1.5D tau-p internal multiple prediction in Seismic Unix

Andrew Iverson, Kris Innanen and Daniel Trad

ABSTRACT

The inverse scattering series developed by Weglein et al is utilized for the prediction of internal multiples. The algorithm is implemented in 1.5 dimensions in the tau-p domain. While the method has shown promise in its ability to predict multiples there are still challenges to overcome to become a standard in processing. The issue addressed here is the computational expense of the method, which is shown to be decreased using Seismic Unix and parallel processing. The computational time for the chosen model is reduced by a factor of approximately 120 in comparison to the MATLAB implementation. It is also shown how artifacts from the prediction in 1.5D tau-p can be minimized through a time domain tau-p transform and as shown by Sun and Innanen (2015) a spatial cosine taper.

INTRODUCTION

An ongoing issue in creating the seismic image is the removal of unwanted noise in the data. When recording land seismic data there are various types of noise sources that degrade the final image. Land seismic specific issues often involve the near surface due to topography changes, relatively unconsolidated material, and the potential for heterogeneity. For this project the type of noise targeted for removal is due to multiple reflections in the subsurface.

Using the Inverse Scattering Series (ISS), the location in time of multiples can be predicted solely with the seismic data and no additional subsurface information. In practice, there are difficulties with implementation of the method due to the computational expense. Recently the algorithm has been applied in various domains with increased success (Sun & Innanen, 2016). Through parallel processing and implementation into Seismic Unix computational run times will be compared.

INVERSE SCATTERING SERIES

The subset of the inverse scattering series takes the recorded wavefield to give all possible internal multiples (Weglein et al., 1997). This method will only predict long-path multiples assuming epsilon is chosen correctly. Giving equation (1) below to predict interbed multiples from the seismic data alone.

$$\begin{aligned} b_3(k_g, k_s, \omega) &= \frac{1}{(2\pi)^2} \iint_{-\infty}^{\infty} dk_1 e^{-iq_1(\epsilon_g - \epsilon_s)} dk_2 e^{iq_2(\epsilon_g - \epsilon_s)} \int_{-\infty}^{\infty} dz_1 e^{i(q_g + q_1)z_1} b_1(k_g, -k_1, z_1) \\ &\times \int_{-\infty}^{z_1 - \varepsilon} dz_2 e^{-i(q_1 + q_2)z_2} b_1(k_1, -k_2, z_2) \int_{z_2 + \varepsilon}^{\infty} dz_3 e^{i(q_2 + q_s)z_3} b_1(k_2, -k_s, z_3), \end{aligned} \tag{1}$$

Where in equation (1)

$$q_x = \frac{\omega}{c_0}\sqrt{1 - \frac{k_x^2 c_0^2}{\omega^2}}, \tag{2}$$

b_3 is the interbed multiple prediction, b_1 is the prepared input data, q_x is the vertical wavenumber and ϵ is the depth below free surface of the source (s) and receiver (g), k is the Fourier conjugate variable, z_1, z_2 and z_3 are the depths chosen to satisfy lower-higher-lower relationship and ε is the search limiting parameter (Sun and Innanen, 2014). Equation (1) predicts seismic multiples in the Fourier domain through the specific combinations of events which obey the lower-higher-lower relationship in the data. It is shown how two deeper events can be added which can be subtracted from a deeper event to create the equivalent multiple (Figure 1).

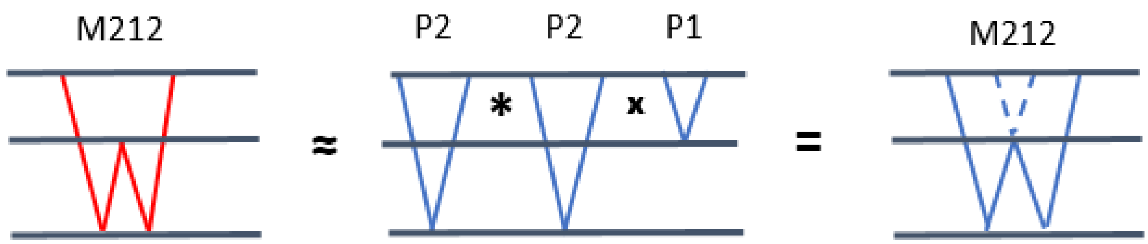

FIG. 1. Schematic displaying how a multiple can be replicated with a combination of primaries through a convolution (*) and correlation (x)

The benefit of the method is that no subsurface information or input of multiple generating horizons is required. The method predicts all multiples in the data through combining subevents in the data. It does this for every possible combination of events. And when there are spatial dimensions this is done for all events at all offsets. The result is a large computational requirement due to combining every possible sub event to predict all internal multiples.

Reduction to 1.5D tau-p domain

Equation (1) can be simplified and reduced to a 1.5D domain by assuming a v(z) medium. This is accomplished by assuming that the source and receiver wavenumbers are equivalent.

$$k_g = k_s, \tag{3}$$

Using this assumption alters the vertical wavenumber from equation (2) to give the following

$$q_g + q_s = 2q_g = k_z, \tag{4}$$

Giving the 1.5D Version of the algorithm

$$b_3(k_g,\omega) = \int_{-\infty}^{\infty} dz_1 e^{ik_z z_1} b_1(k_g,z_1) \int_{-\infty}^{z_1-\varepsilon} dz_2 e^{-ik_z z_2} b_1(k_g,z_2) \times \int_{z_2+\varepsilon}^{\infty} dz_3 e^{ik_z z_3} b_1(k_g,z_3), \tag{5}$$

The input data and method can be altered so that the procedure is carried out in any domain which has shown increased multiple prediction accuracy (Sun & Innanen, 2016). The tau-p domain will be implemented due to its noted improvements. Equation (5) can be written in the tau-p domain as demonstrated in Coates & Weglein (1996) giving equation (6).

$$b_3(p_g,\omega) = \int_{-\infty}^{\infty} d\tau_1 e^{i\omega\tau_1} b_1(p_g,\tau_1) \int_{-\infty}^{\tau_1-\varepsilon} d\tau_2 e^{-i\omega\tau_2} b_1(p_g,\tau_2) \times \int_{\tau_2+\varepsilon}^{\infty} d\tau_3 e^{i\omega\tau_3} b_1(p_g,\tau_3), \tag{6}$$

In the tau-p domain the data must be prepared to be input into the algorithm outlined below (Sun & Innanen, 2014). For the 1.5D version the input data is prepared by first transforming to the tau-p domain.

$$d(x_g,t) \overset{\tau p}{\rightarrow} D(p_g,\tau), \tag{7}$$

Then 1D Fourier transformed over τ

$$D(p_g,\tau) \overset{Fp}{\rightarrow} D_1(p_g,\omega), \tag{8}$$

Then scaled by $-2iq_s$

$$B_1(p_g,\omega) = -2iq_s D_1(p_g,\omega), \tag{9}$$

Applying the inverse Fourier transform over ω to give the prepared data for the algorithm.

$$B_1(p_g,\omega) \overset{iFp}{\longrightarrow} b_1(p_g,\tau), \tag{10}$$

1.5D INTERNAL MULTIPLE PREDICTION

Next the method will be evaluated in 1.5D as there are increased computational demands due to the spatial dimension. In 1D the calculation is sufficiently small that the computational time is minimal. To reduce computation time, the method is written in Seismic Unix (SU). Seismic Unix is an open source programming language based in C provided by the Center for Wave Phenomena at the Colorado School of Mines. This is a compiled language which can better manage memory. The internal multiple prediction functions in Seismic Unix were written using the MATLAB versions as a guide, thus these SU programs are an approximate translation to this language. Any variations in runtime can in part be attributed to the differences in the two languages. This will be compared to those versions written in MATLAB from the CREWES toolbox (Eaid et al., 2016).

Each step in the process from input data to prediction in 1.5D will display the Seismic Unix implementation alongside the current MATLAB standard. The geologic model used is displayed below (Figure 2). For the 1.5D a simple geologic model is used for ease of comparison between the platforms. Displayed in the model are the two primaries and the first order multiple.

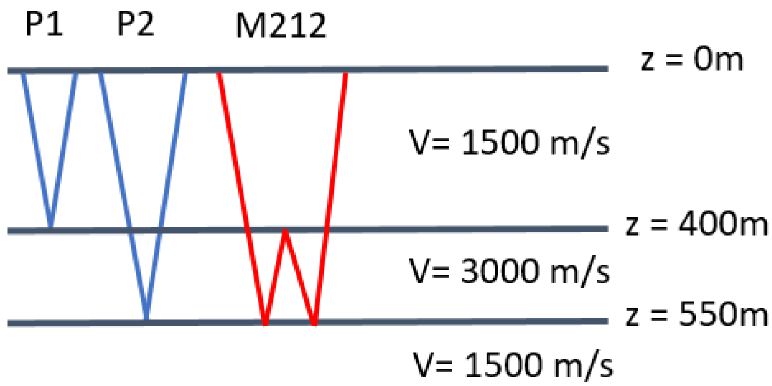

FIG. 2. Geologic model displaying velocities and depths used

Using finite difference modeling a shot record was created in MATLAB using afd_shotrec from the CREWES toolbox. Finite difference allowed for the modeling of all orders of multiples within the recorded window. The resulting model is displayed both in MATLAB and using SU (Figure 3). The 2D model was spatially sampled every 10m and a temporal sample rate of 0.002s, with a grid that is 512x256 samples. The seismic shot record was created by convolving the result with a 30Hz Ricker wavelet.

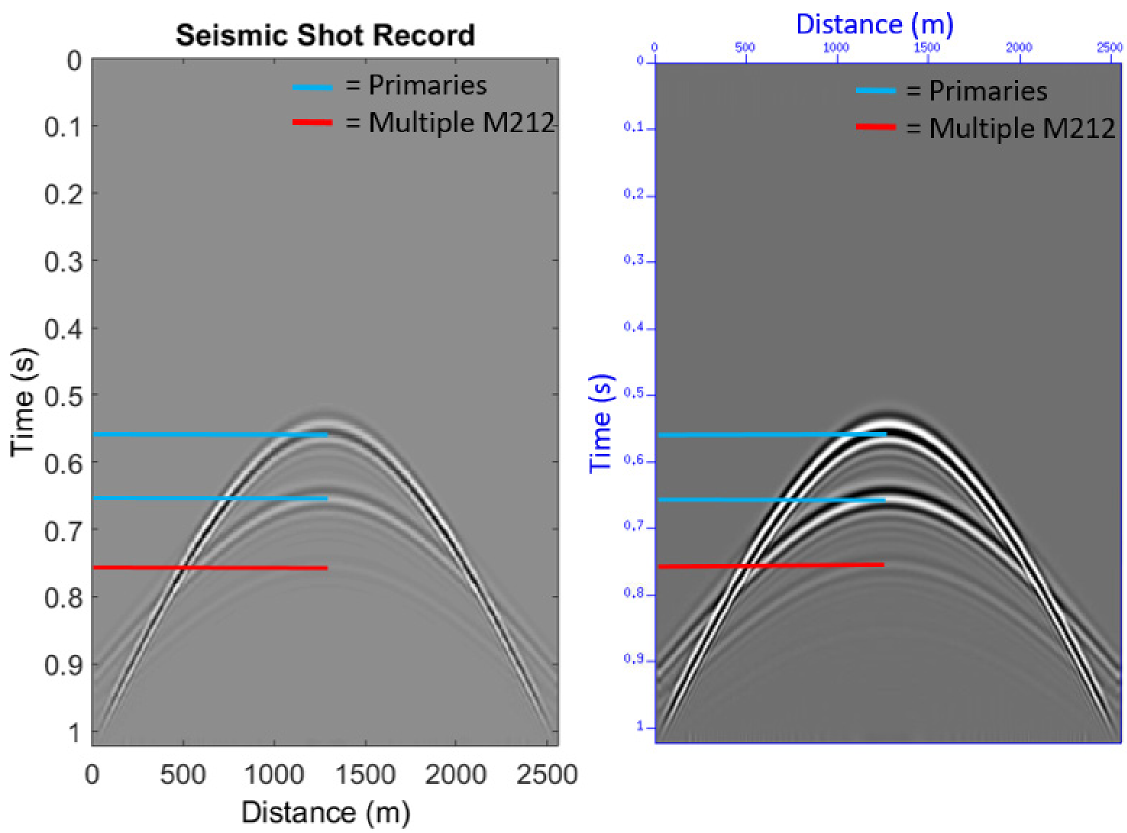

FIG. 3. (Left) Seismic data in MATLAB (Right) Seismic Data in SU

The displayed shot record shows the two primaries and a large first order internal multiple plus higher order multiples. The data must be prepared for the internal multiple prediction algorithm. From the CREWES Toolbox the first step involved applying a surface mute to ensure there are no erroneous values near the shot location. Also in the tau-p preparation function in the CREWES toolbox, is a spatial cosine taper that is applied for artifact minimization (Sun and Innanen, 2015). The data is then transformed into the tau-p domain for the application of internal multiples. A scale factor from Weglein ISS theory is applied in the Fourier domain shown in equation (9). In Seismic Unix the built in FFT (Fast Fourier Transform) outputs only the positive frequencies. At this stage the scale factor is applied to only these positive frequencies. The data is now prepared for internal multiple prediction (Figure 4). Due to medium only varying in the vertical direction the prediction will be completed only on the positive slowness values.

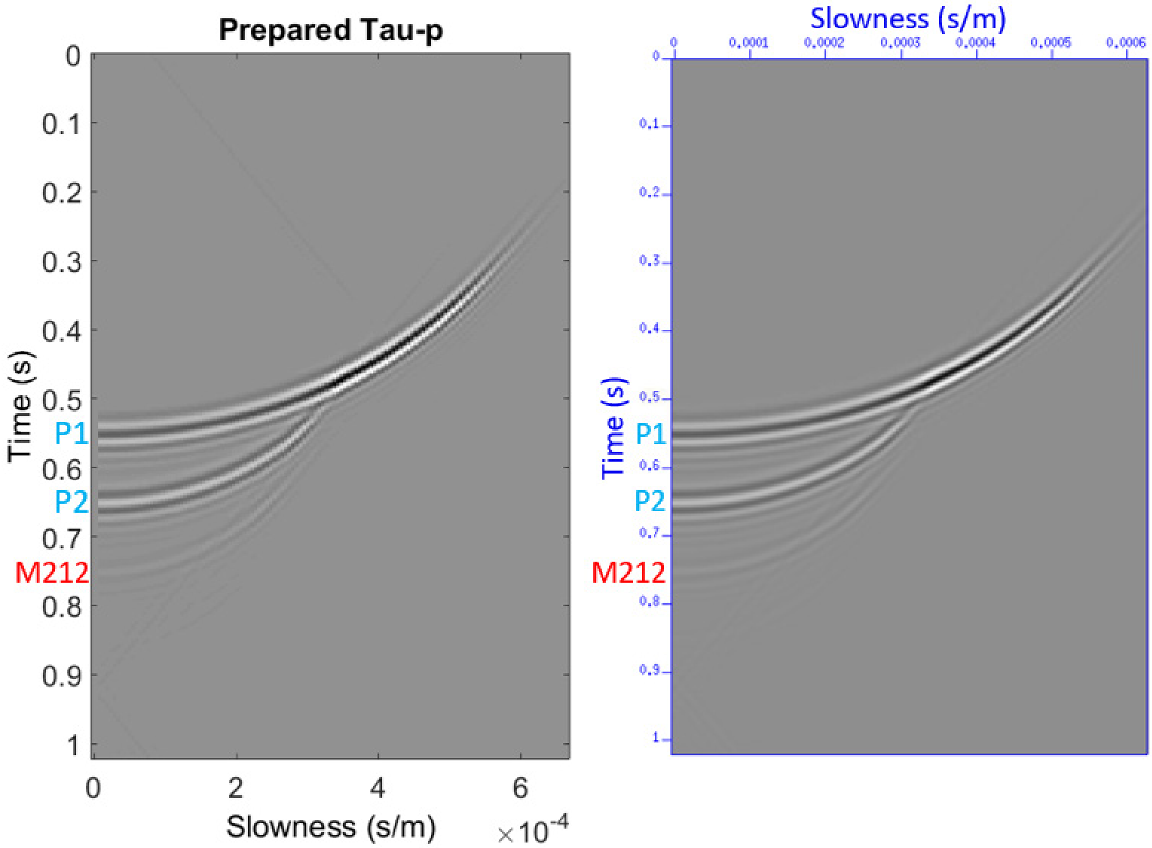

FIG. 4. (Left) Prepared data in tau-p domain in MATLAB (Right) Prepared data in tau-p domain in SU

Next the internal multiples will be predicted using the 1.5D tau-p version of the algorithm both in MATLAB and Seismic Unix. The MATLAB version is displayed first (Figure 5). An epsilon value of 30 was used for both MATLAB and SU applications. The prediction for the positive slowness values will be duplicated to the negative slowness values about zero p. The prediction is then inverse Fourier transformed to give the prediction in tau-p. The tau-p prediction is then inverse tau-p transformed to give the final prediction in x-t.

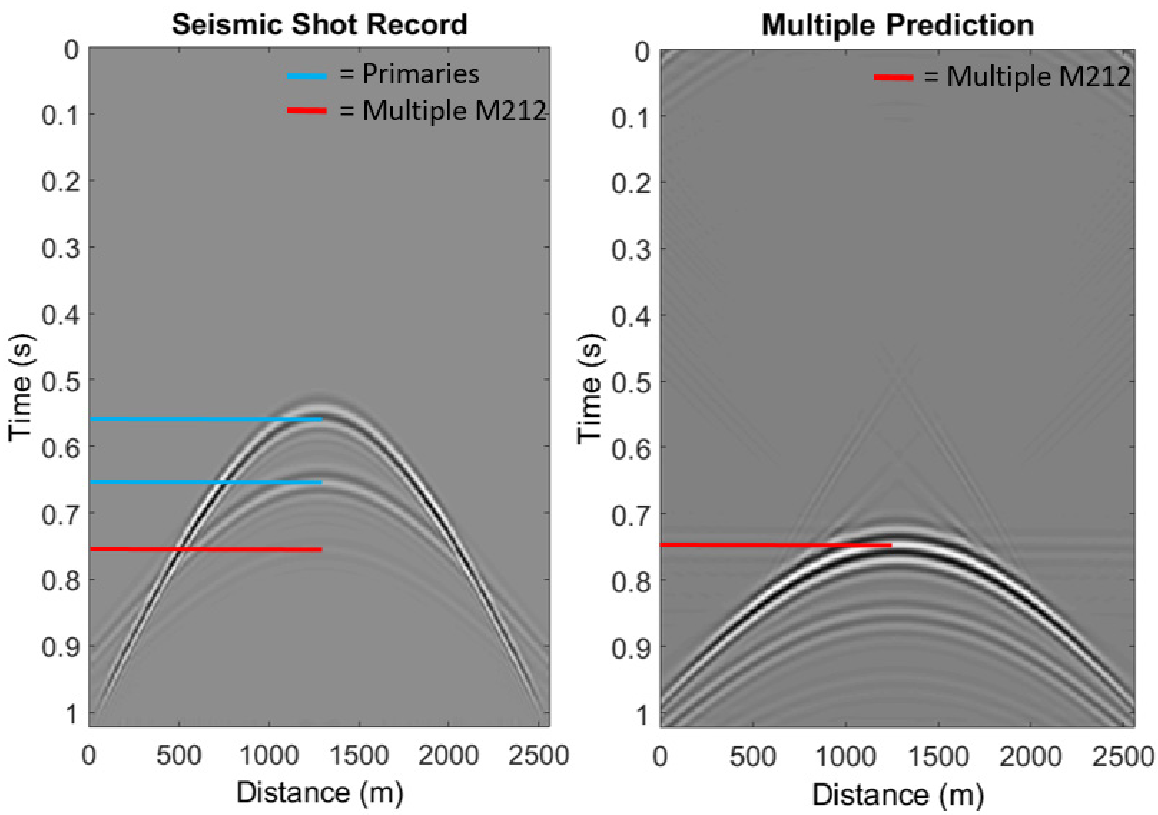

FIG. 5. (Left) Synthetic seismic shot record (Right) 1.5D tau-p multiple prediction in MATLAB

The MATLAB version has accurately predicted the internal multiples present in the data set. The chosen epsilon value appears to have been sufficiently small to allow for the prediction of the multiple but not so small as to predict energy from the primaries. The computational time for the prediction was approximately 10 minutes for this single record. This data set was 512x256 samples. Numerically this was only computed on approximately 128 slowness values instead of the 256 total samples, due to the v(z) medium being identical for both positive and negative spatial dimensions. The negative values were filled in using conjugate symmetry. Next the prediction is carried out in Seismic Unix (Figure 6). This prediction was also completed on the positive slowness values. The Prediction is then inverse Fourier transformed to give the prediction in tau-p. The tau-p prediction is then inverse tau-p transformed to give the final prediction in x-t. Finally the x-t result is replicated about the shot location to give the prediction for the entire synthetic shot record.

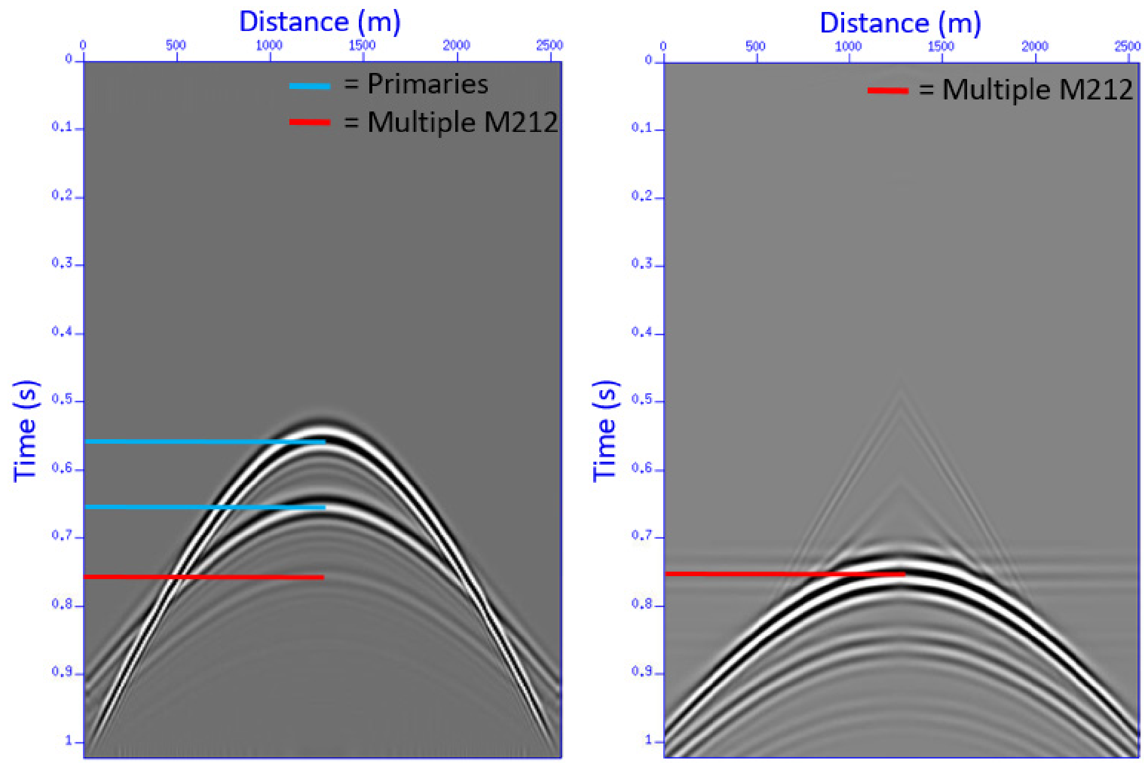

FIG. 6. (Left) Synthetic seismic shot record (Right) 1.5D tau-p multiple prediction in Seismic Unix

The prediction in SU has also successfully predicted the multiples in the data. Comparing to the MATLAB version the two results are comparable and both have similar artifacts. The prediction implemented in SU took approximately 21 seconds to complete. Parallel processing was also applied to the algorithm in SU. The 1.5D version of the prediction algorithm is well suited to parallelization as the algorithm is simply repeated over all slowness values. The results of prediction on one slowness do not impact the prediction of another. With the use of 16 threads the computation time was further reduced to approximately 5 seconds.

Artifact Minimization

In both the MATLAB and SU implementations, there are two main artifacts from the prediction that will be addressed. There is a horizontal event which appears to be the zero-offset trace which has been extrapolated to all offsets. In SU there is the option for the calculation of the tau-p transform in either the Fourier domain or time domain. With the utilization of the time domain transform this artifact is reduced (Figure 7). The second set of artifacts present is the steeply dipping linear events above the prediction. This can be resolved with the use of a harsher cosine taper (Sun and Innanen, 2015). The initial prediction used a slight cosine taper to assist with this issue. Using a taper where the amplitudes approach zero on the spatial edges appears to assist with this issue (Figure 7). This taper does have the potential to be damaging to the amplitudes but since at this stage adaptive subtraction is required, the cleanest possible prediction is needed to assist the adaptive subtraction.

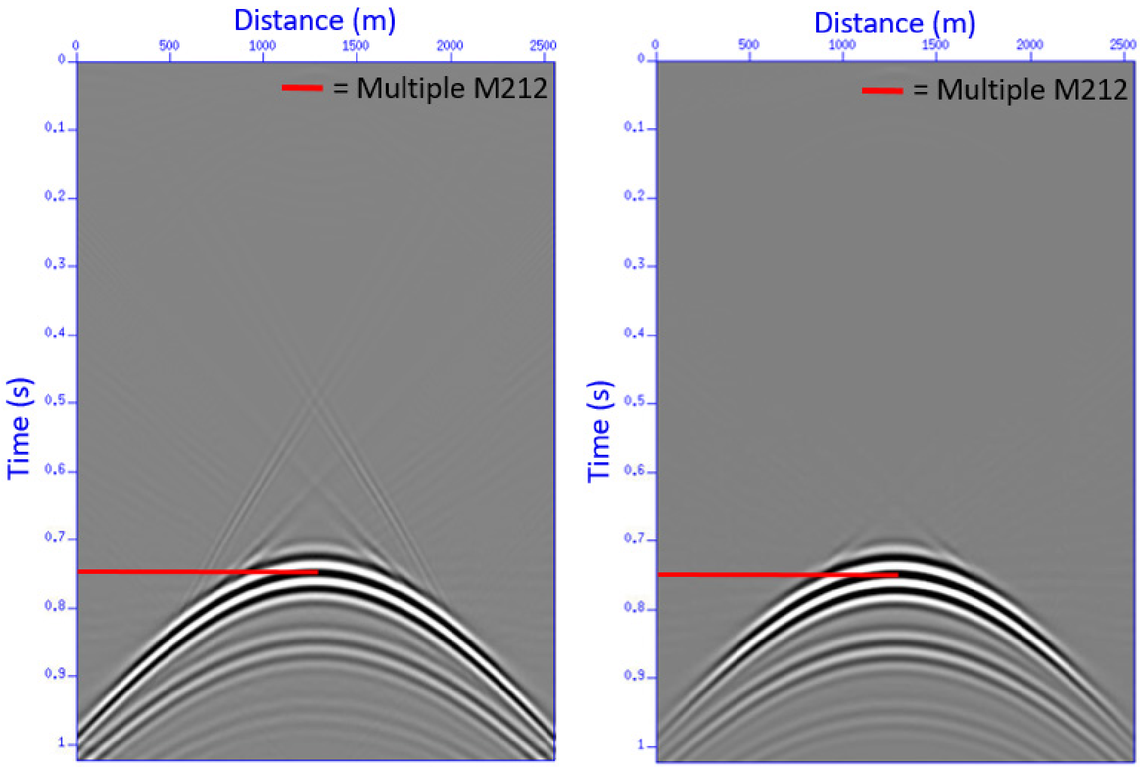

FIG. 7. (Left) Prediction using the time domain tau-p transform (Right) Prediction using an aggressive cosine taper and time domain tau-p transform

With the use of the time domain tau-p transform and a harsh cosine taper the result is an accurate prediction of internal multiples mostly free of artifacts. This SU workflow appears to be able to provide an accurate internal multiple prediction with minimal artifacts and in an efficient timeframe. Due to the efficiency of SU, the time domain transform results were computed and inverse transformed over all slowness values.

CONCLUSIONS

One issue that remains with the inverse scattering series for internal multiple prediction is the computational requirements to perform the algorithm. To optimize the computational time required the algorithm was implemented into Seismic Unix. This combined with the implementation of parallel processing gave significant decreases in computational time from the approximate 10 minutes or 600 second run time in MATLAB to the 5 second run time in SU. Also demonstrated is how the use of both a time domain tau-p transform and a harsher cosine taper can improve the prediction through a reduction in artifacts.

ACKNOWLEDGEMENTS

The authors would like to thank the sponsors of CREWES for the support of this work. This work was also funded NSERC through the grant CRDPJ 461179-13. Andrew Iverson would also like to thank QEII, NSERC and SEG for their support.

REFERENCES

Coates, R. T., and Weglein, A. B., 1996, Internal multiple attenuation using inverse scattering: results from prestack 1D & 2D elastic synthetics, SEG Technical Program Expanded Abstracts 1996, pp 1522-1525.

Eaid, M., Sun, J., Keating, S., and Innanen, K. A., 2016, 1D and 1.5D internal multiple prediction in MatLab, CREWES Annual Report, 28.

Sun, J., and Innanen, K. A., 2014, 1.5D internal multiple prediction in the plane wave domain, CREWES Annual Report, 26.

Sun, J., and Innanen, K. A., 2015, Internal multiple prediction in the tau-p domain: 1.5D synthetic results, CREWES Annual Report, 27.

Sun, J., and Innanen, K. A., 2016, Literature review and discussions of inverse scattering series on internal multiple prediction, CREWES Annual Report, 28.

Weglein, A. B., Gasparotto, F. A., Carvalho, P. M., and Stolt, R. H., 1997, An inverse-scattering series method for attenuating multiples in seismic reflection data, Geophysics, 62(6), 1975–1989.

Xiao, C., Bancroft, J. C., Brown, J. R., and Cao, Z., 2003, Multiple suppression: A literature review, CREWES Annual Report, 15.