Proceedings of Meetings on Acoustics

Volume 19, 2013

<http://acousticalsociety.org/>

ICA 2013 Montreal

Montreal, Canada

2 - 7 June 2013

Acoustical Oceanography

Session 2aAO: Seismic Oceanography

2aAO2. Inversion of density in the ocean from seismic reflection data

Berta Biescas Gorriz*, Barry R. Ruddick and Valenti Sallares

***Corresponding author's address: Oceanography, Dalhousie University, 1355 Oxford Street, Halifax, B3H 4R2, Nova Scotia, Canada, berta.biescas@dal.ca**

Previous works in seismic oceanography explain that acoustic reflections are primarily associated with temperature vertical variations, so seismic images in the ocean can be interpreted as thermal contrasts maps. Temperature and salinity are the physical properties that describe structures in the ocean. However, the main physical parameter that controls oceans dynamics is the density and, since the ocean is a compressible fluid, potential density is the property that determines the stability, mixing and mesoscale motions of the particles. We have inverted oceanic impedance from seismic data and then derived density and potential density surfaces from the oceanic impedance. Results of the inverted potential density have been compared with seismic reflectors to show the relation between isopycnals and reflectors. We have also compare the seismic profiles of the GO Survey with the space-coincident CTDs and space and time-coincident XBTs to understand the nature of the reflectivity and its relation with the potential density in the ocean.

Published by the Acoustical Society of America through the American Institute of Physics

INTRODUCTION

Seismic oceanography (SO) applies the multichannel seismic reflexion (MCS) method to detect thermohaline structures in the ocean from the reflectivity generated through them. The MCS method (Yilmaz, 2001), traditionally used for Solid Earth studies, uses an active source to generate acoustic waves, whose reflections are recorded in multiple receivers that are towed behind a moving vessel. The reflectivity of the ocean is obtained along lateral sections of hundreds of kilometres to full ocean depth with vertical and horizontal resolutions on the order of 10 m. The reflectivity is a function of the impedance (Z) contrasts of the ocean. For a continuous medium, the reflectivity function is approximately (Oldenburg *et al.*, 1983):

$$CR(y) = \frac{1}{2} \cdot \frac{d[\ln(Z(y))]}{dy} \quad (1)$$

Impedance is a function of the temperature, salinity and pressure of the ocean and follows next expression:

$$Z(T, S, p) = \rho(T, S, p) \cdot ss(T, S, p) \quad (2)$$

Where ρ and ss are respectively the density and the sound speed in the ocean.

Previous works (Nandi *et al.*, 2004; Ruddick *et al.*, 2009) explain that acoustic reflections are primarily associated with temperature vertical variations, so seismic images in the ocean can be interpreted as maps of thermal gradients. Temperature and salinity are the physical properties that describe structures in the ocean. However, the main physical parameter that controls oceans dynamics is the density and, since the ocean is a compressible fluid, potential density is the property that determines the stability, mixing and mesoscale motions of the particles. The goal of this work is to compare seismic reflectors in the ocean with the isopycnal surfaces to improve the understanding and interpretation of the SO data.

The results of this work are based on the comparison between coincident seismic and oceanographic data acquired in the GO survey (Hobbs, 2008). The GO survey, that was designed with the purpose of testing different SO systems, was carried out in the Gulf of Cadiz, Northeastern Atlantic Ocean, in April-May 2007. Two different methods have been analyzed. The first method compares seismic and potential density data derived from oceanographic probes (XBTs and CTDs) and the second method compares seismic and potential density data derived from the inversion of seismic amplitudes.

RESULTS: COMPARISONS BETWEEN MESOSCALE SEISMIC REFLECTORS AND ISOPYCNALS

Potential Density Derived from Oceanographic Probes

The seismic reflectors with the longest lateral coherence and coincident with at least two CTDs, were digitized in profiles GO-LR-01, GO-LR-05 and GO-LR-07 (red curves in Figures 1, 2 and 3), to obtain their coordinates in terms of depth and lateral distance along profile. Potential density was calculated from oceanographic data at the coordinates where the seismic reflectors were coincident with the oceanographic probes. XBTs and CTDs casts were deployed along these profiles on board of the RRS Discovery and FS Poseidon. The XBTs (thermal profilers) were acquired on board of the RRS Discovery, time-and-space coincident with the seismic data and with a $\sim 3\text{km}$ lateral spacing. The CTD (thermal, salinity and pressure profiles) casts were deployed on board of the FS Poseidon, which was following the RRS Discovery with a delay of 1-3 hours, so CTD data were only space-coincident with the seismic data and had a lateral spacing of $\sim 25\text{km}$. The advantage of using the CTDs is that the potential density derived from them is more accurate because these probes measure independently conductivity, temperature

and pressure. However, they had a very low lateral resolution and they were not time-coincident with the seismic data. On the contrary, the XBTs probes were more dense in the horizontal dimension, so it was possible to track better the reflectors and besides, these data were time-and-space coincident with the seismic acquisition. However, these probes do not measure salinity, which is needed for calculating the potential density. To solve this problem, a T-S relation for the area of the Gulf of Cadiz was derived using a non-linear relation from a neural network (NN) (Bishop, 1995). The application of NN for T-S relations was first presented by Ballabrera-Poy *et al.* (2009) and it was validated for SO by Kormann *et al.* (2011). The NN T-S relation was trained using 181 CTD data from the Thalassa Leg2 Cruise, done in September 1997, in the Gulf of Cadiz, and has the same model as the one described in Kormann *et al.* (2011). The high correlation between temperature and salinity anomalies in the ocean makes depth and temperature anomaly to be excellent predictors for the salinity anomaly. The accuracy of the NN for potential density calculation was tested by using the trained NN to estimate salinity from the GO 43 CTD-measured temperature profiles and then calculating potential density. The results of this calibration are shown in Figure 4. The difference between potential density calculated from the CTD-data (temperature and salinity) and from the NN-data (CTD temperature as a predictor and NN-derived salinity) has a total rms of 0.07 kg/m^3 for all the 43 CTDs. The maximum errors are located in the shallowest and deepest part of the profiles and in the intrusions (Figure 4b). Based on this analysis, an error of 0.07 kg/m^3 is considered for the potential density data derived from XBTs. Another reason for choosing the NN T-S relation is that it is possible to use an only one continuous function derived for the entire water column and for the entire area of study. As the T-S NN curve shows (Figure 4d) the salinity derived from the NN has a good agreement with the CTD one independently of the presence or not of a meddy. This fact, is also important in order to use the NN T-S relation for the inversion of entire seismic profiles, as presented in the second method.

FIGURE 1: Seismic profile GO-LR-01 acquired in the GO Survey, May-June 2007, Gulf of Cadiz, North Atlantic Ocean. Blue open circles indicate the positions of the time-and-space coincident XBTs. Red open circles indicate the positions of the space-coincident CTDs, which were acquired with 1 1/2 hour time difference respect to the seismic data. The solid circles correspond to the analyzed data of Table 1. The distance between cmps is 6.25 m and the total length of the tracked reflector (red curve) is $\sim 25 \text{ km}$. The original stack section and image were generated by Dirk Klaeschen in the GO project.

Results are summarized in Tables 1 and 2. The values of the potential density, from both CTDs and XBTs, along the seismic reflectors, show changes in density that exceed the estimated uncertainty. The top reflector of the meddy in GO-LR-05, was plotted over the isopycnal contours derived from the coincident XBTs in Figure 5. This plot shows, within error bands, that potential density along the seismic reflector has a change of $0.4 \pm 0.07 \text{ kg/m}^3$ from the top to the lowest part of the reflector. The slopes of the reflectors in long wavenumbers, on the order of $\sim 10 \text{ km}$, corresponding to the reflectors analyzed in this work, are higher than the isopycnals' slopes. Therefore, it suggests that seismic reflectors can not be interpreted directly as isopycnals, by default and for all the thermohaline structures.

FIGURE 2: Seismic profile GO-LR-05 acquired in the GO Survey, May-June 2007, Gulf of Cadiz, North Atlantic Ocean. Blue open circles indicate the positions of the time-and-space coincident XBTs. Red open circles indicate the positions of the space-coincident CTDs, which were acquired with 1 1/2 hour time difference respect to the seismic data. The solid circles correspond to the analyzed data of Table 1. The distance between cmps is 6.25 m and the total lengths of the tracked reflectors (red curves) are $\sim 50\text{km}$ (left) and $\sim 21\text{km}$ (right). The original stack section and image were generated by Dirk Klaeschen in the GO project.

FIGURE 3: Seismic profile GO-LR-07 acquired in the GO Survey, May-June 2007, Gulf of Cadiz, North Atlantic Ocean. Blue open circles indicate the positions of the time-and-space coincident XBTs. Red open circles indicate the positions of the space-coincident CTDs, which were acquired with 1 1/2 hour time difference respect to the seismic data. The solid circles correspond to the analyzed data of Table 1. The distance between cmps is 6.25 m and the total length of the tracked reflector (red curve) is $\sim 25\text{km}$. The original stack section and image were generated by Dirk Klaeschen in the GO project.

Potential Density Derived from Seismic Data Inversion

The second method consists on the comparison between seismic reflectors and potential density derived from the inversion of the seismic data of the profile GO-LR-12 (Figure 6). The seismic data were inverted following the method presented by Papenberg *et al.* (2010) with two main differences: i) density was not considered laterally homogeneous and ii) a T-S relation derived using NN (described above) was used. The steps applied for the inversion are summarized in Table 3. The results from the inversion are plotted using isopycnals countours in Figure 7 after applying a lateral and vertical smooth of 100 m and 20 m respectively, to remove short wavelength variations of density that were considered as noise. The inverted potential density shows the smallest density gradients of $d\rho/dz \sim 4 \cdot 10^{-4} \text{kg/m}^{-4}$ in the center of the meddy, the largest gradients of $d\rho/dz \sim 12 \cdot 10^{-4} \text{kg/m}^{-4}$ in the top boundary and

TABLE 1: Potential density values from CTD data along seismic reflectors of profiles GO-LR-01, GO-LR-05 and GO-LR-07 (Figure 1,2 and 3). The errors are derived considering an error in depth of the seismic reflector of $\pm 30m$ because of the vertical resolution of the seismic data.

CTD	cdp	2twi (s) $\pm 0.02s$	depth (m) $\pm 30m$	potential density (kg/m^3)
GO-LR-01				
10	1782	1.00 ± 0.02	750 ± 30	1031.80 ± 0.02
11	4955	0.99 ± 0.02	741 ± 30	1031.69 ± 0.03
GO-LR-05				
20	415	0.66 ± 0.02	498 ± 30	1031.48 ± 0.06
21	1884	0.74 ± 0.02	557 ± 30	1031.57 ± 0.07
GO-LR-05				
25	14371	1.10 ± 0.02	828 ± 30	1031.78 ± 0.03
26	21031	1.08 ± 0.02	812 ± 30	1031.04 ± 0.03
GO-LR-07				
32	3278	0.92 ± 0.02	690 ± 30	1031.68 ± 0.04
33	5199	0.79 ± 0.02	597 ± 30	1031.57 ± 0.04
34	7111	0.62 ± 0.02	466 ± 30	1031.44 ± 0.04

TABLE 2: Potential density values, from combined XBT data and salinity derived from NN, along seismic reflectors of section GO-LR-05 (Figure 2). Errors are derived from the validation of the use of NN for potential density calculation.

XBT	cdp	2twi (s) $\pm 0.02s$	depth (m) $\pm 30m$	potential density (kg/m^3)
345	22201	1.11	835	1031.86 ± 0.07
344	21114	0.98	737	1031.77 ± 0.07
343	19974	0.90	677	1031.7 ± 0.07
342	18894	0.86	647	1031.66 ± 0.07
341	17814	0.88	662	1031.68 ± 0.07
340	16588	0.95	715	1031.75 ± 0.07
339	15543	1.03	775	1031.80 ± 0.07
324	4626	0.84	632	1031.63 ± 0.07
321	3486	0.8	602	1031.6 ± 0.07
320	2906	0.74	557	1031.53 ± 0.07
319	2346	0.7	527	1031.49 ± 0.07

$d\rho/dz \sim 6 \cdot 10^{-4} kg/m^{-4}$ outside the lateral right boundary. Aspect ratios of $f/N \sim 0.2 - 0.03$ are associated with these gradients. The strongest slopes of the isopycnals are located along the lateral edges, while in the center of the lens the slopes are almost zero. These observations agree with the study done by Armi *et al.* (1989). Seismic reflectors lay over the zone of maximum isopycnal slope, however they clearly do not track them. Results show variations of potential density along the coherent seismic reflectors, which agrees with the results obtained with the first method.

DISCUSSION AND CONCLUSIONS

We have used two methods to compare the seismic reflectors' slopes with the isopycnals. Both of them show that mesoscale seismic reflectors do not track isopycnals. Eventhough impedance contrast is affected by density contrasts (equation 2), the contribution of density contrast to the reflectivity in the ocean is smaller than the contribution of the sound speed contrast as quantified by Sallarès *et al.* (2009), due to two effects. Firstly, considering vertical distances on the order of $\sim 10m$, density changes ($d\rho/\rho \sim [0.01 - 0.05]/1030 \sim [10^{-5} - 5 \cdot 10^{-5}]$) are smaller than sound speed changes ($dss/ss \sim [0.1 - 1]/1500 \sim [7 \cdot 10^{-5} - 7 \cdot 10^{-4}]$) in the water

FIGURE 4: Comparison between the CTD (blue) and T-S from NN (red) data for : a) potential density versus depth, b) potential density versus conservative temperature; and T-S curves of the 43 CTD used for the T-S NN calibration, from c) CTD data and d) salinity from the NN T-S relation. Pink curves are isopycnals and red curves are contours of constant impedance. The T-S within the small square in d) correspond to an individual cast.

FIGURE 5: Digitized seismic reflector (black) on the top boundary of the meddy detected in GO-LR-05 and isopycnals calculated from the coincident XBTs (countours). The empty squares mark the XBT positions. The noncontinuous lines show the depth error when digitizing the reflector. The detailed values are shown in Table 2.

column, over most of the thermohaline structures. Secondly, oceanic impedance changes seem to be more correlated to sound speed than to density. Figure 8 displays a CT-SA diagram with a CTD example of the area of study. This diagram shows that isolines of constant sound speed have a small angle ($\sim 10^\circ$) crossing the isolines of constant impedance, while the isopycnals cross isolines of constant impedance with an angle of $\sim 45^\circ$. This means that changes in sound speed are highly correlated with changes in impedance, while density changes can be associated to small or any change in impedance. Therefore, thermohaline changes associated with high

TABLE 3: Processed-oriented inversion method

1. True amplitude MCS processing
2. Reflexion coefficients recovering (CR) from seismic deconvolution
3. High frequency impedance data recovering from CR, $Z(i) = Z(i-1) * \exp(\Delta z * CR(i) * 2)$, equation 1
4. Low frequencies filtering, $\lambda > 100m$ were removed from seismic data
5. Low frequency impedance data recovering from oceanographic data. The location of the used XBTs are displayed with open blue circles in Figure 6. Simultaneous XTBs were filtered for $f < 100m$ in the vertical dimension and were interpolated, from 3 km to 6.25 m along the horizontal dimension. The T-S NN relation was used to obtain impedance from the XBT data.
6. Final impedance model= low frequencies from oceanographic data + high frequencies from seismic data
7. Temperature and salinity calculation from impedance data using the NN T-S relation and GSW functions

FIGURE 6: Seismic profile GO-LR-12 acquired in the GO Survey, May-June 2007, Gulf of Cadiz, North Atlantic Ocean. Blue open circles indicate the positions of the time-and-space coincident XBTs. Red open circles indicate the positions of the space-coincident CTDs, which were acquired with 1 1/2 hour time difference respect to the seismic data. The distance between cmps is 6.25 m. Below the seismic image, the comparison of the inverted potential density and the one derived from the XBT is presented for 4 probes deployed along the meddy: 420, 425, 430 and 440. The original stack section and image were generated by Dirk Klaeschen in the GO project.

reflectivity, i.e. strong contrasts in impedance could have low density variations and the opposite. The diagram also shows that isolines of constant impedance are almost parallel to the salinity axis, which explains that thermal gradients are the main contributors of the reflectivity in the ocean as previously observed by other authors (Nandi *et al.*, 2004; Ruddick *et al.*, 2009). Taken the CTD data as an example, the intrusions associated to the lateral interleaving at the

FIGURE 7: Contours of inverted potential density overlapped to the seismic profile GO-LR-12.

edge of the meddy, develop strong contrasts in sound speed and impedance, i.e. strong reflectivity, but they are parallel to the isopycnals.

Seismic images used in SO, display always the strongest seismic reflectors with stronger colours relatively to the rest. So the reflectors along the strongest changes in impedance, and so in sound speed, will be the ones that will be enhanced over the others, which may not fit the changes in density. The conclusion is that, we can not generally interpret seismic reflectors as isopycnals or surfaces with reversible dynamics along them. Inversion of the seismic parameter to physical parameter of the ocean is recommended before interpreting dynamical processes involved in the ocean from SO data. The inversion in density carried out in this work is in good agreement with previous observations and very promising for future studies.

FIGURE 8: T-S diagram as a CTD obtained within a meddy in the GO Survey. Isopycnals (blue), curves of constant sound speed (magenta) and curves of constant impedance (red) are included in the diagram.

ACKNOWLEDGMENTS

The first author is funded by a FP7-PEOPLE-2010-IOF Marie Curie contract. We thank all the participants of the GO Cruise for the excellent data base acquired, with a huge potential for the calibration and understanding of the SO technique.

REFERENCES

- Armi, L., Herbert, D., Oakey, N., Price, J., Richardson, P., Rossby, H., and Ruddick, B. (1989). “Two years in the life of a Mediterranean salt lens”, *Journal of Physical Oceanography* **19**, 354–370.
- Ballabrera-Poy, J., Mourre, B., García-Ladona, E., Turiel, A., and Font, J. (2009). “Linear and non-linear t-s models for the eastern North Atlantic from Argo data: Role of surface salinity observations”, *Deep-Sea Research I* **56**, 1605–1614.
- Bishop, C. (1995). *Neural network for pattern recognition* (Oxford University Press).
- Hobbs, R. (2008). “GO Geophysical Oceanography: A new tool to understand the thermal structure and dynamics of oceans, D318 Cruise Report”, Technical Report, <http://www.dur.ac.uk/eu.go/cruise/report.html>.
- Kormann, J., Biescas, B., Korta, N., de la Puente, J., and Sallarès, V. (2011). “Application of acoustic full waveform inversion to retrieve high-resolution temperature and salinity profiles from synthetic seismic data”, *Journal of Geophysical Research* **116**, C11039.
- Nandi, P., Holbrook, W., Pearse, S., Páramo, P., and Schmitt, R. (2004). “Seismic reflection imaging of water mass boundaries in the Norwegian Sea”, *Geophysical Research Letters* **31**, L23311.
- Oldenburg, D., Scheuer, T., and Levy, S. (1983). “Recovery of the acoustic impedance from reflection seismograms”, *Geophysics* **48**, 1318–1337.
- Papenberg, C., Klaeschen, D., Krahmann, G., and Hobbs, R. (2010). “Ocean temperature and salinity inverted from combined hydrographic and seismic data”, *Geophys. Res. Lett.* **37**, L04601.
- Ruddick, B., Song, H., Dong, C., and Pinheiro, L. (2009). “Water column seismic images as maps of temperature gradient”, *Oceanography* **22**, 193–205.
- Sallarès, V., Biescas, B., Buffett, G., Carbonell, R., Dañobeitia, J., and Pelegrí, J. (2009). “Relative contribution of temperature and salinity to ocean acoustic reflectivity”, *Geophysical Research Letters* **36**, L00D06.
- Yilmaz, O. (2001). *Seismic data analysis: processing, inversion, and interpretation of seismic data*, second edition (Tulsa Oklahoma: Society of Exploration Geophysicists).