Principles of Oceanographic Instrument Systems: Sensors and Measurements

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Introduction

Instrumentation is a subject with one foot in engineering and the other in science. It does not incorporate enough techniques peculiar to itself to be called a discipline; rather it is generally treated as a sub-discipline of mechanical engineering, electrical engineering, or physics. Instruments are devices that interact with physical systems in a precise way, generally for the purpose of acquiring information. Sensors interface between the physical world and the artificial world of electronics or other man-made systems. Instrument systems are more than simply sensors; they acquire information or perform manipulations. Thus instrument systems make measurements. Oceanographic instrument systems work in the ocean or remotely to acquire oceanographic information. The mechanical platforms and vehicles used in these systems represent a specialized set of techniques covered in a separate subject. In this subject, the portion of the system that acquires and processes information is treated.

Outline

- Function of Instrumentation
    - Information
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        - Observation, measurement, detection, sample
        - Communication
        - Recording
        - Manipulation
    - Control
        - Manipulation
        - Process Control
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    - Acoustic
        - Travel-time, Doppler
    - LDV
    - Electric field
    - Surface drifter
    - Dropsonde measurement
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        - ADCP, Moored Profiler (M&M)
- Sensor Systems
    - CTD
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        - Digitization
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    - VMCM
        - Vector measuring
        - Sampling
        - Vector averaging
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    - SOFAR floats
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        - SOFAR channel
        - Tracking
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    - BASS
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        - Array of sensors
        - Tripod
        - Processing

    - LDV
        - Doppler signal
        - Bragg cells
        - CCD FFT
    - Particle Sizer - LISST
        - Angle measuring optics
        - Photo-Avalanche Array
        - Settling tube

- Telemetry buoy
    - S-Tether
    - Satellite link
    - Sensors
    - Inductive modem
    - Acoustic Telemetry
        - Coding
        - Processing signal
- ADCP
    - Doppler
    - Broadband
    - ADV
    - DopBeam
- ABSS
    - Acoustic Backscatter
    - Amplifier
    - Multifrequency
- Seismometer
    - Sensing Element
    - Deployment
    - Data Recording
    - Real-time Data Return
- Sidescan Sonar
    - Transducers
    - Time Varying Gain
    - Image Processing
- Inertial Measuring Unit
    - Rate Gyros
    - Accelerometers
    - Power Considerations

Lecture notes

This file contains compiled lecture notes, organized as follows:

Lectures 1 and 2: Instrument Systems and Limits to Measurement + Problems

Lectures 3 and 4: Eulerian Current Measurements and the Acoustic Current Meter

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

Lectures 7 & 8: Remote Sensing - Satellite, Radar, VHF Radar, LDV, ADCP, and ADV

Lectures 9 and10: Optical Instrumentation - Transmissometer, OBS, LISST, AC-9, Radiometer, Spectral Radiometer, In-Situ Flow Cytometer

Lectures 11 and 12: Water Properties, CTD; and High Precision Digitizers

Lectures 13 and 14: Optical Sensors - Shadowgraph and Nephelometer

Lecture 15: Modular Acoustic Velocity Sensor - A Commercial Prototype

Lecture 16: Microprocessors, Embedded Processors, Modern Sensing Systems

Lecture 17: Economics of Instrumentation

Lectures 1 and 2: Instrument Systems and Limits to Measurement

A system is completely defined by its input and output specifications. For example, an instrument system might measure, record, and display a physical variable. The exact way this is done is unimportant as long as the specifications are met. We often deal with components of an instrument system such as sensors, amplifiers, or recorders but in general these are not complete and their characteristics depend on what they are connected to. The concept of a system being defined by its specification is useful because it frees us from thinking about specific implementations. Instead we may treat the system as a black box and concern ourselves solely with the inputs and outputs.

The input to an instrument system is the physical variable to be sensed. Thus the input to a thermometer is temperature, to an acoustic receiver is sound pressure, and to a current meter is velocity field. That the thermometer has self-heating and also may be velocity dependent is a problem to be met inside the system but should not concern us at this stage. For simple measurements, there may be little benefit in thinking of the physical variable independent of the sensor but in more complicated measurements there is an advantage. For example, the physical quantity may be highly variable and require that a long observation be made to obtain the desired statistical significance. This must be recognized immediately and not be masked by the averaging characteristics of some sensor. Furthermore, a clear understanding of the physical variable will aid in sensor design.

The sensor in an instrument system converts the physical signal to a more easily manipulated form. The use of the term signal in this context implies a separation of the physical variable into a meaningful part, the physical signal, and a non-meaningful part, noise. This separation often starts in the sensor. Any introduction of false information at the sensor or loss of true information is generally impossible to correct with subsequent processing. So the behavior of the sensor is one of the most critical concerns in an instrument system. The physical signal is composed of direct variations in a physical property such as pressure, concentration, or temperature. The output of the sensor is a voltage, displacement, resistance change, or other easily amplified, averaged, or stored characteristic.

After the physical signal is transformed to some other form by the sensor, it can be conditioned by amplifying, filtering, correlating, or sampling. Amplifying can generally be done with little degradation of signal to noise ratio. The term signal to noise ratio defines the ratio of useful information to unwanted information. Extra information added by the amplifier is unwanted. So if it adds information, this is noise. Similarly if in addition to amplifying the signal, it loses a part of it, this reduces the signal to noise ratio. Broadband electrical noise is generated by thermal excitation of electrons in a resistor. Because electronic amplifiers have resistive components, this thermal noise is introduced by amplification. It becomes the limit of the system in those cases where the sensor signal has very low level (as in the case of radio or acoustic receivers) and care must be taken to deal with this noise source and not permit it to become worse than the theoretical limit.

The thermal noise of a resistor is called Johnson noise. Considered as a current source in series with the resistor, or as a voltage source in parallel with the resistor, two expressions for the noise can be written:

$$i_n^2 = 4KTB/R; \; e_n^2 = 4KTBR$$

where i_n^2 = mean squared noise current (amps)
e_n^2 = mean squared noise voltage (volts)
K = Boltzmann's constant - $1.38 * 10^{-23}$ J/K
T = temperature (K)
B = bandwidth (Hz)
R = resistance (ohms)

From this it can be seen that cooling the amplifier may be required for achieving the best noise figure and this is done for certain space radio receivers and in some photo detectors such as CCD arrays. However for the rest of us, the only reasonable thing to do is lower the bandwidth.

Bandwidth is the range in frequency passed by the system. Analog filtering and sampling determine the bandwidth. In a communication system, the bandwidth determines how fast information can be transferred and there is a tradeoff between a fast system and a reliable one. The simplest way to limit bandwidth is with a low pass filter since the bandwidth below a certain frequency is limited to that frequency while the bandwidth above is infinite. In high frequency systems, a narrow band filter is used.

When the signal has been filtered, it is often sampled. In modern instruments, it is generally digitized because the signal to noise ratio for digitized data is very high and can be maintained through storage and subsequent processing with little degradation. At this point the problem of aliasing arises. The sampled data contains limited information about signal at frequencies higher than the sampling frequency. In fact, if there is signal at higher frequency than the sampling frequency, it will appear as energy at some lower frequency and thus degrades the data at the lower frequency. This is almost always undesirable. The solution is to filter before sampling and sample at twice the frequency of the high frequency limit of the signal passed by the filter. The high frequency limit may be imposed by the nature of the physical signal, by the response of the sensor, or by a filter in the signal conditioner.

A system should have an output that is either directly coupled to a human observer or is indirectly coupled to one through subsequent processing. This defines the output of the system. It might be a display or a data port. But before final presentation, some human engineering is required to match the display to the capabilities of the observer. Modern commercial instruments do this reasonably well but prototype instruments are sometimes incomplete in this area.

Recording in temporary form is required in a large class of instruments used in oceanography, those unattended and submerged. Other systems must deal with permanent data storage. Recorders are used to do this storage. They have data limits. However the earlier in the processing sequence that the data can be stored, the more chance there is for subsequent processing. This is in conflict with the need to extend the deployment time and the fixed data capacity. Important compromises must be made here. An extreme case is sometimes heard where it is desired to record everything, everywhere, all the time. This does not require an instrument system; it is the universe running in real time. Consideration of the requirements of an eventual human observer helps resolve some of these conflicts. If the observer can only hope to deal with a small fraction of the possible observables, some reduction in what is recorded may be reasonable. In fact the increase in data capacity of hard drives and compact flash memory brings home the realization that the bottleneck in data capacity may be the human ability to unpack and absorb stored data.

In the 1950's recording was limited to film, chart paper, and punched paper tape with a few poor tape recorders. The bathythermograph smoked glass slide was very much with us as a mechanical recorder. At the end of the 1960's the digital cassette tape recorder appeared and was used in the 1970's extensively. In that decade, some giant audio tape recorders were packaged for ambient noise recording. Solid state memory began to be used in the 1980's for recording small amounts of data and bubble memory was tried for larger amounts of data at WHOI in 1983. The digital cassette tape with 2 megabytes (MBytes) of data was the standard for a decade. Digital streaming recorders and optical disks with up to 100 MBytes were used with moderate difficulty in the late 1980s. In situ processing was the alternative to these clumsy devices. However laptop computers broke the back of the problem and now 250 GByte hard disk drives ($0.66/GB Feb 3, 2003) and 1 GB Compact Flash memory cards make the need for in situ processing of data less urgent.

Data telemetry in real time or in delayed transmission still presents a data bottleneck, particularly satellite data communication. This data throughput limit is partly the bandwidth of the channel and partly power limits in the transmitting instrument. For any technology, acoustic, radio, optical, at various range and noise environments, there is a cost of energy per bit transmitted. Even for optical fiber there is some cost although in observatories, much of the charm is the extreme economy of data transmission. There is still some need to be conservative in data quantity.

When data are presented in graphic or tabular form in publications or reports, their information content is much less than even 2 MBytes. If one knew in advance what processing was needed to reduce the data to that which would be published, one could save a lot of post-processing time. Obviously only a small part of the data in an experiment is published, the rest serving to prove the validity and develop the statistics of the sample and isolate the phenomena to report. Still it is a sign that one is largely in the observational rather than the measurement phase if one cannot do some data compression in situ. This reduction must be done sometime if it is to become understandable to an observer.

Problem Set - Noise and Sampling

1) What is the voltage noise of a 100K resistor at room temperature and a bandwidth of 10 MHz? Watch units.

2) An FM radio receiver may see an antenna with 300 ohm impedance. (This is reactive, not resistive, but a maximum power match might use a transformer to reflect the input transistor impedance to that value. Think of a 300 Ω noise source at the input.) A commercial FM station is ~ 100 MHz and the radio channel (not TV) is 30 kHz wide. What signal strength is needed to get 0 db S/N? [db = 20*$\log_{10}$(voltage ratio)]

3) A deep space probe at a range of 10 astronomical units drives its 2 meter diameter 900 MHz antenna with 10 watts. What is the signal received at a 10 meter diameter dish antenna on earth? What is a reasonable baud rate at room temperature? At liquid helium temperature?

Lectures 3 and 4: Eulerian Current Measurements and the Acoustic Current Meter

Eulerian current measurements are those made from a fixed array. They represent the flow field rather than particle trajectories. Fluid mechanics is formulated as a field theory so Eulerian measurements are natural to it. However it is not possible to measure the flow field continuously in space or time and one must be wise in sampling the physical variable, the current field. Even not counting deviations of the sensor from ideal behavior, variability in the flow due to waves and eddies, and spatial structure due to fronts can alias the measurements if they are not frequent enough or close enough together.

In the 1960's, the moored current meter array program got underway to measure transport in the Gulf Stream and other major water movements. Savonius rotors for speed and vanes for direction were used to sense the current and the number of revolutions and the vane direction with respect to the case. These measurements and the case direction with respect to north were recorded every 15 minutes. Surface floats were used because acoustic command releases were unreliable and subsurface moorings would have been hard to recover. By the end of the decade, two problems were discovered: the currents varied too much to trust the spot direction measurement to be representative and the surface float introduced motion to the mooring that the Savonius rotor rectified and over-read. Near the surface, the inability of the vane to follow wave reversals led to large errors in measurement. However these problems went away when the moorings went subsurface in the 1970's with improved releases.

At the end of the 1960's, it was recognized that the new low power digital integrated circuits would permit vector averaging wherein the vane and compass would be read every time a rotor turned a fixed distance. The motion could than be decomposed into north and east flows.

Toward the end of the 1970's, interest turned to the surface layer where air-sea interaction is important. To correctly average wave motions, the Davis-Weller fan blade current meter was developed. This instrument had a good cosine response, low inertia, and linear response. Thus it could even track reversing flows in waves. Two pairs of fans at right angles to one another are mounted with their axes of rotation perpendicular to a shaft extending from one endcap. They are far from the disturbance of the instrument case and sufficiently separated to avoid disturbing one another. Each pair of fans has a good cosine response (the ability to respond to the component of flow along the rotation axis) and is linear to a low threshold.

The VMCM, as the fan current meter is called, has replaced the older VACM, the vector averaging Savonius rotor current meter, for all mechanical flow measurements where there is vertical motion. However for measurements near the bottom boundary, the electromagnetic current meter, or EMCM, is sometimes used. This sensor depends on the electric field induced in a conductor moving in a magnetic field. The electric field is mutually perpendicular to the magnetic field and the current. A coil in a sphere or oblate spheroid produces the magnetic field used in the measurement. There are sets of electrodes to sense the electric field around the equator of the shape. Two components of flow can be measured with a single coil and three can be measured with a second coil at right angles to the first. The magnetic field is chopped and the electric potential is synchronously detected. Large potential offsets occur with even the best electrodes and a DC measurement is impossible. Even with a chopped technique, asymmetries in the field or electrodes produce a slight zero offset, the error in defining zero flow. Perhaps more importantly, the sensed volume of EM sensor is within the boundary layer of the sphere or spheroid, a complicated region to measure flow and one with hysteresis if the flow is accelerated.

The coil takes a lot of power compared to the mechanical current meters and efforts to reduce the power degrade the sensitivity. However the freedom from moving parts and the small size of the sensor recommend it and it is the commercial sensor of choice for boundary layer measurements and measurements in heavy fouling environments.

All the current sensors mentioned are physically intrusive and must disturb the flow. It would be better to measure the flow remotely, particularly if the flow might reverse and sweep back over the sensor after being disturbed. Acoustic and optical sensors permit more or less unobstructed flow measurements. There has also been one EM measurement with a Helmoltz coil to generate the field that is less obstructing to the flow but uses a lot of power. The remote measurements fall into two classes, scattering and transmission.

Scattering sensors, the acoustic Doppler current meter and the laser Doppler velocimeter, depend on scatterers naturally occurring in the water, unlike the case for laboratory instruments which depend on artificial seeding of the flow with latex spheres. These scatterers can be a troublesome part of the problem. In the case of acoustic Doppler current meters, the scatterers appear to be small bubbles, thermal inhomogenieties, and small organisms. The LDV depends on mineral or organic particles with a size of 10 to 20 microns. If there is no scatterer of the right size in the volume, the signal drops out and this is a serious problem for a frequency tracker. While this is a dominant problem for the LDV, the opposite problem occurs for the acoustic Doppler velocimeter. There, the scattering volume is so large that many different velocities may be present at once, giving a spread of frequencies in the received signal.

Since 1990, the Acoustic Doppler Current Profiler (ADCP) has become a dominant current meter in coastal and even deep-sea moorings. First used on ships in a downward looking mode, it now is bottom mounted in trawler proof cages and on subsurface moorings looking nearly to the surface. A recent modification has permitted the ADCP looking up to measure wave directional spectra. The range is order 100 meters at 300 kHz acoustic pulse frequency with 1-meter resolution and order 300-meter range at 150 kHz. In 1994, broadband ADCPs became available with coded transmissions that permitted more than one pulse to be in the water at a time, breaking a previous range-repetition rate limitation. Now a number of manufacturers are producing competing ADCPs, generally broadband, to capture the mass market of current profiling.

The acoustic Doppler technique has also been adapted to compete with a former LDV niche as the Acoustic Doppler Velocimeter (ADV). This instrument is bistatic, meaning the transmitting beam is crossed with a receiving beam and the measurement volume is defined by the beam intersections. There is no range ambiguity (unless a reflection from a surface puts acoustic energy back in the measurement volume) so the velocity acquisitions can be made very rapidly, giving many measurements that can be averaged to bring the velocity uncertainty down to an acceptable value, even for turbulence measurements.

In 2003, there are several serious contenders for a moored acoustic Doppler current meter. The Aanderaa RCM9 and RCM11 use four beams from a small diameter cylinder in line with the mooring looking out in four horizontal directions. The RCM11 rejects the downstream axis in determining the 2-D flow. SonTek and Nortek also produce a moored version of their ADV for replacement of the VACM and RCM5 rotor vane instruments. These are being tested and have acquired a small following.

Acoustic travel time current meters depend on the difference in travel time for propagation of sound in opposite directions to measure the component of flow along the acoustic axis. The group velocity of sound through the water plus the speed of the water with respect to the sensors determines the travel time of the pulse.

$$t_1=d/c-v$$
$$t_2=d/c+v$$
$$dt=2dv/c^2$$

where d=distance between transducers,
c=phase speed of sound in water, equal to group velocity because water is non-dispersive for sound,
v=**v*****d**/d, the component of velocity along the path.

Eddies smaller than the sensor volume are averaged over because the effect of one side of the eddy is canceled by that of the other side.

The sample rate of the volume-averaging sensor is set by the need to sample twice for the shortest time an eddy with the characteristic size of the sensor is advected through the sensor volume. We make the frozen field hypothesis in which the changes in the turbulent eddies are assumed to be small in the time it takes to advect them past a point. The smallest eddy that can be resolved by the sensor has a diameter d and at an advection velocity V, a transit time d/V, requiring a minimum sample rate 2V/d where V is the maximum expected velocity. The penalty for failing to do this is that spatially resolved but under sampled eddies will contribute energy to a lower wave number part of the spectrum and alias the true spectrum. If there is no interest in eddies at that small a scale, a larger sensor volume could be used or extra samples could be taken and averaged before recording.

A puzzle concerns the averaging length of the acoustic travel-time sensor. The turbulence spectrum would be expected to start to fall faster than -5/3 at the wavenumber equivalent to the pathlength. A slope of -3 is predicted by one model after the wavenumber exceeds the reciprocal of the pathlength. However the observation is that the spectrum continues to fall at -5/3 at least out to the scale of the beam width and possibly even beyond. In fact, acoustic travel-time current sensors seem to resolve as high a wavenumber in turbulent flow as any sensor including LDV.

Either pulses or continuous wave signals can be used to measure the travel time. If continuous waves are used, phase measurements rather than pulse arrival times are used. The measurement of phase can be done quite precisely and at lower power because it is inherently a slower measurement, averaged over many cycles. This is the technique used in the FSI acoustic current meter (Neil Brown design). If the velocity is great enough to shift the phase more than 180^o an ambiguity arises which can be removed by trading an infinite wave train for a short burst and getting close to the right answer from the travel time of the burst. The advantages of the cw burst phase measurement are lower power and lower impedance resulting from transformer coupling.

Power however is less important than the total energy needed to make a measurement and the more power hungry technique of determining the arrival time of a pulse precisely can be traded off with the very short time required to make the measurement. For example, fifty measurements can be made with the pulse detection method in the time it takes to make one phase measurement. Since each measurement stands alone and no history of phase is used in the measurement, each sensor can be multiplexed for only a brief time to the detector and many acoustic axes can be measured with no more energy than a single-phase measurement. The benefit can only be realized if there are many axes to measure, otherwise all the energy saved will be lost in turning the detector on and off.

As an aside, it can be noted that the reason fast things take more power all other things being equal is that capacitance in circuits is approximately fixed by the physical dimensions of semiconductor junctions and the only way to charge them rapidly is to lower the resistance of the series gates and circuits and increase the current. Improvements in solid state devices include decreasing the size of junctions, which improves their frequency response at a given power.

While acoustic travel time devices to measure current have the advantages of physical averaging, continuous signals not subject to dropout, and reduced flow disturbance due to their minimum structure, they have the problem of uncertain zero point calibration. Being linear through zero velocity, nothing distinguishes the origin. Instead, the zero point must be determined by lab calibration. Offsets in measurements can best be determined and corrected for by the method of reversals. Ideally, the acoustic current meter could be rotated 180^o in the flow and the measurement repeated. Subtracting the two would cancel the offset and double the signal. This is impractical to do in most cases but it is possible to electrically reverse the connection of the transducers to the rest of the circuit by multiplexing them with a reversing connection.

This brings us to BASS, an acoustic current meter array for measuring turbulent fluctuations in the boundary layer. The benthic acoustic stress sensor multiplexes four acoustic axes on each of six sensors to a single pair of time delay detectors. Each pair of axes is swapped to minimize sensitivity to zero point drift. Incidentally the board count and power are also reduced. The only penalty is difficulty in keeping the impedance low through the multiplexors. BASS illustrates the parameters of an instrument design fairly well. The volume of the acoustic current sensor is the first filter on the physical environment and restricts both the scale of the physical variable that can be studied and the wave number that must be sampled to avoid aliasing. Second, the sample rate can be chosen to prevent under sampling with an assumed maximum current. Third, substitution (in this case reversal) is used to minimize the effects of zero point drift. Finally, limitations of electrical energy and data storage capacity are present to make the choice of data rates and speed of measurement critical.

BASS has seen a diversity of its uses to include an acoustic vorticity meter and a wave boundary layer sensor named the BASS Rake from its tines. The vorticity meter was first thought of to measure the shear in the surface boundary layer in the presence of waves. The large velocity of waves makes small errors leak into apparent shear. But the waves in an unstratified region, the surface mixed layer, are irrotational so have zero vorticity. The three-axis measurement of vorticity can theoretically reject wave velocities retaining only true shear. The BASS Rake concentrates the acoustic axes of a BASS current meter array into horizontal planes very near the bottom, the region where the wave boundary layer may exist. Ultimately the number of transducers in this region may become very large while the transducer size becomes quite small to resolve velocity variations over millimeters. This requires a different switching scheme with low impedance switches to multiplex the receiver to many transducers.

A single sensor BASS has been designed to fill the low cost requirement for a moored current meter that could be deployed in a large array, up to 100 instruments to study for example, benthic weather. Originally conceived as a modular sensor for inclusion in other instrument suites, it is named MAVS for Modular Acoustic Velocity Sensor. It is a three axis acoustic travel-time sensor with integral microprocessor and battery. Normally it includes a compass to rotate the velocities into earth coordinates and often it includes a tilt meter to erect the currents if the meter is tilted. In its 2004 version, solid state three-axis magnetometers coupled with solid state two-axis accelerometers both resolve the horizontal magnetic field direction and tilt. It can also measure other environmental variables including temperature, pressure, conductivity, turbidity, and analog voltages generated by external modular sensors. Thus MAVS has become a generalized data system as well as a 3-D current meter. The critical part of MAVS is the sensor head for current measurement. This is a pair of injection molded rings supporting eight transducers that define the velocity sensing volume. Each acoustic axis is inclined 45° to the horizontal and spaced 90° in azimuth but the transducers are paired in each ring so the axes form a closed, bent contour. Also, there are spokes supporting the rings from a central tube that carries the wires from the transducers to the electronics case but the transducers are not at the ends of the spokes. The offset of the acoustic axes from the straight structural elements avoids any acoustic path being in the plane of a wake, no matter what the direction. Finally, the rings are faired in the direction of the acoustic path so that when the flow is instantaneously along a path, the wake is minimum. This has resulted in a nearly perfect horizontal cosine response (horizontal being the plane of the rings) and a very good vertical cosine response. There is a cost of this performance in that the turbulence shed by the more bulky faired rings is about four times that in BASS, where the transducers alone have significant bulk. The wires being inside the support tube makes them rigid and reduces offsets in zero point due to motion of the cables as in BASS. There is however a pressure compensation problem in which the urethane that encapsulates the wires in the tube compresses with hydrostatic pressure and must be allowed to move as it gets smaller. In the present design, a urethane tube open at one end to seawater allows expansion internally to compensate for the shrinkage of the potting.

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 km / (0.01s*10cm/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.

Problems

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?

Lectures 7 & 8: Remote Sensing - Satellite, Radar, VHF Radar, LDV, ADCP, and ADV

The distortion of flow around a physical sensor may affect the measurement, particularly of current, and a remote sensing technique may be preferred over a direct contact. But some problems require such a large view or are so inaccessible that remote sensing by radar or by satellite may be necessary. The problems of ground truth, atmospheric distortion, and scattering model are critical to these measurements. It is well beyond this course to consider the construction of satellite sensors but the assimilation of data from these sensors is appropriate.

Altimeters provide profiles along their flight paths that to first order can map instantaneous sea level. By geostrophy, surface slope in sea level causes a horizontal pressure gradient that is balanced by current shear. Thus the change in sea level across the Gulf Stream by about 1/2 meter is directly related to the Gulf Stream current of about 3 knots. The waves on the sea surface, principally due to wind, are both a problem for precise sea level measurements and a signal of waves (through altitude variance) that can be used to map winds. Geodetic effects, atmospheric refraction (the wavelength of radar waves may vary with temperature and humidity), and orbit uncertainties come into the altimeter measurements. Often the problem that limits utility of altimeter measurements is the spacing of the paths and the frequency of repeat passes.

One of the older remote measurements has been radiometer measurement of surface temperature. First from aircraft, later from satellites, the surface temperature can be determined by two or more infrared detectors. The assumption is that the radiating surface is a black body and the ratio of two points on the spectrum defines the temperature of the body. Atmospheric absorption is a major problem for this observation and becomes more so as the amount of atmosphere through which the observation is made increases. Water vapor is the principal culprit since there are no absorption bands for the diatomic gases in the infrared but there are for H_2O and CO_2. By adding a third detector the water vapor absorption can be determined and subtracted. But it is still a difficult measurement. Modern sensors such as the AVHRR do a very good job. Rain is still a problem, but as in so many cases, the problem can be turned into a rain sensor which provides valuable information in its own right.

Scanners of various types have been flown, both multispectral and imaging, generally focussed on the land such as LandSat. But although SeaSat only flew for a short while, its images were extraordinary. Promises to replace SeaSat have been made for 15 years and SeaWiffs is still promised as of February 1997. Imaging satellites do not see through clouds. But they can see internal wave signatures, probably through modulation of reflectivity by stretching and compressing the ambient surface waves.

The real contributor to wave measurements has been Synthetic Aperture Radar (SAR). The radar obtains scattering images with amplitude and direction information. Scattering from waves relies on the Bragg relation, that the scattering occurs when the spacing of the scatterers (the wind waves) is an integral number of radar wavelengths. Only when the Bragg condition is satisfied is there appreciable scattering. Work by Bill Plant and others has shown that there is backward propagation of wind waves at a reduced amplitude which shows in the SART images and is real. A great deal of effort has gone into the scattering model for this process. It works for aircraft (and balloon) instruments and for land based instruments.

By varying the frequency and by measuring the Doppler shift in the scattered frequency, the wave spectrum can be determined from land-based radar or VHF radio transmitters. The Doppler shift can be compared to the expected wave speed and a current determined from the difference in the observed from the expected. Thus a radar or VHF radar (CODAR or OCSR for example) can measure current as well as waves. Furthermore, if the water is shallow, the shallow water waves propagate at a different speed from the same wavelength in deep water so the depth of the water can be determined in some cases. This is a new field that is just being validated now (1995-7).

Acoustic remote sensing for current by Doppler is well established with the ADCP. Velocity profiles almost to the surface or to the bottom are routine from fixed and moving platforms. Wideband permits higher accuracy in shorter averaging periods to replace the older narrow band ADCPs. Single level vector current meters like the SonTek ADV are permitting turbulence measurements to be made acoustically, a regime only available to LDVs and hot wires before.

Lectures 9 and10: Optical Instrumentation - Transmissometer, OBS, LISST, AC-9, Radiometer, Spectral Radiometer, In-Situ Flow Cytometer

The ocean is moderately transparent to light in the visible portion of the spectrum, more so in the blue than in the red. Pure water and oligotrophic seawater reach an attenuation length of 50 meters in the blue. Further in the ultraviolet, absorption increases as the tail of electronic transitions in the far UV become significant while in the infrared, vibrational and rotational absorption bands increase absorption. Within the transmission window in the visible, spectral absorption by dissolved organic compounds, gelbstoff, may make the water yellow or green, and scattering by particles may decrease transmission roughly proportional to the projected area of the particles. These effects on light transmission can be used to study what is in the water besides inorganic salts.

Scattering of light by small particles is Rayleigh scattering when the particles are smaller than the wavelength of the radiation, geometric scattering when the particles are much larger than the wavelength, and Mie scattering when the size is comparable to the wavelength. The range in sizes in the ocean varies from sub-micron for fine clay and certain plankton and bacteria to centimeter aggregates of marine snow. Mie scattering is relevant to part of this range (red light emitting diode (LED) light is typically 0.6 μ) and in Mie scattering, the optical index of the particle also must be considered. Detailed studies of pure populations of particles might confirm this description of scattering but natural seawater contains particles of many sizes, shapes, and compositions.

Inorganic particles are relatively dense and have a high index of refraction. Organic particles are close to water in density and index of refraction. But aggregates of clay may have an average density much less than the clay of the individual pieces and an index closer to water. So there is a wide range in size, composition, index, and density of particles in the ocean. In fact, it has been observed that the total mass contained in each decade range of size is roughly the same from fine clay to whales. Clearly this can't continue indefinitely and still conserve mass.

Zaneveld produced the first major improvement over the Secchi disk, as far as a widely used instrument, with the optical transmissometer. He observed that forward scattering is sensitive to large particles as well as small particles. A measure of loss in unscattered light is a good measure of total projected area of particles. In the transmissometer, or c-meter, light from a chopped red LED is collimated to 15 mm (to sample a larger volume and to be only 3 milliradians in beam angle). This beam passes through 25 cm of seawater (1 m pathlength and down to 5 cm pathlength instruments have been made) and is refocused on a photodiode. The signal from the photodiode is synchronously detected to reject light not coming from the chopped source. Baffles further reject sunlight. Light scattered more than 18 milliradians is lost. Full-scale output, that possible with pure water and no windows (a theoretical result, not ever realized) would be 5 volts and no transmission is 0 volts. Considering reflective loss at the two glass/water interfaces and 8.7% loss for pure water at 670 nm, 4.565 volts is the highest it can read. In air, with a higher index mismatch but no attenuation in the fluid, about 4.75 volts is expected and this is the precruise calibration that is monitored unless really clean seawater is available.

The c-meter has a Beer's law dependence on concentration so -log attenuation is proportional to concentration. Transmission is voltage measured/voltage full scale with windows. Attenuation is 1-Transmission. Actual concentration of suspended particles must be deduced from the attenuation signal by calibration against actual samples of population of stuff in suspension, neither aggregated not disaggregated. Such samples are very hard to obtain except if the transmissometer is lowered with bottles on a CTD/Rosette sampler. Then particle sizes can be measured with a Coulter counter, and dry weight of particles can be measured on a filter.

At high concentrations of particles, coastal regions and estuaries, the transmissometer may lose sensitivity at the low end, even a 5-cm transmissometer. Blacker than black. But a backscatter instrument may still have a signal proportional to concentration. The Optical Backscatterance Sensor (OBS) measures light scattered back into a broad cone of backscatter angles. This is insensitive to concentrations of milligrams/liter but still works for gm/l. At extremely high concentrations, 10-100 gm/l, it can work as a transmissometer in a range where signal falls with increasing concentration. It too needs samples of suspended sediment for real calibration of gm/l/volt.

In situ size distributions can be determined with LISST, based upon an inversion of the scattering angle distribution. Since large particles scatter light by small angles and small particles scatter into large angles, a photodiode array can obtain a distribution of scattering angles from a distribution of particles and this angular scattering function can be inverted for size distribution. Unscattered transmission can be measured at the same time for total attenuation.

Spectral properties of the scattering or absorption give information about organic components and living components of seawater. The chlorophyll content can be determined crudely with a fluorometer, in which chlorophyll fluorescence is excited by blue light and green scattering at 90° is sensed. More specifically, the spectral distribution of fluorescence can be determined, as it is in the AC-9 fluorometer, to distinguish living chlorophyll from various degradation products that also fluoresce. An even more sophisticated fluorescence instrument, the Sapphire, excites multifluorescence bands with various excitation wavelengths to obtain a fingerprint of coastal waters capable of identifying river sources by the specific compounds giving specific responses.

As a tracer of water mass and as a probe of water mass transformation, multispectral techniques are valuable, but as a simple detector of organic vs. inorganic sediment, fluorometers suffice and can be used in conjunction with scattering or transmission instruments to estimate organic transport.

The downwelling radiation from daylight is important for growth of phytoplankton in the photic zone. Measurements of light at the surface and at depth can be made with a radiometer. Directional information is useful to model the radiative transfer through an absorbing and scattering medium but the phytoplankton are mostly influenced by total illumination. Nonetheless, downwelling and upwelling radiation is measured with lowered radiometers. From surface light levels to bioluminescence at depth, the range is about 10 orders of magnitude, a real problem for a sensor. Shutters with pinholes are sometimes useful for such a large range. Log response with photomultipliers can be achieved by adjusting the voltage and thus the electron multiplier gain for constant output and measuring the voltage. Alternatively, the gain can be switched to one of several ranges and the range and output recorded. But in the upper ocean, the range of light levels is within the range of photosensors without shutters. Log amplifiers can be used to obtain the dynamic range required without range switching. These use the exponential relation between current and voltage in a forward biased diode to compress the range much as the constant current output of a photomultiplier can give a voltage proportional to the log of illumination.

The spectral radiation upwelling from the sea is useful for remote sensing by satellite. of phytoplankton abundance. Absorption of light in the blue by chlorophyll relative to the green and red can be detected remotely by color. Spectral upwelling and downwelling radiometers are used to support satellite programs. The light available after dispersion by a prism or grating is much less than the total downwelling radiation and high gain is needed in the detector. Of greater importance, since we live in a signal to noise limited world, is the scattered light. Inside a spectrometer, all the light not being detected at the receiver must be extinguished and not allowed to scatter by multiple bounces into the detector. One solution is to build a double monochromator. The first monochromator passes the wavelength of light to which it has been tuned with little attenuation but the wrong wavelength light that has found its way out the exit aperture is attenuated by a factor of 100 or 1000. The second monochromator passes the tuned wavelength with little attenuation as well but the wrong wavelength light that enters is again attenuated by 100 or 1000 which is sufficient to put it below the level of concern. If a single monochromator is used, great care must be taken with baffles to absorb the unwanted light. A reflection of the incident beam before dispersion can swamp the spectral signal. But even the dispersed light can be a problem if it is scattered to the detector.

The spectral radiometer developed by the NIO group in Goa uses a thermoelectrically chilled CCD array as a photodetector. The lowered temperature reduces the dark current, allowing a longer integration time to increase sensitivity without blooming from dark current. But the value of receiving all the wavelengths simultaneously, as in a film spectrometer, permits reasonable integration times, as 1 second or less. Second order dispersed light in the blue part of the spectrum can fall on the red end of the CCD array. This is a problem that can be ameliorated with a blocking filter at the red end of the CCD. The entire spectrometer can be made compact which keeps the optical speed high while keeping the weight down.

The Goa spectral radiometer did not have a perfect cosine-integrating window. The purpose of the window is to weight the downwelling radiation appropriately. That light which falls on a horizontal surface is the downwelling radiation. Frosted hemispheres and frosted plane windows are used to obtain the desired directional sensitivity. Each seems to decrease the available light an unacceptable amount but the absence of some diffuser gives irregular directional sensitivity. Upwelling radiation tends to be dim and blue and the sensitivity has to be quite high to see a signal above dark current from more than a score of meters deep.

Optical fluorescence is a valuable tool in the lab for phytoplankton identification. The flow cytometer measures the optical properties of single cells as they pass through a cuvette. In the lab, the stream of cells is concentrated into a fine column by flow focussing. In this technique, the cell containing flow is surrounded with a cell-free sheath of filtered water. Then both are accelerated by a constriction in the channel diameter and the cells are constrained to a column only about 10 μ in diameter. This region is illuminated by a laser (formerly another bright light) and the scattering at 90º is measured, the fluorescence at several wavelengths measured, and the responses categorized to define a specific phytoplankton. Big green fluorescing cells may be one type while small red fluorescing cells are another. This tool has opened up the study of nanoplankton and picoplankton at sea and now flow cytometers are taken to sea as well as used ashore to process samples taken at sea. A development is underway to put the flow cytometer in the sea for tows and profiles.

The biggest problem foreseen for the in situ flow cytometer has been the fluid focussing requiring filtered water and precise pumping. For the in situ instrument, a coincidence requirement has been implemented that selects only cells on the flow axis and in the center for measurement. There is no sheath flow. Rather, two infrared beams focussed in the center of the flow, one slightly above the other, are used to select particles that by chance are in the center of the channel. Then the scattered light from a frequency doubled laser (blue/green) is measured and the fluorescence at two wavelengths. These are recorded and the other signals are ignored.

Lectures 11 and 12: Water Properties, CTD; and High Precision Digitizers

The equation of state of seawater, which relates the density to temperature, salinity, and pressure, has been determined with great care by laboratory methods. Of almost as great interest as the density (and more for water watchers) is the salinity. The direct determination of salinity is awkward. It is defined as the weight of solids in one kilogram of seawater when evaporated and all the carbonates converted to oxides, bromine and iodine converted to chlorine and all organic matter completely oxidized. (Forch, Knudsen, and Sorensen, 1902 from Sverdrup, Johnson, and Fleming.) Direct evaporation doesn't work because chlorides are lost. But a simpler indirect measure can be based on the constant composition of seawater (same ratios of ions everywhere, only the water content varies). This involves titrating the chloride (and other halogens) with silver nitrate and indicating with potassium chromate. The relation is

$$\text{Salinity} = 0.03 + 1.805 \times \text{Chlorinity}.$$

Even that is slow and awkward so an attempt was made to determine the salinity by electrical conductivity measurements. The comparison was made between conductivity of diluted standard seawater and full strength standard seawater at a common temperature. The relation was fairly linear even though seawater is more then a very dilute solution. Once the relations were worked out from measurements, it became possible to measure salinity by putting the unknown sample in a temperature bath and measuring the ratio of its conductivity to that of a known sample in the same temperature bath. Schleicher and Bradshaw did some of this work.

The next step was to determine the temperature coefficient and this permitted correcting the measurement without a temperature bath. The principal variable responsible for conductivity changes in seawater is temperature, not salinity, so the temperature had to be measured very accurately and the lab work done very carefully. All this permitted salinities to be run at sea from Nansen bottles, which improved accuracy somewhat because salt samples can sometimes spoil if kept too long. But the observations were from only a few points in the profile. Then Neil Brown added pressure measurements and made an in situ sampler, the STD. Schleicher and Bradshaw did the pressure effect on conductivity (by now a three variable problem) and Brown and Allentoft extended the conductivity ratio measurements. As an aside, it took Brown and Allentoft about a year to discover that they had an error from contamination of the diluted seawater samples by the glassware which had been cleaned with chromic acid and then exchanged ions from the glass for some time.

The STD was a new window on the ocean and immediately presented problems for interpretation by showing fine structure (called microstructure then, in the middle 1960's). The STD corrected the conductivity measurement with analog circuitry using temperature and pressure. Then computers began to go to sea and Brown realized a better algorithm could be applied to raw conductivity, temperature, and pressure measurements by computer than by using the analog corrections. Furthermore the original data could always be reprocessed if the algorithm was improved. Finally the precision and accuracy of the measurement could be improved and the size of the sensors reduced to push the microstructure observations into the centimeter scale. It was the latter that drew Brown to WHOI in 1969 to develop the microprofiler.

Temperature can be measured to about 2 millidegrees with reversing thermometers and salinity can be relied upon to a few parts per million. To improve on this, Brown shot for resolution of salinity to 1 ppm which required resolution of temperature to 0.5 millidegree. Stability had to be very good to make calibrations to this standard meaningful. For standards work, the platinum thermometer is used and Brown chose that for the CTD. To minimize size and retain high stability with the conductivity measurement, Brown chose a ceramic, platinum and glass conductivity cell. For pressure he used a strain gauge bridge on a hollow cylinder.

Original plans to make his own thermometer, in a helium filled ceramic capillary tube, were discarded when it was discovered how hard the ceramic work was. Endless difficulties in glass to ceramic and glass to metal seals developed and overcoming these in the conductivity cell which had no voids was hard enough. A commercial platinum thermometer was chosen, Rosemont, with a time constant of 300 ms and a specified stability of 10 millidegrees in a year but in practice somewhat better.

The conductivity cell was a four electrode configuration to minimize electrode effects and had a symmetry that made it insensitive to local contamination of the electrodes. It was 3mm in diameter and 8mm long so it was hoped it would resolve centimeter scale structure. The 300 ms response time of the thermometer meant that for 1 cm resolution, descent rates of 1/2 cm/s would be required. This was a bitter result and Brown added a fast response thermistor to correct the temperature measurement at faster descent rates. Later he increased the size of the conductivity cell (the first one had a flushing length at speeds above 10 cm/s of about 3.5 cm despite its small size) and the new cell flushed in about 8 cm. With a thermistor response time of 30 ms, a 10 cm vertical resolution was possible at descent speeds of 50 cm/s or 30 meters per minute, a reasonable winch speed.

The requirement of resolving structure to 10 cm at a descent rate of 30 meters per minute meant a sample rate of 10 per second. (The original resolution target was higher and the first microprofiler had three channels running at 32 ms each in parallel.) The present CTD successively digitizes conductivity, pressure, and temperature at 32 ms each meaning it obtains a complete sample every 96 milliseconds which is fast enough.

The range in temperature is 30 degrees from freezing to the warmest surface water. For packing efficiency, straight binary integers are used and 2^{15} is 32,768. Thus a 16 bit measurement of temperature gives 0.5 millidegree resolution and 0 to 32.8 degree range. (For some work, a -2 degree lower end is needed and this has since been incorporated.) Conductivity varies over the same range because it tracks temperature. 16 bits generally permits salinities up to 38 ppt to be measured to 1 ppm precision. The depth range is 6500 meters (or a pressure range of 6500 decibars) for much of the ocean and with a digitizer capable of 16 bit resolution, this permits 10 cm depth resolution, again right on target for the resolution of the sensors. But to make a measurement to a part in 65 thousand and have it remain accurate and stable is not easy. Furthermore the conductivity measurement must be made at about 10 kHz because of electrode polarization.

In resistance bridges, the stability of ordinary precision resistors, RN60's, is 10 ppm/degree C. Vishay precision resistors are 1 ppm/degree C. The switches used to put the resistances in or out of the circuit have resistances of a few tens of ohms typically, although FET's are now available with on resistances of less than 0.2 ohms. The resistance of relays is typically 0.01 ohm but they require power to close and can only close in a about 1 millisecond. So Brown made his digitizer work from voltage sources rather than the more traditional resistances. In particular, the voltage sources were ratio transformers.

Transformers are voltage devices and are based on the voltage around a circuit depending on the change of flux through the circuit.

$$V = d\varphi/dt.$$

In a transformer winding nearly all the circuit and essentially all the flux containing part is wrapped around the core of the transformer. Another winding around the same core has the same flux through it. By wrapping all the way around the core, the flux contained in the output circuit increments by integers times the flux through the core whenever a turn is added to the winding. The flux leakage in a toroid core is small, perhaps 10 ppm, determined by the geometry and the relative permeability of the core and air. Thus the EMF in the secondary is related to the voltage in the primary by the turns ratio of the secondary to the primary. Two things can wreck this, current in the secondary which causes a resistive voltage drop, and too low a frequency so that the core saturates and loses the leakage flux advantage.

In Brown's digitizer, there are three stages of ratio transformer, each having one primary winding and five sets of secondary windings in binary ratios. The precision of the divider effect of these ratios is determined by the counting of turns (only 32 for the secondary at the most, and 160 for the primary) so the precision is built in from the start. The windings are added in series with FET switches and a comparator determines if the total output of the sum of the windings is greater or less than the signal to be measured before deciding to add or delete a winding. At balance there is no current flowing in the windings.

The signal is produced by an impressed voltage across an essentially resistive sensor and this voltage is matched to a sample taken from one of the windings on the ratio transformer so the whole thing is independent of the exact voltage used to drive the ratio transformer, being only the ratio of the output voltage to that driving the sensors.

Where are the problems in this marvelous scheme? There are capacitive effects that couple voltages into the output windings and create errors. However they are out of phase with the proper magnetically coupled signals and drive voltages. Thus if the detector is carefully adjusted to be synchronously in phase with the driving voltage, it should reject all out-of-phase components. In practice these voltages can get to be so large that they saturate the comparator near balance and must be tuned out. The major components can be balanced out with trimpots during instrument checkout. The residual is variable and still troublesome.

Since the error signal is exactly in quadrature with the signal, it too can be detected but by a detector running synchronously in quadrature to the drive signal. The output of this detector can then be used to control a quadrature voltage to be added back to the signal in opposite sense to drive the effective resultant quadrature signal to zero. This works very well.

Improvements to further reduce the leakage flux in the ratio transformers and the quadrature error have permitted the technique to be used to advance the state of the art in laboratory standards and NBIS (Brown went commercial in 1974) is now making voltage standards used by NBS (no relation).

The CTD is now a standard oceanographic instrument and has replaced the Nansen cast as a hydrographic tool. The data is sent up conducting cable as a frequency-shift-keyed signal. It is recorded as an acoustic signal on tape and decoded and repacked in a deck unit and output to a computer for digital recording and preliminary processing. The algorithm is clumsy in that it sticks close to the actual relations derived from the laboratory data sets. These were derived by going from salinity to conductivity not the other way around. More seriously, dynamically one wants to know density and this is now computed as a second step when it could be done directly. Some of these things are being taken care of. This is characteristic of the second decade in the life of a successful instrument. But maybe a direct measurement of density is appropriate or of some other essential variable. Successful instruments tend to stop development at the same time that they stimulate an observational field.

Lectures 13 and 14: Optical Sensors - Shadowgraph and Nephelometer

For some purposes it is less important to measure the physical variables in the environment than to detect variations in them or to determine the pattern of those variations. The search for salt fingers illustrates this case. One ocean mixing process contending for the role of a major global process in 1972 was double diffusion, in particular salt fingering. But although there was indirect evidence for the widespread existence of salt fingers in the ocean, they had never been directly observed. In the laboratory, the most effective way to observe them was by optical shadowgraph, a technique that displayed the vertical pattern of the convecting cells. I used the same approach to detect them in the ocean.

Where warm salty water overlies cool fresher water, perturbations of the interface between the two grow into vertical cells which exchange heat laterally faster than salt and convect the salt and heat downward within the cells. This occurs because heat diffuses two orders of magnitude faster than salt. The downward moving finger loses heat faster than salt, becomes cool and salty, and continues sinking. The rising finger gains heat faster than salt, becomes warm and fresh, and continues rising. Theory predicts the scale of the fingers to be about 1 cm in the ocean and to have temperature differences of a few millidegrees and salt differences of less than 10 ppm. This gives an index of optical refraction difference of a few parts per million, depending on the temperature and salinity. While small, optical techniques are capable of great sensitivity and they can be detected.

Lecture 15: Modular Acoustic Velocity Sensor - A Commercial Prototype

Measurement requires instrumentation but oceanographic research often is done with prototype instruments since the measurement produced by that instrument reveals processes that have general validity and only a few copies of the instrument will ever be needed. Sometimes, the measurement must be made frequently and in many places so that a production run of instruments is required. Commercial production is then appropriate. Successes in commercial transitions of instruments include the CTD, XBT, rosette sampler, and ADCP. These each produce measurements required by many research scientists, environmental engineers, and mission agencies including navies. The transition of a research tool to a commercial instrument is unfamiliar to most academics and is not always rewarding professionally or financially. But the correct solution to many measurement problems requires just such a transition to reduce the cost, increase the availability, and improve the reliability of the instrument in question.

The Benthic Acoustic Stress Sensor, BASS, developed from 1978 to 1981 and refined and improved continuously to 1996 became a candidate for such commercial production in 1993 as a result of NSF support to develop the instrument as a 3-D modular acoustic velocity sensor with manufacturability as well as measurement excellence the development target. Electronically, BASS was nearly ready for this transition, simply requiring updating of obsolete components and miniaturization through migration from DIP to surface mount packages. Several stages of board condensation occurred during the period of development, simplifying the miniaturization task. This resulted from improvements in FETs permitting elimination of the 12 volt logic level (FETs can now be switched with 5 volt levels where 12 volts was required formerly) and four layer boards that increased component density. But the real problem was the optimization of the sensor head, the flow intrusive element.

An excellent acoustic current meter has good cosine response in the vertical as well as in the horizontal. This means that flow at speed s measured with an acoustic axis at an angle θ to the flow direction should give a reading of $s*\cos(\theta)$ or, more generally, the resolved velocity vector from an array of acoustic axes should reflect the angle of the flow direction with respect to the principal coordinate axes of the sensor - u, v, and w - with $u=s*\cos(\theta)*\cos(\varphi)$, $v=s*\sin(\theta)*\cos(\varphi)$, and $w=s*\sin(\varphi)$ where φ is the angle of elevation of the flow direction from the horizontal plane and θ is the angle of the projection of the flow direction on the horizontal plane from the u direction. The $\cos(\varphi)$ part is the vertical cosine response. This is generally hard for a sensor to achieve if it has been optimized to have a good horizontal cosine response, the $\cos(\theta)$ part. To make a commercial instrument with wide utility, good response to both planes of rotation are desirable. Furthermore, the sensor should be free of cabling problems (zero offset dependent on cable dressing) and should be readily manufacturable. This seemed to be the place to start the development effort. The last well characterized current meter was the Davis-Weller VMCM and a commercial current meter to replace it should have equally well characterized response. Small, free of flow noise, cable tension carrying, robust, free of fouling, water proof, pressure insensitive, temperature insensitive, uv insensitive, and cheap were all characteristics desired if possible as well.

The freedom from sensitivity to cable dressing mandated that the conductors be buried in the sensor itself and potted through to the instrument housing. Mooring cable tension carrying required that a cage surround the sensor to carry tension or that the sensor have a tension carrying member pass through the center. Most of the other desired properties could be achieved by having the sensor injected plastic but there were stiffness constraints that were uncertain without metal or at least glass or graphite fiber in part of the sensor. While these constraints suggested a central strut of metal with injected plastic for the transducer supports, the requirement of good vertical cosine response meant that the transducers must be very small or the supports faired or both. The MAVS I prototype sensor is faired along the direction of the acoustic axis since only in that direction of flow is there a flow distortion problem. The transducers are small, 5 mm diameter for MAVS I vs 10 mm for BASS. The path length is 9.5 cm vs 15 cm for BASS. The transducers are glued into the plastic injected rings and the wires are run along the ring and covered with the same material as the transducers. There is still some problem getting a pressure resisting and water proof seal where the wires enter the central steel strut. But the vertical cosine response is good, within 15 % of perfect at its worst near 45º elevation. The cost of this benefit is that at all angles of flow, the wake of the sensor is greater because of the projected area of the fairing. This wake increases the flow noise fourfold over BASS at every speed. The cost of a cable tension carrying sensor with good vertical cosine response is a degradation of turbulence sensing capability.

The next target, after manufacturability of the sensor, was cost. Cost scales surprisingly well with volume. Since complexity remains as size is reduced, one might think that cost would remain fixed but it isn't so in commercial devices at large volumes of production. Parts costs decrease somewhat as component size decreases to a point. But the savings really result from handling, stocking, shipping, deployment, and lab bench costs where they scale with volume (or sometimes with weight). Logistics are a dominant part of the cost of medium scales of production and these are reduced if the devices are small. So miniaturizing MAVS was a target. Presently, the MAVS I design using standard BASS electronic circuits with DIP ICs is on a single four layer circuit card 11 1/2" long by 3 1/4" wide and there are few wire connections, only those to the transducers and the outside world. Construction of the board is about equal in difficulty to one of the harder boards of conventional BASS. Circuit costs are thus modest. Housing costs are again proportional to volume and the volume is 1/4 that of a conventional BASS (1/8 that of an earlier BASS). Closure of the housing and integration of the sensor to the housing is a concern and simple, corrosion free endcap retainers have been sought. Plastic may be the housing of choice for freedom from the requirement for surface treatment but aluminum is also satisfactory.

All prototype instruments and most limited production instruments require the user to be trained. In fact, the single major cost in such instruments is customer support by engineers. Part of this is customizing, part is training, and part is hand holding through early stages of familiarization with the instrument. Integrated circuits at \$1.00 each are complex but have no customer support, only a data sheet. To reduce or eliminate the major cost of engineering support and customer service, the instrument must be simply described with a data sheet and must be primitive in its operation with fewer bells and whistles than a Timex watch. This means that the program running in MAVS must be what nearly every user can live with and must be easy to understand. The modular concept prevails here. A module can be used in a more complex system that is customized to the users need but itself is primitive. MAVS may simply spit out four digital words representing u, v, w, and θ. Alternatively, a second version may spit out five digital words including φ (tiltmeter added). This could be done every time a line to the MAVS is strobed or could be continuous at 10 Hz for the time the line is held high. Battery and logger are not included and this simplifies the engineering support. Power is low and tolerant, 5 ma at 14 to 25 volts while measuring, 2 ma standby, 0 ma if power is removed and comes on line 2 seconds after power is restored. This is almost so simple that no phone number need be supplied, just like an IC.

The part that is furthest from the academic subject of instrumentation is marketing. Yet there is a transition in manufacturing technique and thus cost between the 100 unit batch and the 1000 unit batch. I suspect there are other breaks near 100,000 and 10 M but I don't expect to learn about them. To move to the 1000 unit batch, marketing must be done. This involves confidence building, exposure, preparation of the marketplace, salesmen, advertising, and careful pricing. This is so far from most academics' experience that a commercial partner or licensee is desirable. Confidence is built by getting prototypes into the hands of knowledgeable and critical users who will certify a good instrument to their colleagues. Exposure requires that user communities see results derived from the instrument. Trade shows, technical magazines, and international expositions are opportunities to prepare the marketplace for a new product before it is being manufactured in commercial quantities. MAVS I, a commercial prototype is being shown at the General Oceanics booth at Oceanology International in Singapore in May 1997 and is being offered in response to a request for bid by a group of Korean customers who want a direct reading acoustic current meter. This is hoped to prepare the marketplace. G.O. has an international sales network so that when interest is generated in one sector of the market, the instrument can be sold in other markets soon after. As orders permit the batches to become larger, the cost may (or may not without care) drop and the price can be reduced. At this point, I will have achieved my goal of providing a new measurement capability, modular current sensors by the sixpack. Then benthic storms can be tracked as weather is tracked on land. Drifting instruments can measure turbulence as they measure temperature now. Nets, AUVs, benthic cameras can be equipped with current sensors as easily as temperature or pressure sensors. Inlets, streams, sewers, even large tanks can be instrumented with flow sensors to monitor fluid movement. Sloshing in aircraft fuel tanks can be detected. A good current meter is just over the horizon.

Lecture 16: Microprocessors, Embedded Processors, Modern Sensing Systems

Digital electronics became common in underwater sensing systems about 1970. The technology was CMOS to achieve the low power that autonomous, battery powered operation required. Complimentary Metal-Oxide Semiconductors were an odd corner of digital circuitry then because they were slow. But they had no quiescent power and only drew charge from the power source when they made a transition. At that time, computers used TTL or DTL logic but drew current even when there were no transitions. RCA devised a line of logic circuits with designations like CD4000 and they sort of mimicked what was available in TTL up to about CD4050, but not exactly. The arrangement of the pins was slightly different. After about 4050 the CMOS engineers decided to make plug in replacements for the TTL equivalents. At that time, RCA made a CMOS microprocessor, the 1802, and since it was entirely CMOS, at low clock speeds, the power was very low. NASA chose it for space missions. Even when there were other more capable microprocessors available at low power a decade later, they continued to use the 1802 based on their long experience with it. So space probes out beyond Saturn are running code on the 1802 or COSMAC as it was called.

At 12 volts, CMOS is limited to about 5 MHz and at 5 volts, a more acceptable level since it is compatible with TTL, the limit is about 2 MHz. While this is not an impossible limit for a uP, (the 1802 was customarily run at 1.2288 MHz, a frequency that provided standard UART baud rates by binary division) it did cause problems for interfaces to sensors. Counters were unable to keep up with high frequency devices, even 1 MHz was too fast for ripple counters. The development of finer masks in the semiconductor industry reduced the capacitance of the gates in CMOS devices and for awhile, Fairchild, a late entry to the CMOS industry, had faster CMOS, typically 5 MHz at 5 volts. But Fairchild ceased production and Harris bought RCA's CMOS product line. And finally, high speed CMOS, a CMOS version of the TTL line replaced most enhancements of CMOS but with the TTL standard pin out. This series, 74HC00 and up is typically 12 MHz at 5 volts. Since

Lecture 17: Economics of Instrumentation

There is a sequence endlessly repeated in science of improvement in observational capability followed by new observations followed by development of new models requiring better observations to test them. One link in this sequence is development of instrumentation. This is often expensive and at least one step removed from the direct goal of a science program manager. In oceanography, instrument development has ridden the coattails of science. If a science program required an observation that could not be made because no technique existed, then an instrument development program might be permitted. In large programs there might be a general recognition that some instrument development would be appropriate and a sum set aside for it.

Rarely has an instrument been developed in the science sector because it would save money. This principle, which is dominant in the private sector, is rarely considered in science. I believe this is short sighted and should be corrected. However a realistic economic model is needed to assess the costs of developing a new instrument versus some alternative action.

Some examples may be appropriate for this discussion. The first is the Fast Profiler, an alternative to the slower winch lowered profiler. There is the direct development cost, the risk of technical or economic failure, the production costs, and the training and operating costs to be balanced against the savings in ship time. There are then the alternatives to the Fast Profiler such as a constant speed winch, streamlined profiler on a wire, expendable telemetering profilers, remote sensing. An analysis of ship supported observations versus aircraft and satellite observations could be included. It is easy to see why one tries to make a case for instrument development based on a need for the unique measurement that the new instrument can make.

Another example is a bigger tape recorder. Such a development might be economically pursued as a direct research effort. In practice it is being developed as part of many systems independently. Again an economic analysis should concern the development costs, production costs, and training and operating costs to be balanced against the costs of doing it many times as a part of other projects. It can be assumed that the need for a bigger recorder can be justified on absolute scientific need. But in fact there is a cost benefit relation to the size of the data set that is recovered. An alternative to a large data set is a more intelligently selected data set but this implies more development costs for the processing algorithms and tests of the algorithms.

A third example is a bottom mounted acoustic Doppler velocity profiler for shelf studies. In fact such an instrument was developed commercially and is now available. This affects other velocity profiling programs and the economic decision might well be how much can be saved by a single instrument of high cost over an array of lower cost spot current meter sensors.

There are also some examples of instrument developments that did not ride on the coattails of science in oceanography. Most recently the NASA funded RELAYS instrument system has been funded without any particular user or problem in mind. NASA has used this technology development procedure successfully in its other programs and is at home with it. RELAYS will collect oceanographic data from moorings, drifters, and its own sensors and transmit them by satellite to the users. National cost benefit analysis may be required to demonstrate the economic advantage of this system in the next twenty years over not having it.

Construction of new research vessels also is not specifically targeted for a single scientific task. The magnitude of the cost and its general benefit to the community frees us from the need to tie it to a scientific problem. However here too an economic evaluation is appropriate and rarely done. For example there is now a plan to use the Glomar Explorer as a scientific research vessel that could remain on station for 6 months exchanging scientific parties and crew by air. The cost of the Explorer is something like one-third the cost of the rest of the oceanographic academic research fleet. An economic analysis might reveal that although it is attractive to have this new capability, it is not as effective as keeping the existing capability. Then again it might show that the benefits of occupying a station for this length of time is so great that it is a saving over conventional ships.