Hybridised Weighted Boot-Strap Differential Semblance

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SUMMARY

Velocity analysis is often necessary in pre-stack seismic processing to produce a good estimate of subsurface velocities. It requires the picking of moveout velocities on the semblance spectra. The semblance spectra is hampered with noise and lack of resolution around the peak representing the best move out velocity approximation. In this paper we introduce a new semblance scheme to reduce spectral noise and increase resolution in the semblance domain. The new scheme is based on a simple amalgamation of previously developed semblance enhancement methods. These methods are; the local-similarity weighted semblance, velocity-sensitivity weighted semblance and boot-strapped differential semblance. Velocity sensitivity semblance weights all traces based on sensitivity in the semblance spectra to changes in velocity, the local similarity weighting accounts for correlation between the stacked gather trace and all traces within the gather on a temporally localised scale and the boot-strapped differential semblance scheme weights the semblance spectra based on enhancing sensitivity to lateral differences in amplitudes. We test the proposed scheme on synthetic and real trace gathers. The test results show that our approach significantly improves the resolution and noise attenuation in the semblance spectra albeit to other semblance schemes.

Key words: Semblance, Boot-strapping, Normal Moveout, Weighting, Differential Semblance

INTRODUCTION

In seismic processing, the construction of a velocity model that best depicts the subsurface is crucial for optimal final imaging. A precursor to the construction of this final model is velocity analysis. Conventional normal moveout (NMO) velocity analysis is utilised to produce a move-out or stacking velocity field in the time domain which in turn can be used to construct interval velocities. A good interval velocity model is important as an initial model for full waveform inversion (Tarantola, 1984; Virieux and Operto, 2009). Velocity analysis can be done via several approaches. Some common methods are; constant velocity stack analysis, constant gather analysis and semblance analysis (Yilmaz, 2001).

In this paper we focus on semblance based velocity analysis. NMO velocity model building aided by analysis of semblance or velocity spectra (Taner and Koehler, 1969; Neidell and Taner, 1971) involves measuring coherency in amplitudes within a common midpoint (CMP) gather after application of NMO correction for a range of trial NMO velocities. Peaks in coherency correspond to the best NMO velocity estimate. Unfortunately the resolution of the semblance spectra can be hampered by noise in the data, and insensitivity in NMO corrected amplitudes at small apertures. Various methods have been developed to improve the resolution of the velocity spectra for an array of different issues. In (Sarkar and Baumel, 2000) the authors introduced a trend based semblance operator to account for the inability in traditional semblance to account for polarity anomalies due to amplitude versus offset (AVO) phenomena. The trend utilised was based on the Shuey simplification of the Zoeppritz equation (Shuey, 1985) where the fitting parameters in the trend were found through the minimisation of the trend model. The new semblance operator was referred to as 'AB' semblance. In (Fomel, 2009) this work was extended by providing an explicit form of the 'AB' semblance through derivation of the trend fitting parameters.

In (Luo and Hale, 2010, 2012) the authors developed a modified expression of conventional semblance with an embedded weighted function which accounted for sensitivity in velocity changes with offset. They were able to demonstrate improvements in the overall resolution of the velocity spectra. More recent work (Liu et al., 2014; Chen et al., 2015) applies a modified semblance operator based on weighting the corrected traces by a measure of local similarity between a reference trace and each trace in the corrected gather as originally introduced in (Fomel (2007a)). This approach further improves the resolution of velocity spectra. In (Abbad et al., 2009; Abbad and Ursin, 2012) random sorting of traces in the gather of interest is utilized and applied to semblance based on a differential operator, see (Brandsberg-Dahl et al., 2003). This method called boot-strapping enhances the influence of lateral sensitivity in the data. As with the weighted schemes, they were also able to obtain higher resolution in the semblance spectra.

In this paper we develop a new semblance calculation scheme that combines the velocity sensitivity weighting methodology of (Luo and Hale, 2010, 2012) and the local similarity weighting scheme of (Liu et al., 2014; Chen et al., 2015) by embedding both weighting functions in the normalised correlation coefficient form of the semblance operator. This modified operator is called the 'hybridized-weighted' semblance operator. We then utilise this new modified operator with the iterative boot-strap differential semblance scheme of (Abbad and Ursin, 2012).

The new scheme was tested on a four layer synthetic model and compared with other existent schemes mentioned previously. The tests demonstrate that the new scheme potentially provides an increase in resolution around peaks in coherency and attenuated spectral noise from the velocity spectra.

METHOD

Normal Moveout

Consider an uncorrected CMP gather with *N* traces and *M* samples. This can be represented by a matrix called *q* equation (1)

$$q = \begin{pmatrix} q_{0,0} & \cdots & q_{N,0} \\ \vdots & \ddots & \vdots \\ q_{0,M} & \cdots & q_{N,M} \end{pmatrix} \quad (1)$$

Where $q_{j,k}$ are the signal amplitude at the *j*th trace and *k*th sample at offset offset x_j, j=1,...,*N* and k=1,...,*M*. The goal of velocity analysis is to approximate the move out characteristics of reflection events in *q*. More often than not, in isotropic media, the reflection moveout is approximated by the normal move out (NMO) equation (2)

$$t_x(x_j,t_k)^2 = t_k^2 + \frac{x_j^2}{V_{nmo}^2} \quad (2)$$

Where $t_x(x_j,t_k)$ is the travel time at offset x_j, t_k is the zero-offset travel time and V_{nmo} is the move out or stacking velocity. For a particular move out velocity, we look to shift the trace $q_{j,\cdot}$ at offset offset x_j by time offset $t_k - t_x(x_j,t_k)$ while searching for the best fit V_{nmo} in the hopes that the time shifts approximated at each trace will horizontally align the reflection signal. To apply the correction we evaluate equation (2) for $t_x(x_j,t_k)$ then use sinc interpolation on $q_{j,k}$ at $t_x(x_j,t_k)$.

Conventional Semblance

Determination of a good estimate of the optimal V_{nmo} for NMO move out, or V_{nmo} by convention, can be achieved in various ways. Techniques often used in velocity analysis are constant velocity stack (CVS), constant velocity gather (CVG) analysis, semblance analysis, travel time tomography and most recently full waveform (FWI). In this paper we will focus on semblance analysis. In semblance analysis using the NMO approximation, we start by choosing an array of *L* trial move out velocities; $V=(V_1,V_2,\dots,V_{L-1},V_L)$. For each trial velocity V_i we substitute V_i into equation (2) for V_{nmo}. Using $t_x(x_j,t_k)$ we correct the arrival times in $q_{j,k}$ for all *j* and *k*. We then substitute $q_{j,k}$ into the conventional semblance operator (Taner and Koehler, 1969; Neidell and Taner, 1971) equation (3).

$$S_C(k) = \frac{\sum_{k-\tau/2}^{k+\tau/2}\left(\sum_{j=1}^{N} q(j,k)\right)^2}{\sum_{k-\tau/2}^{k+\tau/2}\sum_{j=1}^{N} q(j,k)^2} \quad (3)$$

Where Sc(k) $S_c(i,k)$ is the measure of coherency produced via the semblance operator and *k*th sample, $q_{j,k}$ is the amplitude at the *j*th trace and *k*th sample of the corrected gather. *N* is the number of traces in the gather and τ is the size of the time window utilised to temporally smooth the semblance spectra. The outer sum on the numerator and denominator are for temporal smoothing. This is applied here by convolving the result of the inner summation with a boxcar filter of length τ. Notice that the S_c is also depending on the trial velocity so defines in fact a two-dimensional array.

Semblance Weighting Functions

Equation (3) can be expressed in the form of the normalised squared correlation coefficient (Neidell and Taner, 1971; Fomel, 2009). Using this fact, (Luo and Hale, 2012; Liu et al., 2014) express a modified semblance operator in the form of the normalised correlation coefficient with an embedded weighting term in the sums (equation (4)).

$$S_W(k) = \frac{\sum_{k-\tau/2}^{k+\tau/2}\left(\sum_{j=1}^{N} w(j,k)q(j,k)r(k)\right)^2}{\sum_{k-\tau/2}^{k+\tau/2}\sum_{j=1}^{N} w(j,k)q(j,k)^2 \sum_{k-\tau/2}^{k+\tau/2}\sum_{j=1}^{N} w(j,k)r(k)^2} \quad (4)$$

Where w(j,k) are offset j and trace k independent weighting coefficients and r(k) are …… (Luo and Hale, 2012) the weighting function equation (5) hase been used where the change in move out velocity is parametrized by a new unitless, time dependent parameter $b(k)$.

$$w_{VS}(j,k) = \left(1 - b(k)\right) + b(k)\frac{c(k)x(j)^2}{t_x(j,k)} \quad (5)$$

Where:

$$c(k) = \frac{t_k N}{\sum_{j=1}^{N} x^2}$$

To determine the value of the $b(k)$ (Luo and Hale, 2012) firstly apply some constraints to this parameter. Those constraints being that $b(k)$ is bounded in the range of 0 to 1. This constraint is applied to ensure that S_w remains in the realm of conventional semblance values. The semblance is then minimized over values of $b(k)$ between 0 and 1. To do so, the roots of the derivative of (4) with respect to $b(k)$ are calculated with $w_{VS}(j,k)$ substituted for $w(j,k)$.

Another type of semblance weighting was introduced by (Liu et al., 2014; Chen et al., 2015). This weighting scheme known as local-similarity weighting (equation(7)) aims to improve the resolution of the velocity spectra by weighting all traces in the gather of interest by an attribute known as local-similarity. This method requires that the local-similarity between all traces in the corrected gather and a reference trace be calculated and the resultant measure be utilised to weight the traces for each set of corrected gathers corrected by each trial velocity in the semblance calculation. The calculated weight is embedded into the semblance calculation via equation (4) .

$$w_{sw}(j,k) = \kappa[q(j,k), q_r(k)] \tag{7}$$

Here, $w_{sw}(j,k)$ is the weighting function and $\kappa[q(j,k), q_r(k)]$ is the measure of local similarity between the signal $q(j,k)$ at time k and offset j, and the amplitude from a reference trace $q_r(k)$ at time sample k. $q_r(k)$ can equal the zero-offset trace $q(0,k)$ or it could be a trace formulated by stacking the gather using conventional or more sophisticated stacking methods. As pointed out in (Liu et al., 2014; Chen et al., 2015) better results in the local similarity calculation can be achieved using a stacked trace as the reference trace, if the signal to noise ratio is too low. This is due to the fact that stacking methods tend to attenuate random noise.

To find $\kappa[q(j,k), q_r(k)]$ we follow the methodology of (Fomel., 2007a; Fomel, 2007b; Liu et al., 2014; Chen et al., 2015) in which we obtain the local similarity through solving a least-squares problem with shaping regularization of the localized components of the vector form of the normalized correlation coefficient.

Boot-Strap Differential Operator

In (Abbad et al., 2009) boot-strapping is applied to the gather pre-application of the discretised form of the differential operator (subtracted from a factor of 1), see (Brandsberg-Dahl et al., 2003; Abbad et al., 2009). Boot-strapping involves randomly sorting the traces on the offset jth axis of the gather. The differential semblance operator with standard trace ordering may be insensitive to lateral changes at small apertures, boot-strapping works to reduce this problem by increasing the lateral sensitivity of the gather. One minus the Boot-strapped differential operator can be expressed as (8).

$$\Phi(k) = \left(1 - \frac{\sum_{j=2}^{N} \sum_{k-\tau/2}^{k+\tau/2} \left(q(\bar{j},k) - q(\bar{j}-1,k)\right)^2}{2(N-1) \sum_{j=1}^{N} \sum_{k-\tau/2}^{k+\tau/2} q(\bar{j},k)^2} \right) \tag{8}$$

Here the bar above $\bar{j}$ denotes the trace index after the gather has been pre-sorted with boot-strapping. Multiplying the differential operator by a semblance operator, (this can be conventional or weighted), results in what (Abbad et al., 2009) is refered to as boot-strapped differential semblance (equation (9)) .

$$S_{BDS}(k) = \Phi(k)\xi(k) \tag{9}$$

Here $\Phi(k)$ is the inverse differential operator (8) and $\xi(k)$ is a place holder for a semblance operator. This place holder can be replaced with equations (4) or (3).

This idea can be developed further by first sectoring the traces in the gather into two categories (Abbad and Ursin, 2012). These categories are near- and far-offset traces. The traces in both categories then have boot-strapping applied to them. Following the boot-strapping procedure the two categories a re-merged with traces placed in alternating order and the differential operator is applied to the resorted data. This procedure can be further enhanced by repeating the procedure in an iterative fashion (Abbad and Ursin, 2012). For O iterations this methodology can be expressed as equation (10).

$$S_{HRBDS}(k) = \left(\prod_{i=1}^{O} \Phi(k)\right)\xi(k) \tag{10}$$

Hybridized-Weighted Boot-Strap Differential Semblance Scheme

Both velocity-sensitivity (5) and local-similarity (7) weighting provide means to improve the resultant velocity spectra when substituted into the modified semblance operator (4). To take advantage of these enhancements we introduce a novel weighting approach based on simply combining both velocity-sensitivity and local-similarity weight into one hybridized-weighting function equation (11)

$$w_{hyb}(j,k)=\kappa[q(j,k),q_r(k)]\left((1-b(k))+b(k)\left(\frac{c(k)x(j)}{t_x(j,k)}\right)^2\right) = w_{sw}(j,k)w_{vs}(j,k) \tag{11}$$

The construction of the new weighting function is simply the multiplication of $w_{sw}(j,k)$ and $w_{vs}(j,k)$. This new weight is substituted into the modified semblance operator (4). To further attenuate spectral noise, the modified semblance with hybridized weighting is substituted in for ξ in equation (10).

RESULTS

A synthetic CMP gather (Figure 1a) was modelled using analytic Green's function via the Madagascar module 'sfkirmod' (Haddon and Buchen, 1981). Here a four layer reflection profile was produced with a linear velocity profile $V(t)$=1500+360 . t, with a dominant signal frequency of 10Hz, with 1501 samples at a sample rate of 0.004 seconds. Six different semblance schemes were tested and compared. These were; conventional semblance, velocity-sensitivity semblance, local-similarity semblance, hybridized-weighted semblance with no boot-strap differential operator, hybridized-weighted boot-strap differential semblance after 5 iterations and the same scheme but with 10 iterations. Results are shown in Figure 1 where the vertical axis shows sampling time and the horizontal axis trial move out velocities. Colours represent values of the corresponding semblance where red represent large values and black small values. We would like to see distinct spots of large semblance values indicating the NMO velocities for arrival times of reflected signals, As expected, both velocity-sensitivity (1c) and local similarity (1d) semblance operators show a marked improvement in the spectra in comparison with the conventional semblance operator (1b). The hybridized weighting semblance with no boot-strap differential operator has results comparable to that of (1d). Closer analysis of (1e) and (1d) show that although the two are comparable, the new weighting term introduces high frequency noise to the spectra, conversely (1e) also improves the definition of the semblance peaks of interest. (1f) and (1g) where 5 and 10 iterations of boot-strap differential have been applied to the hybrid weighting semblance resolves the issue of additional noise by attenuation whilst keeping the higher definition introduced by the hybridized-weighting term. One downfall of the boot-strap differential term is that if too many iterations are applied then the semblance peaks may become over-attenuated as can be seen in (1g).

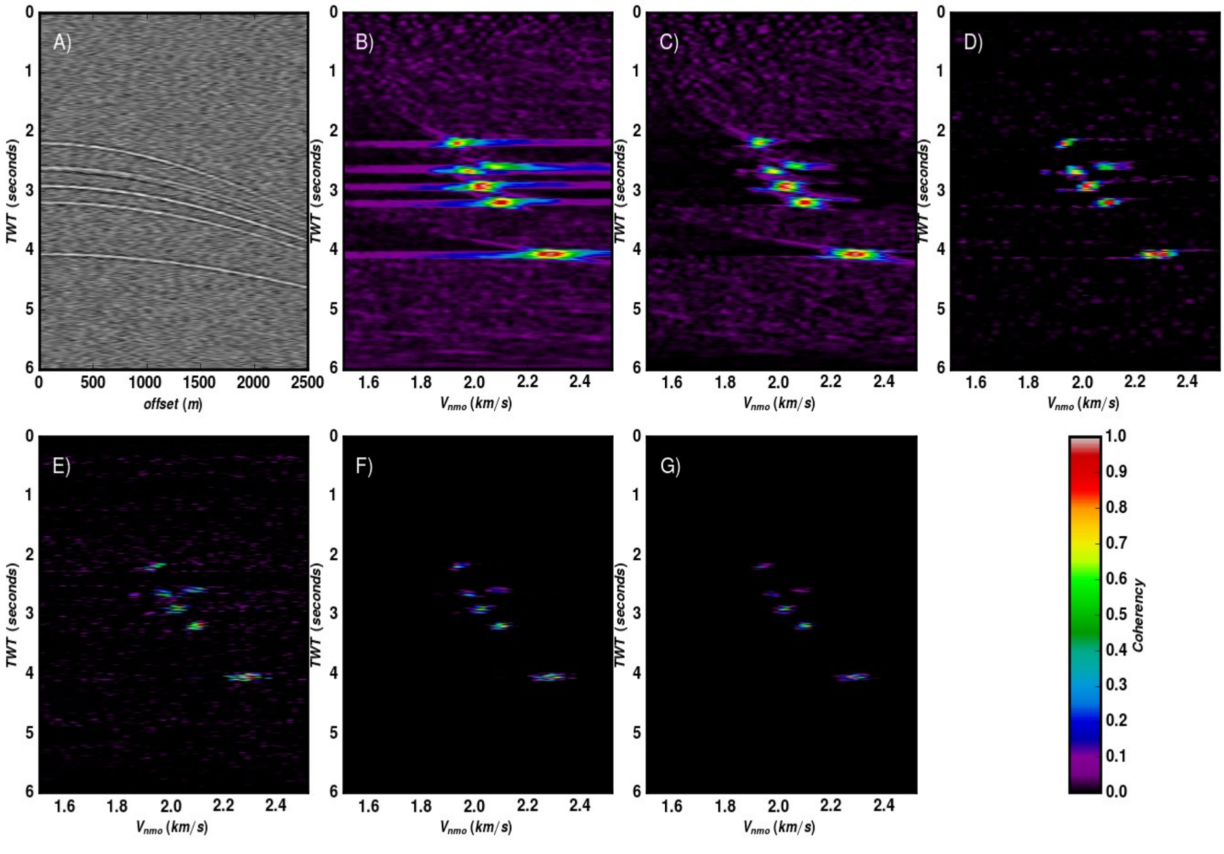

Figure 1: A comparison of six different semblance schemes on; a) a CMP with 4 interfaces. b) Using Conventional semblance, c) using velocity-sensitivity semblance, d) using local-similarity weighted semblance, e) using hybridized-weighted semblance with no boot-strap differential operator, f) using the new hybridized-weighted boot-strap differential semblance after 5 iterations, g) using hybridized-weighted boot-strap differential semblance after 10 iterations.

Figure 2 shows a comparison of the semblance at time = 4.1 seconds for all semblances (b) to (f) from Figure 1. The vertical axis are values for the trial NMO velocities while the vertical axis represents the semblance values. In this figure we can see that semblance on the flanks of the peaks seen in both conventional and velocity-sensitivity semblance are removed in local-similarity, hybridized and hybridized boot-strap semblance (5 iterations). Closer comparison of the last 3 semblances mentioned that further reduction in the semblance on the flanks is present in hybridized-weighted and hybridized-weighted boot-strap differential semblance in comparison to the local-similarity semblance. It is clear that some higher frequency noise is present in the hybridized-weighted semblance this noise is reduced by the boot-strapped differential procedure.

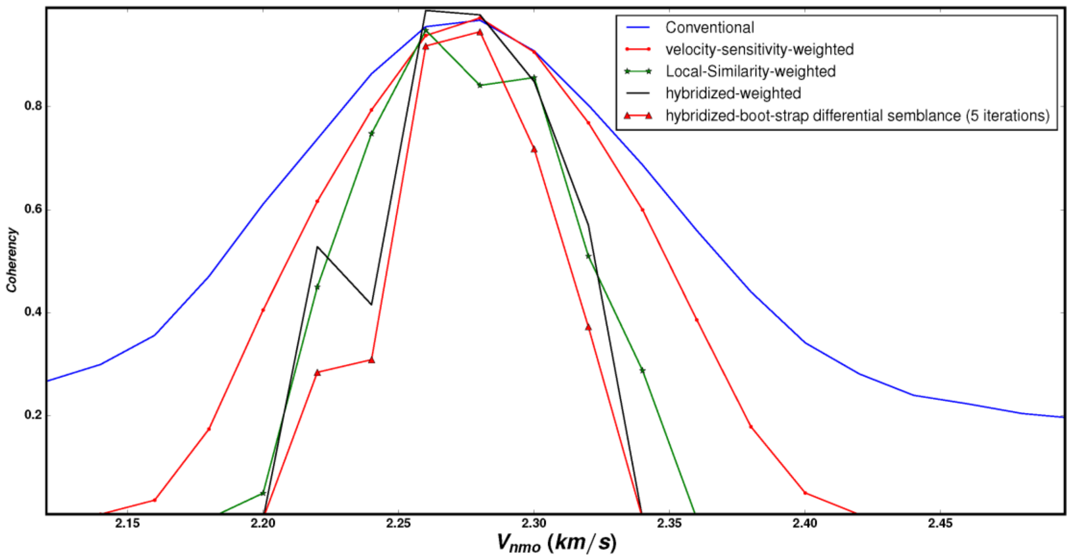

Figure 2: Comparison of different semblance schemes at a time-slice of 4.1 seconds through the semblance spectra.

A comparison of all weighting operators with 5 iterations of boot-strap differential semblance (Figure 3) shows that the hybridized weighting (3e) although comparable to Local-similarity (3d), provides the sharpest result overall. The semblance is again analysed at a time slice of 4.1 seconds (Figure 4). The boot-strap differential semblance scheme helps to sharpen the semblance peaks in all weighted semblance terms but overall, the sharpest peak is the boot-strap differential semblance with hybridized weighting.

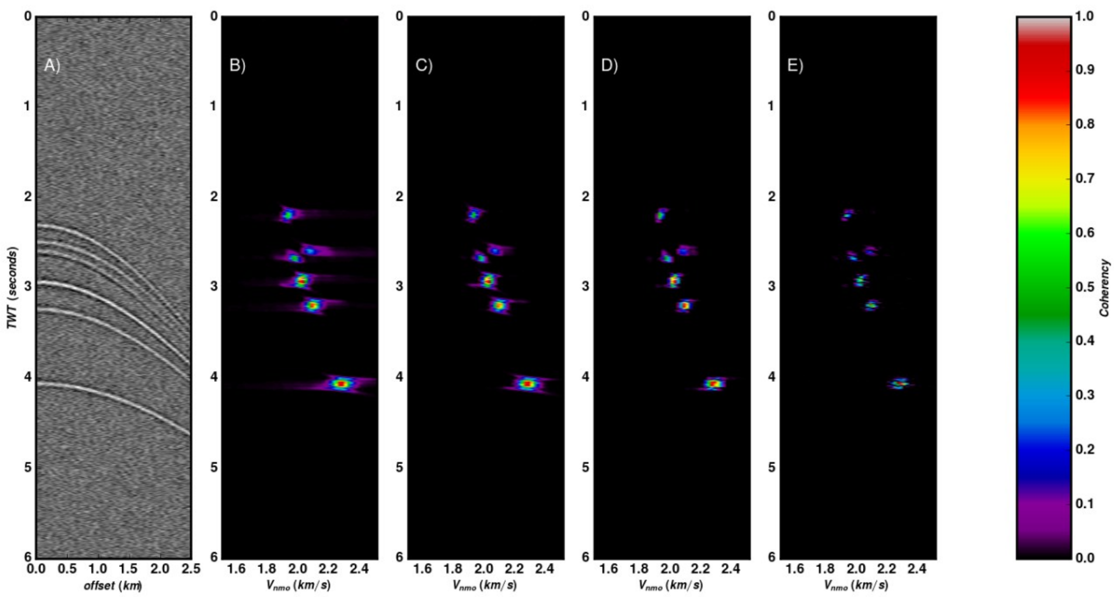

Figure 3: A comparison of 5 iterations boot-strap differential semblance on 4 different semblance operators for; a) a CMP with 4 interfaces. b) Using Conventional semblance, c) using velocity-sensitivity semblance, d) using local-similarity weighted semblance, d) using hybridized-weighted semblance with no boot-strap differential operator, e) using hybridized-weighted boot-strap differential semblance after 5 iterations.

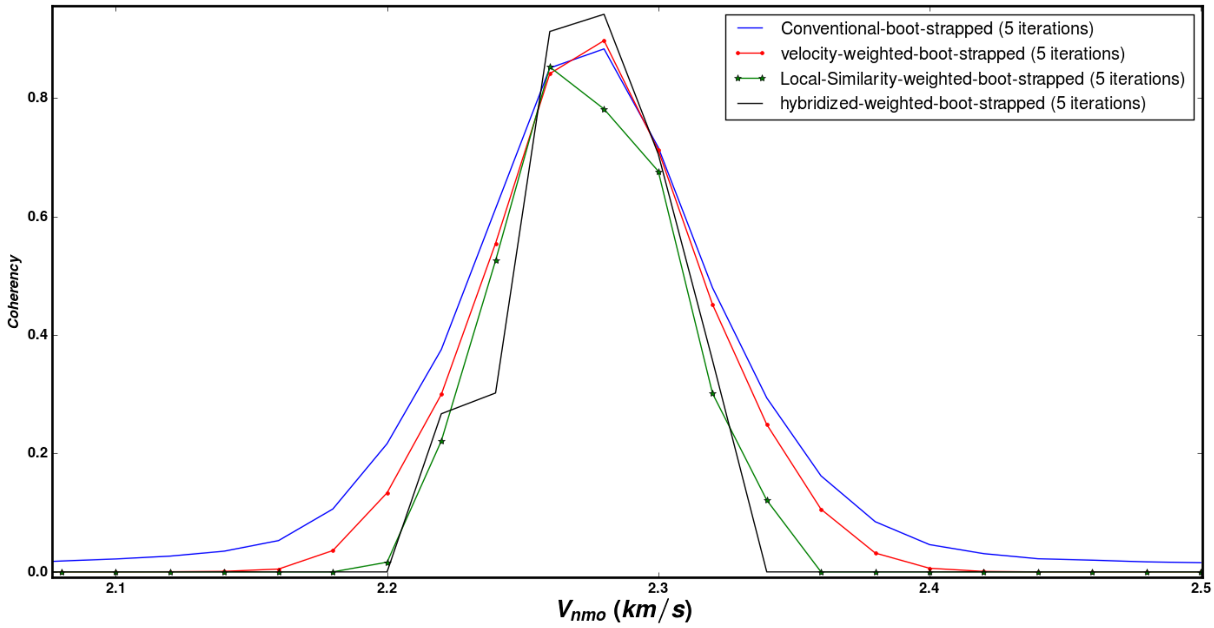

Figure 4: Comparison of different weighted boot-strapped differential semblances at a time-slice of 4.1 seconds through the semblance spectra.

CONCLUSIONS

An amalgamation of weighting terms embedded in the semblance operator with the boot-strapped differential operator offers a scheme for improving resolution and reducing noise in the velocity spectra. Combining the local-similarity weighting term with the velocity-sensitivity weighting term and embedding this combination in the weighted semblance function provides a new measure of semblance that improves the definition of semblance around the peaks at the cost of additional high-frequency spectral noise. By using this new weighting term with the boot-strapped differential semblance operator (Abbad and Ursin, 2012), we can get the benefits of improved sharpness around the semblance peaks and the attenuation of spectral noise. The new semblance scheme was tested on a four-layer isotropic synthetic data. The results are in agreement with those presented in (Abbad and Ursin, 2012; Luo and Hale, 2012; Liu et al., 2014) in that all introduced methods work towards improving the quality of the semblance spectra. The new scheme presented here can be applied readily in any standard processing workflow, to help improve the quality of velocity fields produced via velocity picking. The new scheme may also help with velocity spectra analysis in non-hyperbolic and azimuthal velocity analysis aiding in the development of anisotropic models. The hybridized weighting term provides greater definition at semblance peaks at the cost of introduced high-frequency noise. Embedding this weighting term into the semblance operator and utilising this operator in a boot-strap differential semblance scheme introduces this advantage of higher definition and whilst removing any high-frequency noise introduced by the weighted semblance operator.

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