Acoustical Oceanography and Shallow Water Acoustics

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ABSTRACT

In this paper, we review some recent new results in shallow, coastal waters from both ocean acoustics (the study of how sound propagates and scatters in the ocean) and acoustical oceanography (the study of ocean processes using acoustics as a tool).

I. INTRODUCTION

Shallow water, in the context of this paper, is operationally defined as 10m-500m depth, i.e. from just outside the surf zone to just beyond the continental shelfbreak. Acoustically, we will mainly consider the low frequency band of 10 Hz to 1500 Hz, in that this is the band in which sound travels the furthest. (An optimal frequency of a few hundred Hz can often be found, where the decrease of the water column attenuation with decreasing frequency is countered by increasing bottom attenuation with decreasing frequency (Jensen et al, 1993).) This operational definition obviously excludes some interesting frequencies and oceanographic phenomena, but it is hard within a brief paper to discuss all possibilities.

In doing this overview, we will look at bio-geo-chemico-physico-acoustico ocean science and technology, with the caveat that it must interact with acoustics. There is also a distinction we should keep in mind between acoustics applications (e.g. Navy sonar applications, acoustic communications, mineral and resource exploration, etc.) and ocean science (e.g. physical oceanography, marine geophysics, and new ocean acoustics). Before proceeding, however, we should perhaps rule out marine chemistry, in that the one new chemical effect projected for ocean acoustics, decreased sound attenuation due to ocean acidification, has recently been shown by detailed calculations not to be acoustically significant (Duda, 2009). No other new ocean chemistry related effects have been postulated that interact appreciably with acoustics.

II. OCEAN ACOUSTICS

Let us begin our detailed topical looks with the area of ocean acoustics. One might initially think that there are no new ocean acoustics effects to be found in shallow water, in that this technical area has been heavily worked on since WWII. Indeed, Chaim Pekeris' landmark paper on the nature of shallow water modal propagation dates from 1948 (Pekeris, 1948), and was based in large part on research from the war era. However, there are still new acoustics effects to be found. Recently, there have been a number of significant new findings in shallow water acoustics due to sound interacting with "coherent oceanographic and bottom features." In the 1995 Shallow Water Acoustic Random Medium (SWARM) experiment, observations were made by Badiey (Badiey et al., 2002) of fully 3-D ducting of sound between nonlinear internal waves (solitons) on the continental shelf. This large acoustic effect (6-8 dB observed acoustic intensity fluctuations) had been predicted both by theory (Katznelson and Pereselkov, 2000) and by computer simulation (Finette and Oba, 2003), but not observed. A conversation at an Acoustical Society of America meeting between theorist Boris Katznelson and experimentalist Mohsen Badiey brought the unexplained observation of the effect and the theory together, one of the more useful byproducts of our scientific meetings. More recently, acoustic ducting effects by curved nonlinear internal waves were predicted by Lynch et al (2010) (see Fig. 1), and subsequently have been observed by Reeder et al (manuscript in review) in the South China Sea. Another recently observed 3-D shallow water acoustics effect is the so called "horizontal Lloyd's Mirror", which was predicted theoretically (Lynch et al, 2006) and very recently seen in the Shallow Water 2006 (SW06) experimental data (Badiey et al, 2010). Other 3-D acoustics effects due to crossing internal waves, truncated internal waves, and acoustic tunneling and coupling through internal waves have also been predicted, and it is felt that it is only a matter of time until they are observed, now that we know what to look for.

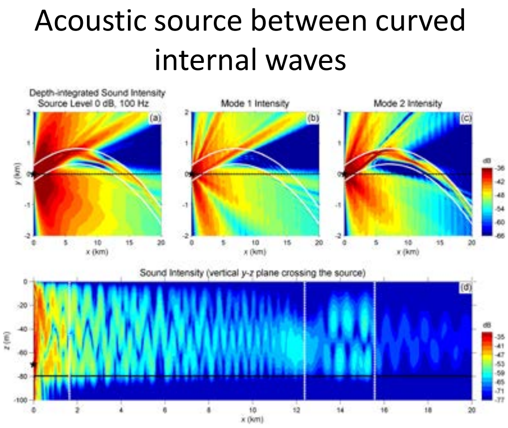

Figure 1. Top panels show top view of acoustic energy propagating through curved internal waves. Bottom panel shows side view, and distinct modal structure.

Another prediction of 3-D shallow water acoustic effects due to coherent oceanography is due to Shmelev (Lynch et al, 2010), who has modeled with a fully 3-D parabolic equation what the effects of long bottom sediment ripples would be on the acoustic field. The ripples act in a very similar fashion to the internal waves, trapping sound between them, as can be seen in Figure 2. The interest here is that this is also a very strong ducting effect due to a common oceanographic (seabed) feature. Eventually observing this effect should be simple enough, as the ripples are stationary over acoustic transmission times, and moreover are easy to map and see via echosounders and sidescan sonars.

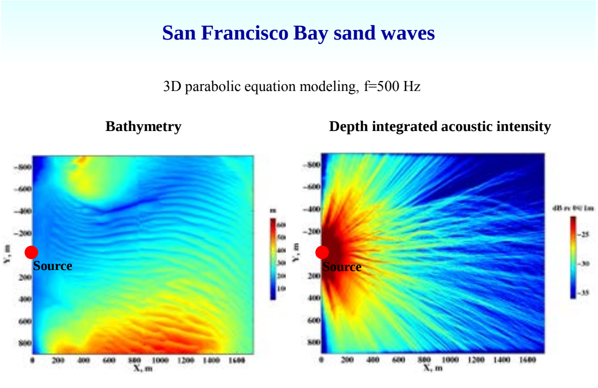

Figure 2. Left hand panel shows sediment ripples in San Francisco Bay, CA. Right hand panel shows 3-D parabolic equation model of the acoustic effects of these sand ripples at 500 Hz, displaying appreciable acoustic ducting.

A number of other possible ducting effects can be discussed, due to fronts, eddies, surface waves, etc., but hopefully the few discussed above should give the reader a flavor for these effects.

III. MARINE BIOLOGY

One of the most active areas of marine biology in shallow water is marine mammal studies. Since many marine mammals vocalize, their study via acoustics is quite effective, and also legal. (Use of active acoustic sources to study marine mammals is generally frowned upon nowadays.) Given our frequency range of prime interest, larger marine mammals, i.e. whales, will be the main focus of our studies.

Passive tracking of vocalizing whales is of great interest to marine biologists, and the technology for doing so using multiple receivers and time delay cross correlation processing is well developed. Such systems, usually consisting of three or more non-colinear receiver buoys/moorings, give excellent x-y plane tracks of the whales they hear.

Recently, Lin et al and Newhall et al (Journal of the Acoustical Society of America, in press) have extended the technology that can be used for such tracking to a vertical and horizontal line array combination (VLA-HLA). Such an instrument is deployed at a single location, and can track marine mammals in full 3-D as well as in time. By using acoustic back propagation of modes (or rays), horizontal beamforming, and vertical amplitude ratios of modes (or rays), one can get a fully 3-D spatial localization estimate for a vocalizing animal (see Fig.3). The correlation of the animals tracks with other animals, the prey fields, the physical oceanography, the bathymetry, etc is of great scientific interest. The depth (dive) profile is also of much interest. We note that this technique, while it can be made cheaply and easily enough on the instrumental side might not be so attractive to biologists who are not working directly with ocean acousticians, as the back propagation, beamforming in shallow water, and mode/ray ratio techniques are actually rather complicated in technical detail, as opposed to cross correlation techniques, which are intuitive and easy to work with.

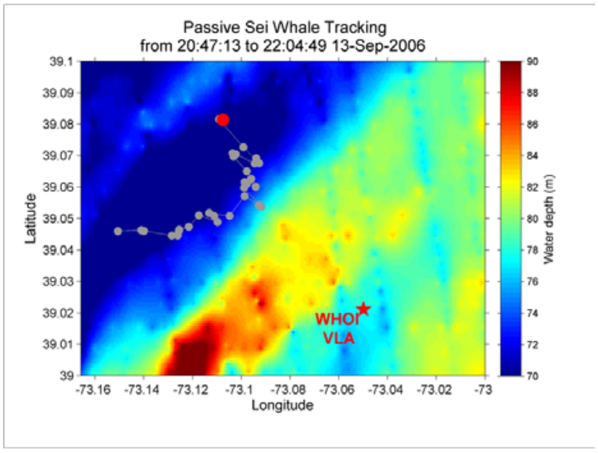

Figure 3. Result of passive tracking of a sei whale using vertical and horizontal arrays with backpropagation processing.

Besides marine mammals, fish can also be examined by relatively low frequency acoustics, especially fish with resonant swim bladders, as these tend to resonate at the 500 Hz – 3 kHz range. Presently, studies of fish schooling and its effect on low frequency acoustics is being pursued by using an acoustic source mounted on an autonomous underwater vehicle (AUV) that actually transits up to and through the fish school. The schools can be assembled artificially by a "fish attraction device" (FAD), and imaged experimentally by both cameras and sidescan sonars mounted on the AUV.

IV. PHYSICAL OCEANOGRAPHY

Perhaps a little controversially, I will claim that low frequency acoustics (50-1000 Hz) is not a very good tool for doing shallow water/coastal physical oceanography. It can be readily shown by an experimental design analysis (resolution and variance of the ocean estimate versus cost) that conventional oceanographic sensors give better results at lower cost than low frequency acoustics (e.g. tomography). Rather, for low frequency shallow water acoustics, one needs high quality oceanography *input* to create the soundspeed fields, from both measurements and models. Acoustics is a receptor of environmental information here, rather than a donor.

Physical oceanography data and models can presently provide 4-D realizations of the ocean soundspeed field down to around the M2 (12.42 hour principal lunar semidiurnal) internal tidal band, and to spatial scales of ~ ½ km. However acoustics, even low frequency acoustics, is sensitive to rapidly changing soundspeeds at all spatial scales, even a few meters, and so acousticians are asking oceanographers for models that go all the way down to space/time scales of meters and seconds. This will allow acousticians to capture the internal wave field, which has strong acoustic effects. Capturing a whole region down to such scales is very hard to do, obviously, whether it be from modeling or observation or a combination of the two. But one can nest fine scale oceanography models on top of large scale models, and indeed if this can be done with two-way "energy transfer" between the large and small scales, the results should be dynamically consistent and "true." Such work is being pursued at present, and should be of value to both the acoustics and physical oceanography communities.

In closing this section on oceanography, I should mention that tomography with mid –frequency acoustics (order 3-5 kHz) has found some use in shallow seas (see e.g. Yamoaka et al, 2002). Also, high frequency (hundreds of kilohertz to megahertz) imaging of internal waves and finestructure has produced some new and interesting insights (see, e.g. Tang et al, 2007).

V. MARINE GEOLOGY

There are two additional new areas of shallow water acoustics that are of great interest at present: 1) bottom surveying using acoustics and AUVs and 2) the 3-D acoustics of canyons and the continental slope.

AUV technology provides an amazing new subsurface platform for all manner of ocean science and technology instrumentation, and acoustic instrumentation is high on the list. Sidescan sonars, Acoustic Doppler Cureent Profilers, chirp sonars and acoustic communications systems already abound on these vehicles. More recently, we have looked into how low frequency sources at or near the bottom could be used in conjunction with AUVs carrying one or more hydrophones to measure bottom shear properties using Scholte waves. Scholte waves are fluid-solid interface waves that only can be generated by having source and receiver near the bottom, and which provide one with an estimate of the shear speed in the near bottom sediments. Since current AUVs can “fly” on the order of a meter above the bottom, they can actually sense such waves, and thus provide a new technology for shear measurement. In Fig. 4, we show a “Scholte wave peak” measured by Hankel transforming the received pressure versus range. The wavenumber location of this peak is a measure of the shear speed (Holmes et al, 2006).

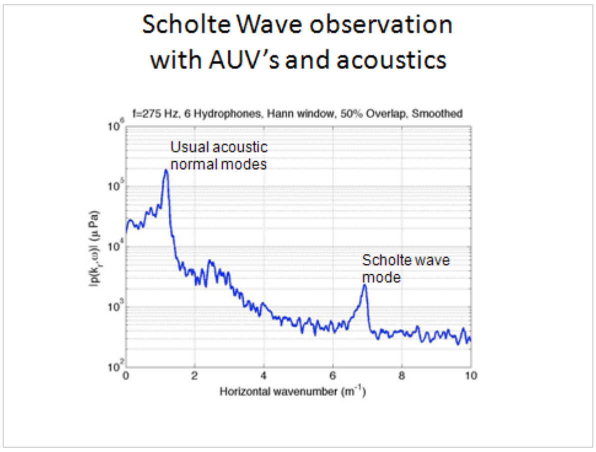

Figure 4. Normal acoustic trapped mode peaks in wavenumber, along with Scholte wave peak (in rhs of figure). This is data generated from a bottom source and a near bottom AUV listening to it.

Finally, there is the shallow to deep water transition zone to consider, i.e. the continental slope and the canyons that frequently cross cut it. These regions produce sideways bottom reflections, and so are acoustically interesting from that point of view. They are also of interest to geologists (e.g. the slopes have complex stratigraphy and the canyons are major sediment conduits), biologists (both the slope and canyons are highly populated areas for marine life), and physical oceanographer (the slopes often have large associated fronts, and the canyons also are active across shelf transport sites.)

Recently, Lin et al (private communication) have shown some very interesting along-canyon focusing of acoustic energy, as well as across-canyon cutoffs of sound, both in data and computer models. There are indications that there should be significant geological, as well as oceanographic and biologic, imprints on acoustics signals within canyons, and so there is growing interest in performing a larger scale community experiment on this exciting, yet challenging ocean feature.

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