Automatic selection of reference velocities for recursive depth migration

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*Pseudo-differential Operator Theory in Seismic Imaging
The problem:

- Many recursive wavefield extrapolators require a limited set of reference velocities for efficient implementation.
- How should these reference velocities be chosen?
Objectives:

- Efficient computation
  - a minimum number of reference velocities
- Accurate wavefield extrapolation
  - reference velocities ‘close’ to model velocities

Velocity profile (deep)

too few reference velocities?

~3000 ms\(^{-1}\) (~230%)
Some specific requirements

- **PSPI** – lower and upper bounding velocities ($v_{\text{min}}, v_{\text{max}}$)
  - ideally minimize large interpolations
    (wavefield is a weighted summation)
- **Split-step** – more accurate focusing
  with a slower velocity

![Velocity profile (shallow)](image)

- ~40 ms$^{-1}$ (~ 2%)
- ~320 ms$^{-1}$ (~ 17%)
- ~70 ms$^{-1}$ (~ 4%)
- ~70 ms$^{-1}$ (~ 4%)
- ~80 ms$^{-1}$ (~ 5%)
Basic approach 1: Linear progression

- choose an approximate velocity spacing $dV$
  
  $$nV = \text{round}((v_{\text{max}} - v_{\text{min}})/dV)$$

  $$v_{\text{step}} = (v_{\text{max}} - v_{\text{min}})/nV$$

- what is a good choice for $dV$?
  
  - empirical testing required
  
  - reasonable for both low and high velocities?

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**Velocity profile (deep)**

- ~500 ms$^{-1}$ (~10%)
- ~500 ms$^{-1}$ (~20%)
Basic approach 2a: Geometric progression

- choose an appropriate percentage step $v_{\text{prcnt}}$
  
  $v(i) = (1+v_{\text{prcnt}}) \times v(i-1)$

- Kessigner (1992) recommends $v_{\text{prcnt}} = 0.15$

  - start at $v_{\text{min}}$ for profile?
  - start at $v_{\text{min}}$ for complete velocity model?

(perhaps if using lookup tables)

![Velocity profile (deep)](image)

- $\sim 750 \text{ ms}^{-1} (~15\%)$
- $\sim 370 \text{ ms}^{-1} (~15\%)$

- choose a preliminary dv (geometric?)
- equally spaced bins over $v_{\text{min}}:v_{\text{max}}$ (e.g. $n_{B_{\text{temp}}}=6$)
- bin the velocities to give probability density $P_i$, $\sum P_i = 1$
- optimal number of bins by statistical entropy $S=\sum P_i \log P_i$

$$n_{B_{\text{opt}}} = \text{round}(\exp(S)+0.5)$$

(e.g. $n_{B_{\text{opt}}}=5$)

Probability distribution of velocity in temporary bins
• calculate cumulative probability distribution $Y_i$, 
  \[ Y_i = \sum P_i \]
• each optimal bin to hold $1/nB_{opt}$ (e.g. 0.2)
  - start at $v_{min}$
  - linearly interpolate from temporary bin boundaries (e.g. at 0.2, 0.4, 0.6, 0.8)
• Is this optimal? - bins not necessarily close to peaks
New peak search method

• cluster velocities
  - new cluster where jump exceeds $v_{prcmtmax}$
• Now, within each cluster:
• use Bagaini method for optimal number of bins $n_{B_{opt}}$ 
• create a new probability distribution with finer bins
• descending sort of $P_i$'s, choose all $P_i$'s where $\sum P_i < 0.9$
• place $v_{\text{temp}}$ at all $P_i$'s, include $v_{\text{min}}, v_{\text{max}}$
• use 'greedy search' to combine closely spaced $P_i$'s
  - start search at bin spacing of 1, then 2, etc.
  - weighted linear average to move $v_{\text{temp}}$
• stop when at $v_{\text{temp}} = n_{B_{opt}}$
ClusterVels Bagaini: $v_{\text{PrcntStep}}=0.09$, step > $1.5 \times v_{\text{PrcntStep}}$, 6 refvels

ClusterVels mod Bagaini: $v_{\text{PrcntStep}}=0.09$, step < $1.5 \times v_{\text{PrcntStep}}$, 7 refvels

ClusterVels Peak Search2: $v_{\text{PrcntStep}}=0.09$, step > $1.5 \times v_{\text{PrcntStep}}$, 6 refvels
Marmousi bandlimited reflectivity
PSPI with velocity clustering algorithm

data: deconpr 50 13 .0002 whiten [4 16 35 60] static -60ms
shot: ricker fdom 24 ghost array phsrot -68 (to zp) whiten [4 16 35 60]
Marmousi bandlimited reflectivity
Marmousi shallow reflectivity

Bandlimited reflectivity

depth m
distance m
Linear

PSPI reference velocities: Linear
Geometric
Bagaini

Peak Search

PSPI reference velocities: Peak Search

depth m

distance m
Modified Bagaini: clusters
Marmousi shallow reflectivity
Linear
Geometric

PSPI reference velocities: Geometric

depth m

distance m
Bagaini

Peak Search

PSPI reference velocities: Peak Search
Modified Bagaini: clusters
Static shifts - affect focusing
a) source wavefield in \((x,z,t)\)  

b) reflected wavefield in \((x,z,t)\)  

horizontal reflector (blue)  

c) direct + reflected arrival at \(z=0\)  

d) another perspective of (c)  

(figures courtesy J. Bancroft)
With a static shift of the source and/or receiver wavefield, the extrapolated wavefields will not be time coincident at the reflector, causing Focusing and positioning errors.
Complications for Marmousi imaging:
- free-surface and water bottom
- ghosting and multiples modify wavelet
- source and receiver array directivity
- two-way wavefield, one-way extrapolators
- heterogeneous velocity
Marmousi source array: 6 airguns at 8m spacing, depth 8m
receiver array: 5 hydrophones at 4m spacing, depth 12m
Modeled with finite difference code (courtesy Peter Manning) to examine response of isolated reflector at 0° and ~45° degree incidence.
After free-surface ghosting and water-bottom multiples, the Marmousi airgun wavelet propagates as \(~24\) Hz zero-phase Ricker with \(60\) ms delay.
Deconvolution

- The deconvolution chosen for the Marmousi data set is a simple spectral whitening followed by a gap deconvolution (40ms gap, 200ms operator)
- this yields a reasonable zero phase wavelet in preparation for depth imaging
• the receiver wavefield is then static shifted by -60ms to create an approximate zero phase wavelet
• if the receiver wavefield is extrapolated and imaged without compensating for the 60ms delay, focusing and positioning are compromised, as illustrated using a simple synthetic for a diffractor
reflectivity x: 4000-6000 z: 0-1000

Marmousi bandlimited reflectivity

depth m

distance m
PSPI whiten [4 16 35 60] cvel .2% clip 6

data: deconpr 50 13 .0002  whiten [4 16 35 60] static 0ms
shot: ricker fdom 24 ghost array phsrot -68 (to zp) unwhiten
PSPI whiten [4 16 35 60] cvel .2% clip 6

data: deconpr 50 13 .0002 whiten [4 16 35 60] static -16ms
shot: ricker fdom 24 ghost array phsrot -68 (to zp) unwhiten
PSPI whiten [4 16 35 60] cvel .2% clip 6

data: deconpr 50 13 .0002 whiten [4 16 35 60] static -32ms
shot: ricker fdom 24 ghost array phsrot -68 (to zp) unwhiten
PSPI whiten [4 16 35 60] cvel .02% clip 6

data: deconpr 50 13 .0002  whiten [4 16 35 60] static -56ms
shot: ricker fdom 24 ghost array phsrot -68 (to zp) unwhiten
PSPI whiten [4 16 35 60] cvel .02% clip 6

data: deconpr 50 13 .0002 whiten [4 16 35 60] static -56ms
shot: ricker fdom 24 ghost array phsrot -45 (to zp) whiten [4 16 35 60]
Marmousi bandlimited reflectivity
- shifted to match Zhang et al. (2003)
Zhang et al. (2003) - positioning not accurate
PSPI reference velocities: peak search
- shifted to match Zhang et al. (2003)
Marmousi bandlimited reflectivity (as before)
Marmousi shallow reflectivity

Marmousi bandlimited reflectivity

depth m

distance m
Marmousi target reservoir

PSPI reference velocities: modified Bagaini
Marmousi target reservoir
Marmousi target reservoir

PSPI reference velocities: Peak Search
Marmousi target reservoir

PSPI reference velocities: modified Bagaini

depth m

distance m
Marmousi target reservoir
Marmousi target reservoir
PSPI reference velocities: modified Bagaini
PSPI reference velocities: Peak Search
PSPI creates discontinuities at boundaries – smoothing may be good!
Conclusions

• Preprocessing to zero phase, shot modeling, and correction of static shifts important for imaging

• Optimal selection of reference velocities desired to maximize accuracy and efficiency of wavefield extrapolation

• Linear or geometric progression does not take into account distribution of velocities

• Bagaini et al. method does not necessarily pick reference velocities close to model velocities

• New peak search method selects reference velocities close to model velocities
Conclusions (cont)

- However, Bagaini method performs well on Marmousi!
- Our PSPI implementation provides a good standard for judging our other algorithms