Lectures 5 and 6: Lagrangian Current Measurements and Integrating Current Meters

An important concern of physical oceanography, geochemistry, and planktonic distribution of organisms is "where does the water go?" Is there a physical variable that is directly related to this question? A simple-minded idea is that the physical variable that answers this question is the track of a particle of water or of a parcel of water. This is a Lagrangian concept, the description of a particle path. The problem is that in a large Reynolds number flow (the ocean is a large Reynolds number fluid, say $1,000 \text{ km} / (0.01\text{s}*10\text{cm/s}) = 10^9$) particle trajectories are likely to be variable and only in a statistical sense describe the flow. Even if one assumes that turbulence will smear the picture on the small scale but a mean current will advect these smeared trajectories in a clear way across the ocean, it is difficult to get a reasonable picture with a small number of marked particles.

The physics of fluids depends on a pressure field to accelerate fluid. This gives rise to a velocity field, the more commonly measured quantity. The displacement field is yet farther from the basic physical variable and thus more complex. Yet Lagrangian measurements are chosen for certain types of problems, generally ones with long integration times. Surface drifters are the crudest kind of current meters. The surface water advects a float and its position is monitored. The drift bottles of the 1960's, released in large numbers from light vessels with notes inside to determine where they washed up, were useful for showing the onshore - offshore seasonal variations in surface drift. Satellite tracked floats with drogues at some modest depth have been useful in tracking the Gulf Stream and its rings. Deep free-drifting Swallow floats exploded the notion of the level of no motion in the late 1950's.

The SOFAR float program was an outgrowth of the Swallow float programs of the early 1970's. The principle is that a neutrally buoyant float at some midwater depth will be a nearly perfectly tagged water particle. It can be tracked acoustically. As a sensor, this more nearly tracks the physical variable (water particle displacement) than does the surface drifter with its windage and wave response. Initially and occasionally still, these Swallow floats were tracked by ship. However in the 1970's, low frequency sound was used to signal over long ranges to fixed bottom-mounted hydrophones. The low frequency sound was attenuated little and the spreading loss was cylindrical rather than spherical because it was ducted in the SOFAR channel. Precise timing permitted the determination of position from two tracking stations and when a third station was available, clock drift could be checked.

To bring this report of Swallow floats up to the year 2003, PALACE or Profiling Autonomous Lagrangian Circulation Experiment drifters have been deployed by the hundreds. Russ Davis, to measure the current around Antarctica, has deployed many ALACE (not profiling) drifters in Davis Straits. These are not tracked acoustically but return to the surface periodically to transmit their locations by Argos satellite. The ALPS program is presently deploying 3000 such floats uniformly around the world oceans. Each reports its position every 30 days and is expected to survive for about 4 years.

The Swallow Float is less compressible than seawater (generally 1.5ppm/psi versus 3ppm/psi for water) yet can be made to float in aluminum cylinders capable of 2000m depth range or spheres

of glass capable of any ocean depth. It must carry energy to power its signaling device and its sound transducer and electronics. This scales the package. For short ranges and several weeks' duration, a 13-inch diameter glass sphere has been used. For 1500km ranges and two-year duration, 8-foot long 12-inch cylinders are required.

Doug Webb's SOFAR floats use a tuned cavity resonator to convert electrical power to sound power. As the frequency is lowered and the weight of the structure held constant, the efficiency of this sound projector drops. However the attenuation of the lower frequency sound also drops and for long ranges this dominates the equation for loudness at the receiver. It has been optimized at about 2% efficiency for a 220Hz sound source. If the energy can be spread over a longer time interval, the power can be lower but the timing can remain as precise. This does require that the bandwidth be broad. But it need not be broad at every instant, only over the entire pulse. Recently a frequency slide has been employed in which a very narrow band sound source has had a variable tuned cavity, like a trombone, in which the frequency is slowly varied during the transmission. Precise timing is possible with the received signal correlated against a pattern of the transmitted frequency slide.

Moving away from the bottom hydrophone arrays, another receiver was needed. Al Bradley designed an autonomous listening station, ALS, to receive and decode the SOFAR float sounds. The individual floats are kept track of by a window when the signals are expected (four times a day) and a correlation is performed to determine the most probable arrival time of the chirp signal. The integration of the system is a nice illustration of instrument design. The physical variable to be detected is an acoustic signal. The ambient noise in the ocean is the background that must be rejected. A single loud noise such as an explosion would be above ambient, but is hard to generate from a lightweight sound source. Equivalently, a continuous tone with the same total energy would be equally detectable but not contain the timing information necessary to determine position. A chirp permits both objectives to be met. Because the sound source is so narrow band, a chirp going from 220Hz to 221Hz in 2 minutes is used.

Inverted SOFAR tracking has become common with the RAFOS floats. Instead of lots of powered sound sources floating around and a few fixed receivers, a few fixed sound sources and lots of drifting receivers are used. Tom Rossby developed this small Swallow receiver that pops up and dumps its positions over the last submerged period to a satellite, then dies. Self-propelled floats are also possible. The power to move faster than the current is less than the power to transmit signals. They can be thermally powered from the temperature difference in the thermocline and Webb's Slocum float, Davis's Spray, and Charlie Ericksen's glider are in competition for the AUV longevity record.

The last part of the instrument system is the presentation of the data in a comprehensible form to a human observer. The data from SOFAR floats is plotted as spaghetti diagrams after laborious computer processing. However this form is mostly incomprehensible. Except for obvious entrainment in a Gulf Stream ring, it is difficult to understand much from the output. Some scientists have turned the Lagrangian measurements back into pseudo Eulerian measurements by taking velocities of floats as they passed through position squares. Then energetics were computed. It may yet be a question of numbers. With enough floats, patterns may emerge and the ocean

equivalent of hydrogen bubble or differential particle imaging velocity flow visualization may be possible. In the laboratory, this has been valuable for showing flow structures, a result not possible from statistical descriptions.

Long baseline measurements can, in principle, provide average information about the properties along that line. Because sound is the only signal that will go long distances through the water, acoustics is the probe technique. Two things can be measured, the travel time and the signal phase and amplitude as it arrives. By using the travel-time differences for reciprocal paths, the average water velocity along that path can be measured. The range of this acoustic current meter can be ocean basin scale although none has been made at that scale yet.

The phase and amplitude information as well as the absolute travel-time tells about the speed of sound along different ray paths. Over a fixed long baseline, the variation in travel time for the last arrival of an acoustic pulse is a measure of the average speed of sound along the sound speed minimum path. This is the ray path nearest the sound channel axis. If the arrival time is delayed on successive days, the average speed of sound is reduced as would occur if the average temperature was lowered.

This result is not very likely because the water near the sound channel axis is pretty cold already and an effect of eddies and meanders is more pronounced on the warmer water nearer the surface. The ray paths passing through the shallower layers actually arrive before those near the channel axis because the greater speed of sound in the warmer water on the upper half cycle and in the higher pressure water on the lower half cycle of these ray paths more than make up for the longer distance of the paths. (The actual paths are nearly flat.) By a careful ray analysis of the received signal, different paths can be separated (the rays form caustics for each mode and the arrival time for each can be distinguished) and used to probe the sound speed for different depths. Thus a multilayer model can be fit by the long baseline observations of amplitude as a function of arrival time, or more precisely its variation.

The inverse techniques of tomography are now being applied to multi-source, multi-receiver arrays at ocean basin scales. These techniques permit three-dimensional patterns of sound speed anomalies to be mapped. The resolution is determined at best by the number of unique source-receiver paths available. Tests of this acoustic tomography have occurred using four sources and five receivers. Greater numbers are now being used. Walter Munk and Carl Wunch pioneered a kind of global ocean "weather" monitoring program. Presently the limitations on these programs are bioacoustic concerns about the effect of low frequency sound on whales and other sea mammals.

Two techniques and an observation were vital to making the acoustic tomography project possible. The observation was that ocean acoustic paths are phase stable so that rapid changes in multipath structure is not a problem. The first technique was the precise self-navigation of an acoustically tracked mooring to remove the effect of mooring motion from the measurement. Bob Spindel was one of the first to use microprocessors in underwater instruments for this work. The other development was the low frequency sound sources of Webb's.

<u>Problems</u>

1. An optical encoder is used to digitize the orientation of compass and vane in the vector averaging current meter. There are seven tracks on an encoding disc that are each divided into clear and opaque sectors to modulate seven LED-photodiode pairs. It is awkward if two sectors change at once since a slight mismatch in the threshold of the detectors might cause one sector to be detected before the other in either order. The Gray code is a binary code in which only one bit is permitted to change at a time. Using the rule that the lowest order bit possible be changed at each transition, generate the seven bit cyclical Gray code.

2. In the absence of drag, compute the vertical oscillation period of a Swallow float with half the compressibility of seawater.

3. A current meter with a recording capacity of 10 million bits is to be deployed for a year. A resolution of 0.1 cm/s is required and over-scaling at 25 cm/s is acceptable. How long must each sample be averaged for? If a time word of 24 bits is added, specify a record format including the time and an array of current samples that is only 10% less efficient. How large a memory is needed to store this array before recording? To modernize this problem when large memory is ubiquitous, consider the transmission of data by satellite where limited data capacity is still a problem.

4. A 10-kilohm thermistor is to be used to measure microscale ocean temperature fluctuations. No more than 100 microwatts can be dissipated in the thermistor without unacceptable self-heating. The expected signal is 1-ppm change in resistance. What is the minimum time that can be taken for the thermistor measurement and still achieve a signal to noise ratio of 0db (equal signal and noise)? If the thermistor response time to a step change in temperature is 16 ms, how accurately can an interface in temperature be defined when traversed at 30 cm/s?

5. In an acoustic current meter with a 15 cm diameter averaging volume, a 30 cm/s current is expected. How rapidly must the sensor be sampled to avoid aliasing? If sampled at ten times that rate, what would the spectrum be expected to look like?

6. Vorticity can be measured by sending sound in opposite directions around a triangular path and measuring the difference in travel time for the two directions. Design a scheme for doing this from three buoys, two of which are transponders. Can some or all of them be free drifting?