Range-dependent acoustic tomography by oceanic feature modeling for the monitoring of upwelling (Cabo Frio, Brazil)

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***Abstract*— The Cabo Frio zone presents an important coastal-oceanic system of great interest for biological and economical ressources. Among others, the coastal upwelling is one of the specific feature that occurs frequently in the area. As presented in a previous feasibility study, the main parameters of the upwelling can be tracked by acoustic tomography in vertical slices, using a feature model parameterization. In this paper, acoustic propagation simulations are used to study the sensitivity of acoustic measurements to a more advanced upwelling feature model. More specifically, it is shown how the frequency diversity and source position have a strong effect upon the subjacent ambiguity function involved in the inversion process. The Bartlett processor performances are compared for different frequency and hydrophone setup, showing that an increase of the number of transmitted frequencies compensates for the lack of hydrophones, and reduces efficiently the ambiguities. Furthermore, it is shown that a frequency-coherent cost function reduces strongly correlation between feature model parameters, enabling to resolve more efficiently the environment.**

I. Introduction

The coupling of ocean modeling, acoustic inversion and data assimilation is a complex problem, particularly in coastal environments. This work investigates the use of an oceanic feature model for the acoustic monitoring of coastal upwelling in Cabo Frio (23°S), Brazil.

The Brazilian coast at Cabo Frio region develops an unique coastal-oceanic system when the coast orientation changes and continental shelf break topography reinforces the interaction between the oceanic and coastal systems [1]. The most important coastal feature off Cabo Frio region is the upwelling (Fig. 1).

The traditional way to obtain synoptic oceanographic data is a difficult and high cost task, often ineffective and not sufficient to capture qualitatively or quantitatively, relevant mesoscale features. Different methods to solve this problem have been developed, as using orbital data, altimetry or sea-surface temperature (SST), although they do not provide the three-dimensional mass field data. Merging of satellite measurements and oceanographic feature models into regional ocean circulation models is another approach developed recently. The possibility of obtaining the synoptic three-dimensional temperature field by acoustic tomography seems to be relevant, due to the fast acquisition and processing, and the synopticity of the thermohaline that it provides, describing in more details the mesoscale structures, often masked by traditional methods of collecting data.

As proposed in [2], when tracking a specific range-dependent oceanic feature, the integration of the *a priori* knowledge can be done through the use of a specific feature model for the parameterization of the environment. Feature models consist of simple mathematical expressions that are commonly used to mimic the typical oceanographic features, and were initially developed for oceanic modeling and forecasting purposes. It was shown in [3] that feature models provide significant improvements on the prediction of transmission loss with respect to range-independent models.

A previous work showed that the acoustic monitoring of the central position of a seasonal thermal front was feasible by coupling a basic feature model and appropriate inversion techniques involving broad-band and full-field acoustic propagation modeling [4]. Here, the same technique is applied to a different feature model that describes the coastal upwelling that occurs on the southeastern coast of Brazil and in particular the Cabo Frio area. The tracking of a simplified upwelling feature parameter through the filtering of acoustic transmission data was shown in a previous paper [5]. To apply this technique on more realistic environmental scenarios, the feature model has to be complexified, to be able to capture more details of the upwelling feature and prevent filter divergence under real conditions. For this reason, this paper applies a more detailed feature model to the transect of interest, and studies in which manner the feature parameters impact the acoustic pressure field. Further works will consider several transects that cross the upwelling front, thereby enabling the reconstruction of

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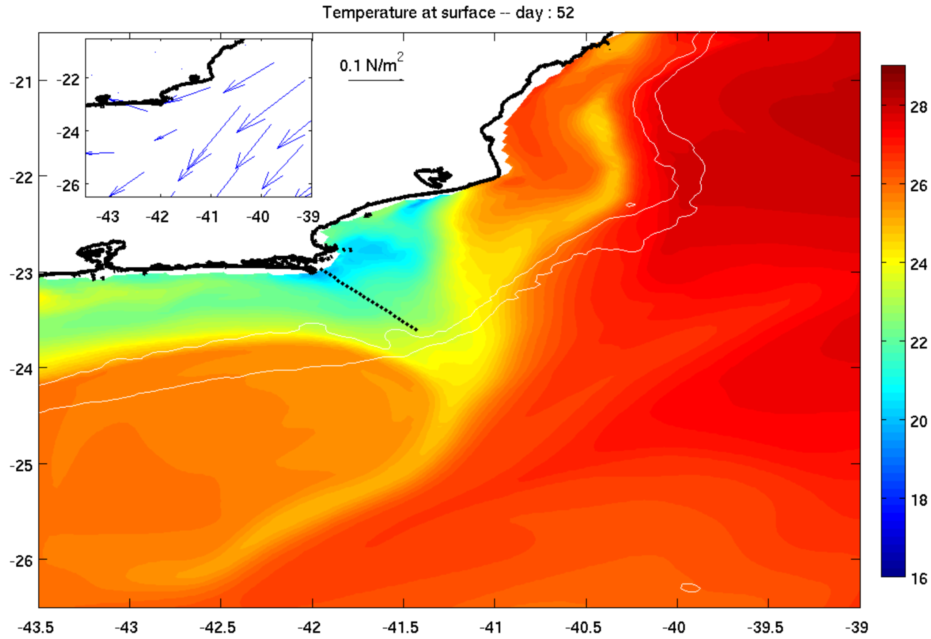
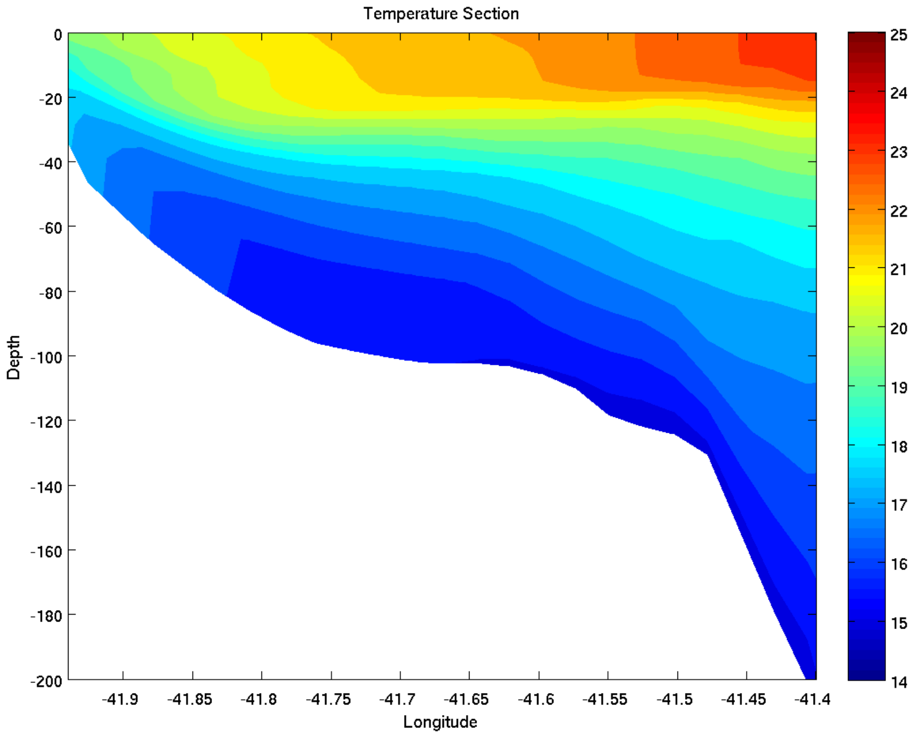


(a)



(b)

Fig. 1. Temperature field (°C) simulated with the Regional Ocean Model System (ROMS) for Cabo Frio area. (a) Surface temperature on the whole area. The upwelling feature is well present near the coast. The corresponding wind field is shown in the upper left corner. The dots define the section shown in the bottom picture. The two white lines show the limits of the shelfbreak, with a rapid varying bathymetry between 200 m (inshore) to 1000 m (offshore). (b) Vertical section of the temperature field. Cold water are upwelled near the coast.

the subsurface conditions over the whole zone by introducing appropriate correlation functions.

The paper is organized as follow: in the first section, the Cabo Frio coastal upwelling and its principal mechanisms are described, followed by the description of the upwelling feature model. The second section briefly begins with the properties of the oceanic simulations involved in this work, and the associated acoustic sensitivity study is then illustrated in the third section for different geometries and signal parameters. The paper is concluded in the last section.

II. THE CABO FRIO COASTAL UPWELLING

A. The Coastal Upwelling Feature in Cabo Frio

During the spring and summer months, coastal upwelling is common and robust in the Cabo Frio region. During upwelling events, the inshore surface temperature is about 17°C–18°C. In oceanic region, the Brazil Current (BC) is flowing to southeast direction transporting at surface the Tropical Water (TW) with temperatures around 25°C–27°C. Therefore, the sea surface temperature difference between coastal and oceanic regions is most of the time greater than 10°C, when the Cabo Frio upwelling occurs. As shown in [6] and [1], the interaction of these two systems (BC and coastal upwelling) can create an environment that impacts the density field.

The upwelling signal is marked by the rising at surface of the South Atlantic Central Waters (SACW) into the coastal region. This water mass is carried by the BC at 200m–500m levels poleward near Brazil southeast shelf break. The principal mechanism responsible of CF upwelling is the persistence of southwestward winds. These winds represent the western branch of the South Atlantic Subtropical Height. Due to the continental margin orientation, the surface Ekman layer transport is oceanward and SACW thus moves inshore as in classical coastal upwelling [7].

According to [8] and [1], there are other mechanisms that may play a supporting role in the Cabo Frio upwelling scenario. It can be mentioned the ocean bottom bathymetric configuration and the recurrent formation of BC cyclonic meanders offshore are two of those mechanisms. In [7], it was shown that instable cyclones meanders interact with coastal systems and play an important role in enhancing the coastal upwelling. However, Ekman pumping seems to be the main factor responsible for the Cabo Frio coastal upwelling.

B. Feature Models

The philosophy of the feature modeling approach is to develop a first-order system for a very complex nonlinear system such as a regional ocean where most processes strongly interact and where processes cannot be studied separately. Once the first-order structures are placed within a numerical models dynamical framework, the nonlinearity stimulates further interaction among features and should create realistic four-dimensional complex fields. Thus, changing the parameter values of the feature models, it could be possible to study the interaction between features and the different dominant (and possibly candidate) processes in isolation [1], [9].

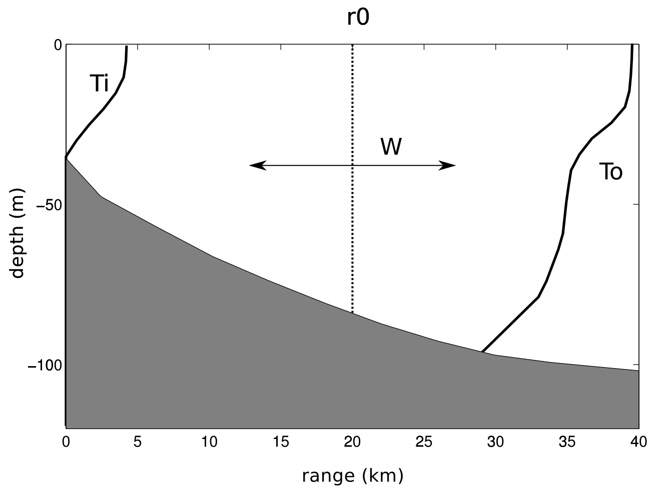


Fig. 2. A schematic representation of the coastal upwelling feature model structure and its parameters.

The feature model approach enables the representation of the coastal upwelling in a low-dimensional scheme. In this framework, a basic feature model was first developed in [5] to test the principle of sequential tracking of strength parameter by acoustic tomography. In order to cope with more realistic and variable situations, this paper generalizes the proposed upwelling feature model. Sensitivity tests can be done by varying the upwelling parameters to generate different scenarios which can then be studied for determining the complex relationships between acoustic propagation and upwelling characteristics, and optimize the acoustic setup. In a next step, the feature model will be used as a parameterization scheme to perform acoustic inversion of the environment and to estimate the values of feature parameters that bets describe the upwelling.

C. The Coastal Upwelling Feature Model

A schematic representation of the proposed feature model structure for the upwelling region near Cabo Frio is shown in Fig. 2. It is derived from the continental shelf-slope front feature model and thermal front feature model developed by [9] and [3], and updated by [10] and [1], respectively. The upwelling frontal temperature distribution $T(r, z)$ is parameterized as

$$T(r, z) = T_o(z) + [T_i(z) - T_o(z)]m(r), \tag{1}$$

where

$$m(r) = 0.5 + 0.5 \tanh\left[\frac{r - r_0}{W}\right] \tag{2}$$

is a meld function, r is the cross-frontal distance from the central axis of the front r_0, z is positive vertically upward, W characterizes the width of the front, $T_i(z)$ is the inshore temperature profile, and $T_o(z)$ is the offshore temperature profile (Fig. 2). In this work, the two temperature profiles are parameterized by their surface (surf) and bottom (bot) values, applied to adimensionnalized profiles.

III. Acoustic sensitivity on Upwelling situations

Coastal environments show specific features also from the acoustic propagation viewpoint. First, mesoscale features often present high dynamics. Second, the shallow depths imply strong acoustic interactions with the range-dependent seafloor and subseafloor. It is well established that in such situations, travel-time based tomography is difficult to use with real measurements because of the lack of resolvable independent arrivals. A full-field based tomography method must thus be envisioned. In this work, the considered measurements are a broad-band multi-frequency complex acoustic field on a vertical array of hydrophones. In the present case of an upwelling front in a coastal area, the environment is characterized by rapid variations of the temperature and the bathymetry along the range. Therefore, no adiabatic assumptions can be made regarding to modal propagation.

In the present study, the modal propagation takes into account the range-dependent bathymetry and the acoustic bottom properties. The geoacoustic parameters used for this area are: compression speed = $1600\,\mathrm{m/s}$, density = $1.8\,\mathrm{g/cm^3}$, attenuation = $0.2\,\mathrm{dB}/\lambda$. In future work, the precise geoacoustic model will be inferred from multibeam, seismic and sediment core dataset obtained in the framework of the EC FP7 Ocean Acoustic Exploration project [11].

A. ROMS-based simulations

In the present paper, we apply the feature model parameterization on a more realistic coastal scenario, simulated with the Regional Ocean Model System (ROMS) model as a tool for the numerical experiments. This model solves the primitive equations of motion using S-coordinated vertically, which is a generalization of σ-coordinate, allowing resolution variable mainly in the Ekman layer of surface and bottom. In ROMS, we progress in resolving the error of the pressure gradient due to co-σ [12], with boundary conditions appropriate to topography and irregular coastline, for free surface contours of sea and open ocean. The grid model was constructed with spatial resolution between 3 km to 5 km, which is able to reproduce features such as meanders, eddies and coastal upwelling. The bathymetry is extracted from the database ETOPO-2 [13]. The period of integration was 2 years and 6 months. The mass fields used in the experiment were taken from [14]. The field of initial mass was built upon climatological data for the month of January. In the open field contour, the data forcing was performed with monthly climatological values, and interpolated in the time domain the values of two consecutive months synchronized to the period of simulation. Boundary conditions and radiational Flather were used to solve, respectively, the barotropic and baroclinic velocity.

The implementation evolved for one year with NCEP daily wind stress for stabilization. After this, a high resolution hourly NCEP wind for January of 2001 was imposed to provide a scenario of the upwelling cycle in the Cabo Frio region.

The outputs of ROMS simulation are then projected on the feature model parameterization scheme (by a least-square minimization of the temperature field) to obtain the representation of the scenario in terms of time-evolving feature model parameters. In this paper, a unique time snapshot is selected to illustrate the sensitivity study (Fig. 3). This snapshot shows an upwelling situation, and is therefore representative of the typical features that have to be detected acoustically.

B. Acoustic ambiguities

The sensitivity of the acoustic-based cost function to the feature model parameters need to be explored. Furthermore, because the feature model involves several parameters, the problem of inter-correlation is also addressed. The projection of one realization of a ROMS simulation on the feature model parameter space constitutes our reference ("true") environment (Fig. 3). The feature model parameters are varied around representative values to test the corresponding effect on the cost function.

The cost function to minimize is based on the Bartlett processor on the N transmitted frequencies, defined as [15]

$$\phi(\boldsymbol{m}) = \frac{1}{N}\sum_{n=1}^{N} 1 - \frac{\boldsymbol{p}^{\dagger}(\boldsymbol{m},\omega_n)R(\omega_n)\boldsymbol{p}(\boldsymbol{m},\omega_n)}{||\boldsymbol{p}(\boldsymbol{m},\omega_n)||^2||\boldsymbol{d}(\omega_n)||^2} \tag{3}$$

where $\boldsymbol{m}$ is the model vector (here, the feature model parameters), $\boldsymbol{p}(\boldsymbol{m},\omega)$ is the predicted (replica) field vector of the acoustic-pressure observations across the vertical array at the frequency ω, and $\boldsymbol{d}(\omega)$ is the vector of acoustic-pressure measurements across the vertical array at the frequency ω. $R(\omega)$ is the corresponding spatial correlation matrix of the complex acoustic data at the frequency ω, defined as

$$R(\omega) = \boldsymbol{d}(\omega)\boldsymbol{d}^{\dagger}(\omega). \tag{4}$$

The $\dagger$ symbol denotes the conjugate transpose. Using this normalization, the best match between data and replica is achieved when the cost function is equal to 0, and the absence of correlation is equal to 1.

For this sensitivity study, the acoustic source is placed near the coast and a virtual vertical array spanning the whole water column is placed at 40-km range from the source. Figure 4 shows the values of the Bartlett processor when varying two parameters simultaneously, with a fixed covariance matrix defined by the acoustic transimissions through the reference environment. The resulting ambiguities reveal a strong dependence in the number and range of frequencies involved in the cost function. These frequencies are voluntarily kept in the lower frequency range to maintain a sufficiently high signal-to-noise ratio over the 40-km range of propagation, under real conditions.

Several observations can be made from these forward simulations. First, the trade-off between uncertainty (large and lower secundary peaks) and sensitivity (sharp and higher secundary peaks) is realized when combining multiple frequencies of different ranges. Typically lower frequencies are less sensitive, but more robust to spatial inhomogeneities, and

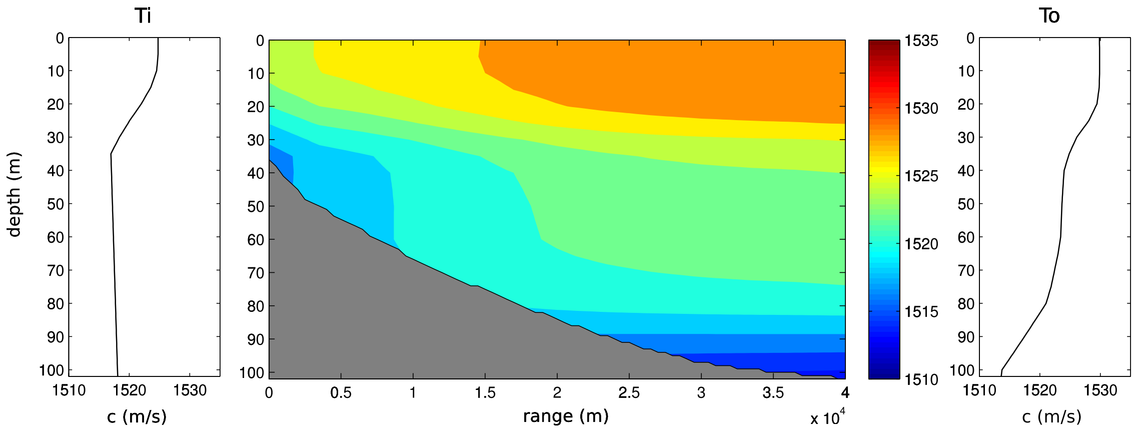


Fig. 3. Reference environment constructed from the feature model, based on the ROMS simulation output. Inshore and offshore profiles are shown on each side of the 2-dimensional temperature field.

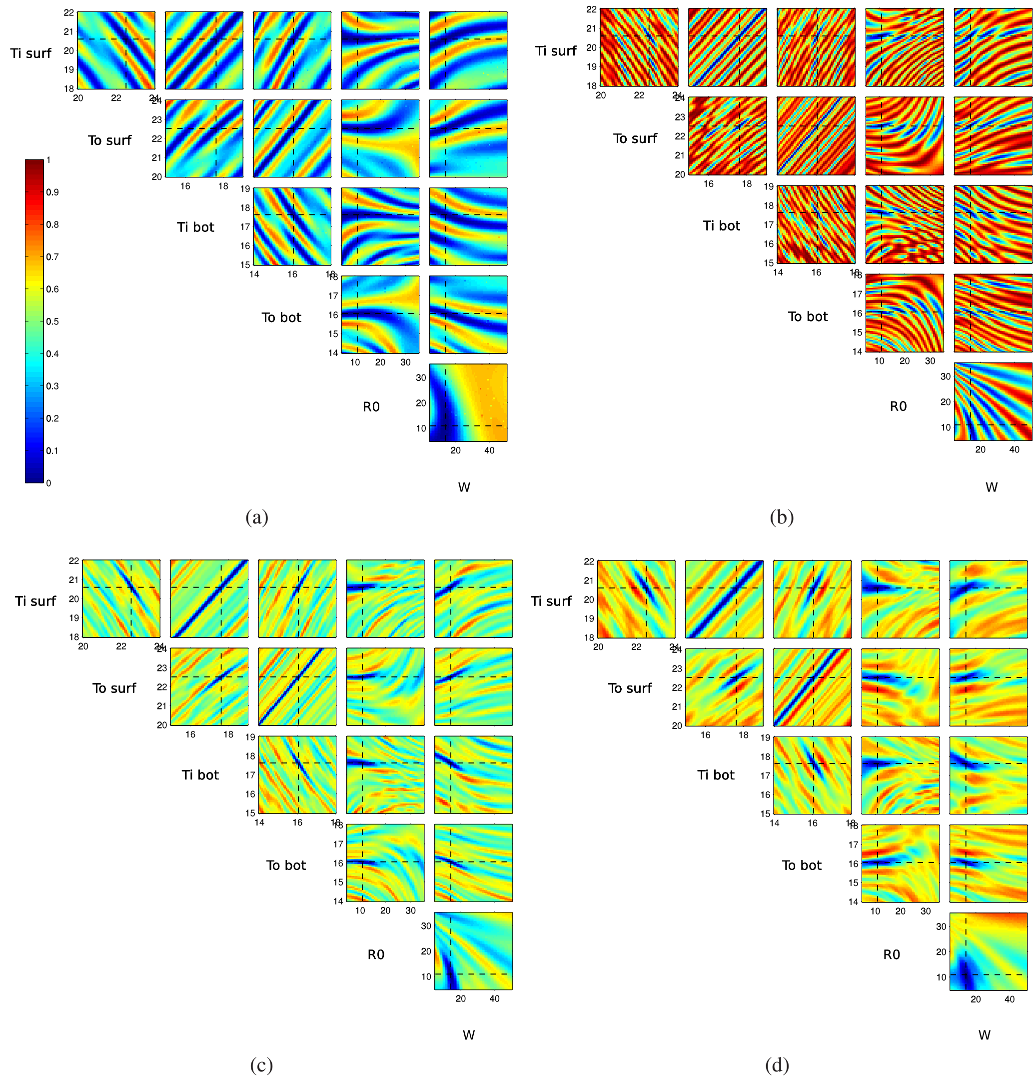


Fig. 4. Two-dimensional ambiguities for the feature model parameters of upwelling, using a source placed at 20-m depth, with (a) 200 Hz, (b) 400 Hz, (c) third-octave frequencies between 200 Hz and 400 Hz. The figure (d) show the ambiguities when the source is placed at 5-m depth, with third-octave frequencies between 200 Hz and 400 Hz. For each plot, only two parameters are varying, the other remaining fixed at their true values. The values of the reference upwelling parameters are indicated by the dashed lines.

higher frequencies are more sensitive to spatial variations, reducing the uncertainty around the estimates, but decreasing the robustness of the observables. Secondly, even with multiple frequencies, important correlations remain between temperature values (e.g., the respective ambiguities between the bottom temperatures and between the surface temperatures). Finally, Fig. 4d shows that the source position may also impact the observability. Indeed, the ambiguity related to a source position of 5-m depth shows less local minima of low level, improving therefore the discrimination of upwelling situations with respect to the 20-m depth position.

When working with a more realistic hydrophone setup (16 hydrophones, between 60-m and 90-m depth), the discrimination of environments decreases. To compensate this effect, an increase of the number of tranmitted frequencies can be used (see, e.g., [15]). Figure 5 shows the resulting ambiguities for a 16-hydrophone array, with two different frequency sets, consisting of 5 and 20 frequencies over the same frequency range 200Hz–600Hz. The average value of the cost function is typically lower, but a dense number of frequencies enables to minimize the number and depth of local minima.

When using very sparse array, an effective method to increase the sensitivity to the environmental parameters is to modify the cost function to a frequency-coherent processor. As shown in [16], the frequency-domain model-based matched filter (FD-MBMF) enables to invert geoacoustic parameters of a shallow water environment with a light instrumentation (4-element vertical array), exploiting the frequency diversity instead of dense spatial sampling. The FD-MBMF is expressed as:

$$\phi(\boldsymbol{m}) = \left(\prod_{h=1}^{H} 1 - \frac{|\boldsymbol{d}_h^{\dagger} \boldsymbol{p}_h(\boldsymbol{m})|^2}{||\boldsymbol{d}_h||^2 ||\boldsymbol{p}_h(\boldsymbol{m})||^2} \right)^{\frac{1}{H}} \tag{5}$$

where H is the number of hydrophones, and the vectors $\boldsymbol{p}_h$ and $\boldsymbol{d}_h$ are defined as

$$\begin{aligned} \boldsymbol{d}_h &= (d_h^{f_1} d_h^{f_2} \ldots d_h^{f_N}) \quad \text{[data]} \\ \boldsymbol{p}_h &= (p_h^{f_1} p_h^{f_2} \ldots p_h^{f_N}) \quad \text{[replica].} \end{aligned}$$

As for the Bartlett processor (3), the best match between data and replica is achieved when the cost function is equal to 0, and the absence of correlation is equal to 1. Figure 6 shows the resulting ambiguity for a 4-element array, spanning 60-m to 75-m depth. Compared to Fig. 5, the use of this cost function reduces strongly ambiguities for all parameters and keep a high level of discrimination between upwelling parameter values. It should be noticed that for some couple of parameters, the ambiguity is in the opposite direction than observed for the Bartlett estimator (see, e.g., the bottom temperatures ambiguity). However, the problem of robustness should be further adressed, especially when environmental mismatches are expected.

IV. Conclusion

In this paper, the sensitivity of two different acoustic-based cost functions regarding varying upwelling situations is explored. A parametric feature model based on realistic upwelling situations enables to study the ambiguities between the feature model parameters. Effect of frequency setup and source position were studied. These results confirm that frequency diversity enables to reduce ambiguity and to increase the robustness of the cost function. Moreover, it was shown that a frequency-coherent processor enables the use of very sparse array, showing no losses of sensitivity to the upwelling parameters when reducing drastically the number of hydrophones. In the future, the upwelling feature model will be tested as a new range-dependent parameterization scheme of the temperature field for acoustic tomography purposes.

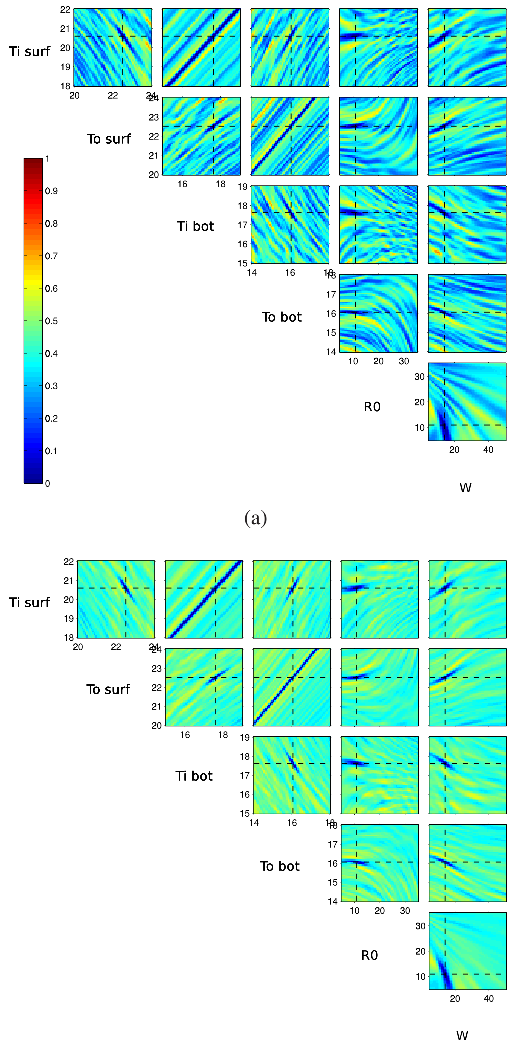


Fig. 5. Two-dimensional ambiguities for the feature model parameters of upwelling, using a source placed at 20-m depth and a 16-element array spanning the lower part of the water column, with (a) third octave frequencies and (b) twelfth octave frequencies, between 200 Hz and 600 Hz. For each plot, only two parameters are varying, the other remaining fixed at their true values. The values of the reference upwelling parameters are indicated by the dashed lines.

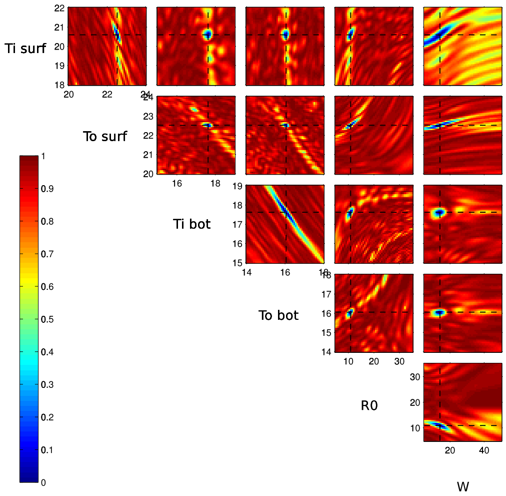


Fig. 6. Two-dimensional ambiguities for the feature model parameters of upwelling, using a source placed at 20-m depth and a 4-element array spanning 60-m to 75-m depth. The cost function is the FD-MBMF, involving the 13 twelfth octave frequencies between 200 Hz and 400 Hz. For each plot, only two parameters are varying, the other remaining fixed at their true values. The values of the reference upwelling parameters are indicated by the dashed lines.

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