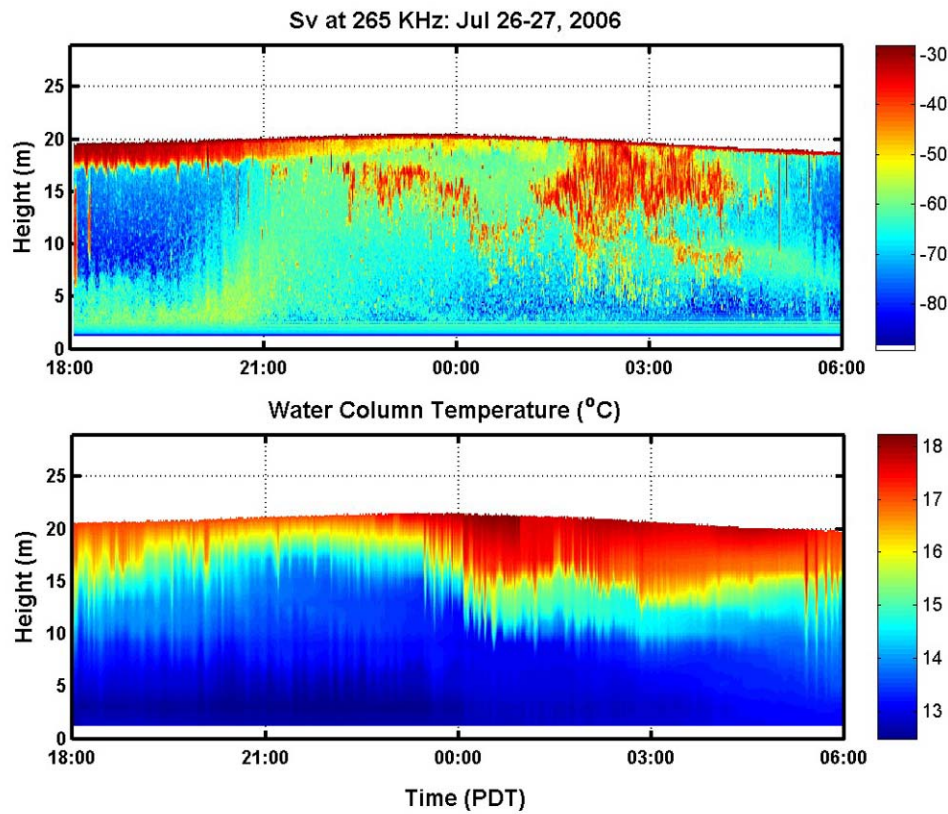




**Figure 3: The water column temperature profile (top panel) reveals variations throughout the water column. A weak thermocline persisted at depths of less than 1 m to ca. 5 m (14 to 15 m height above the seabed), but plumes or intrusions of warmer water penetrated to various depths, including to the seabed during the later part of the 6 day period illustrated. Relative irradiance at the seabed varied during the daytime hours, but peak levels near solar noon were remarkably constant (bottom panel).**

If one relies strictly on the images presented in Figs. 1 through 3, the dominant pattern appears to be a simple migration from the seafloor to the surface at sunset each night, and back to the bottom beginning before sunrise. The profiles in Figs. 1 and 2 each contain 8,641 independent scattering profiles, each with 220 depth intervals. Overplotting of pixels masks the fine detail. While an overview is essential, it is useful to expand the scales. An expanded version of the data from 1800 July 26 through 0600 July 27 reveals a complex overall pattern (Fig. 4, top panel). A close examination of the profiles reveals patterns that differ from frequency-to-frequency, an anticipated result that can be traced to the non-linear, non-monotonic scattering from the zooplankton at these frequencies. There are also large differences with time and depth at single frequencies. At the expanded scale (Fig. 4) there is clear evidence of a migrating diffuse layer. This layer was associated with the bottom during the day, rose into the water column at night, and returning to a deeper location before sunrise. This layer was more distinct, slowly meandering in depth for a few days early in our occupation of this site (e.g., July 11 and 12). Similar patterns were observed in 2002 and 2005. In terms of biovolume, an analog of displacement volume and biomass, the organisms in this diffuse layer were dominated by copepod-like scatterers with lengths of  $< 1\text{ mm}$  with biovolumes of  $ca. 1000\text{ mm}^3/\text{m}^3$ . Copepods with lengths of  $ca. 1\text{ mm}$  were also present at biovolumes of  $100\text{ mm}^3/\text{m}^3$  in this layer. Elongate scatterers with lengths of 3 and 6 mm were present as well, with biovolumes of  $10\text{ mm}^3/\text{m}^3$  at each of these two sizes.

Gas bubbles (< 3 microns radius) were detected near the seafloor in abundances of between  $10^5$  and  $10^6 / \text{m}^3$ . Bubbles with radii of 8 and 12 microns were present in abundances of  $< 100 / \text{m}^2$ . The smaller of these two bubble groups disappeared after rising about 3 m into the water column, and the larger bubbles declined to near zero abundance at *ca.* 9 m above the seabed. The sizes in both of the larger bubble groups increased slightly as they rose in the water column. On the night of July 26-27, organisms that had been near the seafloor filled the water column, eventually returning to a location near, but slightly above the seafloor, beginning their descent well before sunrise (*ca.* 0300 PDT). First light was *ca.* 0600 PDT.



**Figure 4:** *Acoustical volume scattering at 265 kHz for 12 hours centered on midnight at LOCO site K1 revealed both a normally migrating diffuse layer dominated by scatterers with Sv spectra typical of small copepods (top panel). The rise of this layer from near the seabed was synchronized with sunset. A second layer with the acoustic spectral characteristics of a mix of copepods and elongate scatterers with body shapes similar to that of mysids or euphausiids descended from the surface into a weak thermocline. The thermocline deepened near slack water and its depth continued downward as the tide receded (bottom panel). The thin layer roughly followed the depth of the thermocline. The deepening upper mixed layer contained a patch that was a mix of zooplankton and micronekton. Observations at a higher spatio-temporal resolution revealed the presence of high target strength scatterers, e.g., small pelagic fish, within both the thin layer and the patch.*

About 2230, a thin scattering layer formed at a depth of *ca.* 2.5 m. If, for zooplankton, one adapts the criteria for a thin layer as formulated for phytoplankton (Dekshenieks *et al.* 2001), on that particular night this layer barely qualified as a “thin” layer. Its location suggests that the organisms in the layer

were attempting to maintain an association with a weak thermocline (Fig. 4, bottom panel) or with some other characteristic of the water that was present near the thermocline. The pattern is consistent with a temporally coherent vertical migration of a thin layer that was horizontally discontinuous, or patchy. These observations were also consistent with night time shipboard echo sounder records.

Possibly as the result of horizontal advection, a plankton patch was observed in the upper mixed layer, beginning at about 0130 PDT. When observed at higher resolutions both the layer and the patch can be seen to contain discrete scatterers with target strengths and spectra consistent with those of fish. The patch itself contained scatterers that exhibited the spectral scattering characteristics of copepods or fish eggs  $< 1$  mm in size with a total biovolume of *ca.*  $10,000 \text{ mm}^3/\text{m}^3$ . This is the equivalent of a cube of plankton that measures 2.15 cm on each side. Two additional sizes of organisms were also present, with lengths of 2 and 3 mm. Biovolumes in these two size classes were *ca.*  $1,000$  and  $100 \text{ mm}^3/\text{m}^3$  respectively. Elongate scatterers, 10.5 mm in length were also present at a biovolume of  $6,300 \text{ mm}^3/\text{m}^3$ . Bubble sizes and abundances were similar to those detected elsewhere in the water column.

Schools of small pelagic fish (e.g., just after 1800 PDT) were observed visually during the day from LOCO support ships, including the R/V Thompson. From the inshore TAPS records, it appears that the schools dispersed at night, re-forming the next morning when there was sufficient light for schooling. The volume scattering strength spectra in the migrating diffuse scattering layer, the thin layer, and the patch were consistent with low abundances of fluid sphere and elongate scatterers that are used as surrogate scattering models for small zooplankton (e.g., copepods) and micronekton (e.g., mysids). On days not included in this discussion, the patterns shown in Figs. 1 through 3 were fairly typical of those illustrated. Taken as a whole, the data strongly suggest that a night time thin layer originated just under the sea surface at sunset, with the organisms performing a reverse migration into the water column, sometimes splitting into coherent thin layers at multiple depths. Reverse migrations are fairly common in the zooplankton community, as are normal vertical migrations where organisms move into the water column at night, returning to a place they perceive as relatively safe during the day. This can be near the seabed (Kringel *et al.* 2003) or near the surface (Ohman *et al.* 1983). The migrations we observed appear to be behavior-driven, and in the light of data our co-PIs collected in Monterey Bay they are probably related to foraging. In 2006, the Monterey Bay thin layers consistently started a return to the surface at *ca.* 0300 PDT, arriving there in multiple cohorts well before sunrise. This layer contained organisms that scatter sound with a frequency dependence similar to that observed for copepods and other small, quasi-spherical particles, e.g., fish and copepod eggs. Biovolumes for organisms with lengths  $< 1$  mm were about 40X greater in the thin layer originating at the surface than in the diffuse layer that rose from the bottom, i.e., *ca.*  $40,000 \text{ mm}^3/\text{m}^3$ . Organisms that scattered sound like 12 mm krill were present in the 1 m thick thin layer at similar abundances, with less biomass above and below the layer. The number of bubbles with radii  $< 4$  microns reached values of *ca.*  $63 \text{ M} / \text{m}^3$ , higher than was measured just under the sea surface at the same time. Bubbles with radii of 8.5 microns were also present. Their numbers reached *ca.*  $10,000 / \text{m}^3$  within the layer, dropping to near zero just above and below the layer. Fourteen micron radius bubbles appeared to be passing through the layer, with fewer bubbles both below and above the layer peak. The bubble density was asymmetric, higher below the layer than above, suggesting possible accumulation of rising bubbles at the thin layer depth. This was also the case for the bubbles  $< 4$  micron in radius. Our estimates of bubble sizes and numbers in the water column are consistent with acoustical resonator measurements from Monterey Bay (Medwin 1977). Medwin and Breitz (1989) used optics to find that the peak in the size spectrum for subsurface bubbles was  $< 30$  microns. While much of our data remains to be analyzed, our initial results seem consistent with their results and those of Wu (1981). Multiple physical mechanisms have been identified to explain the distribution of small bubbles in the sea (Monahan and Lu 1990). Considerable



literature exists on small bubbles in the sea, and our plans include additional comparisons of our measurements with results obtained by other investigators, including Medwin, Farmer, Crawford, Vagle, Su, Thorpe, Leighton and Humphries. Most studies on bubbles in the sea have emphasized physical processes such as breaking waves, stimulated by an interest in air-sea interactions and ocean-atmosphere gas exchange. Our primary focus involves the possibility that small bubbles may be generated as a result of dissolved O<sub>2</sub> saturation as a result of photosynthesis where phytoplankton concentrate in very thin, shallow layers in the water column. We have shown that such bubbles may be produced by epi- or endo-benthic marine algae in the top few mm of a sandy seabed (Holliday *et al.* 2003b; Holliday *et al.* 2004). In addition to *in situ* generation, a seabed source of bubbles in a shallow, sandy area such as the shelf of Monterey Bay could be an added, or alternate, explanation for the presence of small bubbles in thin layers. A flux of small bubbles rising slowly upward could possibly be delayed or trapped at depths with high concentrations of marine snow or mucous derived from living organisms, or within dense thin layers of phytoplankton.

## **IMPACT/APPLICATIONS**

The data collected in the LOCO work in Monterey Bay during 2002, 2005 and 2006 strongly suggest that fine-scale vertical structures in the plankton and their diel vertical migrations are ecologically important. As aggregating mechanisms they impact food availability for several trophic levels and they are critical for larval organisms before they are able to swim and forage effectively. When our data are examined in the light of the different data sets (e.g., phytoplankton and chl-a profiles, plankton species, small scale physical oceanography, etc.) collected by our co-PIs in LOCO, we will be able to address questions involving physical and biological forcing in the coastal ecosystem. The LOCO data sets are truly unique. Having access in real-time to data from the TAPS and ORCAS variants deployed by the BAE Systems and URI teams has proven extremely valuable, allowing the investigators to adapt their sampling efforts in a way that assured that the same fine-scale phenomena were actually sampled by a large suite of appropriate sensors. The distribution of marine life at all trophic levels impacts current and future naval systems, especially those used in the littoral (coastal) zone, where both mine detection and clearing operations must be conducted prior to engaging in expeditionary warfare. The abundance and distribution of marine life also plays an as yet poorly understood role in controlling reverberation statistics at lower acoustic frequencies through food web interactions. The phenomena we have studied impacts the propagation and scattering of both light and sound. Information gained will be invaluable for designers of new sensors to be used in the battlespace environment.

## **TRANSITIONS**

Some of the multi-frequency technology that we developed under sponsorship of ONR has been transitioned to operation in the North Pacific and Bering Sea areas by NOAA's National Marine Fisheries Service / Alaska Fishery Science Center and the Pacific Marine Environmental Laboratory (PMEL). We will be adding the new capabilities in our inverse code to the custom software that is used to process the data NOAA is currently collecting in the Bering Sea with a moored 8-frequency TAPS. This will also provide a capability for extracting the densities of small bubbles from TAP-8 archival data collected in the Coastal Gulf of Alaska in 2003, 2004, and 2005 and in the Bering Sea during 2006.

## RELATED PROJECTS

We continue to support NOAA and PMEL personnel regarding TAPS-8 data processing. This project is funded by NOAA/COP through NOAA's Alaska Fisheries Science Center. Several posters and talks have been prepared and presented (Bond et al. 2006; Holliday et al. 2005b; Napp et al. 2004). We have also prepared and submitted a paper for publication in Deep Sea Research on the data they collected in the coastal Gulf of Alaska, and we are organizing at least one additional paper about those data. Our co-PIs at NOAA have now collected two years of data from the Bering Sea shelf area north of the Aleutian Islands. We will be assisting NOAA in the processing and publication of papers related to the collection of those data, which are now transmitted hourly to shore via the Iridium satellite network.

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## **HONORS/AWARDS/PRIZES**

In 2006 NOAA named a new 32' coastal research vessel the R/V D.V. Holliday. This vessel can sleep up to four persons and is configured to operate up to 100 nm offshore. Instrumentation currently includes Simrad EK60 multi-frequency echosounders (38, 70, 120 and 200 kHz) and a Simrad SM20/SM2000 200 kHz multi-beam sonar. Additional scientific gear includes passive acoustic sensors, an ROV and an AUV, underwater video, a Seabird SBE19+ CTD, a WeatherPak 2000 weather station, an IKMT plankton net, and a NOAA shipboard computing system. Her homeport is in San Diego, CA, and the vessel is currently used for advanced research in fisheries and plankton acoustics, as well as for routine fisheries acoustic surveys along the US Pacific coast.