TRACE INTERPOLATION AND EXTRAPOLATION WITH PARTIAL CRS STACKS

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ABSTRACT

Data regularization, seismic trace interpolation and extrapolation are advantages of partial ZO CRS stacks. We edit the SIGSBEE2A synthetic data record to create sparse data. The gaps are chosen randomly in mid-offset and near-offset ranges. We compare the results of the interpolation with the traces we deleted from the record. The interpolation by partial stacks preserves arrival times and frequencies very well. Especially the arrival times in near-offset are preserved with sub-sampling accuracy. Some interpolated traces contain low-intensity noise over the entire frequency bandwidth. The direct wave should be excluded from the interpolation because of its linear move-out and the hyperbolic approach of the partial CRS stack. Extrapolation is a challenge to the partial CRS algorithm. The Fresnel zone defines physical limitations for the CRS apertures. We extrapolated traces at offsets exceeding twice the Fresnel zone. No surprise that this violation of physical limits leads to amplitude artifacts. These effects start appearing at about 1.5 times the Fresnel zone as extrapolation distance. However, extrapolation within the limits of the Fresnel zone supplies a reliable extension of the reflection events. Although the partial stack determines the attributes for the zero offset ray trace interpolation for offset seismograms can be performed and even an extension of the spread is possible. Best interpolation results are obtained for short or intermediate offsets.

INTRODUCTION

Many tools in reflection seismic data processing require regular data. Particularly wave equation methods rely on a regular distribution of the acquisition. This requirement needs either an interpolation and regularization of the data or to properly take the acquisition footprint into account. The CRS method, namely the partial CRS stack, provides a tool to regularize and interpolate data where the same parameters are used as in the CRS stack, i.e., no additional stacking parameter determination is required.

The partial CRS method (Baykulov and Gajewski, 2009b) is derived from the conventional ZO CRS stack (Müller, 1999). The common reflection point is calculated over a window comprising the midpoint-displacement coordinate and a limited number of contributing half-offset traces. This calculated trace is saved for every half-offset coordinate. The CRS approach improves the SNR and provides the ability to interpolate traces. Therefore, it can create supergathers consisting of significantly more traces than the original data record.

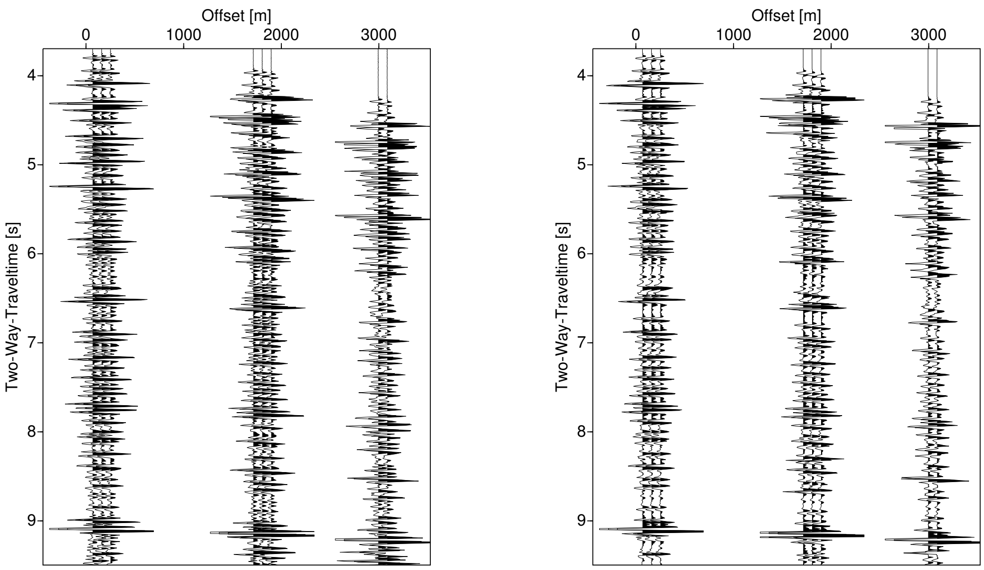
In this paper we will investigate trace interpolation and extrapolation on a synthetic data record which enables direct comparison of real and interpolated or extrapolated traces. Sine the CRS stack determines the attributes for zero offset we expect the best results of interpolation for the near offset traces. First, we will use the CRS stack on the synthetic Sigsbee2A data record to interpolate traces, which previously were deleted from the shot-gather. We compare the deleted traces to the interpolated traces and analyze the improvement of the SNR by this routine. The extrapolation to extend the acquisition is investigated in a second numerical experiment.

TRACE INTERPOLATION

Interpolation of seismic traces has a long history in seismic processing. The most prominent interpolation technique is the generation of ZO traces. Since more than 60 years the ZO stack provides the first image in the CMP processing chain.
Regular geophysical data acquisition has a major influence on the stability and reliability of various processing algorithms, especially waveform-based techniques. However broken geophones, varying geophone spacing, rivers or other obstacles may lead to data gaps. Once the geophone spacing gets too large wave equation-based processing algorithms may encounter aliasing effects. Another problem specific to marine data acquisition originates from missing near offset data. This data is essential for surface-related multiple elimination (SRME; cf. Verschuur et al. (1992)). Dümmong et al. (2009) show that in a 2D-medium prediction errors of the SRME were considerably reduced after partial CRS stack interpolation of near offset traces. First we consider the interpolation of seismic traces where we investigate different offset ranges (near, mid, and far offsets).

Time Domain

Figure 1(a) shows the original traces taken from the Sigsbee2A data record. Next to it, in Figure 1(b) the result of the interpolation over the data gaps is shown. A first inspection reveals a fairly good comparison



(a) Original traces in CMP 200

(b) Interpolated traces in CMP 200

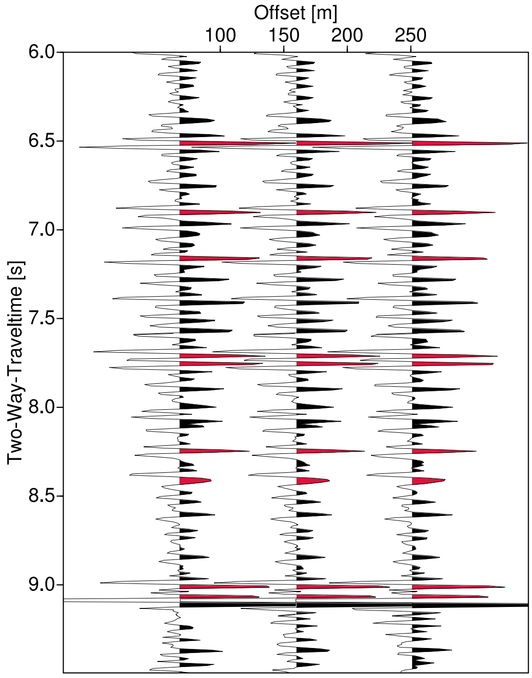
Figure 1: Comparison of the original traces (a) and the interpolated traces (b)

of the interpolated and original traces for the considered offset ranges. To investigate differences in arrival times a detailed manual event picking analysis was performed. In the near-offset domain the arrival times differ by the order of 10^{-3}s. In mid-offset and far offset the absolute error increases to the $10^{-2}s$. Part of these errors might be caused by the manual picking. The error for most offsets is in the sub sampling range of these data.

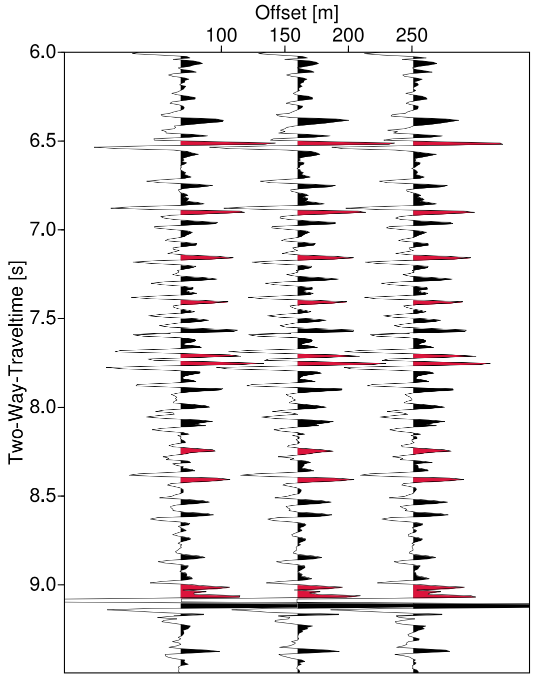
The direct wave is located at the right temporal position but displays a significant change of the signal form. This effect is caused by the linear move-out of the direct wave. This behavior cannot be reproduced with the hyperbolic approach of the partial CRS-algorithm. Muting or windowing the data to exclude direct waves and events with linear moveout will help to avoid the observed feature.

The individual reflection events in Figure 1(b) appear more distinct than those in Figure 1(a). The amplitudes in between the major reflection events are decreased. This is interesting to note because the Sigsbee2A data set is noise-free. The multiple scattered energy of the complex Sigsbee2A model seems not be correlated in this gather resulting in an improvement to the overall appearance of the main events. The signals of the interpolated traces beyond 9.5 second TWT show a considerably reduced coda after the event. The traces around 3000m offset even display an almost event-free seismogram beyond 9.5s. We will now have a more closer look to some waveforms of the interpolated traces.

In figure 2 we compare the segments of the original data from 6s TWT to 9.5s TWT with an interpolation over the simulated near-offset gap. In this close ups one can observe the amplitudes of the first three traces of the CMP-gather. In the time range from 6.0s to 6.5s the amplitudes are very discrete in the original traces. The corresponding amplitudes in the interpolated traces are smaller and slightly broader. This mild amplitude smearing can be observed on the entire interpolated gather.



(a) Segment of original near-offset data



(b) Segment of interpolated near-offset data

Figure 2: Comparison of segments of figure 1 from 6s to 9.5s TWT

We marked several events in red, which appear to be major reflection events and to some extent have experienced some change in amplitudes. The first red event at 6.5s TWT is an event with very high amplitudes. This event was interpolated accurately, as well as the next event at 6.9s TWT. Whereas the event at 7.2s and the event at 7.4s show a decrease in intensity and broadening of the signal. The following double amplitude at 7.7s TWT again is interpolated correctly with a slight decrease in intensity. Moving on to the events between 8.2s and 8.5s, the first event has decreased and broadened significantly while the second event was amplified and sharpened. The major double amplitude at 9.0s has suffered smearing over the first two cycles. The first event has experienced the strongest amplitude smearing and amplitude decrease. It is interfering with the second event. The second event is also slightly decreased in amplitude but is still recognizable as a discrete major event. The third amplitude after the red events again has been interpolated very well.

These slight differences visible in figure 2 show that major events in the near-offset domain are interpolated very well, with minimal changes in amplitude and signal form. Although the CRS stack is a kinematic approach the amplitudes have been preserved very well. Minor events, i.e., signal generated noise in form of scattered energy are prone to low intensity amplitude smearing and minor interference in the interpolated traces. On the other hand, travel times are well preserved, leaving major reflection events at their correct positions in time. This is essential to avoid imaging errors in later processing steps.

For amplitude preservation it is crucial to consider a small offset aperture in the partial stack. In figure 3 we show unpublished results obtained by Mikhail Baykulov, who compared the amplitudes of a reflection picked from the original traces of a land data set with the amplitudes picked from traces generated by partial stacks for the same offsets as in the original CMP gather. The comparison shows that with a careful choice of apertures and proper weighting the partial CRS stack procedure can be performed in an amplitude preserving fashion.

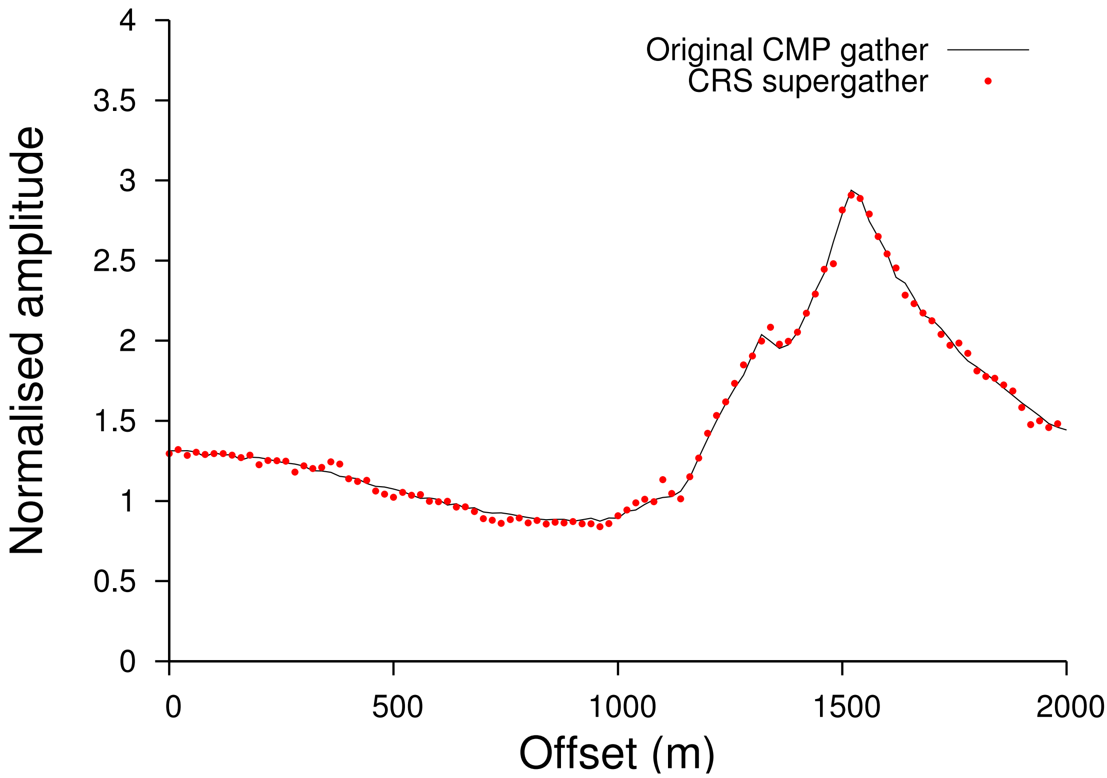
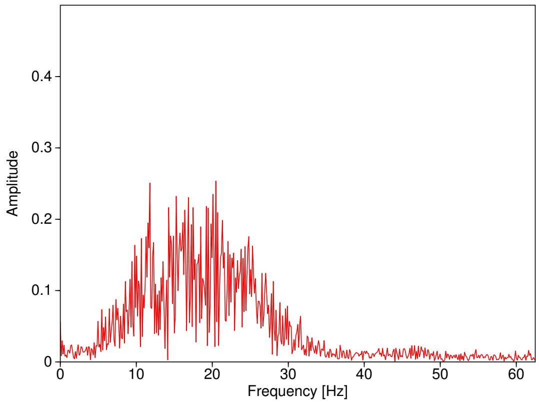


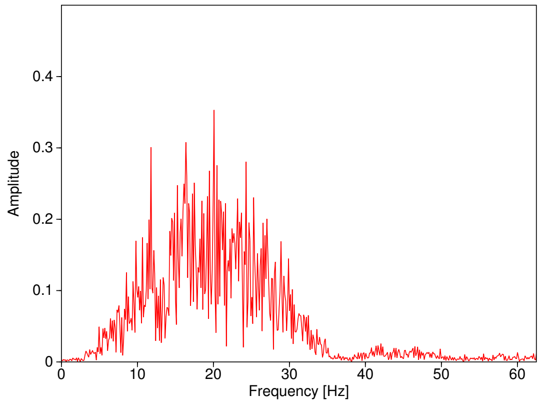
Figure 3: Comparison of picked amplitudes of a reflection from the original traces of a land data set with the amplitudes picked from traces determined by partial stacks for the same offsets (figure courtesy of M. Baykulov).

Frequency Domain

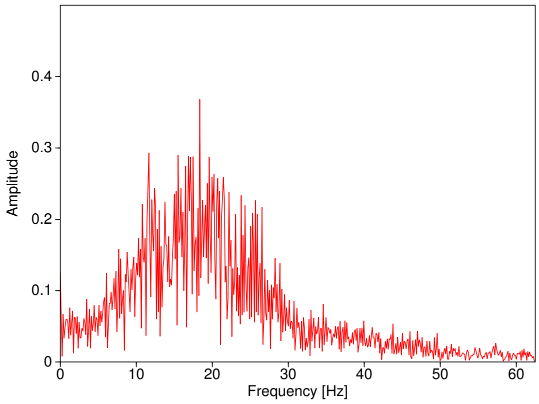
The overall positive impression of the CRS based interpolation of the Sigsbee2A data is confirmed by the amplitude spectra of the traces shown in figure 4. The figures in the left column show spectra of the interpolated traces at an offsets of 68m, 1805m, and 3086m chosen exemplary as near-offset, mid-offset and far-offset traces. The spectra of the matching original traces are presented in the right column. Similar to the time domain a very good comparison of the spectra of interpolated and original traces is observed. The bandwidth of the traces reaches from 5Hz to 30 Hz. In the near-offset trace the spectrum of the interpolated trace appears smoother than the spectrum of the original trace. In the original spectrum we can see four peaks at approximate frequencies of 11Hz, 16Hz, 20Hz and 23 Hz. While in the interpolated spectrum the only peak clearly appearing is at 11Hz. However, one can spot a frequency drop from 11Hz to 13 Hz, which is clearly present in both spectra. This gap appears in the mid-offset trace spectrum as well. As opposed to the near-offset trace some noise appears over the whole frequency range, best visible from 0Hz to 5 Hz and from 30Hz on to the end of the bandwidth. The spectra for the far-offset show similar feature as already discussed for the near- and mid-offset ranges. The comparison of these spectra leads to the conclusion of smoothed frequency peaks, low intensity noise and well-interpolated frequency trends in the interpolated traces.



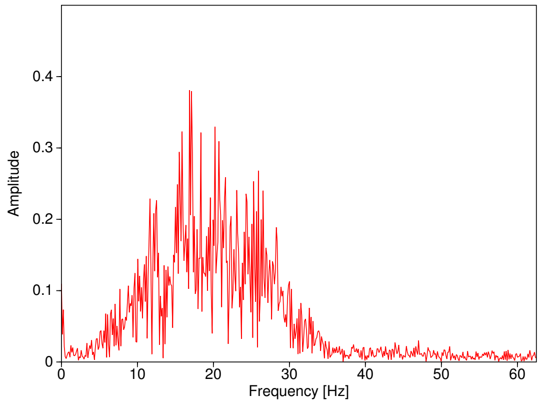
(a) Amplitude spectrum of interpolated trace at 68m



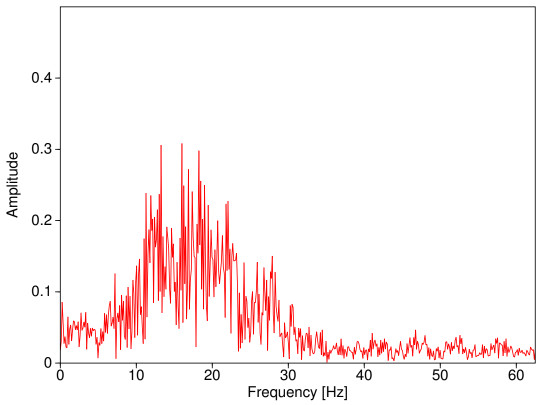
(b) Amplitude spectrum of the original trace at 68m



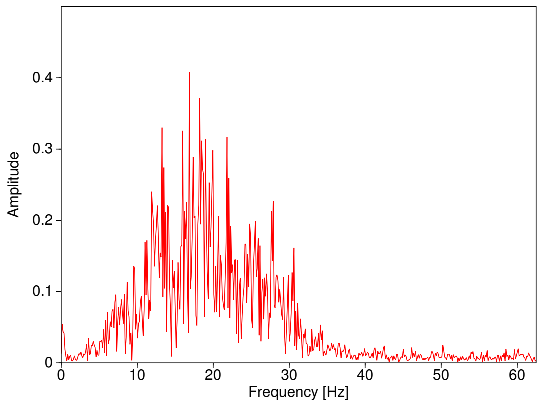
(c) Amplitude spectrum of the interpolated trace at 1805m



(d) Amplitude spectrum of the original trace at 1805m



(e) Amplitude spectrum of the interpolated trace at 3086m



(f) Amplitude spectrum of the original trace at 3086m

Figure 4: Interpolated (left) and original (right) amplitude spectra of traces at near offset (68m), mid offset (1805m), and the far offset (3086m).

EXTRAPOLATION

It should be mentioned that extrapolating traces to extend the acquisition using ZO CRS partial stacks is potentially error prone. The CRS attributes are determined for the zero offset ray and consequently best results of partial stacks are expected at near offsets. The previous section has shown that the partial ZO CRS stack approach performed reasonably well even at intermediate offsets. At large offset the application

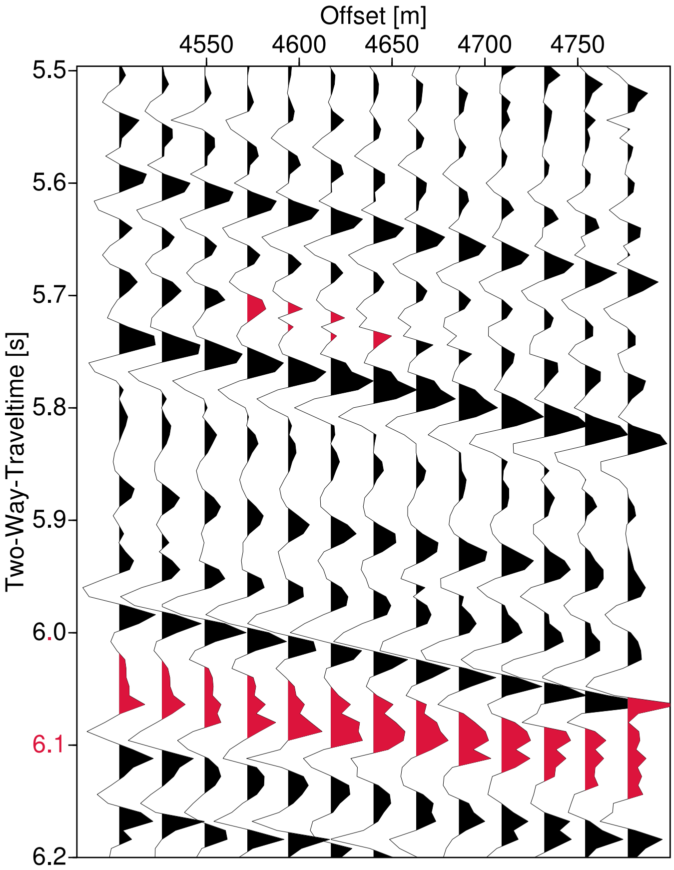


Figure 5: Close-up of extrapolated data from 4500m to 4799m offset

of the offset partial CRS stack is advisable. These technique, however, would require to search for five CRS attributes in the 2-D case and would lead to a different workflow. Despite the stretch of physical limits, we use the ZO partial CRS stacks here to extrapolate the acquisition.

The extrapolation process creates traces beyond the physical offset of the acquisition setup. These traces constitute an additional contribution to the total quantity of traces for further processing. Physical boundaries set a limit to the possibilities of extrapolation, not only because CRS attributes are determined for zero offset but also because the partial CRS apertures have a close relation to the Fresnel zone in the subsurface. Extrapolation over the limit of the Fresnel zone bears the risk of introducing artifacts such as signal changes or artifacts that will disturb the stacking processes. Traces calculated beyond the limits of the Fresnel zone are calculated on the base of data, which were already extrapolated. We chose the partial CRS apertures exceeding the Fresnel zone by more than the factor of two, intentionally exceeding the physical limitations.

The data starts at 4s TWT because the direct wave is not to be considered in the evaluation of the extrapolation process, as discussed above. The section of the extrapolated traces yields a reasonable result. The move out, as well as the arrival times of the traces within a broad range are preserved and the reflection events from the interpolated part in the supergather are continued in a reasonable fashion. The first two major reflection events are continuous over the entire offset, whereas the smaller amplitudes at 5s TWT smear for an offset greater than 4400m. The packet of reflections from 5.1s to 6.3s TWT is continuous to the offset of 4400m. Beyond that offset some variations occur because the physical limitations were exceeded (application at large offset, apertures larger than the first Fresnel zone).

In figure 5 we zoomed in this part of the extrapolated section. It can be observed, that the major reflection events at 5.6s, 5.74s and 5.97s TWT stay discrete and continuous. The amplitudes increase proportional to increasing offset. Splitting of the signal can be seen at 5.7s TWT in the traces at 4595m

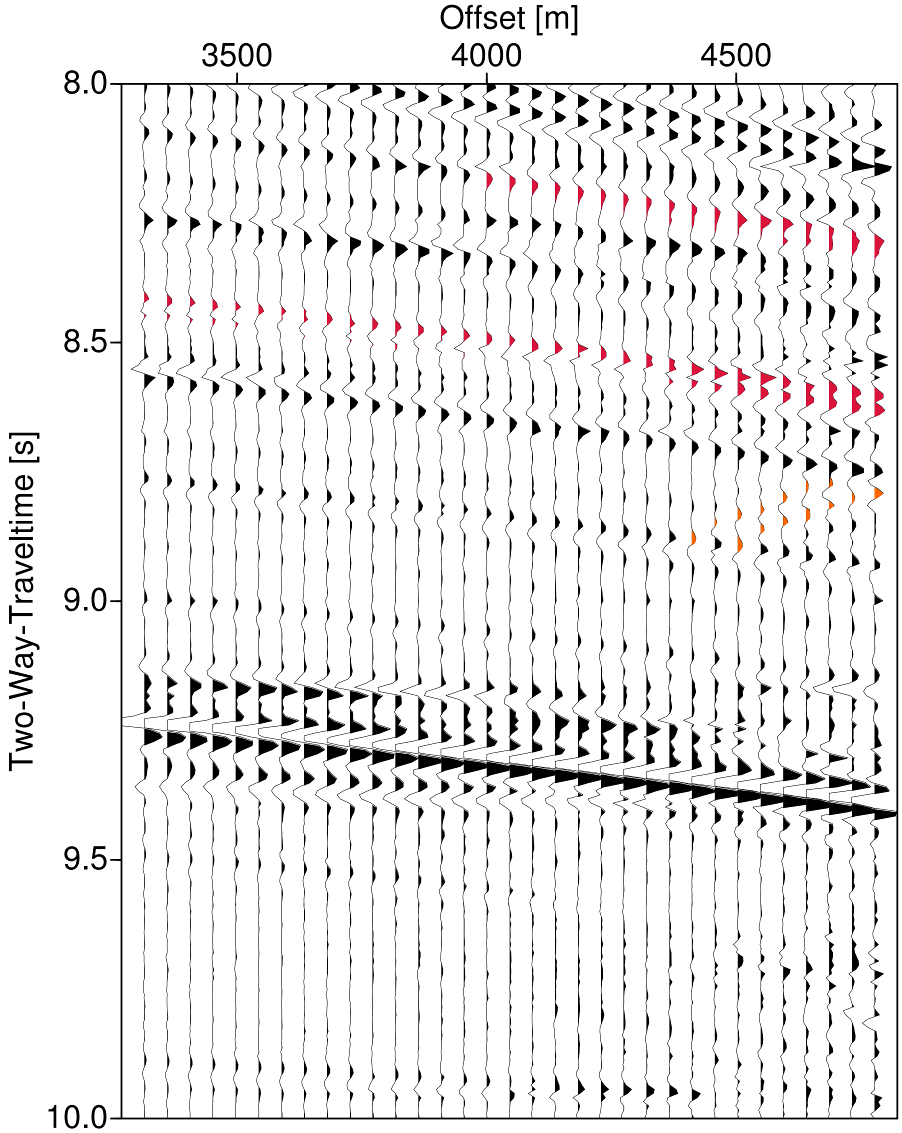


Figure 6: Extrapolation artifacts in close-up from 3299m to 4799m offset and 8s to 10s TWT

up to 4685m offset. Another effect contributing to the spotty image is the smearing of amplitudes, which can be seen in the reflection events at 5.87s, 5.92s and especially 6.05s TWT. The reflection event at 6.05s TWT smears, so that it interferes with the major reflection event prior to it. We present another close up of the extrapolated gather in figure 6. The window in figure 6 was chosen to demonstrate extrapolation artifacts as a result of an over-sized partial CRS aperture.

As expected when exceeding the physical limitations of a method amplitude artifacts appear. Two effects were marked red in figure 6. Starting at 8.1s TWT reflections smear at an offset greater than 4500m. Another amplitude artifact was marked orange and starts at 8.6s TWT and 4500m. At an upward angle of 30^o two apparent reflection events separate from the actual reflection, creating a cone like geometry. Further artifacts can be seen in the entire zone, where the physical limitations were exceeded. They would corrupt further processing steps.

The extrapolation within the Fresnel zone provided results almost as promising as the interpolation process. Once we expand the partial CRS apertures it becomes more likely that unwanted artifacts are produced. This may create misleading information in the supergather. Amplification and smearing of amplitudes will distort the results of further processing. The extension of the aperture above the first Fresnel zone clearly breaks the physical limits of the method. However, the application of the ZO partial stacks at intermediate and large offsets does not compromise the results seriously.

CONCLUSION AND OUTLOOK

The interpolation process using the zero offset partial CRS stack has shown promising results. The arrival times of the interpolated gather coincide with the original gather within minimum numerical tolerance. The major reflection events were interpolated very well, while minor reflection events have been slightly decreased compared to the original traces. If these minor events are caused by scattered uncorrelated energy, this effect is expected owing to the stacking processes involved in the interpolation procedure. The amplitudes were preserved very well. The same conclusion applies to the frequencies of the interpolated seismograms albeit, some low-amplitude noise was introduced to the frequency band of some traces. A problem is related with the interpolation of the direct wave or generally of events with linear moveout. This moveout cannot be handled properly by the hyperbolic approach of the partial CRS stack, leaving the interpolation results of the direct wave incorrect and misleading. Data gaps exceeding the first Fresnel zone and therefore, exceeding physical limits of the applicable apertures lead to interpolation errors. The interpolation of near offset traces with partial stacks works very reliably. These traces are crucial for processes like SRME (Surface Relate Multiple Removal). Partial stacks can be used here as a data conditioning tool as well as a regularization method for wave equation based methods.

The extrapolation process has shown to be a potentially dangerous task because numerous factors are stretching the physical limits. The extrapolation offset should not exceed the first Fresnel zone. Otherwise artifacts in amplitude and possible signal changes are the result. Extrapolation within the limits of the first Fresnel zone can contribute valuable traces to the gather.

The partial CRS stack approach for trace interpolation and data regularization provides a fast tool for these tasks. No additional parameter searches are necessary and the fidelity of the interpolated traces is high. In future investigations it will be interesting to compare the interpolation process of the partial CRS stack to trace interpolation algorithms in the f-x (e.g., Spitz, 1991; Naghizadeh and Sacchi, 2009)) or f-k domain (e.g., Pann and Fields, 1986)). Since the CRS attributes are determined for the zero offset ray, best results can be expected at near offsets. However, the presented numerical examples have shown that the partial stack approach generated reliable interpolated traces even at intermediate and large offsets, i.e., at the end of the acquisition. For large offsets a partial stack method based on the offset CRS technique might give even better results than the zero offset partial CRS stack. Offset CRS requires the determination of 5 CRS attributes in the 2-D case. The extension of the zero offset partial CRS stack approach to 3-D is straight forward (Baykulov and Gajewski, 2009a).

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REFERENCES

Baykulov, M. and Gajewski, D. (2009a). 3-D partial CRS stacks. *WIT Report*, pages 15–20.

Baykulov, M. and Gajewski, D. (2009b). Prestack seismic data enhancement with partial common reflection surface (CRS) stack. *Geophysics*, 74:49 – 58.

Dümmong, S., Baykulov, M., and Gajewski, D. (2009). A workflow for the processing of reflection seismic data with crs attributes. *SEG, Expanded Abstracts,*, 28:3173–3177.

Müller, T. (1999). *The Common Reflection Surface Stack Method - Seismic imaging without explicit knowledge of te velocity model*. PhD thesis, Universität Karlsruhe (TH).

Naghizadeh, M. and Sacchi, M. (2009). F-x adaptive seismic-trace interpolation. *Geophysics*, 74:9–16.

Pann, K. and Fields, J. L. (1986). Seismic trace interpolation using f-k filtering.

Spitz, S. (1991). Seismic trace interpolation in the f-x domain. *Geophysics*, 56:785–796.

Verschuur, D. J., Berkhout, A. J., and Wapenaar, C. P. A. (1992). Adaptive surface-related multiple elimination. *Geophysics*, 57:1166–1177.