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Coherent refraction "noise" in multibeam data due to oceanographic turbulence

John E. Hughes Clarke

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Oceanographically driven variations in sound speed have long been understood to be a significant source of error in multibeam bathymetry ("smiles and frowns"). The usual assumption, however, is that the water mass changes relatively slowly so that around the vessel the lateral structure can be considered uniform (i.e. no horizontal gradients).
In the presence of significant vertical current shear, however, there may in fact be rapid horizontal variations in the sound speed structure, resulting in locally tilted and rapidly oscillating veloclines. Under these conditions, the sloping velocline will distort the refracted ray path. Because these slope variations are related to the width and height dimension of turbulence at the shear boundary, a false roughness is projected onto the seafloor reflecting that scale. While most sound speed sensitivity studies have focused on perturbations of strong veloclines, under such conditions the density gradient actually suppresses turbulence. In contrast, at weak veloclines the Richardson number may be low enough that turbulence is enhanced. Thus, somewhat counterintuitively, often these short-wavelength refraction-related distortions are actually amplified in weakly stratified watermasses.

Field examples of interface turbulence, visible in water column imaging, are shown to correlate well with the pattern of refraction-generated false seabed roughness.

Biographical Notes

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Abstract

Oceanographically driven variations in sound speed have long been understood to be a significant source of error in multibeam bathymetry ("smiles and frowns"). The usual assumption, however, is that the water mass changes relatively slowly so that around the vessel the lateral structure can be considered uniform (i.e. no horizontal gradients).

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While most sound speed sensitivity studies have focused on perturbations of strong veloclines, under such conditions the density gradient actually suppresses turbulence. In contrast, at weak veloclines the Richardson number may be low enough that turbulence is enhanced. Thus, somewhat counterintuitively, often these short-wavelength refraction-related distortions are actually amplified in weakly stratified watermasses.

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Introduction

Multibeam surveying involves properly accounting for the refracted ray paths of each beam through a heterogeneous ocean. To remove these distortions the sound speed structure has to be known. As the sound speed structure is primarily a result of vertical variations in the oceanography (temperature and salinity), a discrete profile is usually assumed to represent a horizontally stratified ocean. Over time and space, this stratification alters, but the normal assumption is that between the sampling points the change is so gradual, that the layers can be assumed to be locally horizontal.

That assumption is built into the ray trace (refraction) calculations. Refraction takes place relative to the normal to the interface, which for a level interface is vertical. All these assumptions, however, break down if the lateral variations in sound speed are significant. In that case a 3D ray trace model really needs to be used.

At this time, sound speed sampling typically takes place either by static profiling (generally at time scales of several hours), or by underway profiling (where sampling periods of as short as 5 minutes are feasible). With vessel speeds of 8 knots (4m/s) this results in a minimum along-track sampling distance of more than 30+ line km (static) or ~1.2 km (underway).

Oceanographic Processes that Perturb the Velocline

Superimposed on the pressure effect, the sound speed in the ocean is driven by temperature and salinity. Variations in either of these result in density changes. The two biggest external inputs of density contrast are solar heating and fresh water inflow, both acting at the surface. Due to the balance between mixing at the upper and lower interfaces (wind shear at the surface, bottom friction at the seabed) a peak gradient in density (the pycnocline) is often developed (a thermocline and/or halocline) at the boundary between the two mixed layers. That pycnocline is in turn usually the peak in the sound speed gradient (the velocline).

Once the density stratification is present, the flow field above and below the pycnocline can be quite different due to baroclinic processes. This results in shear between the two layers. That shear can affect the relief of the pycnocline in two end member ways:

A) - The shear can potentially induce mixing in the pycnocline in the form of billows (Fig. 1), commonly referred to as Kelvin Helmholtz (KH) waves (Thorpe, 1971). Those distortions can grow or die depending on the balance between the buoyancy (density gradient $d\rho/dz$) and the flow shear (du/dz). For high density gradients the turbulence is suppressed whereas for high shear, the turbulence can be enhanced. That balanced is parameterized by the gradient Richardson number Ri.

$$Ri = -\frac{g}{\rho}\frac{\frac{\partial\rho}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2}. \qquad (1)$$

KH waves can exist at many scales. Those recognized so far in the ocean tend to have wavelengths shorter than ~ 300m and amplitudes between 1-10m. Thus, there is no mechanical way that the resulting 3D sound speed structure can be directly sampled from an underway vessel. Therefore, if present, their distortion of the bathymetry is unavoidable.

Fig. 1: EM710 water column image of Kelvin Helmholtz waves. 100m high, 3.5km long section. From left to right, the waves are seen to grow, overturn and mix. Data extracted from section shown in Figure 7.

KH waves are generally short lived, as their onset results in intense mixing of the pycnocline region. In their wake, a layer of reduced density gradient remains and the sound speed structure becomes much more uniform again. Thus, from a surveying point of view, their influence on refraction will be limited to the periods when they are actively forming.

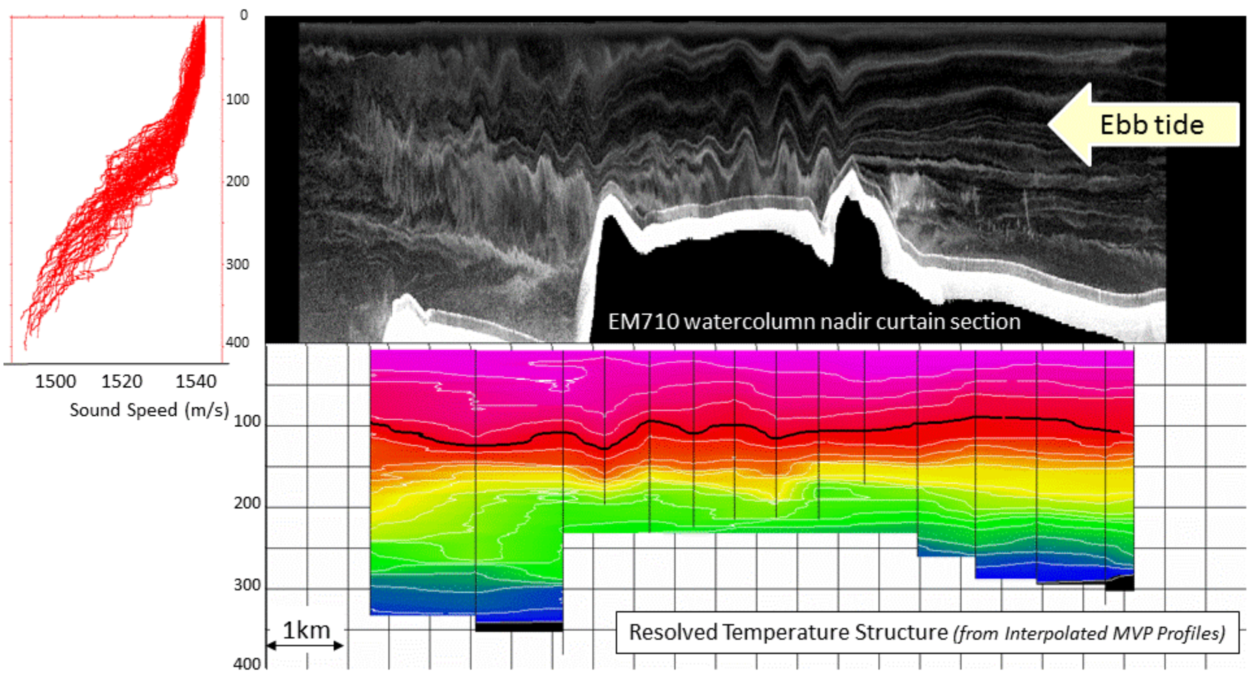

Fig. 2: Example of internal waves generated by flow over topography. Peak tidal currents of 2 knots (from right to left) are flowing over a sill in a constricted channel (Saipan-Tinian Channel, USNS Henson, 2011). The EM710 water column vertical section (top) indicates that the internal waves have a characteristic wavelength of about 500m and an amplitude of about 10-30m. At the same time an MVP300 was deployed to a depth of 200-300m at ~500-800m spacing. The resolved temperature results (lower image) clearly are unable to capture the structure of the internal waves (colour scale from 12°C to 30°C, 1°C Contours in white, 10°C contours in black).

B) - Even if turbulence is not enhanced, the pycnocline can still be perturbed, for example by flow over topography (e.g. Fig. 2). Under such conditions, higher flux in the upper layer can result in a depression in the pycnocline downstream of the feature (a lee wave). On cessation of the flow (e.g. the turn of the tide), that depression will then propagate as a wave along the pyncocline. These are called internal waves which generally start as a singular depression (a soliton). As the soliton propagates it breaks up into a train of depressions of decreasing wavelength towards the trailing edge of the wave packet (Apel et al., 1985). These internal waves, can have large amplitudes (5-50m) over wavelengths of several 100's of meters. They will propagate according to their phase speed, which is controlled by the density contrast at the interface and the thickness of the bounding layers. The wave period is defined by the Brunt Vaisala (buoyancy) frequency.

From a surveying point of view, internal waves are significant perturbations of the velocline, but will take place over length scales of several 100 meters or more and thus will manifest as a slowly (and generally smoothly) changing refraction artifact. They may not be apparent from the seabed roughness of a single pass. But they will show up in the overlap zone between adjacent swaths. Even though longer wavelength than KH billows, internal waves are still generally shorter than achievable MVP profile spacing (see example in Fig. 2). Thus they cannot be fully accounted for with existing sound speed sampling technology.

It is worth noting that both types of undulations, KH billows and internal waves, may be present at the same time. By itself, internal wave propagation need not be turbulent. As long as the amplitude is a small fraction of the layer depth (either upper or lower), the wave is unlikely to break. As the layers thin though, (e.g. as the depth reduces) the leading edge of the internal wave packet (the largest part of the soli-bore), may locally become turbulent. At that point billows may form and give rise to a shorter wavelength bathymetric artifacts.

Previous Work Modeling Refraction through Internal Waves

The first modelling of acoustic propagation through internal waves was undertaken in the late 1970's. The primary concern then was for long range sound propagation. One of the first refraction models was a 2D implementation by Baxter and Orr (1982) which represented the thermocline tilting either away or towards the source. This thus did not consider the out-of plane horizontal azimuth alterations of the ray path. That work demonstrated the convergence of ray paths through the convex upward segment of the wave and the divergent effect of the wave troughs (for a downward refracting velocline). It also recognized the shadowing effect, whereby the facet of the wave facing away from the source could lie in an acoustic shadow.

Following on from this, the horizontal refraction of sound modes (effectively depth averaged) was later modeled (Finette and Oba, 2003), and demonstrated the "ducting" of sound in azimuth when the propagation path was closely parallel to the wave crests. Recent extensions of this have considered the curved nature of the internal wave fronts (Lynch et al. ,2010).

As the propagation distances were over kilometers in water depths of just a few 100 meters, all of these models were concerned with rays that were generally less than 5 degrees off horizontal. In contrast, for multibeam refraction, the concern is ray paths that range from vertical (90 degrees elevation) to about 20 degrees off the horizontal. The first full 3D model of multibeam refraction through an undulating interface was Hamilton and Beaudoin (2010). The work herein represents an extension of that approach, considering a wider range of wavelengths, aspect and layer depths.

Acoustic Imaging of Rapidly Fluctuating Veloclines

As we cannot easily mechanically sample oceanographic variability at horizontal length scales less than ~1 km, we have to turn to indirect means of imaging. One of the most promising approaches is to use acoustics to map the 2D or 3D geometry of suspended scatterers in the water column. This approach has been well documented using single-beam sonars with a high gain (Proni and Apel, 1975).

As turbulence and zooplankton scattering is commonly enhanced around the pycnocline, a vertical section of acoustic volume scattering can potentially serve to depict the undulations of that interface. As multiple sub-parallel layers are often present, correlation between the observed structure and a synchronous sound speed profile can aid in defining where the main velocline is located.

From a single-beam sounder, only the wave cross-section projected along the ship track can be discriminated, as there is no knowledge of the actual wave azimuth and true wavelength. In contrast, using multibeam along and across-track scattering imagery, the full 3D depiction of the wave can be seen (Hughes Clarke, 2006). Furthermore, with narrow beams (1° rather than 10-20° for single beams), much better definition of the fine structure can be achieved.

Thus through a combination of sparse sound speed dips, together with the spatial inference from the 3D acoustic volume scattering, the amplitude, wavelength, azimuth and sound speed gradient can be inferred. Using this information one can now model the impact of ray tracing through this 3D structure, rather than the simplified horizontally-stratified assumption. Note that while this will allow one to predict the scale and appearance of these artifacts, this method is not capable of providing a quantitative real-time sound speed field.

Modelling Approach

Any real sound speed profile comprises continuous gradients. For the strongest gradient (normally associated with a thermocline or halocline), the ray path can be near-equivalently modeled by a discrete step representing the net change in sound speed over the narrow layer.

Following the approach of Hamilton and Beaudoin (2010), for the initial model described herein, the ocean is considered to consist of two iso-velocity layers separated by a discrete step. That step, however, occurs on an undulating surface. The ray is assumed to travel straight in the upper layer, refract at the tilted interface and then travel straight below that layer to the seabed.

Using this two layer model, six steps are computed for each beam:

1. The intercept of the straight ray path with the undulating surface.
2. The normal to the surface at the intercept point.
3. The upper layer beam vector relative to that tilted interface
4. The refracted beam vector relative to the interface
5. That refracted beam vector below the interface relative to the local level.
6. And the two-way travel time from the intercept point, using that refracted vector, to the actual flat seafloor.

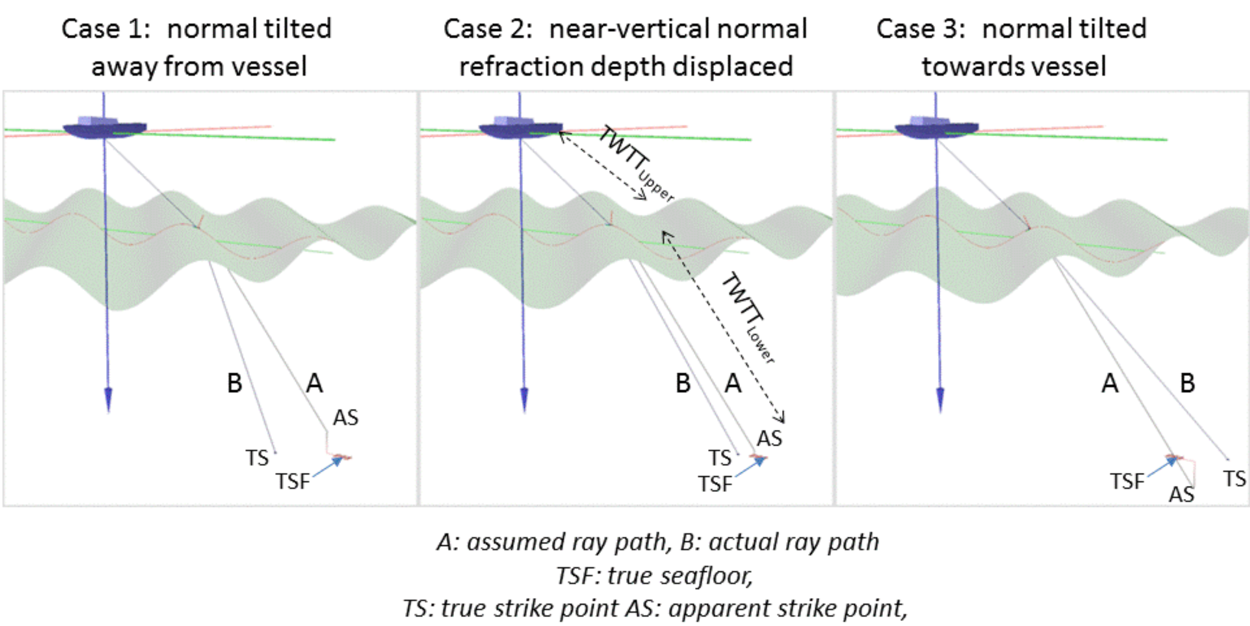

Fig. 3: showing the imaging geometry in the model. Three cases are presented. Case 1: in which the interface normal is tilted towards the sonar, case 3 when it is tilted away, and case 2 when the interface normal is vertical, but the interface is offset.

Knowing the sum of the actual travel time in the upper and lower layers, that travel time is now reused assuming a ray path through a flat velocline at the mean velocline depth. The time consumed in the upper layer is subtracted and the remaining time utilized along the conventionally refracted path in the lower layer. The resultant apparent bottom detection will lie along the assumed ray path (Fig. 3), but located either above or below the actual seafloor.

The error in depth (and horizontal position) between the ray refracted through the perturbed tilted interface and the assumed flat interface results from two contributions:

<u>The vertical displacement contribution</u>

Simply by shifting the velocline up (or down), even without tilting the interface (Fig. 3, case 2) more (or less) time is consumed in the lower layer. This results in an erroneous harmonic mean error at nadir (as no ray vector distortion). As the beam becomes more oblique, the actual interface intercept point moves towards (away) from the sonar with a raised (lowered) velocline. For the case of a downward refracting ray, this result in a closer (further away) location for the actual strike point. The closer strike range offsets the lower harmonic mean sound speed. At about 45 degrees, the depth error contribution of the two effects cancels out and in the far range the sense of the ray path error reverses as the shorter ray path is more significant than the reduced harmonic sound speed. This leads to the classic refraction smile geometry which is symmetrical on either side of nadir.

<u>The tilted interface contribution:</u>

Even if the velocline is not displaced vertically, by tilting it away from the horizontal, the vector in the lower layer will diverge from that assumed. For a nadir beam this always results in a longer ray path, but for oblique beams, it can generate all of shorter or longer ray paths depending on whether the tilt of the normal to the interface is toward the sonar (Fig 3, case 3) or away (Fig 3, case 1). If the tilt is along the shiptrack, the across-track ray inclination will remain the same, but the beam azimuth in the lower layer will shift fore or aft. For a given tilt, as the tilt azimuth is varied, beam strike locations will describe an ellipse around the assumed strike point.

Any real velocline undulation will contain components of both these contributions. Any undulation can be described by its aspect ratio (amplitude to wavelength). For the lower aspect ratio structures the interface slopes will be small and thus the displacement effect will dominate. The bathymetric error will thus be dominated by the absolute amplitude of the undulation. In contrast for the higher aspect ratio structures, the interface tilt contribution will start to dominate. Indeed, very small amplitude undulations which maintain a high aspect ratio (i.e. very short wavelength), can produce bathymetric anomalies equivalent to large amplitude regional displacements.

The surveyor thus needs to consider the aspect ratio and amplitude of the velocline perturbations. Over length scales of kilometers, the regional change in the water mass (e.g. shoaling of the velocline) will be dominated by the vertical displacement. Typical internal waves, represent intermediate aspect ratios (e.g. 10m over 500m) with peak interface tilts of a few degrees which start to contribute to the error (Hamilton and Beaudoin, 2010)..

The highest aspect ratios are those expected from Kelvin Helmholtz type billows. Strictly they are not simple sinusoidal structures and can contain overhanging relief (Fig 1) with shorter undulations superimposed. These can have aspect ratios approaching 1 and thus slopes comparable to and even exceeding the beam elevation angles are feasible. Of course, as the turbulence progresses, the undulating interface becomes homogenized through mixing and thus the gradients are reduced.

The net result is that billows, even though typically developed in weaker sound speed gradients (lower density gradient and therefore potentially lower Richardson number) than internal waves, have a more noticeable effect on short-wavelength bottom tracking noise. This false roughness, superimposed over the true short wavelength seabed relief is not a result of poor signal to noise in the sonar. Rather it is a direct result of coherent perturbations of the velocline.

The next two sections look at how the bathymetric anomalies relate to the velocline undulation geometry, first using the model and then looking at real data.

Model Results

Using the described model, a perturbed velocline was modeled at various azimuths, amplitudes, wavelengths and sound speed contrasts.

<u>Relationship of bathymetric anomaly to phase of wave:</u>

As the aspect of the undulation grows, the sampling of the wave becomes increasingly biased towards the inward facing side of the undulation (Fig 4B). How that impacts the bottom detection depends on the sense of the sound speed step. The following discussion will consider a drop in sound speed with depth (e.g.: warm water over cold). The described logic is reversed for an increase in sound speed.

As that inward face tilts towards the source, the amount of refraction is decreased. As a result the actual ray path is shallower and therefore the apparent depth is deeper. For those fewer solutions sampling the backside of the wave, the layer is tilted away and thus the refraction is more intense resulting in a shorter path and thus an apparent shoaller depth. As originally demonstrated by Baxter and Orr (1982), the ray paths cluster, converging as they pass through the convex crest of the wave and diverging around the concave trough of the wave. Without knowledge of the actual velocline structure, this results in alternating bands of erroneously shoal and deep soundings (Fig. 4C).

The asymmetry of the sampling of troughs and crests grows with beam obliquity (Fig. 4A). If the sound speed gradient is steep enough, there can even be shadow zones formed. The net result is an asymmetric distribution of bathymetric errors with a broad undulation due to the inward face and a shorter but larger magnitude anomaly due to the outward face of the wave (Fig. 4D).

In addition to the resulting bathymetric anomaly, the backscatter intensity is modulated due to the convergence and divergence of the ray paths. This is the same phenomenon responsible for the commonly noted intensity banding seen in sidescan imagery when looking through a thermocline.

While the distortions are both positive and negative, because more of the inward facing side of the wave is sampled than the outward facing, the average bias is actually downward (a net frown, Fig. 4D) as the refraction is on average less than that predicted for a flat velocline.

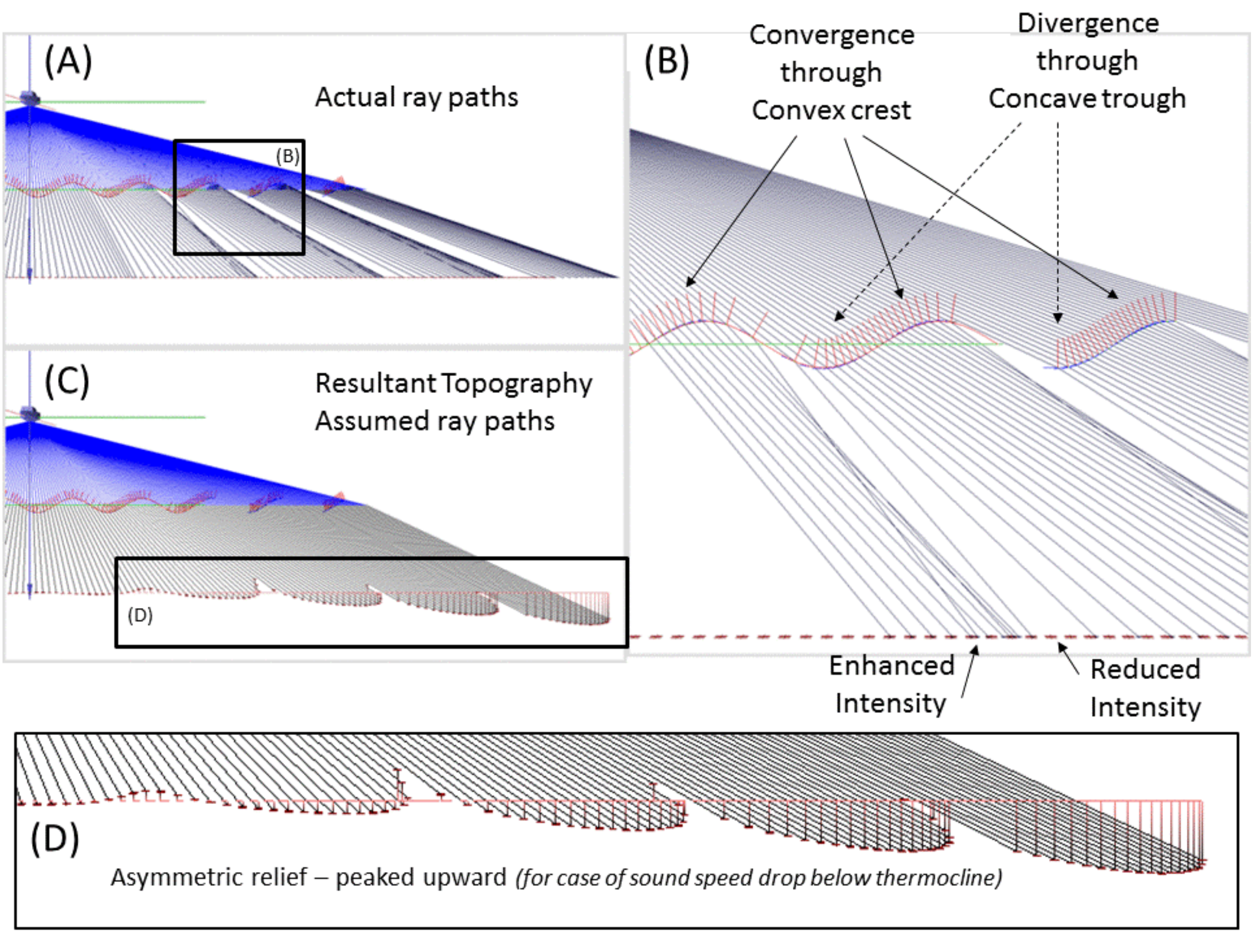

Fig. 4: showing the manner in which the erroneous bathymetric undulations are related to the crests and troughs of the internal waves. The case illustrated is for a step down in sound speed with depth. The convex crests act as zones of ray convergence, whereas the concave troughs (where not masked) act to produce zones of divergence (in the limit a shadow zone). As there is no knowledge of the actual velocline relief, those beams passing through the outboard sloping facets are interpreted as positive bathymetric anomalies and vice versa.

In the limit, as the ray path becomes less steep than the backside of the wave, it is either not sampled, or a complex multi-intersection ray path is described. As multibeam soundings rarely go beyond 70 degrees incidence, this condition would only occur for aspect ratios that produce slopes greater than 20 degrees. This does not occur for typical internal waves, but could easily be the case for KH billows.

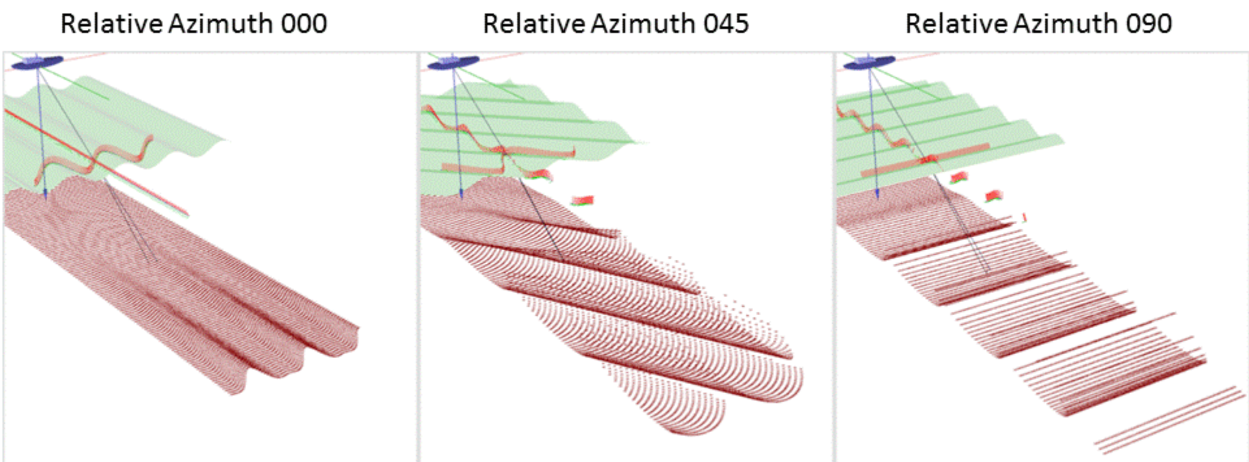

Fig 5: Showing the change in asymmetry of the resultant bathymetric artifacts with wave azimuth relative to the ship track. When the crests are parallel to the swaths, the undulations are symmetric. When the crests are orthogonal to the swath, the undulations are strongly asymmetric. The sense of the asymmetric depends on the sense of the sound speed step at the velocline.

The preceding discussion has focused on undulations across-track. In reality the waves can have any azimuth with respect to the shiptrack. The asymmetric pattern described for a wave oriented parallel to the shiptrack is progressively altered with azimuth. In the limit when the wave crest is orthogonal to the ship track, the ray divergence is fore-aft. The net result is symmetrical undulations that grow with obliquity. As noted by Hamilton and Beaudoin (2010), this results in the lowest outermost beam bathymetric errors (the error at nadir is unchanged). They noted that, in the absence of other constraints, these errors can be minimized by surveying orthogonal to the wave propagation direction.

Projected Orientation:

In the absence of acoustic imaging information about the true azimuth of the undulations, the pattern of the bathymetric anomalies, as registered on the bathymetric swath, can provide a clue. That pattern, however, is a result of the true undulation azimuth and the projection of that pattern from the velocline onto the seafloor.

The resulting distortions that occur at the velocline depth are stretched across-track due to the onward projection of those wave-induced deviations onto the seafloor below. Thus the actual undulation azimuth becomes increasingly rotated towards ship-track normal as the ratio of seabed depth to layer depth grows (Fig. 5).

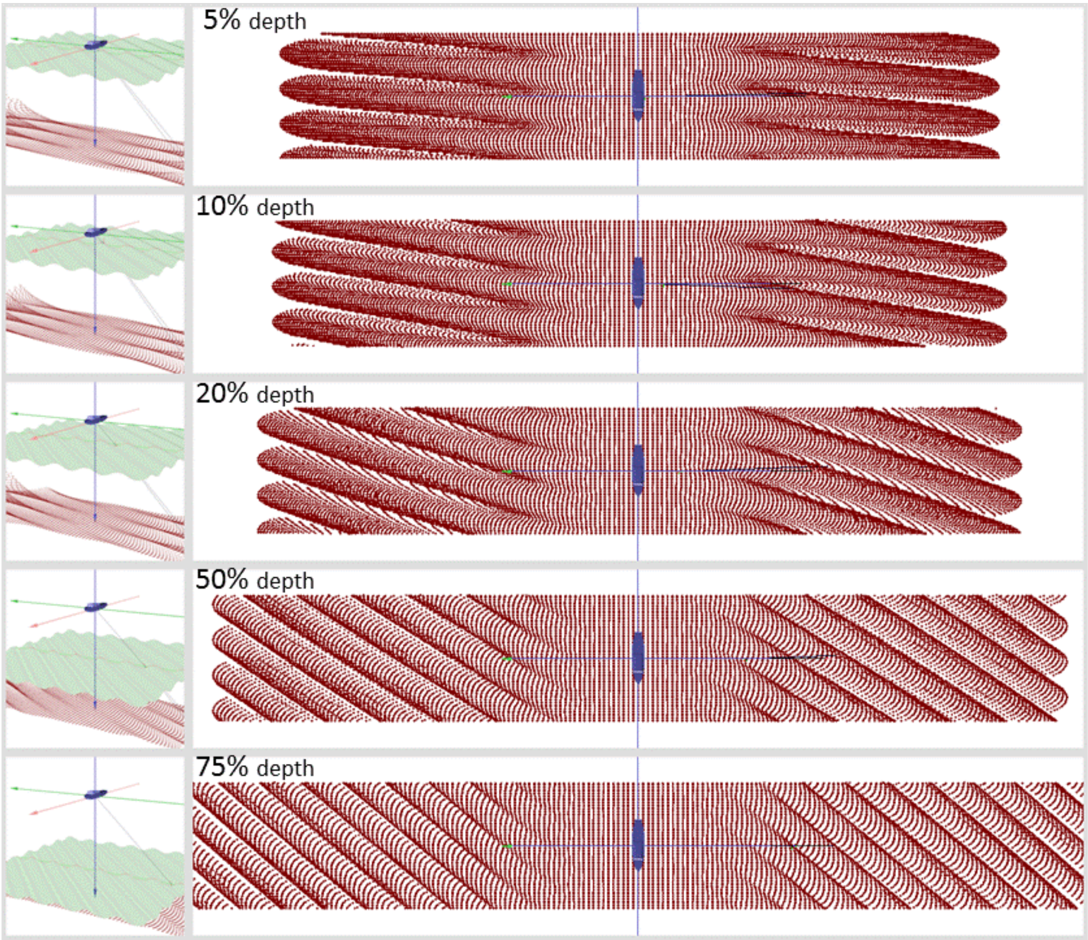

Fig. 6: Illustration of the changing orientation of the projected seabed relief. In all cases, the internal waves are 20% of the water depth in wavelength and are oriented at 45 degrees to the ship's track. The pycnocline elevation below the sea surface is varied from 5% to 75% of the total water depth.

For typical thermocline depths on the continental shelf (20-70m in 50-200m of water), this across track elongation is about a factor of 2 or 3. But for deeper water geometries, where that same thermocline depth is projected onto the seafloor at 1-5 km depths, the anomalies are elongated across-track by a factor of 10-50x. The net result is that, for the deep water case, the anomalies resemble truly shiptrack-orthogonal features. They may thus be confused with the across-track ribbing usually attributed to integration errors.

As the resolution of sonars and associated sensors has improved, across-track ribbing is one of the remaining common concerns limiting multibeam data. Utilizing the wobble analysis method reported by Hughes Clarke (2003), ribbing related to integration issues (imperfect alignment, offsets and timing) can be clearly identified in shallow water (where the ping period is short with respect to the surface wave period). Deep water multibeam data, however, does not enjoy this ease of analysis. Subtle residual ribbing artifacts continue to plague deep-water bottom-tracking and have proved difficult to analyze. This research suggests that much of the apparent wobble signature may in fact be due to projected near-surface velocline issues.

Field Examples

To illustrate how the modeled phenomenon impacts real bottom detection, two examples are presented of field observations of disturbed multibeam bottom tracking. In both cases multibeams are operated with swaths of 65-75° and are logging water column imagery. In both cases, the vessels are steaming over a velocline which is actively being deformed through shear into KH waves. The amplitude, wavelength and azimuth of the waves can be interpreted from the 3D water column imagery. The associated scale and pattern of depth residuals has been derived by subtracting the instantaneous bottom tracking solutions from a reference surface, created by multiple heavily overlapping survey lines.

<u>Example 1: USNS Maury EM710, Florida Current</u>

The first example illustrates KH billows developed on the sheared base of the Florida Current. The shear is taking place in ~ 140-200m of water and the seabed is 250m deep. The sound speed structure (from two static XBT profiles obtained before and during the experiment) illustrates a constant gradient of decreasing sound speed with a drop of 50m/s over the top 200m. ADCP observations (not shown) demonstrate that the upper ~150m of water is moving at about 2-3 knots. At the base of the current, the EM710 water column imagery clearly reveal KH waves with an amplitude of ~ 5-15m and wavelengths in the range 100-300m (Fig. 7). By extracting horizontal slices through the water column (Fig. 7B), the azimuth of the billows can be identified.

Over the 7 km length of the logged transect, the banding in the water column imagery (assumed to reflect a mixture of scattering from microstructure and zooplankton layering) evolves from unsheared, through increasing development of the billows, to overturning, mixing and homogenization. As this happens, the initially parallel structure of the billow crests breaks up into patches before disappearing.

The vessel was undertaking a deliberate zig zag path to test for residuals due to heavy yaw stabilization. The pattern of bathymetric residual errors (Fig 7 C), however, does not correspond to the vessel maneuvers. Rather the orientation of the residuals is aligned with the orientation of the billow crests at about 140m. Notably, the orientation of the residuals changes in azimuth, corresponding to a change in the azimuth of the billow crests. The magnitude of the corresponding periodic bathymetric errors exceed 1% of the total water depth at beam elevation angles of as little as 50° (a sector of +/-65° was utilized). As predicted by the developed model, the positive anomalies are larger than the negative anomalies.

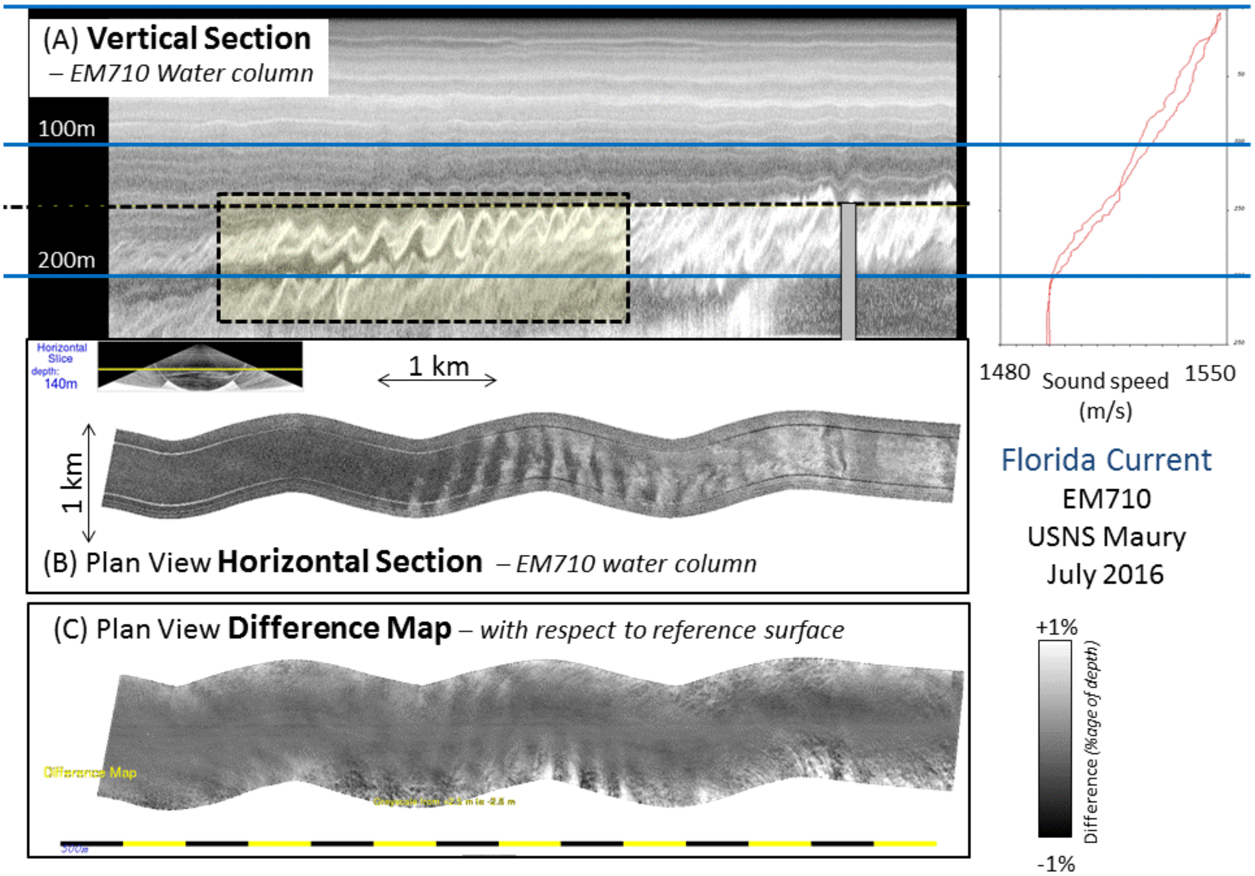

Fig. 7: showing vertical (A) and horizontal (B) sections through EM710 water column imagery acquired while passing over the Florida Current. The lower panel (C) reports the corresponding bathymetric anomaly in the resulting swath sounding data relative to a reference surface.

The survey region extended across the edge of the Florida Current which roughly parallels the edge of the Florida platform (immediately south of the Tortugas). These KH billows are ubiquitous under the base of the Florida current where the current base is close to the seabed. Thus this scale of bathymetric anomaly was present for all survey data acquired from depths of ~ 150 to 400m depth.

<u>Example 2: HSL-16 EM2040D, Tidal Front</u>

The second example (Fig. 8) illustrates the impact of Kelvin Helmholtz undulations on a pycnocline in 30m of water. The data is from an EM2040D operating at +/-75°. The vessel is transiting across a tidal front between a near homogenous water mass, to a ~ 12m deep layer that is slightly more brackish (1 ppt less) and warmer (1°C). The net result is just a 1.5 m/s step in sound speed which, although much smaller than the total sound speed change in example 1, is actually of comparable gradient (0.15m/s per meter compared to 0.25m/s per meter). Notably, the wave amplitude represents ~ 20% of the total water depth, whereas in example 1, the amplitude was just ~5%.

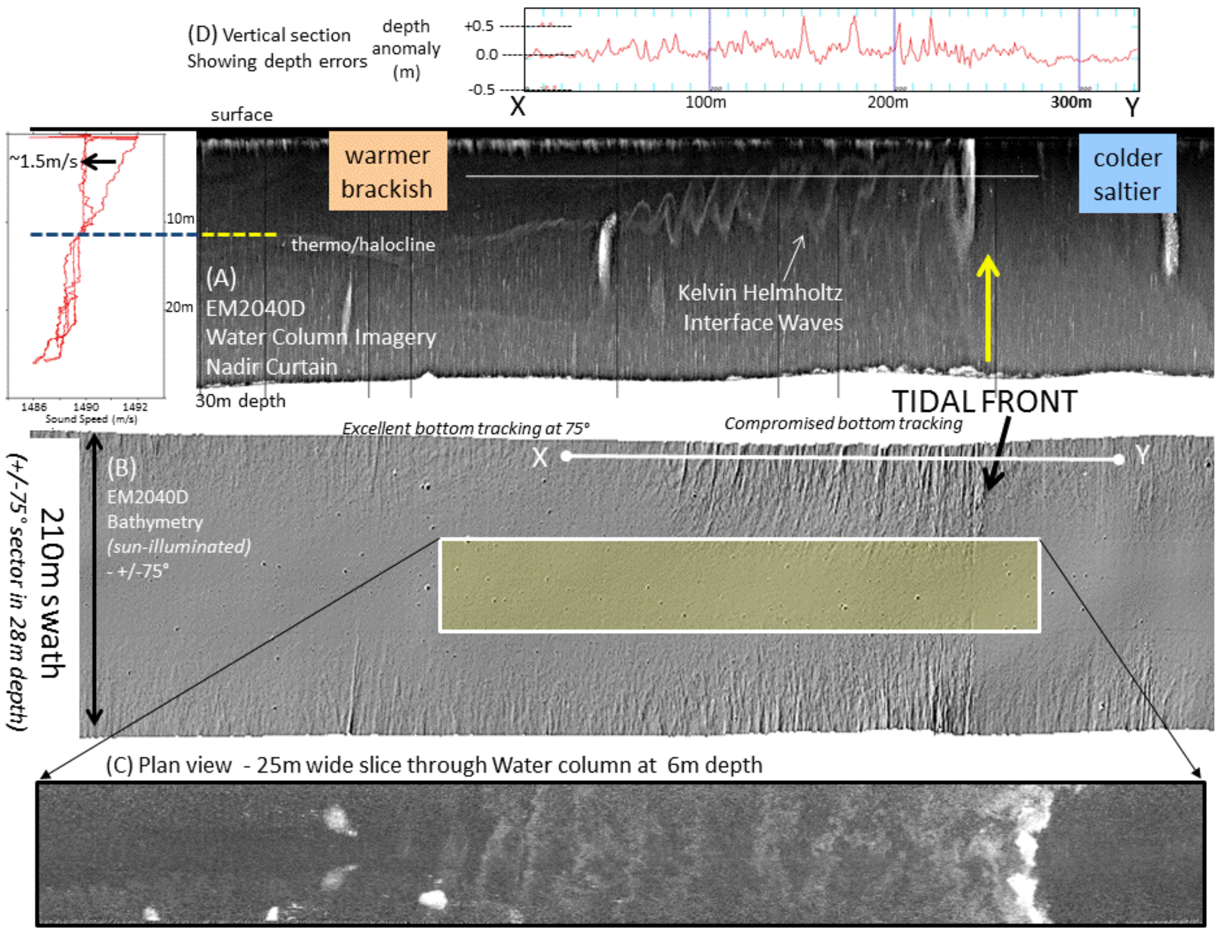

Fig 8: Showing (A) the vertical cross-section from water column scattering (with inset of the two MVP profiles on either side of the front), (B) the resulting bathymetry, sun-illuminated and (C) a horizontal section through the water column scattering at a depth of 6m indicating the orientation of the waves and (D) a cross section through a difference map between this data and a reference surface. The location of this section is indicated by X-Y on the bathymetric map.

No current speed measurements are available to measure the shear. The same structure, however, was repeatedly picked up on successive closely-spaced survey lines and the displacement indicated that the whole front was advecting at about 0.5 knots. KH waves with a wavelength of about 50m and a relief of 3-8m are developed on the velocline. The waves are restricted to the first ~ 300m of the front, perhaps indicating that this is the region of active shear.

A horizontal section through the water column (Fig. 8C) indicates that the billows are oriented along the length of the front which is close to orthogonal to the ship-track. The orientation of the bathymetric anomalies are also close to orthogonal, but are slightly sinuous on the outer edges. The resulting residual bottom tracking anomalies (Fig 8 D) exhibits asymmetric undulations with broader lower amplitude downward errors and abrupt upward peaks of up to 0.75m (~2.5% of depth). The peaks spacing correspond to the KH wave wavelength.

These tidal fronts are a common phenomenon is the southern Gulf Islands in British Columbia. They appear to represent the boundary between advected warmer and more brackish water masses that are moved out of local inlets. Whenever the vessel was surveying either completely in one or other of the two watermasses, these bottom tracking anomalies were absent and excellent definition of small scale seabed relief (boulders (Fig8 B) and ripples) was achieved. But during transects through these fronts, both the vertical accuracy and target detection capability were compromised. Notably the vessel was operating using an MVP-30 running continuously (~ 600m dip spacing). While this was adequate to cope with the regional changes in watermasses, this was not sufficient to monitor these short wavelength velocline undulations.

Conclusions

Oceanographic variability at lengths scales shorter than we can currently mechanically sample, generate coherent refraction-related distortions in multibeam data. These commonly result from two processes: internal wave packets, and turbulent billows due to interface shear.

A model has been developed that predicts the scale and pattern of distortions due to a periodic perturbation of a velocline. The resulting projected pattern reflects a combination of the orientation of the wave and the depth of the velocline relative to the seafloor depth.

As there is currently no means of sampling the water column structure at horizontal lengths scales short enough to capture these roughness elements, the resulting distortions are manifest in data. Two examples are presented showing that these distortions routinely exceed IHO vertical accuracy specifications. Furthermore, for the case of KH billows, the associated short wavelength bottom detection roughness obscures real seafloor features and thus could compromise adequate target detection.

Acoustic water column imaging of layered microstructure and zooplankton scatterers is a promising means of identifying whether the velocline is being perturbed. A 2D slice from just a single-beam sounder is often enough to recognize that this is present. The 3D volume imaging capability of multibeam water column has the advantage of being able to measure the orientation and 3D structure of the perturbation.

Unfortunately, as the water column imagery only reflects the location of passively distorted scatterers, there is no direct means of extracting the actual sound speed structure. By combining the imagery with sparse sound speed profiles, however, and by using pattern recognition techniques, it may be possible to reasonably predict the gross velocline structure.

Future Directions

The initial model presented here, simplifies the velocline as a discrete step. While this adequately reproduces the observed bottom tracking artefacts, in reality, the perturbed region will have a finite gradient and it would be better to model the ray path through an undulating layer with that gradient present.

One of the biggest differences expected between a step and gradient model is that, for the more oblique ray paths, the horizontal distance traveled while traversing the gradient region may correspond to a significant fraction of the wavelength of the undulation. If so then the distortion on the upward and downward components of the wave will be combined. The expected result is that turbulence or waves at shorter scales than this integration path will be averaged out and not significantly contribute to the bottom detection noise.

An additional factor to consider is that an individual beam bottom detection reflects contributions from all the ray paths within the finite solid angle of the beam. Thus again, spatial averaging of those ray paths, may reduce the impact of shorter wavelength velocline perturbations. This effect should be included in future iterations of the model.

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