HF Doppler Acoustic Imaging of the Ocean Surface and Interior

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Abstract. HF phased array Doppler sonar represents a new tool for obtaining Three-dimensional (r,q,t) images of the oceanic surface and interior velocity field. While the capabilities of the approach are unique, the design constraints are also unusual. Examples of both are presented in this work.

INTRODUCTION

With the advent of internally recording instruments in the 1960's, the process of ocean investigation through "time series analysis" began in earnest. A single time (or space) series represents a one-dimensional picture of the four-dimensional world, a solitary light flickering in the darkness. With the advent of satellite remote sensing and Doppler sonar in the 1970's, two-dimensional images became available. While the gains resulting from this advance (and the associated field of image processing) have been enormous, two-dimensional data represent a "tunnel-vision" view of reality. In situations where variability is non-homogeneous/non-stationary or strongly anisotropic, there is motivation to develop three-dimensional sensing systems.

We have developed a series of Phased Array Doppler Sonars (PADS) in an effort to obtain three-dimensional measurements of the oceanic velocity field. These sense the radial component of velocity in a planar sector as a function of range, azimuth and time. To date, the instruments have been used singly, to measure flows in arctic leads, ([1] Figure. 1), upper ocean Langmuir cells [2] and nearshore rip currents. With separated pairs of instruments, the same region can be probed from two perspectives, enabling resolution of two components of velocity (Figure.2). Using this technique x,y,t maps (movies) of the vertical component of vorticity in the nearshore off Duck, N.C. have been formed(Figure. 3). The purpose of this paper is to introduce the technology and to illustrate some of the design constraints unique to this form of HF acoustic remote sensing.

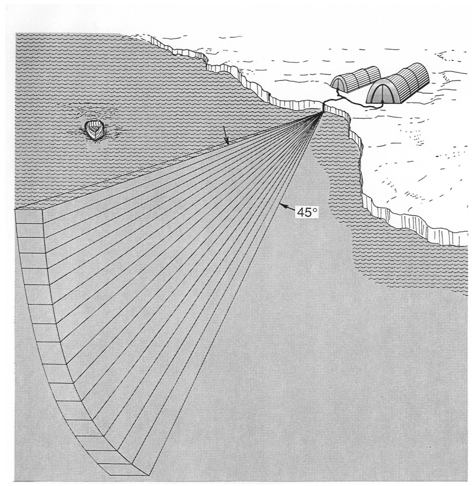

Figure 1. Schematic of the Arctic Leads Experiment (LEADEX) 1992 deployment of the sector scan sonar. The instrument was deployed with the measurement plane oriented vertically to image flows in the mixed layer and upper thermocline.

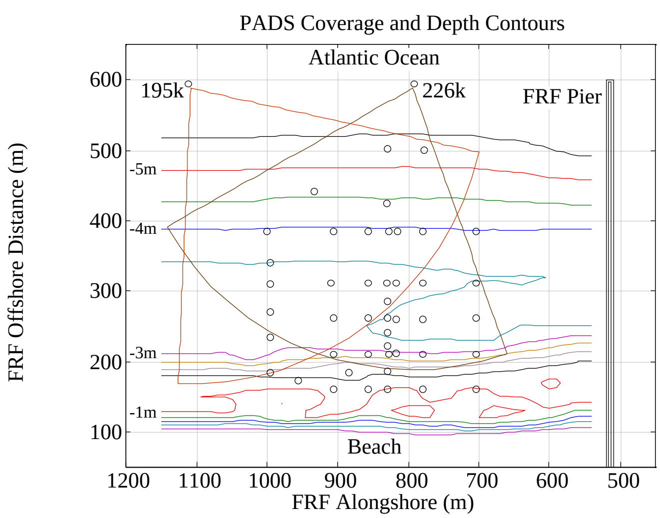

Figure 2. Schematic of the DUCK 97 nearshore deployment of two phased array Doppler sonars. Both components of horizontal velocity can be resolved in the region defined by the overlapping beams. Data were collected over a 60 day period through a variety of conditions.

BACKGROUND

Phased array technology is not new. Acoustic systems have long been used for fisheries research [3], bathymetric mapping [4] and collision avoidance. Jaffe, [5] has explored the feasibility of 4-d volume-time imaging systems. While low-frequency Doppler phased arrays have been developed for military work, application of this technology at ultrasonic frequencies is new.

Our initial system, developed in 1991-92 for arctic research, consisted of a 16-element phased array receiver that operated at 195 kHz with a 10 kHz bandwidth. Data were amplified, demodulated, and digitized within the receiver, and transmitted via optical fiber to the host computer. The transmitter was a single, curved face transducer that produces a 45^{o} by 2^{o} beam. In the arctic deployment (LEADEX), three repeats of a 13-bit Barker code were transmitted, providing a range resolution of 8 m. [6]

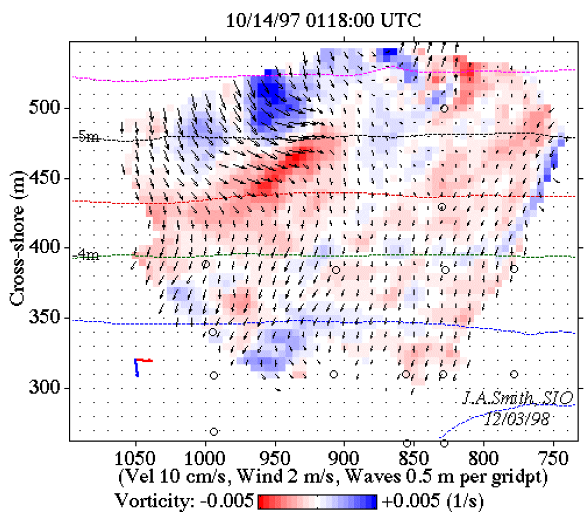

Figure 3. A planar map of the nearshore current field (arrows) at DUCK, as determined by the pair of crossed sonars. The vertical component of vorticity is indicated by the shading. This image represents one "frame" from a 3-d space-time movie of the velocity and vorticity fields.

The data were processed by a National Instruments 2305 Digital Signal Processing Card at a rate of 0.3 Mbyte s^{-1}. Twenty-eight independent beams were formed, spanning a 45^{o} sector. At 2-min intervals, average scattering intensity and radial velocity maps were produced. These were displayed by the host computer and recorded on optical disk.

Subsequent instruments have been developed at 195 and 240 kHz, operating over 90^o sectors. Dense 16 element arrays are used in these second-generation devices (Figure. 4).

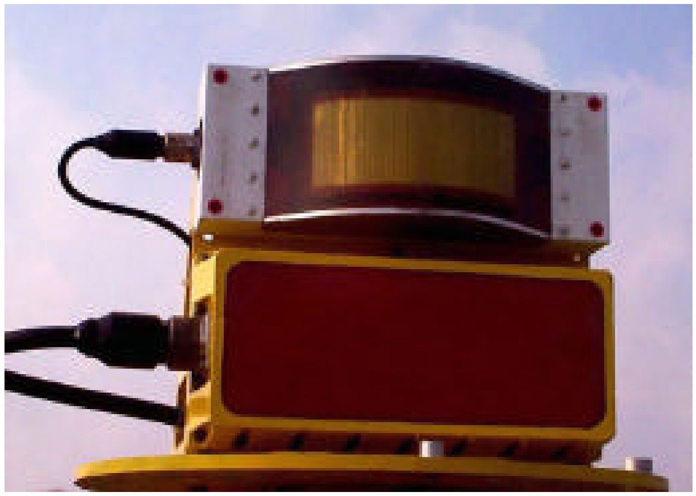

Figure 4. Second Generation Phased Array Doppler Sonar

DESIGN

There are significant technical challenges associated with the development of these PADS systems. From the assembly perspective, a 10^o phase error will result if an individual array element is mis-positioned by .04 cm. Such errors can critically affect beam-forming capability. In terms of data processing, the sonars now produce in excess of 1 Mbyte/s of echo information, steady state. This must be processed in real time with field transportable hardware. Analog challenges include the minimization of acoustic and electrical crosstalk and the matching of phase an amplitude response across the array.

Here we focus on the rather stringent demands placed on the system beam-forming and the resulting beam patterns associated with the volume-scattering application of PADS. Initially, sonar (and radar) systems were developed to detect discrete "targets". The magnitude of the main lobe of a sonar beam relative to its side lobes plays a significant role in the detection of isolated reflectors. If the contrast between main and side-lobe levels is great, false detections will be rare. In detection sonars, beam width is commonly indexed by the "half power point," the angle at which the beam pattern falls 3db below its peak value.

In volume scattering situations, a distributed cloud of targets is encountered. One wishes to detect signals from one region of the cloud while rejecting signals from the rest. Here, the volume of the main lobe relative to the volume in the collective side-lobes is the relevant parameter. This is a function of the shape and shading of a transducer, but NOT its size.

In dealing with multibeam reverberation sonars, one can envision a half-space uniformly populated with scatterers, except in some discrete sector.

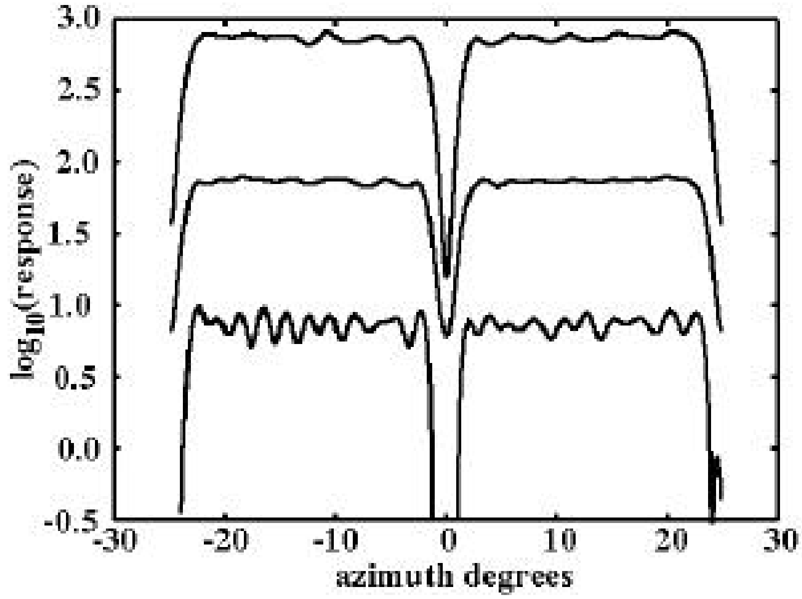

Figure 5. Theoretical "inverse beam patterns" for a 16 element sector scan sonar. A uniform cloud of scatters is assumed except in the region ± 2°in azimuth from broadside. Here an absence of scatters is posited. The array response is given for a Gaussian (top) triangular (middle) and rectangular shading of the receive array. The rectangular window best resolves the edges of the "hole". However the "depth" of the hole is only ~ 10 dB. With increased shading, leakage into the hole is reduced (middle, top) but the apparent width is reduced as well.

The ability of the sonar to image this "hole" in the scattering field, standing off side-lobe leakage from all other beam directions, is a meaningful measure of system performance.

Simulations of this ability are easily conducted (Figure. 5). The results, for a 16-element array, are sobering. A scattering void of width $\pm 2^o$ can be detected, given the geometry of our first generation system. However, an un-windowed array (Figure. 5, bottom) sees the void as only 10dB deep. The suggestion is that in each of the energetic look-directions, the receive energy will be 90% signal and 10% leakage noise. With increasing windowing (5 middle, top) the depth of the null response increases. However, the associated width decreases.

For detecting spatial variations in scattering strength, the performance as simulated is acceptable. Isolated hard targets will "leak" into neighboring bands, but the leakage can generally be identified. However, the precision in Doppler frequency estimates degrades rapidly as the signal to noise ratio falls below 10. For these systems, the "self-clutter" noise is proportional to the received signal strength. Leakage prevents the signal-to noise-ratio from significantly exceeding 10, even in the total absence of electronic or acoustic noise. The development of this technology is thus an uphill battle, with significant emphasis placed on array side-lobe suppression.

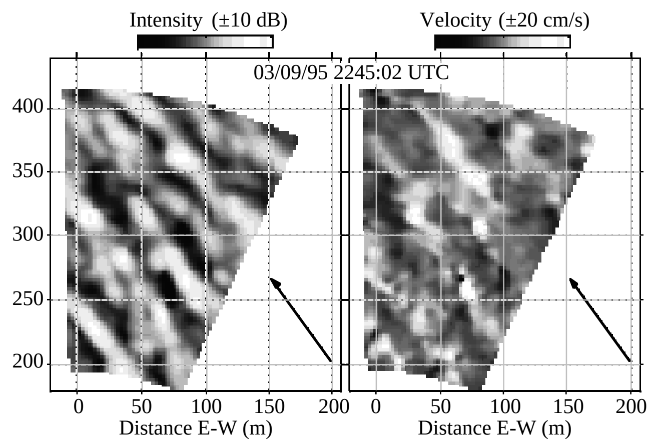

Figure 6. Open ocean observations of Langmuir cells as seen with the phased array. Acoustic intensity (left) is modulated by roughly an order of magnitude as sub surface bubbles (good reflectors) are collected in cell convergences. Corresponding patterns appear in the surface velocity field (right) only after the energetic surface wave motions are averaged out. The cells have a ~ 20 cm s^{-1} signal in this example.

SUMMARY

At present, the major successes of PADS have been in the observation of open-ocean Langmuir cells and near shore current and vorticity structure. It has been found that the spatial patterns of Langmuir cell currents are not aligned with the patterns in scattering strength which result from the collection of sub-surface bubbles in Langmuir convergences (Figure. 6). The Langmuir currents must be detected against a background of surface wave velocities with one or two orders of magnitude more variance. Only PADS technology enables detection of the weak current patterns in the presence of open ocean surface waves. As the processing capability of small computer/DSP cards increases there is significant room for improving the PADS concept. In particular, directionally coding the transmitted pulse will significantly improve angular discrimination, leading to more precise estimates of both velocity and position.

REFERENCES

1. R. Pinkel, M. Merrifield and H. Ramm, *J. Geophys. Res.*, 100(C3). 1995, pp. 4693-4705,.
2. J.A. Smith., *J. Geophys. Res.*, 1998, 92 pp 12,649-12,668..
3. R.B. Mitson, *IEE Proceedings*, 1984, 131-F, No. 3 pp 257-269.
4. C. de Moustier, C., *International Hydrographic Review*, *LXV* (2), 1988, pp 25-54.
5. J.S. Jaffe and P.M. Cassereau, J. *Acoustical Soc. Am*., 1988, 83-4, pp 1458-1464.
6. R. Pinkel and J.A. Smith, *J. Atmos. & Oceanic Technol*., 9, 1992, pp 149-163.