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COMPARATIVE ANALYSIS OF NONHYPERBOLIC MULTIPARAMETRIC TRAVEL-TIME APPROXIMATIONS OF MULTICOMPONENT SEISMIC DATA CONSIDERING DIFFERENCE OF DEPTH BETWEEN SOURCE AND RECEIVER USING OBN TECHNOLOGY

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ABSTRACT. The processing of multicomponent seismic data is already a challenge concerning the velocity analysis. When it is performed for offshore survey, the difficulty increases a lot more with the use of OBN (Ocean Bottom Nodes) technology. The ray tracing asymmetry generated by the wave conversion and the difference of datum between source and receptor are not the only factors which contribute for a strongly nonhyperbolic travel-time event. The layered subsurface models and the large offsets employed in the offshore surveys make the nonhyperbolicity even stronger. Aiming to solve this problem, eight approximations to perform the velocity analysis were tested for two models. The complexity analysis of each nonhyperbolic multiparametric approximation was also studied to understand their behaviors during the optimization process. The relative error between the observed curve and the calculated curve with each approximation was computed for PP and PS reflection events of two models. With these information, it was possible to determine which approximation is the most reliable one for this kind of models.

Keywords: multicomponent, OBN, nonhyperbolic, multiparametric.

RESUMO. O processamento de dados sísmicos multicomponentes já é um desafio com relação à análise de velocidades. Quando realizado para levantamentos marítimos, a dificuldade aumenta muito mais com o uso da tecnologia OBN (Ocean Bottom Nodes). A assimetria no traçado de raios gerada pela conversão de onda e pela diferença de profundidade entre fonte e receptor não são os únicos fatores que contribuem para um evento de tempos de trânsito fortemente não-hiperbólico. Os modelos estratificados de subsuperfície e os grandes afastamentos aplicados nos levantamentos marítimos tornam a não-hiperbolicidade ainda mais forte. Visando resolver este problema, oito aproximações para realizar a análise de velocidades foram testadas para dois modelos. A análise de complexidade de cada aproximação não-hiperbólica multiparamétrica também foi estudada para entender seus comportamentos durante o processo de otimização. Os erros relativos entre as curvas observadas e calculadas com cada aproximação foram calculados para os eventos de reflexão PP e PS dos dois modelos. Com estas informações, foi possível determinar qual aproximação é a mais confiável para estes tipos de modelos.

Palavras-chave: multicomponente, OBN, não-hiperbólico, multiparamétrico.

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INTRODUCTION

The travel-time approximations are significantly important in the reflection seismic processing, more specifically when they are applied to moveout correction and velocity analysis (Yilmaz, 2000).

For homogeneous isotropic media with short offsets and no difference of datum between source and receptor, and PP-wave reflection events, it is used the hyperbolic approximation proposed by Dix (1955). However, this approximation is not valid for PS-wave reflection events, for data with difference of datum between the source and the receptor, large offsets and for layered media. The nonhyperbolicity generated by these factors can be overcome using approximations that consider this effect to perform a reliable determination of the parameters.

In the last decades, several characteristics of the nonhyperbolic behavior were studied and some approximations have been shown in different works aiming to control some nonhyperbolic effect (Malovichko, 1978; Blias, 1983 and 2009; Muir & Dellinger, 1985; Castle, 1988 and 1994; Slotboom, 1990; Tsvankin & Thomsen, 1994; Alkhalifah & Tsvankin, 1995; Li & Yuan, 1999 and 2001; Cheret et al., 2000; Causse et al., 2000; Tsvankin & Grechka, 2000a,b; Fomel & Grechka, 1994 and 2001; Leiderman et al., 2003; Li, 2003; Silva et al., 2003; Ursin & Stovas, 2006; Aleixo & Schleicher, 2010; Golikov & Stovas, 2012). However, most of them were not proposed to be used for multicomponent seismic data, and none of them for a reflection seismic data that considers difference of datum between the source and the receptor.

In this paper, it is proposed to perform the complexity analysis of the objective function and the velocity analysis of several nonhyperbolic multiparametric approximations for two stratified offshore models. A multicomponent seismic data is used, with focus on PP and converted PS events, with the use of the OBN (Ocean Bottom Nodes) technology considering long offsets between source and receptors.

METHODOLOGY

Travel-Time Approximations

Eight approximations were chosen for this study. The first one is the hyperbola equation (Eq. 1), proposed by Dix (1955).

$$t=\sqrt{t_0^2+\frac{x^2}{v^2}} \tag{1}$$

Where x is the vector of offsets, t_0 is the zero-offset travel-time and v is the RMS (Root Mean Square) velocity.

However, this approximation is treated here only as a reference, due to the fact that it is insufficient for the strong nonhyperbolic conditions studied here.

Malovichko (1978) proposed an approximation known as shifted hyperbola (Eq. 2) which was also studied and derived by Castle (1988 and 1994) and de Bazelaire (1988). This approximation was proposed to control the effect of large offsets in inhomogeneous media using the S parameter.

$$t=t_0^2\left(1-\frac{1}{S}\right)+\frac{1}{S}\sqrt{t_0^2+\frac{Sx^2}{v^2}} \tag{2}$$

The S parameter depends on the μ_4 and μ_2 by the relation $S=\mu_4/\mu_2^2$, where $\mu_j(j=2,4)$ is the j-th velocity momentum (Eq. 3).

$$\mu_j=\sum_{k=1}^{n}t_k v_k^j/\sum_{k=1}^{n}t_k \tag{3}$$

and v_k is the interval velocity of the k-th layer and t_k is the travel-time of the k-th layer.

An approximation aiming to analyze the nonhyperbolic behavior concerning the wave conversion was proposed by Slotboom (1990). However, this approximation (Eq. 4) has only the t_0 and v as the unknown parameters, which make it simpler than most of the nonhyperbolic approximations.

$$t=\frac{t_0}{2}+\sqrt{\frac{t_0^2}{2}+\frac{x^2}{2v^2}} \tag{4}$$

Alkhalifah & Tsvankin (1995) proposed an approximation (Eq. 5) that uses the η parameter. This parameter (Eq. 6) is a function of the anisotropic parameters of Thomsen (1986).

$$t=\sqrt{t_0^2+\frac{x^2}{v^2}-\frac{2\eta x^4}{v^2\left[t_0^2v^2+(1+2\eta)x^2\right]}} \tag{5}$$

$$\eta=\frac{\varepsilon-\delta}{1+2\delta} \tag{6}$$

where ε quantifies the difference between the wave velocities along the symmetry axis and perpendicular to the symmetry axis, and δ represents the propagation of P-wave for angles close to the symmetry axis.

An approximation that also uses the S parameter was proposed by Ursin & Stovas (2006). However, for this approximation (Eq. 7), the S parameter is expressed in a quasi-acoustic case as a function of the anisotropic parameters of Thomsen (1986).

$$t=\sqrt{t_0^2+\frac{x^2}{v^2}-\frac{(S-1)\,x^4}{4v^4\left(t_0^2+\frac{(S-1)}{2}\frac{x^2}{v^2}\right)}} \tag{7}$$

Another approximation that uses the S parameter was proposed by Blias (2009). To develop this approximation (Eq. 8), the author performed several numerical tests related to the walkway vertical seismic profile (VSP).

$$t=\frac{1}{2}\sqrt{t_0^2+\frac{1-\sqrt{S-1}}{v^2}x^2}+\frac{1}{2}\sqrt{t_0^2+\frac{1+\sqrt{S-1}}{v^2}x^2} \tag{8}$$

Muir & Dellinger (1985) proposed an approximation (Eq. 9) which uses the anellipticity parameter f, which describes how much the wavefront differs from the spherical shape and tends to the elliptical shape.

$$t=\sqrt{t_0^2+\frac{x^2}{v^2}-\frac{f\,(1-f)\,x^4}{v^2\left(v^2t_0^2+fx^2\right)}} \tag{9}$$

In the Li & Yuan (2001) approximation (Eq. 10), γ is used as the nonhyperbolic parameter. This approximation aims to consider the CP (Conversion Point), which helps to control the effects of a nonhyperbolicity associated to the wave conversion.

$$t=\sqrt{t_0^2+\frac{x^2}{v^2}-\frac{(\gamma-1)}{\gamma v^2}\frac{(\gamma-1)\,x^4}{4t_0^2v^2+(\gamma-1)\,x^2}} \tag{10}$$

Where γ is the ratio between the squared P-wave stacking velocity v_{P2} and the squared converted wave stacking velocity v_{C2} (Eq. 11).

$$\gamma=\frac{v_{P2}^2}{v_{C2}^2}=\frac{\gamma_{eff}\,(1+\gamma_0)}{(1+\gamma_{eff})} \tag{11}$$

The relation γ_{eff} is expressed by $\gamma_{eff}=\gamma_2^2/\gamma_0$, where γ_2 is the ratio between the stacking P-wave and stacking S-wave, and γ_0 is the ratio between P-wave velocity and S-wave velocity which travel along the normal component.

Offshore Models Studied

The models studied in this paper are offshore and presented a layered structure (Fig. 1). They were based on stratigraphic informations obtained from well logs from the Santos Basin, Brazil. The models present a large salt structure sealing the carbonate reservoir.

The use of multicomponent seismic data is fundamental to obtain more accurate results. And considering an offshore investigation, there is a necessity of using the OBN technology to reach the S-wave information. The maximum offset used for these models was 15000 meters. The reflection events analyzed are concerning the base of the salt structure and, therefore, the top of the reservoir.

In Model 1 (Table 1), the 3rd, 4th and 5th layers are part of the salt structure and the carbonate reservoir (V_P = 4010 m/s and V_S = 2012 m/s) is beneath this structure.

Table 1 – The parameters of the Model 1: Layer thickness (Δz), P-wave velocity (V_P), S-wave velocity (V_S) and V_P/V_S ratio.

Layer	Δz (m)	V_P (m/s)	V_S (m/s)	V_P/V_S
Water	2157	1500	0	-
1	496	2875	1200	2.40
2	108	3505	1628	2.15
3	664	4030	2190	1.84
4	262	5005	2662	1.88
5	1485	4220	2210	1.91

In the Table 2, the carbonate reservoir (V_P = 3599 m/s and V_S = 1800 m/s) is present under the 6th layer. The 4th, 5th and 6th layers are the salt structure.

Table 2 – The parameters of the Model 2: Layer thickness (Δz), P-wave velocity (V_P), S-wave velocity (V_S) and V_P/V_S ratio.

Layer	Δ z (m)	V_P (m/s)	V_S (m/s)	V_P/V_S
Water	2101	1500	0	-
1	431	2852	1190	2.40
2	82	3390	1512	2.24
3	525	3461	1590	2.18
4	212	3801	1885	2.02
5	1151	4321	2219	1.95
6	503	3820	1899	2.01

Complexity Analysis

As the numerical analysis was treated as an inverse problem by an optimization criterion, the complexity analysis was important to determine the behavior of each approximation, which one

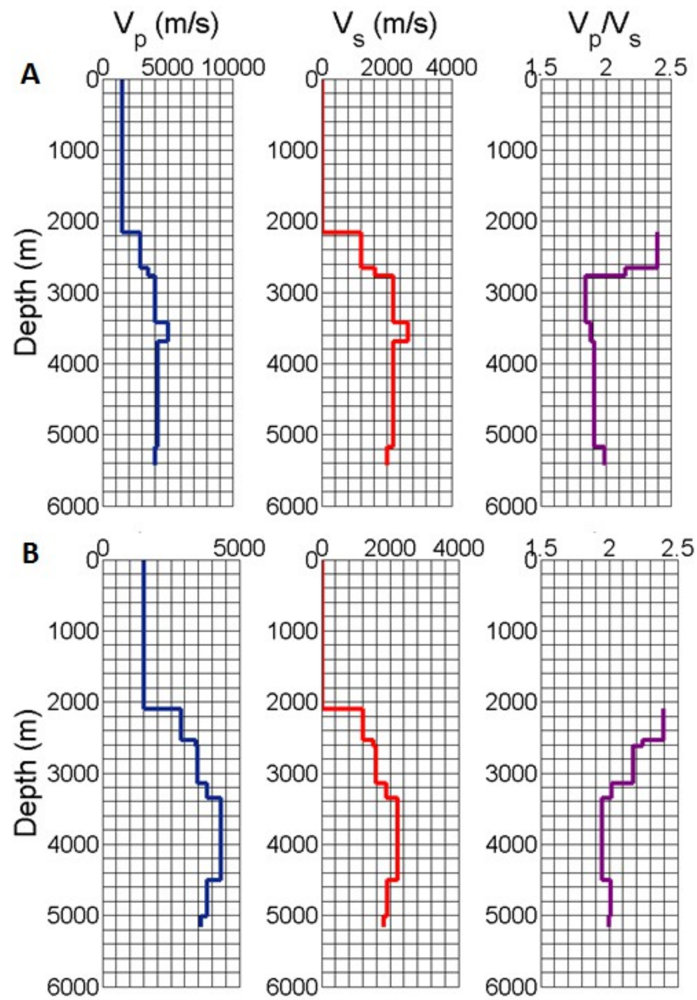

Figure 1 – P-wave velocity (V_P), S-wave velocity (V_S) and V_P/V_S ratio profiles of the (A) Model 1 and (B) Model 2.

is unimodal or multimodal, to figure out the complexity of the optimization for each approximation (Kurt, 2007).

It can be observed that the topographic structure varies drastically with the used approximation. However, the variation with the kind of reflection event is merely concerning the displacement of the structure, which is associated to the difference of values of each parameter. Despite of this, the model influences slightly the topography of the function.

In Figures 2A and 2B, the approximation proposed by Malovichko (1978) showed a homogeneous topological structure concerning the objective function and also presented to be always unimodal (only the global minimum region) without dependence on the model (Figs. 2C and 2D).

Figures 3A and 3B showed that the Alkhalifah & Tsvankin (1995) approximation presents the same kind of variation between the PP and PS events. It also can be observed that between the Model 1 and Model 2 (Figs. 3C and 3D), this approximation presented only soft variations concerning the topological structure related to the model variation.

It can be observed, in Figures 4A to 4D and in Figure 5A to Figure 5D, that the approximation proposed, respectively, by Ursin & Stovas (2006) and the one proposed by Blias (2009) present the same kind of variations between PP and PS events and between the two models. Even presented to be unimodal for the models tested here, they presented multimodal (presents the global and one or more local minimum regions) characteristics in

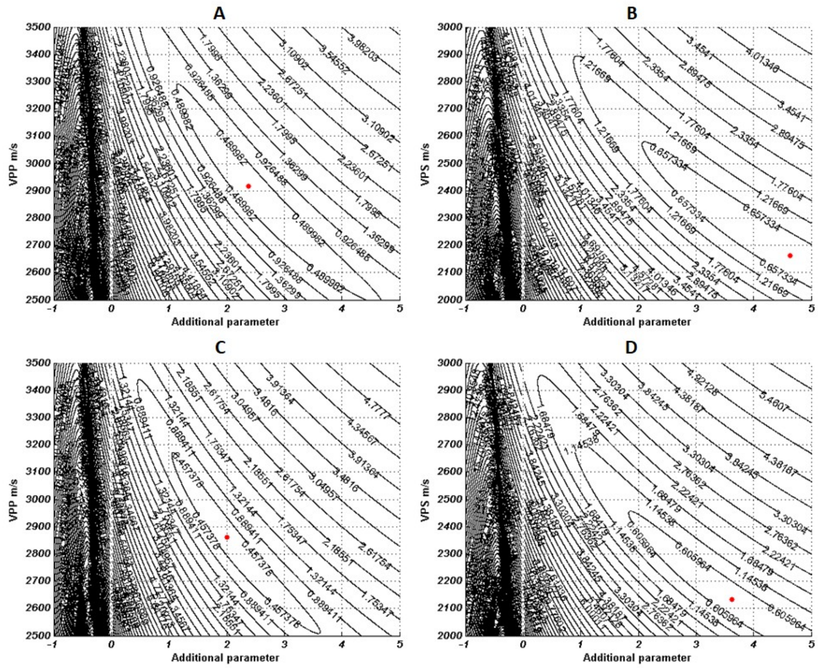

Figure 2 – Residual function maps to demonstrate the complexity of the Malovichko (1978) approximation for the (A) PP and (B) PS event of the (C) Model 1 and (D) Model 2. Red dispersions represent the global minimum regions.

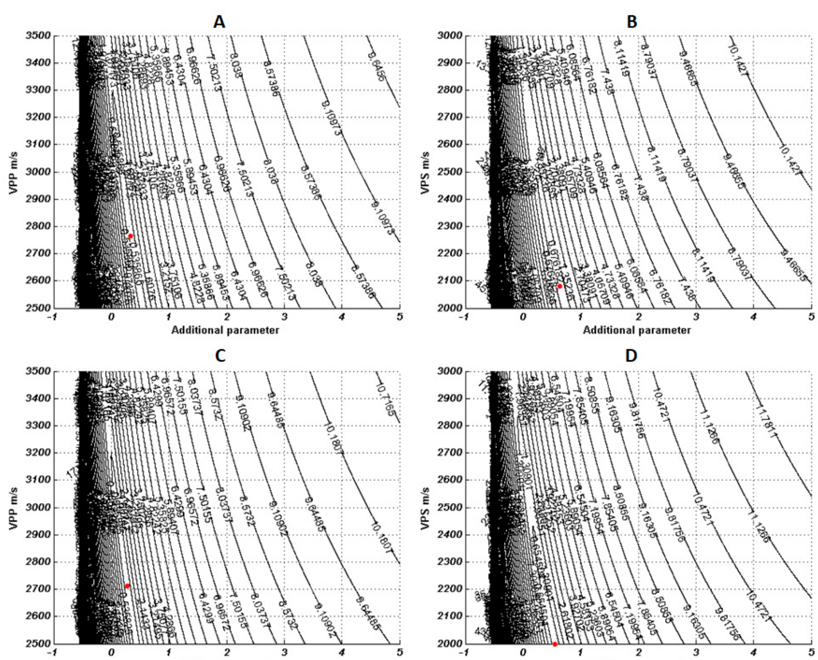

Figure 3 – Residual function maps to demonstrate the complexity of the Alkhalifah & Tsvankin (1995) approximation for the (A) PP and (B) PS event of the (C) Model 1 and (D) Model 2. Red dispersions represent the global minimum regions.

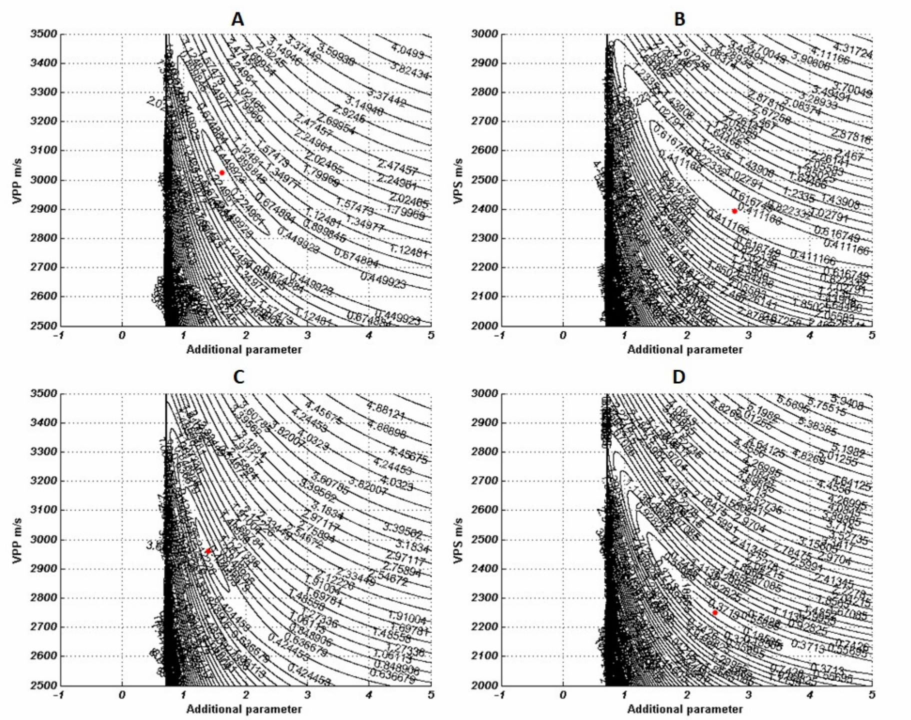

Figure 4 – Residual function maps to demonstrate the complexity of the Ursin & Stovas (2006) approximation for the (A) PP and (B) PS event of the (C) Model 1 and (D) Model 2. Red dispersions represent the global minimum regions.

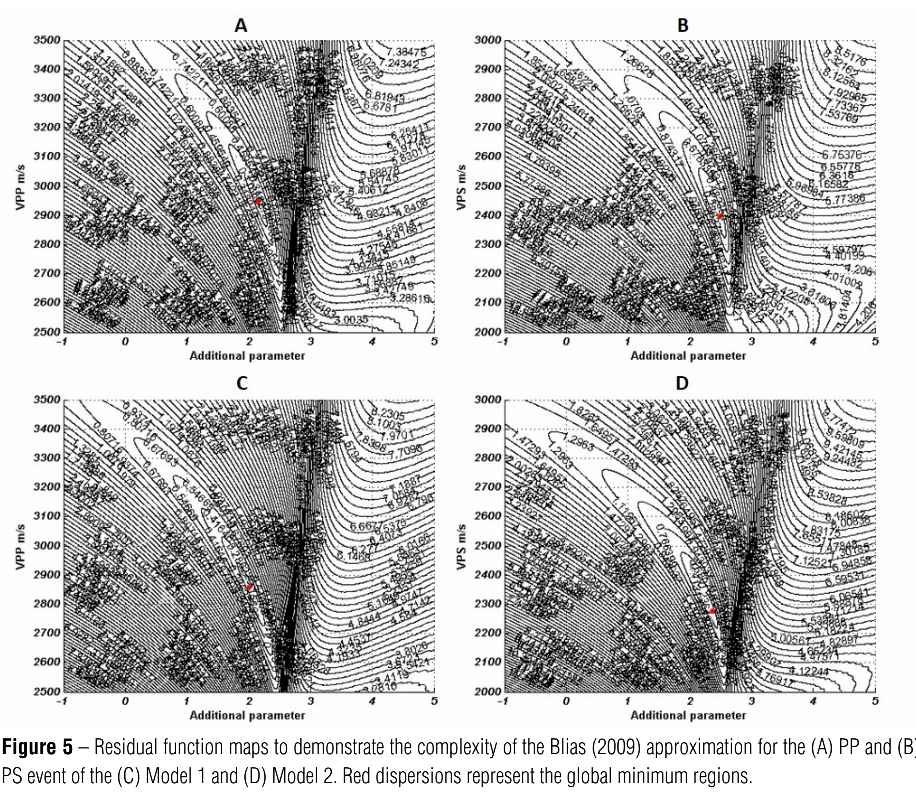

Figure 5 – Residual function maps to demonstrate the complexity of the Blias (2009) approximation for the (A) PP and (B) PS event of the (C) Model 1 and (D) Model 2. Red dispersions represent the global minimum regions.

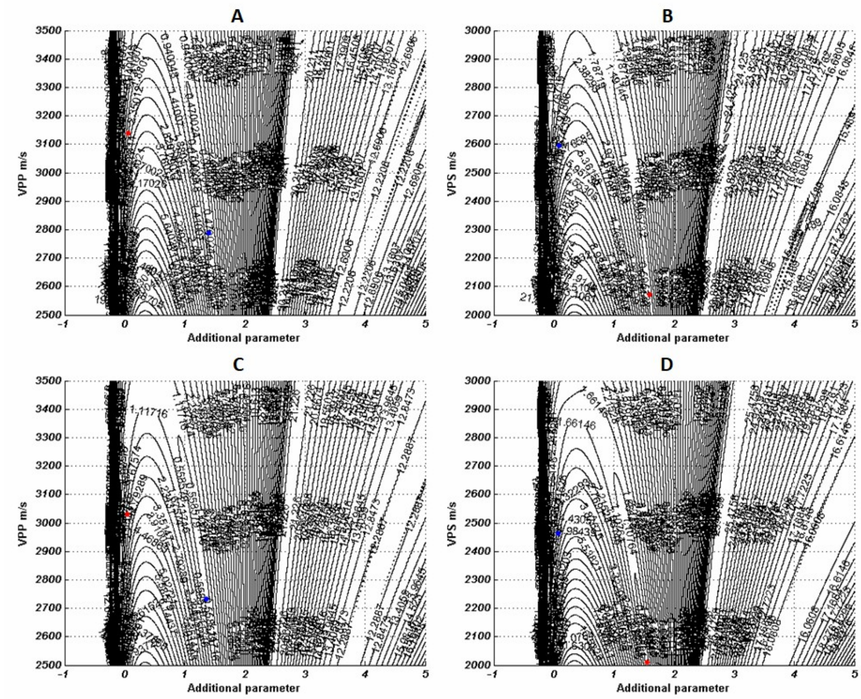

Figure 6 – Residual function maps to demonstrate the complexity of the Muir & Dellinger (1985) approximation for the (A) PP and (B) PS event of the (C) Model 1 and (D) Model 2. Red dispersions represent the global minimum regions and the blue dispersions represent the local minimum regions.

previous works (Zuniga et al., 2015 and 2018), what can increase the difficulty of the analysis for the kinds of models used here for these two approximations.

The approximation developed by Muir & Dellinger (1985) presented a multimodal behavior. However, the variation between the PP and the PS reflection events is different than the others (Figs. 6A and 6B). Its variation is not only concerning the displacement if the objective function structure, but there is also a variation of the position between the global and the local minimum region. This happens due to the local and global minimum region values being too close to each other. The variation between Model 1 and Model 2 (Figs. 6C and 6D) is subtle like the previous approximations.

The approximation proposed by Li & Yuan (2001) showed a multimodal behavior and only a structural variation between PP and PS reflection events (Figs. 7A and 7B). In Figures 7C and 7D, it can be observed the same kind of variations between the Model 1 and Model 2.

Comparison of Travel-Time Approximations

To compare the performance for different approximations, it was analyzed the difference between the observed curve and the calculated curve with each one of the eight approximations for the PP and PS reflection events of the two models. The relative errors in travel-times were computed to perform the accuracy analysis of the approximations.

The approximation proposed by Li & Yuan (2001) showed the best result for the PP reflection event of the Model 1 (Fig. 8). The second best result for this event was shown by Ursin & Stovas (2006) approximation. The third and the fourth best results for this event were respectively shown by Blias (2009) and Malovichko (1978).

The approximation proposed by Li & Yuan (2001) presented the best result for the PS reflection event of the Model 1 (Fig. 9). The approximations proposed by Blias (2009) and Malovichko (1978) presented the second and the third best results, respectively, with the fourth more accurate result being shown by the Ursin & Stovas (2006) approximation.

For the PP event of the Model 2 (Fig. 10), it is observed again the approximations proposed by Li & Yuan (2001) and by Ursin & Stovas (2006) presenting, respectively, the most accurate and the second most accurate results. For this event, Malovichko (1978) approximation presented the third best result, discreetly better than the Blias (2009) approximation.

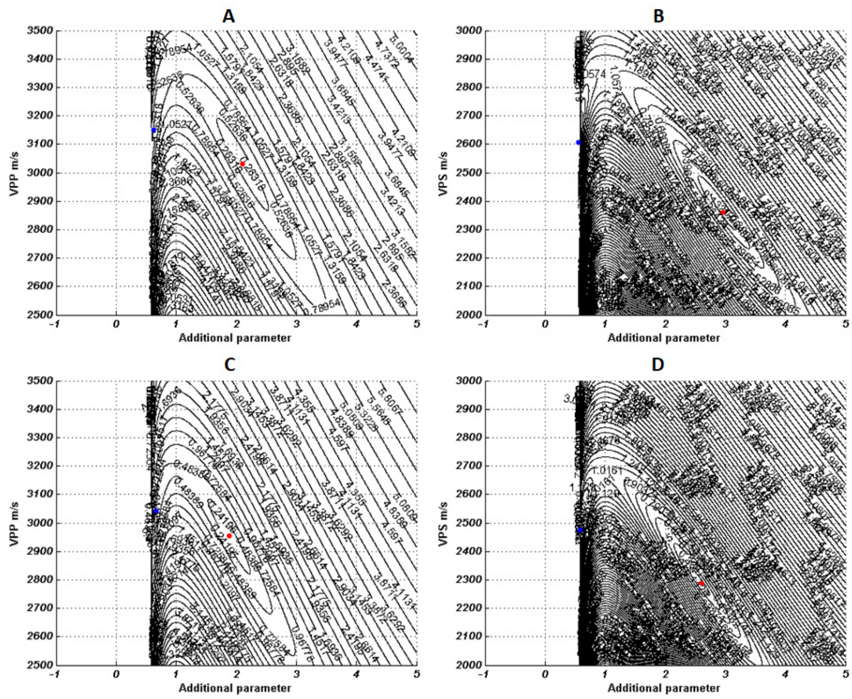

Figure 7 – Residual function maps to demonstrate the complexity of the Li & Yuan (2001) approximation for the (A) PP and (B) PS event of the (C) Model 1 and (D) Model 2. Red dispersions represent the global minimum regions and the blue dispersions represent the local minimum regions.

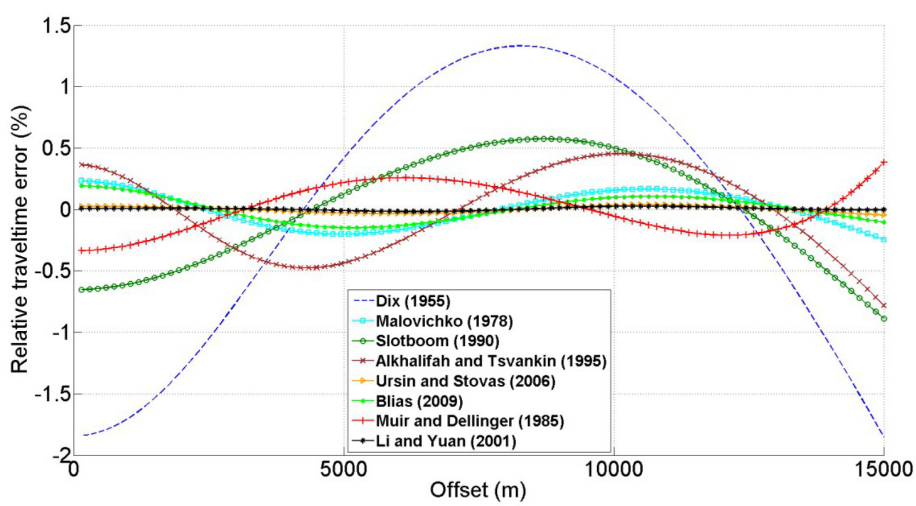

Figure 8 – Relative errors in travel-time between the observed curve and the calculated curve with each approximation, for the PP reflection event of the Model 1.

For the converted wave event of the Model 2, the approximation proposed by Li & Yuan (2001) showed the best result (Fig. 11). The approximation proposed by Blias (2009) presented the second most accurate result. Ursin & Stovas (2006) and Malovichko (1978) approximations presented respectively the third and the fourth best results.

As expected due to the fact of being the simplest approximations tested here, the approximations proposed by Dix

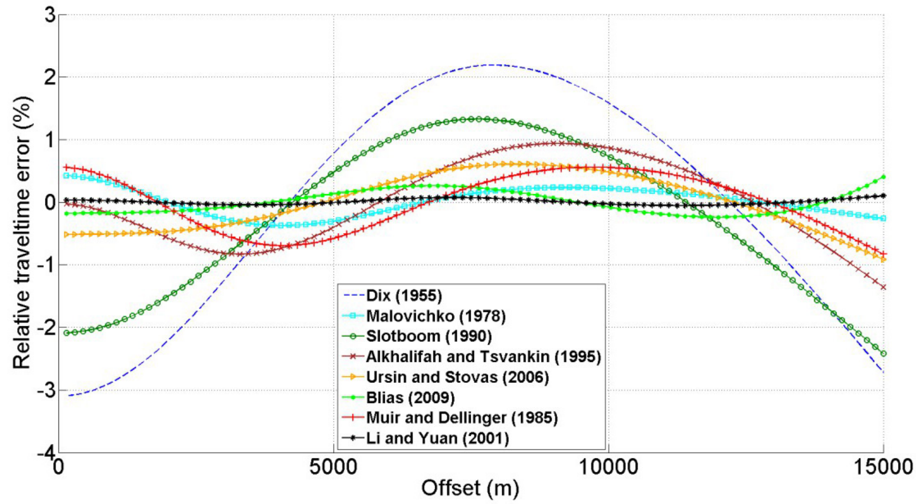

Figure 9 – Relative errors in travel-time between the observed curve and the calculated curve with each approximation, for the PS reflection event of the Model 1.

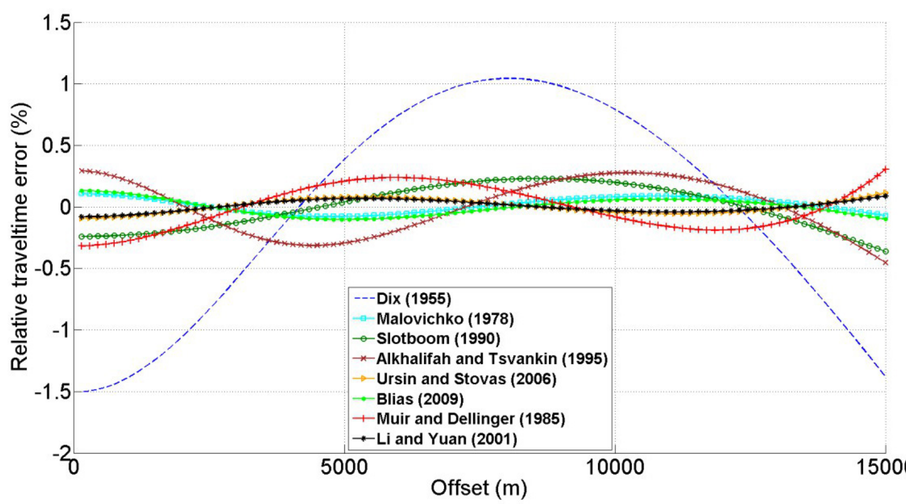

Figure 10 – Relative errors in travel-time between the observed curve and the calculated curve with each approximation, for the PP reflection event of the Model 2.

(1955) and by Slotboom (1990) showed respectively the worst and the second worst sets of results for PP and PS reflection events for both models.

For the nonhyperbolic multiparametric travel-time approximations, the worst set of results was presented by the Alkhalifah & Tsvankin (1995) approximation. Muir & Dellinger (1985) approximation appeared as the second less accurate approximation with three parameters for all the events tested here.

In a general form, Li & Yuan (2001) approximation showed the best results for PP and converted events for both models. Furthermore, the approximation proposed by Ursin & Stovas (2006) presented the second best results for PP events of both models, while the approximation proposed by Blias (2009) reached the second best set of results for the converted wave events. The approximation proposed by Malovichko (1978) showed the fourth best set of results with the maximum error not exceeding 0.5%.

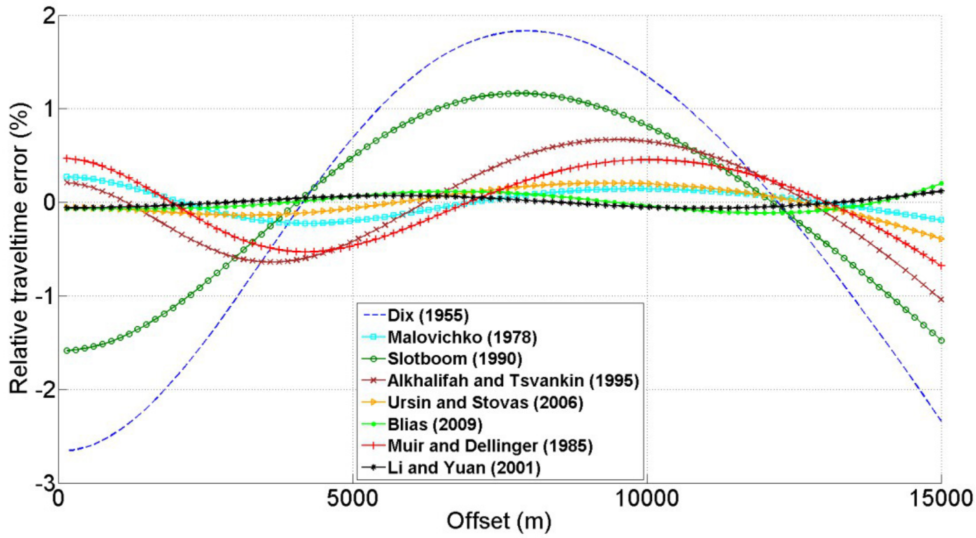

Figure 11 – Relative errors in travel-time between the observed curve and the calculated curve with each approximation, for the PS reflection event of the Model 2.

CONCLUSIONS

The approximation proposed by Li & Yuan (2001) showed, in a general form, the best set of results for each event observed. However, this approximation proved to be multimodal, which always demands the use of a global search algorithm or a multi-start procedure using a local search algorithm.

The approximations proposed by Ursin & Stovas (2006) and Blias (2009) showed the second best results respectively for PP events and converted PS events. The behavior of both approximations was unimodal for all events tested. However, both approximations have already shown a multimodal behavior (Zuniga et al., 2017). Thus, it is challenging to predict their behavior once it appears to depend on the characteristics of the model.

Even with the accuracy shown by the Malovichko (1978) approximation (error not higher than 0.5%), this equation presented the fourth best set of results. However, it proved to be unimodal, which does not require the use of a global search algorithm.

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