Effects of transducer geometry and beam spreading on acoustic Doppler velocity measurements near boundaries.

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Abstract: **The effects of acoustic beam directivity on the accuracy of acoustic Doppler current profiling are discussed. Traditionally, a transducer's main lobe is considered when analyzing Doppler profiler performance. However, excessively large secondary lobes dominate the overall transducer directivity near boundaries and limit profiler performance. Side-lobe suppression design is shown to improve the overall system directivity by almost 50%. Results of transducer directivity numerical modeling are in good agreement with laboratory calibrations. Practical implications of improved directivity for velocity profiling near boundaries are discussed.**

I. INTRODUCTION

When using acoustic Doppler instruments for velocity measurements near boundaries, special considerations must be taken with respect to the beam geometry, beam spreading and sidelobe interference, which may severely degrade the overall data quality, particularly in side-looking profiling applications when operating in shallow waters or when water level is changing. By shallow waters we refer to water depths that are less than 10% of the maximum nominal range for a particular Doppler profiler, (e.g., less than 10-m for a 500-kHz profiler, with a nominal range of 100-m).

Acoustic Doppler current measurement devices were first introduced as a means of measuring vessel speeds in the open ocean [1]. Traditionally, acoustic Doppler profilers (ADPs) have been successfully used in 'unconstrained' environments such as open ocean, deep water moorings, and ship installations. These systems utilize range gating [2] for deducing range away from the sensor (i.e., they sample echo returns at specified time intervals and assume that all of the sampled echoes arrive from the same sampling location). This technique generally requires specialized, highly directional transducers to minimize unwanted reflections and produce accurate and unbiased velocity measurements [2-4] with high spatial resolution.

Figure 1 shows a simplified geometry of different transducer beam widths. Typically, transducers used in Doppler profilers feature beam widths between 1° and 6° (depicted in dark blue), which allows precise positioning of the insonified volume, reduces spatial smearing with increasing range, and thereby yields profiles with higher spatial resolution. When wide beams are used (as ones used by a common echo sounder shown in light yellow in Figure 1) the Doppler profiling system cannot distinguish acoustic returns that arrive from different locations along the same wave front *rN* (denoted by A and B in Figure 1) therefore producing unwanted spatial averaging (or smearing). This smearing may cause velocity bias, in particular when operating near boundaries such as ocean/river bottom, vertical walls, banks, and man-made structures as the signals reflected these obstructions carry different velocity information compared to the speed of the water.

The recent transition of Doppler technology into shallow waters (with larger channel length to width ratios) places tougher constraints on transducer designs used in Doppler systems. This is due to the desire of users to measure in shallow to very shallow waters, operate in highly dynamic water levels and near boundaries, and to increase range and accuracy.

We describe the effects of different beam patterns on the maximum useful range of an acoustic Doppler velocity sensor, velocity precision and bias. Field data collected with transducers of different frequency and beam shapes are

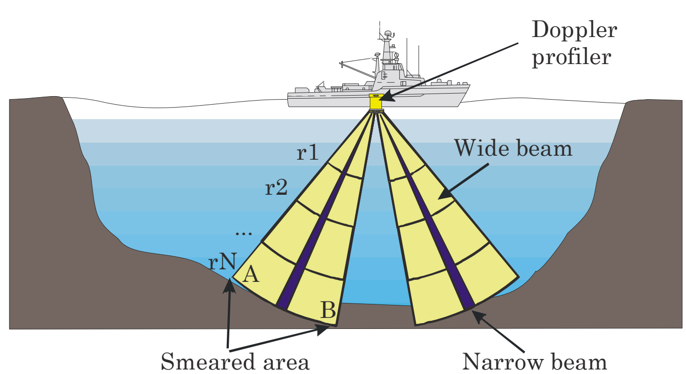

Figure 1: Diagram of acoustic Doppler current profiling from a vessel. Directional Doppler profiling transducers feature beam widths between 1° and 6° (depicted in dark blue), which allows precise positioning of the insonified volume. Wider beams (shown in light yellow) cause increasing spatial smearing with increasing range, which severely limits spatial resolution and induces potential velocity bias, compared to the narrow beam transducers.

examined and compared against analytical acoustic models.

Data analysis helps to quantify range reduction and minimize potential velocity bias due to boundary interference. Results of this analysis produce recommendations that help users to optimize Doppler velocity measurements in order to collect highest quality velocity profile data in shallow water environment.

II. Acoustic Directivity

Consider a disk transducer of diameter d (Figure 2) vibrating in thickness mode (that is when most of the transducer motion occurs along z-axis) at a frequency F_0. The radiated acoustic pressure field at any point in space $p(r,\theta,\phi)$ is a superposition of contributions from individual elements on the transducer surface and can be expressed as [5]

$$p(r,\theta) \propto \frac{1}{R}\int_S \exp\left[-ikr_0 \sin\theta \cos(\phi-\phi_0)\right] dS \qquad (1)$$

where k is the acoustic wavenumber defined as $k = 2\pi F_0/C$, and C is the speed of sound. Although most of the sound energy travels along the z axis, some of the energy diverges away from the main direction (θ=0), because not all of the individual vibrating elements dS on the transducer surface radiate sound coherently with each other. This causes phase mismatch between different sound contributions and leads the energy transfer to the off-main axis direction of wave propagation, thereby producing beam spread.

Directivity of the transducer $D(\theta)$ is defined as the ratio of pressure at a point (r,θ) to the pressure at the main axis θ=0:

$$D(\theta) = p(r,\theta)/p(r,\theta=0) \qquad (2)$$

Simplifying Eq. 1 $D(\theta)$ is expressed as

$$D(\theta) = \frac{2}{\pi}\int_0^{\pi} \cos\left(\xi\cos\phi\right)\sin^2\phi\, d\phi,\ \xi = ka\sin\theta \qquad (3)$$

For a circular piston source Eq 3 becomes [5]

$$D(\theta) = 2J_1(ka\sin\theta)/ka\sin\theta \qquad (4)$$

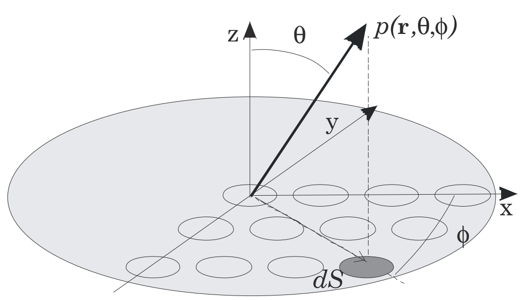

Figure 2: Geometry used for computing directivity pattern using a finite element numerical model. The overall pressure field is computed as a superposition of contributions from individual elements on the transducer face (x-y plane). Adapted after [5].

where J_1 is the cylindrical Bessel Function of the first kind [6].

Commonly in acoustic industry, the central lobe (main beam) width is measured at half power level (3dB). While this measure (rooted in the deep water naval applications) is appropriate for sonar performance evaluation in the open ocean, this may not be the most appropriate indicator of the effective beam width in the new realm of shallow water applications. For a circular piston transducer of a diameter d operating at acoustic frequency of F_0 the main lobe width is obtained approximating Eq. 4 [6] as:

$$\sin(\theta_{main}) = 0.51\lambda/d, \qquad (5)$$

where λ is acoustic wavelength defined as $\lambda = 2\pi/k$. Location of the first side lobe corresponds to the angle at which the sound wave is 180° out of phase with the central lobe:

$$\sin(\theta_{L1}) = 1.6\lambda/d\ . \qquad (6)$$

III. Beamforming

Directivity $D(\theta)$ defined in Eq (2) can be expressed using the amplitude-phase distribution $g(x,y)$ as [5]

$$D(\theta) = \int g(x)\exp\left(ikx\sin\theta\right)dx\,. \qquad (7)$$

By manipulating the aperture function g the phase and amplitude contributions from each surface transducer element dS (Figure 1), produce the desired beam pattern via beamforming. There are two primary techniques that have been traditionally employed to alter beam patterns: amplitude shading and phase shading [5]. A simple numerical model, where the overall beam directivity is computed as a

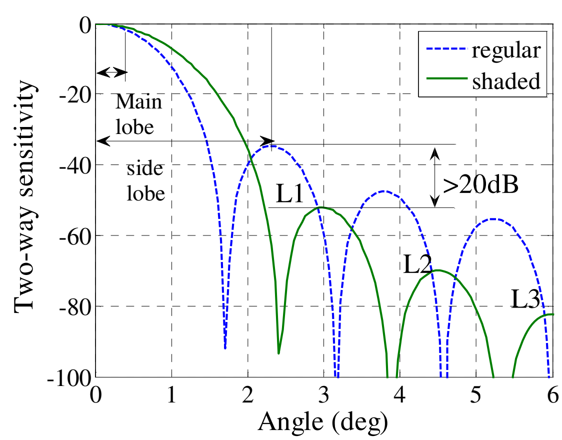

Figure 3: Modeled shaded transducer sensitivity demonstrating side lobe reduction (dashed line) when compared to a regular transducer design (solid line). First side lobe L1 is suppressed by >20dB (100 times); higher order side lobes (L2 and L3) are practically nonexistent. The overall transducer directivity is improved by ~60%, when referenced to -50dB level.

superposition of contributions from individual elements on the transducer surface (Figure 2), is used to simulate the effects of amplitude shading on transducer directivity. The transducer surface is segmented into small elements and integration in Eq 1 is approximated by summation. Since the pattern is symmetric with respect to the z-axis (Figure 2), the computed pressure field is a function of range r and off axis angle θ only. The results of modeling are shown in Figure 3.

Comparing the beam pattern for the regular transducer (solid line) with the shaded design (dashed line) we note a substantial reduction in the off-axis sensitivity outside the main lobe area. Sensitivity of the first side lobe (marked L1) is suppressed by more than 20 dB (100 times) compared to the conventional design. Higher order lobes (L2 and L3) are practically nonexistent (suppression of more than 70 dB). Although the width of the main lobe is slightly increased (by approximately 25%), the overall practical transducer directivity (which takes side lobes into account) is improved by more than 50% (when referenced to 50 dB suppression level) Figure 3.

Based on this analysis SonTek Doppler current profiling systems feature transducers that utilize proprietary side lobe suppression techniques, commonly known in the acoustic industry as shading [3,5].

IV. EXPERIMENTAL VERIFICATION

To verify model results, an independent laboratory characterization of transducer directivity was conducted at the TRANSDEC (TRANSDucer Evaluation Center), division of SPAWAR, San Diego, CA. The TRANSDEC facility is a controlled environment, low ambient noise, and conveniently accessible transducer calibration and underwater acoustic test facility. It consists of a large, man-made anechoic outdoor pool, 300 ft by 200 ft by 38 ft deep containing 6 million gallons of chemically treated fresh water, continuously circulated to maintain isothermal conditions, a bridge with control apparatus, and reference hydrophones.

Tests were conducted in January 2007 by TRANSDEC personnel. Two commercially available transducers, most commonly used in side-looking profiling applications, have been selected for these tests: a SonTek 120-mm diameter shaded beam 500-kHz transducer and a 100-mm 600-kHz conventional transducer. Both transducers were rotated throughout a full 360° circle in 0.16° increments while recording acoustic pressure at the reference hydrophone. Test data are presented in Figures 4 and 5. Figure 4 shows measured (solid line) and modeled (dashed line) beam patterns for the 500-kHz, 120-mm transducer. Modeled data were computed using the shading technique and formulation described by Eq (1) and Eq (7). Considering that the numerical model used for commuting beam patterns is rather simple, agreement between model and the laboratory data is remarkable. In particular the model is able to accurately predict the central lobe and the first side lobe, which are of the

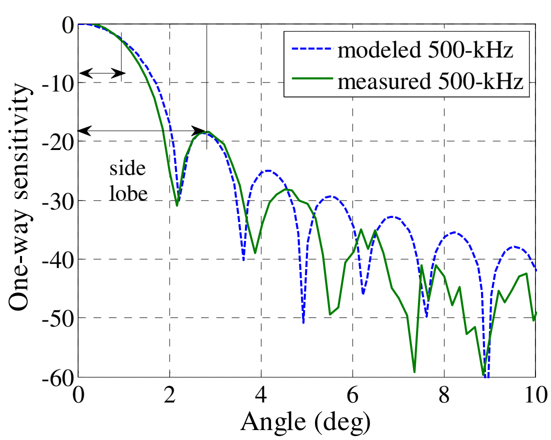

Figure 4: Comparison between modeled and measured shaded transducer beam patterns. Solid line corresponds to measurements collected at the TRANSDEC test facility, San Diego, CA. Dashed line depicts beam pattern computed using numerical model (Eq 3) with the following parameters: F_0=500-kHz, d=120 mm, C=1500 m/s.

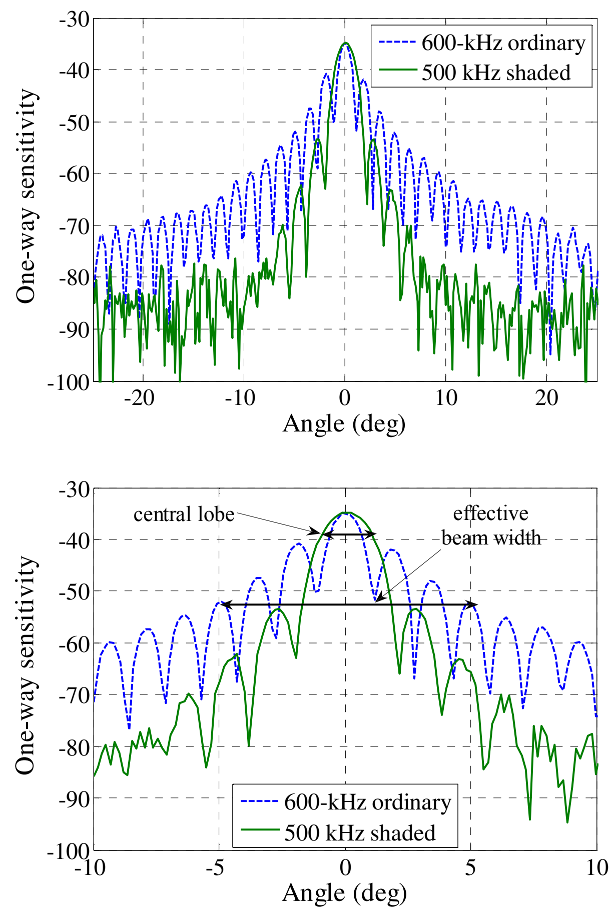

Figure 5: (Top) Comparison between transducer beam patterns featuring shaded (solid line) and ordinary (dashed line) designs. (Bottom) A close up section of the data that emphasizes the main lobe and the first side lobe sections of the beam pattern comparison. Effective beam width used in Doppler system performance evaluation in shallow waters must include side lobe into consideration to produce realistic results. Data were collected at the TRANSDEC facility, San Diego, CA. The diameter of the 600-kHz and 500-kHz is 101 mm and 120 mm respectively.

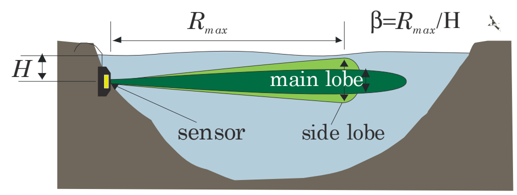

Figure 6: Diagram of a typical Doppler sensor installation in horizontal current profiling applications. R_{max} denoted maximum achieved horizontal profiling range, while H is the installation depth below mean water level. Dark and light green shapes depict center lobe and first transducer side lobe respectively.

most interest in practical applications. However, a more elaborate model is required in order to more accurately reproduce higher order lobes, which is outside the scope of this paper.

Comparison between the shaded and ordinary design beam pattern data collected in the laboratory (Figure 5) shows a dramatic decrease in the off-axis sensitivity. Although the center lobe of the 500-kHz design is slightly wider than the 600-kHz, the substantial reduction in the side lobe sensitivity (~28 dB two way) produces dramatic improvement on the overall directivity for the shaded design (solid line) compared to the ordinary transducer (dashed line) in Figure 5. Effective beam width used in Doppler system performance evaluation in shallow waters must include side lobes into consideration to produce realistic results.

V. Effects of Improved Directivity on Velocity Measurements

How do these transducer design improvements translate into better current profile measurements? In side-looking current profiling applications, a Doppler profiler is commonly mounted at some depth below the surface looking sideways (Figure 6). One of key operational parameters in horizontal profiling is horizontal aspect ratio defined the ratio of the maximum achieved horizontal range R_{max} to the sensor distance to the closest boundary (depth H below mean water level in example given in Figure 6):

$$\beta = R_{max} / H \tag{8}$$

While it is often desirable to collect current profiles over the maximum acoustically achievable system profiling range, this is not always possible in side-looking applications due to the acoustic signal reflections from the top and/or bottom boundaries that interfere with the reflections from the water. When performing Doppler velocity measurement near boundaries it is crucial to ensure that boundary reflections do not contaminate received signal as in most cases acoustic waves reflected from boundaries do not carry any Doppler shift. When these are averaged together with the returns from the water, the resultant velocity measurements will be biased low. To make matters worse boundary reflections (such as shown in Figure 9) are much stronger (30 to 50 dB or 3 to 5 orders of magnitude [3-4], [6]) than the signal from the surrounding water and they can in some cases totally dominate signal return.

Although main beam width has been commonly used in analysis of side-looking profiler applications a narrower main beam does not necessarily warrant better performance in shallow waters (better aspect ratio) as wider side lobes are the dominant source of boundary interference (Figure 7 top plane). Reduced side lobes improve overall directivity and increase

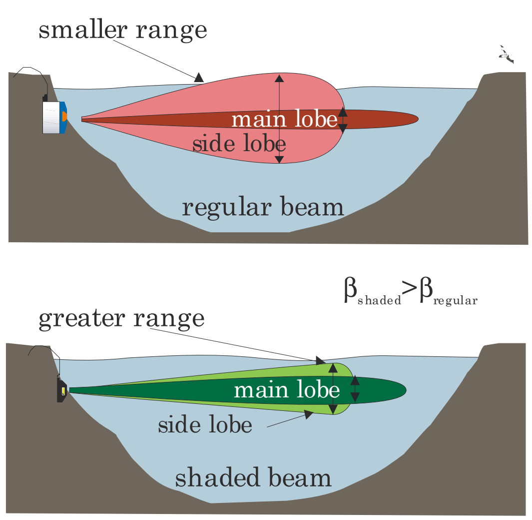

Figure 7: A sketch of transducer shading effects on the maximum achievable range in side-looking profiling application. Note that while the main lobe of the regular design is narrower, the width of the first side lobe is quite large in comparison (top plane). Conversely, the shaded transducer (bottom plane) shows a much narrower first side lobe, making its effective beam width for the horizontal application quite small in comparison. This is critical in achieving larger aspect ratio β.

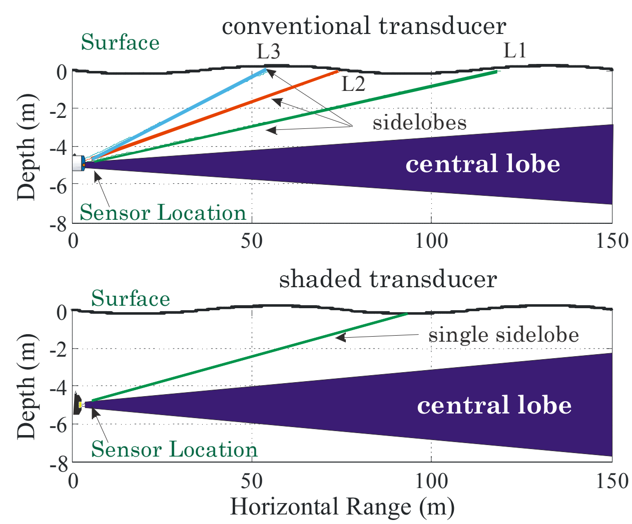

Figure 8: Effects of side lobe suppression on practical aspect ratio in horizontal current profiling. In a conventional design (top plane) the maximum profiling range is limited to approximately 55 m due to interference from the L3 side-lobe. The shaded design (bottom plane) achieves approximately 85 m horizontal range due to a much narrower beam pattern as a result of side lobe suppression. Practical aspect ratio is increased by more than 50%

useful aspect ratio (Figure 7, bottom plane).

Consider that conventional design features side lobes at 2.5°, 4° and 5.5° with suppression levels of 35, 48 and 53 dB respectively (Figure 3). A surface return of 32-dB or a bottom return of 50-dB stronger than signal from the water will contribute 50% of the energy to the total signal and will biased velocity measurements as boundary reflections carry zero Doppler frequency shift.

Figure 8 illustrates this in more detail. Side lobes of a conventional transducer (Figure 7 top) hit the surface at a range of ~55, 70, and 120 m respectively, thereby limiting the maximum practical range to ~55 m (maximum aspect ratio of 11). The shaded design (Figure 8 bottom plane) produces a single side lobe and achieves ~85 m maximum horizontal range. The aspect ratio (defined as a ratio of maximum range to sensor depth) in this case is increased by almost 70%. This improvement allows one to either achieve longer profiling ranges for the same sensor mounting depth or use shallower installations, thereby reducing the overall cost of data collection.

VI. Operational Considerations

When operating side-looking Doppler profilers proper system installation plays a critical role in collecting accurate measurements over the desired horizontal range. The most critical parameters to achieve the required maximum range are: (i) distance to the closest boundary (sensor depth *H*) and (ii) leveled installation (minimal tilt, pitch in particular). Since modern Doppler transducers feature extremely narrow beam patterns (1-5° including side lobes Figure 5) even a small amount of tilt (1°-3°) will cause boundary reflections and dramatically reduce useful operating range.

Although side lobe energy levels are very small, reflections from the opposite boundary may be much stronger than the return signal from the water, potentially affecting velocity measurements. To minimize potential interference, the end of the profiling range should not exceed 90% o the channel width (e.g., if a river is 100-m wide, the profiling range should not exceed 90 m).

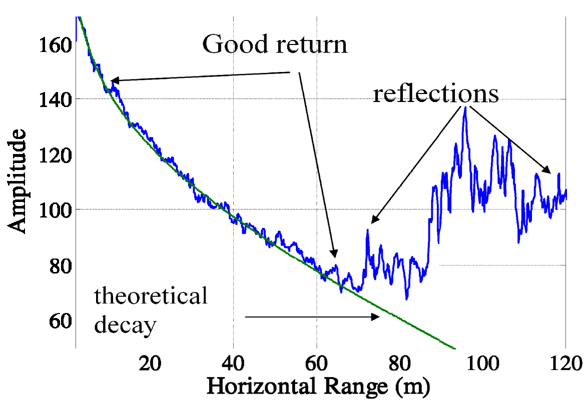

Figure 9: Acoustic signal strength profile as a function of range collected with a software utility BeamCheck. Echo return is free from reflections up to 70-m range and agrees well with the theoretical signal decay, computed according to [3]. Boundary reflections dominate signal return between 70m and 120m. The strongest reflection peak exceeds the ambient signal level by almost 40dB. Data were collected with a 500-kHz horizontal profiler.

To assist with system installation and with setting measurement volume location (profiling range) so as to avoid interference from boundaries (surface and bottom) SonTek horizontal profilers are equipped with a solid state tilt sensor and set of software tools (BeamCheck).

The BeamCheck module aids in performing a site survey that helps to determine the maximum effective range for a particular installation by collecting and average profiles of acoustic echo return (signal strength) as a function of range. An example of the data collected with a 500-kHz horizontal profiler is given in Figure 9. The signal strength profile is free of reflections up to 70-m range and agrees well with the theoretical signal decay computed according to [3]. Boundary reflections dominate signal return between 70m and 120m with the strongest reflection peak exceeding the ambient signal by almost 40dB.

When selecting values for the "begin" and "end" of the profiling range the following steps need to be performed: (1) Use BeamCheck to analyze signal strength curves; (2) Look for any deviations from the smooth amplitude decay; (3) Position profiling extent to avoid any boundary interference.

When determining the maximum measurement range of the horizontal profiling system, the aspect ratio (defined in Eq 7 and depicted in Figure 6), which relates measurement range to depth, must be considered as well. Aspect ratio (Figure 6) is the ratio of the horizontal measurement range to the vertical distance to the nearest boundary, either the surface or bottom. If operating in a river with varying depths, the aspect ratio at the shallowest part of the channel must be considered, and not just the aspect ratio at the end of the measurement volume. In general, the side-looking profiler will provide highly reliable data for aspect ratios up to 20-30. In some cases, it can provide reliable data at aspect ratios up to 40, but significant caution should be taken in these situations to avoid any interference from the boundary. It is critical, especially with larger aspect ratios, to ensure the system is installed level. If the beams are tilted up or down, this could cause the beams to hit the surface/bottom and may affect velocity data even at ranges where the aspect ratio is not particularly high. A careful site survey is critical to the proper setting of side-looking system operating parameters.

VII. Conclusions

Although most previous analysis of acoustic Doppler profilers has been focused on the central lobe width, side-lobe interference is a limiting factor in side-looking applications. A narrower central lobe (main beam) does not necessarily warrant better performance, particularly in terms of achievable range as the water gets shallower. Because boundary reflections are much stronger than the echoes from surrounding water they will bias the overall velocity measurement. Therefore, great care must be taken in ensuring reflection free operation in the presence of boundaries such as free surface, bottom, or opposite channel bank.

The overall beam directivity is a superposition of contributions from different elements (areas) on the transducer surface. Shaded transducer design, described in this paper, has been shown to substantially reduce side lobes (by more than 25-dB). Results of numerical modeling agree well with the independent laboratory tests. Improved directivity due to shading is a driving factor in maximizing the profiling range. Minimal side lobe interference from boundaries assures better accuracy as boundary reflections may bias the overall measurements.

Side lobe suppression is shown to increase maximum achievable horizontal profiling range and increase the useful aspect ratio of a side-looking Doppler profiler. Better transducer design allows one to achieve longer profiling range for the same mounting depth or to use s shallower mounting depth to achieve the same range. Proper installation and setup are equally important in ensuring the best data quality; software tools are available to help with this task.

Overall, the shaded transducer design offers more flexibility in installations, better overall performance, greater accuracy, longer range, and a more robust instrument operation in the presence of obstacles.

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