# An interactive velocity modelling tool in MATLAB

Chad M. Hogan, Gary F. Margrave

## ABSTRACT

An integral part of seismic data processing is the velocity analysis stage. Here we introduce an interactive GUI tool running natively in MATLAB that allows velocity analysis on shot gathers (real or synthetic data). This tool is now a part of the CREWES MATLAB toolbox.

## BASIC THEORY

The basic principle of velocity analysis based on normal moveout correction is described in many texts (e.g. Keary and Brooks, 1991).

Traveltime $t$ from a surface source with horizontal position $x_s$ to a surface receiver with horizontal position $x_g$ via reflection from the bottom of a homogenous layer with propagation velocity $V$ at $z$ meters below the surface can be easily shown to be,

$$t = \frac{\sqrt{(x_g - x_s)^2 + 4z^2}}{V}. \tag{1}$$

Rearranging this equation gives the equation of a hyperbola,

$$\frac{V^2 t^2}{4z^2} - \frac{(x_g - x_s)^2}{4z^2} = 1. \tag{2}$$

Defining zero-offset time $t_0 = 4z^2/V^2$ and offset coordinate $x = x_g - x_s$, and applying a binomial expansion truncated to the first term gives the equation,

$$t \approx t_0 \left( 1 + \frac{x^2}{2V^2 t_0^2} \right). \tag{3}$$

The normal moveout (NMO) at offset $x$ is defined as the travel time difference $\Delta t = t_x - t_0$ between the reflected arrivals at zero offset, $t_0$ and at offset $x$, $t_x$. With this definition, NMO is equal to,

$$\Delta t \approx \frac{x^2}{2V^2 t_0} \tag{4}$$

Solving equation 4 for $V$ gives a basic equation for velocity given a measurement of NMO for a single layer:

$$V \approx \frac{x}{\sqrt{2t_0 \Delta t}} \tag{5}$$

This may be extended to multiple layers, following the method of Dix (1955). In this case, the measured velocity corresponds to the root-mean-square velocity, $V_{rms,n}$,

$$V_{rms,n} = \sqrt{\frac{\sum_{i=1}^n V_i^2 \tau_i}{\sum_{i=1}^n \tau_i}}, \tag{6}$$

where $n$ denotes the root-mean-square (RMS) velocity to the $n$th layer, $\tau_i$ is the one-way travel time of a ray through the $i$th layer, and $V_i$ is the interval velocity of the $i$th layer. In the multilayer circumstance, this RMS velocity corresponds to a sort of "average" of the total package of individual layers overlaying the reflector location. "Stacking velocity" is simply the velocity chosen for the NMO-correction, therefore allowing stacking. Ideally, for layer-cake geometry, the stacking velocity will match the RMS velocity.

A similar NMO equation may be written for the multilayer case,

$$\Delta t_n \approx \frac{x^2}{2V_{rms,n}^2 t_0}, \tag{7}$$

therefore providing the RMS velocity to the $n$th layer. The remaining task, then, would be to "unpeel" this average velocity, one layer at a time, to derive interval velocities for each of the $n$ layers.

This unpeeling process is accomplished via the Dix equation,

$$V_n = \sqrt{\frac{V_{rms,n}^2 t_n - V_{rms,n-1}^2 t_{n-1}}{t_n - t_{n-1}}}. \tag{8}$$

Therefore, to derive interval velocities, we use two adjacent RMS velocities, as well as the traveltime measurements to these two reflectors.

Dipping reflectors and other complicated geometries are not treated with this method. However, for relatively simple layer-cake geology, these methods are adequate for building a model of the velocities of the layers underlying a seismic survey.

## IMPLEMENTATION

The velocity analysis tool is implemented in fully-native MATLAB. This tool is fundamentally based on determining the RMS velocity to each reflector, and then by extracting interval velocities using the Dix equation, Equation 8. These RMS velocities are measured by calculating *trial corrections* for the shot gather for a constant RMS velocity. Once these trial corrections are applied to the original shot gather, there are two primary directions in which one may proceed:

1. Constant-velocity panel selections.

2. Semblance plots.

### Constant-velocity panels

In this method, the entire shot record is NMO-corrected with a constant RMS velocity by removing the NMO estimated by Equation 7. Assuming that the shot record is from a survey over a layer-cake geologic structure, then those reflectors for which the RMS velocity matches the constant velocity used will be exactly flattened, and so will appear as
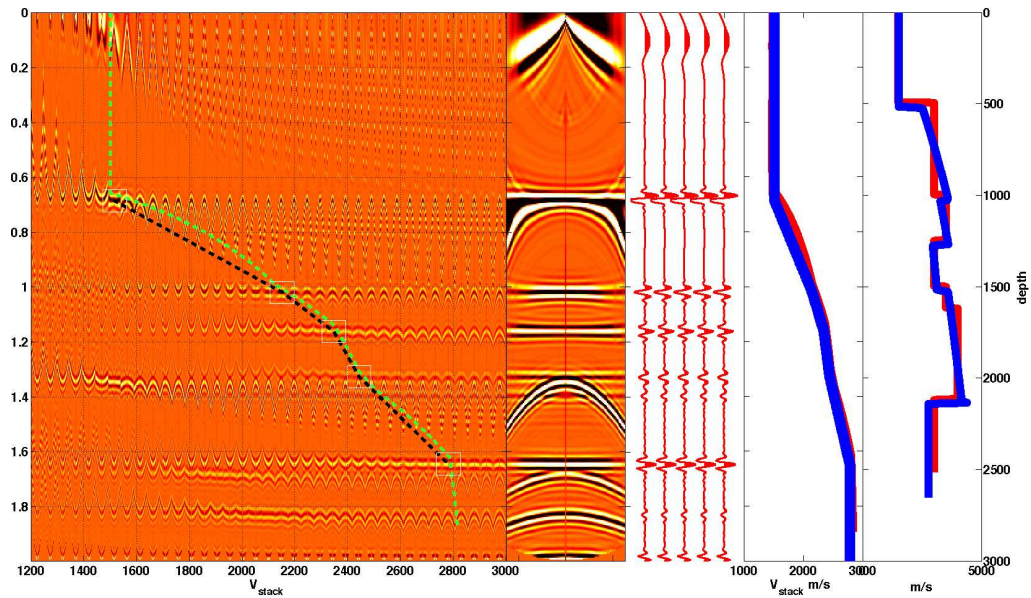
FIG. 1. Velocity panels in the velocity analysis tool. In the right-most plot, the red line shows well-log velocity, and the blue line shows the calculated velocity from the velocity analysis picks. In the second right-most plot, stacking velocity from the well-log is shown in red, with the estimated velocity from the velocity analysis picks in blue. The central wiggle plot shows a repeated stack of the gather with NMO correction applied. The center-left plot shows the shot gather with the NMO correction applied. The left-most plot shows panels of constant-velocity NMO applied. The green dashed line shows stacking velocity as estimated from the well log. The black dashed line shows stacking velocity from the velocity picks, with velocity picks marked with a white square.

horizontal events on the trial-corrected shot. Figure 1 shows, in the leftmost panel, a series of many constant-velocity-corrected shot gathers. Picking the RMS velocity to a given reflector consists of choosing the velocity which gives the best flattening of the reflection event. Selecting the flattened event for each successive reflection event will provide RMS velocities throughout the extent of the recording.

The primary advantage of this method is that it is the most direct method – we are actually selecting the velocity that flattens each horizon optimally. One disadvantage, however, is that it requires the visual inspection of a great many panels, and can be somewhat difficult to choose in noisy or multiple-contaminated data.

### Semblance analysis

Semblance analysis offers a somewhat more processed version of the same information available in the constant-velocity panels. The idea is that, when a reflection event is optimally flattened, its *semblance* will be maximized. In this implementation, we have defined semblance at velocity $v$, $\text{Semb}_v(t)$ to be,

$$\text{Semb}_v(t) = \frac{\left(\sum_x S_v(x, t)\right)^2}{\sum_x S_v^2(x, t)}, \tag{9}$$

where $S_v(x, t)$ a shot record with an applied NMO correction for RMS velocity 'v'. Therefore, the algorithm consists of taking the shot record, applying a constant-$V_{rms}$ NMO correction, summing the shot record over the offset axis, squaring this result, then dividing by the same NMO-corrected gather first squared, then summed along the offset axis. This procedure is repeated for many trial velocities. The resulting one-dimensional traces are typically gathered and plotted in a two-dimensional display, with velocity on the horizontal axis and time on the vertical axis. The semblance is designed to be maximal when the trace is optimally corrected for the RMS velocity at a given reflector. Figure 2 shows, in the leftmost panel, semblance. Note that when the reflectors are flattened, a hotspot shows in the semblance plot. This hotspot may be picked to match an RMS velocity

The primary advantage of this method is that it allows relatively easy identification of the correct stacking velocity, and this procedure may be at least partially automated. The primary disadvantage, however, is that semblance may have local maxima at erroneously low velocities in the presence of multiple reflections. Alternatively, this may be seen as another advantage, as it can allow for the detection of multiples in data.

## USE OF THE VELOCITY ANALYSIS TOOL

To use this velocity analyis tool, simply invoke the interactive tool with the command:

```
» VelocityAnalysis(seis, t, os, vmin, vmax, vstep, refv, refz, type);
```

The arguments are defined as follows.

**seis** is a 2d matrix consisting of a gained, filtered shot record. It is assumed that the each column of this matrix consists of a single trace.
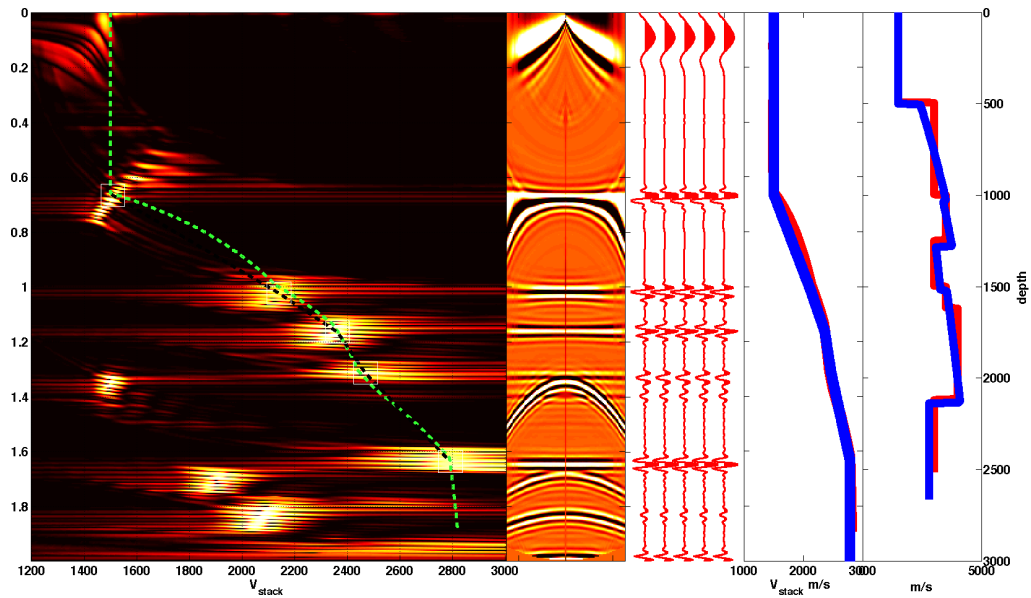
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FIG. 2. Semblance plot in the velocity analysis tool. In the right-most plot, the red line shows well-log velocity, and the blue line shows the calculated velocity from the velocity analysis picks. In the second right-most plot, stacking velocity from the well-log is shown in red, with the estimated velocity from the velocity analysis picks in blue. The central wiggle plot shows a repeated stack of the gather with NMO correction applied. The center-left plot shows the shot gather with the NMO correction applied. The left-most plot shows semblance. The green dashed line shows stacking velocity as estimated from the well log. The black dashed line shows stacking velocity from the velocity picks, with velocity picks marked with a white square.

**t** is the time coordinate, and should have one entry for each sample of each trace in `seis`.

**os** is the offset coordinate for each trace in `seis`.

**vmin** is the minimum RMS velocity that is expected within the velocity model. In practice it is useful to push this safely below the actual minimum velocity (e.g. '1000' when one is expecting a water-bottom at 1500 m/s is prudent).

**vmax** is the maximum velocity expected, and should also be padded as with `vmin`.

**vstep** is the interval that the analysis will use between `vmin` and `vmax`. Although a smaller `vstep` will result in a finer sampling and perhaps a more accurate result, it can also add significant computation time if it is too small.

**refv** is a reference interval-velocity that may be used to aid velocity picking in difficult situation. These reference velocities may be taken from nearby well-logs, previous velocity modelling, estimates from knowledge of the geology, or anywhere else that a reasonable estimate of expected interval velocities may be found.

**refz** is the depth vector corresponding to `refv`, with one entry for each entry in `refv`.

**type** chooses between methods of analysis. If `type=0`, *constant-velocity panels* will be used. If `type=1`, *semblance* will be used.

Once the velocity analysis is invoked, trial NMO corrections will be calculated. This may take anywhere between moments and minutes, depending on the size of the shot record, the total number of trial corrections, the computing power available and more. When these are complete, a display like either of Figures 1 or 2 will appear, depending on the value of `type`.

This display is the fully-interactive velocity analysis interface. There are five main panels in this display. From right to left, they are as follows.

**interval velocity** This panel shows the interval velocity over the region, with depth shown on the vertical axis and velocity on the horizontal axis. Initially, this panel will be blank unless a suitable reference velocity model was supplied on the command line. If a reference velocity model was used, this will be shown as a red line. As velocity picks are made, the estimated interval velocities will be plotted with a blue line.

**RMS velocity** This panel shows the RMS velocity over the region, with depth shown on the vertical axis and velocity on the horizontal axis. Initially, this panel will be blank unless a suitable reference velocity model was supplied on the command line. If a reference velocity model was used, the RMS velocity will be calculated from the interval velocities and this will be shown as a red line. As velocity picks are made, the estimated RMS velocities will be plotted with a blue line.

**test stack** This panel shows several repeated traces of the shot record, stacked. This stack will be automatically updated as velocity picks are made.

**shot record** This panel shows the shot record. Initially it will be uncorrected, but as the velocity picks are made, it will automatically update to show the newly-corrected record.

**analysis panel** This panel is the interactive analysis panel. This panel will show either panels of constant-velocity corrected data, or semblance. Picks are made by clicking on this window in the appropriate location, where either semblance is maximal or the reflector is flat. A pick will be represented by a small white box. A reference velocity model, if used, will plot on this panel as a dashed green line, while the picks will be joined with a dashed black line.

A poorly-placed pick may be individually deleted simply by clicking within the white box. All picks may be cleared and the plot reset by right-clicking within this panel. Note that, since two RMS velocities are required to calculate an interval velocity, no automatic updates or corrections will be displayed until two picks are made.

### Extracting the data

Once all picks have been made and an adequate velocity model has been generated, the data may be extracted by use of the function:

```
» pickdata = GetVelocities(fig);
```

**fig** is the figure number of the interactive velocity analysis tool.

The velocity model information will be returned in the structure `pickdata`. This structure contains five elements:

**pickdata.vrms** The RMS velocity in two-way time.

**pickdata.vave** The average velocity in two-way time.

**pickdata.vint** The interval velocity.

**pickdata.z** The depth coordinate for interval velocity.

**pickdata.t** Time coordinate for velocities.

### FUTURE WORK

Although this tool is useful for velocity analysis in regions where the geology consists of layer-cake structures, it will not perform adequately in complex regions with dipping contacts and non-uniform structures.

Many methods exist for extending velocity analysis beyond homogeneous horizontal contacts. These include dip moveout, 3D velocity modelling anisotropic velocity models, migration velocity analysis, and many more. We hope to see the inclusion of some or all of these methods in the future.

# REFERENCES

Dix, C. H., 1955, Seismic velocities from surface measurements: Geophysics, **20**, No. 1, 68–86.

Keary, P., and Brooks, M., 1991, An Introduction to Geophysical Exploration: Blackwell Science, 2 edn.