matGPR

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What is matGPR?

- ✓ Accessible and advanced GPR analysis and interpretation program …
  - Cross-platform
  - Expandable/ Customizable by its user
- ✓ … based on MATLAB™…
  - … which provides an all-inclusive high level programming and visualization environment.

Is matGPR different?

- Most existing (proprietary) GPR software focuses on productivity and visualization:
  - Fast production of results with emphasis on marketability
  - Standard/proven analytical tools, not always state-of-the-art, frequently of limited choice.
- ✓ matGPR focuses on information extraction from complex data/ understanding complex data
  - Offers extensive array of advanced analytical tools in addition to the standard/proven techniques
  - Has an educational underpinning

Information Processing vs. Simulation

INFORMATION PROCESSING

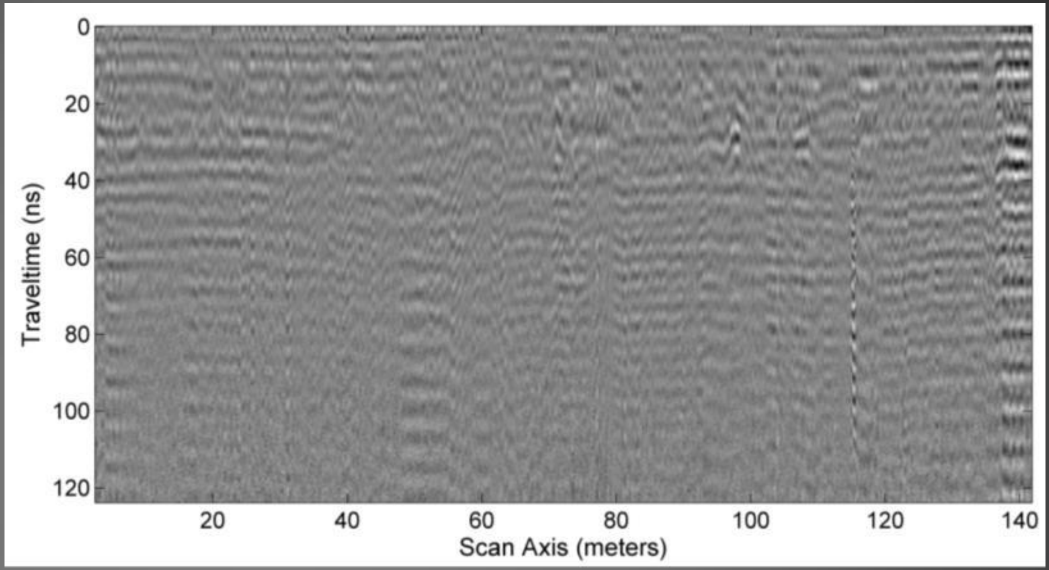
- Reductionist approach
  - Measured data are frequently stochastic or with significant stochastic component
  - Uses stochastic models and procedures to reduce data into components and recover those that are useful.
- Although you can always try to find out what nature is hiding from you,
- Then try to simulate it…

MODELLING AND INVERSION

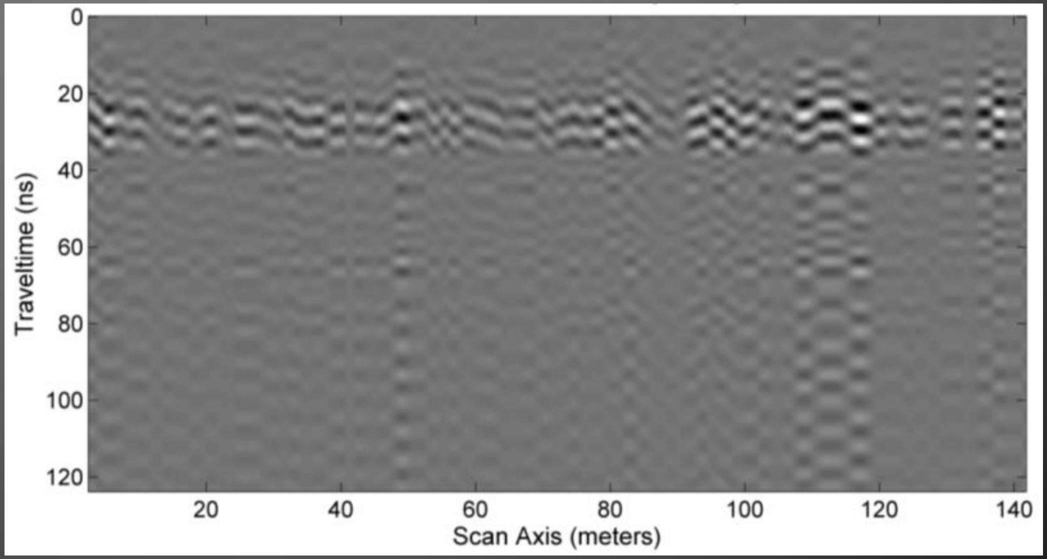
- Deterministic approach
  - **Modelling**: Attempt to describe natural processes with exacting mathematical physics.
  - **Inversion**: Stochastic process that uses exacting mathematical physics to simulate stochastic data.
- Both of utmost importance, but,
- Almost always insufficient because you cannot replicate nature!

Example: what does one do if…

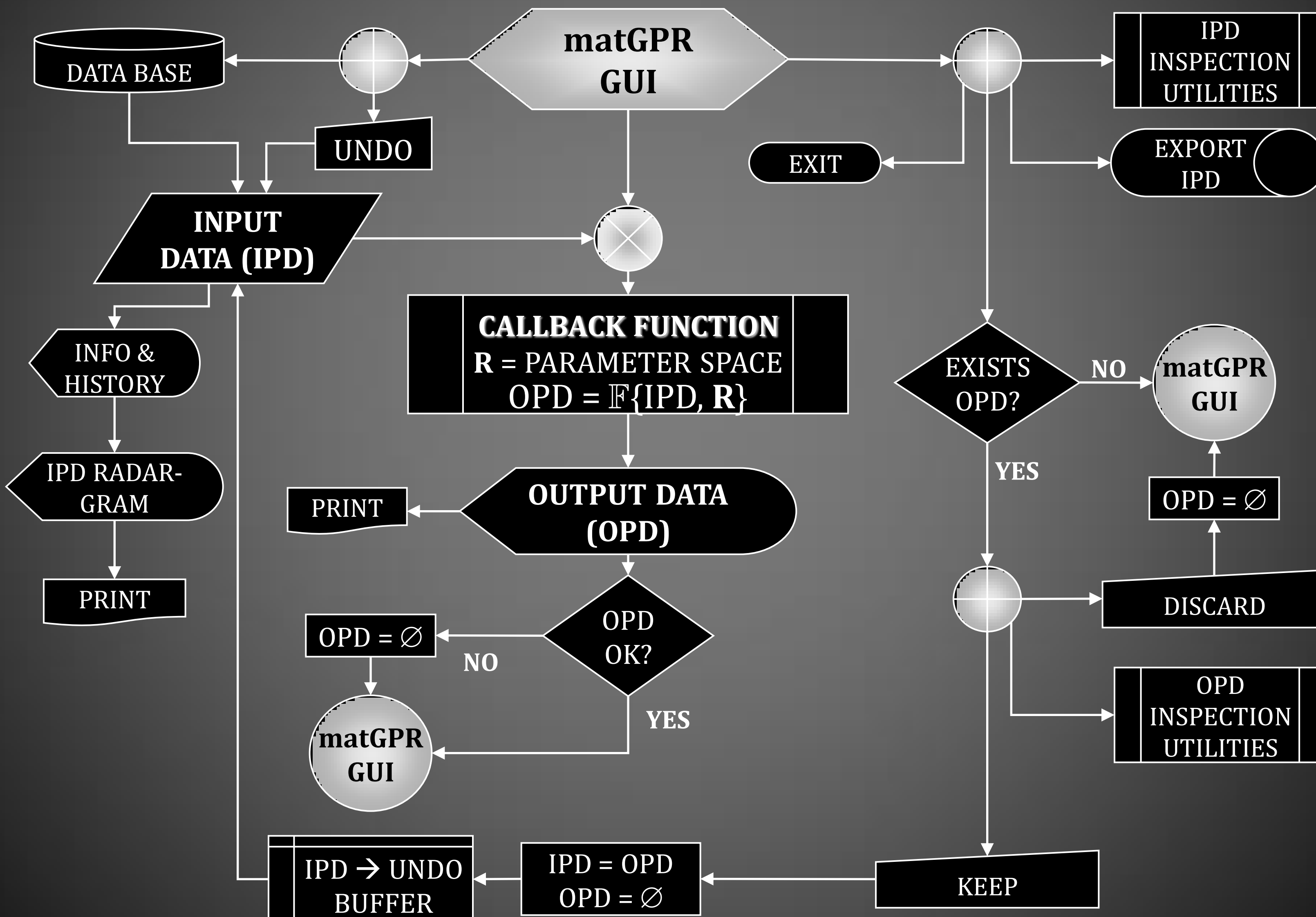
One measures this:



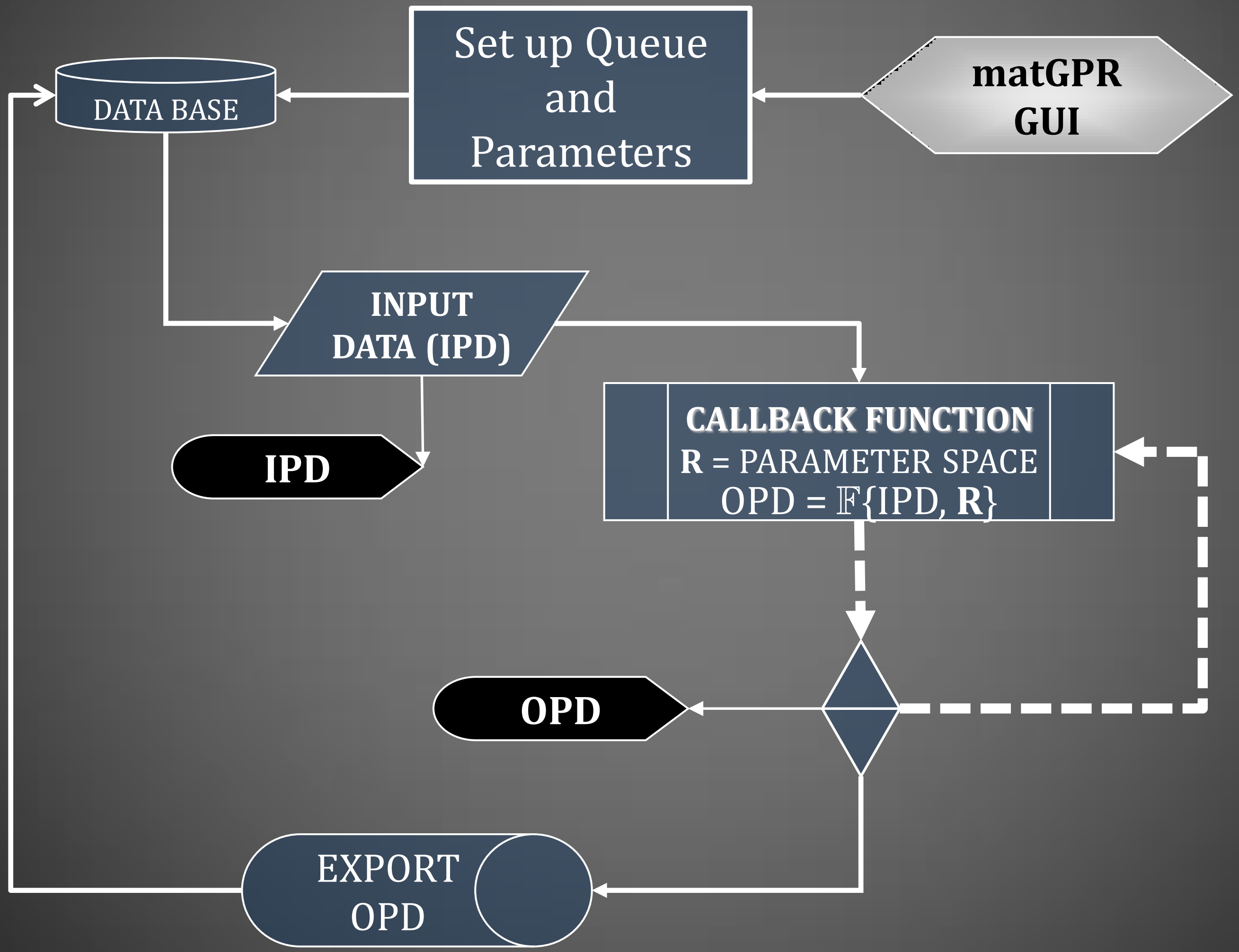
When the only structural information is:



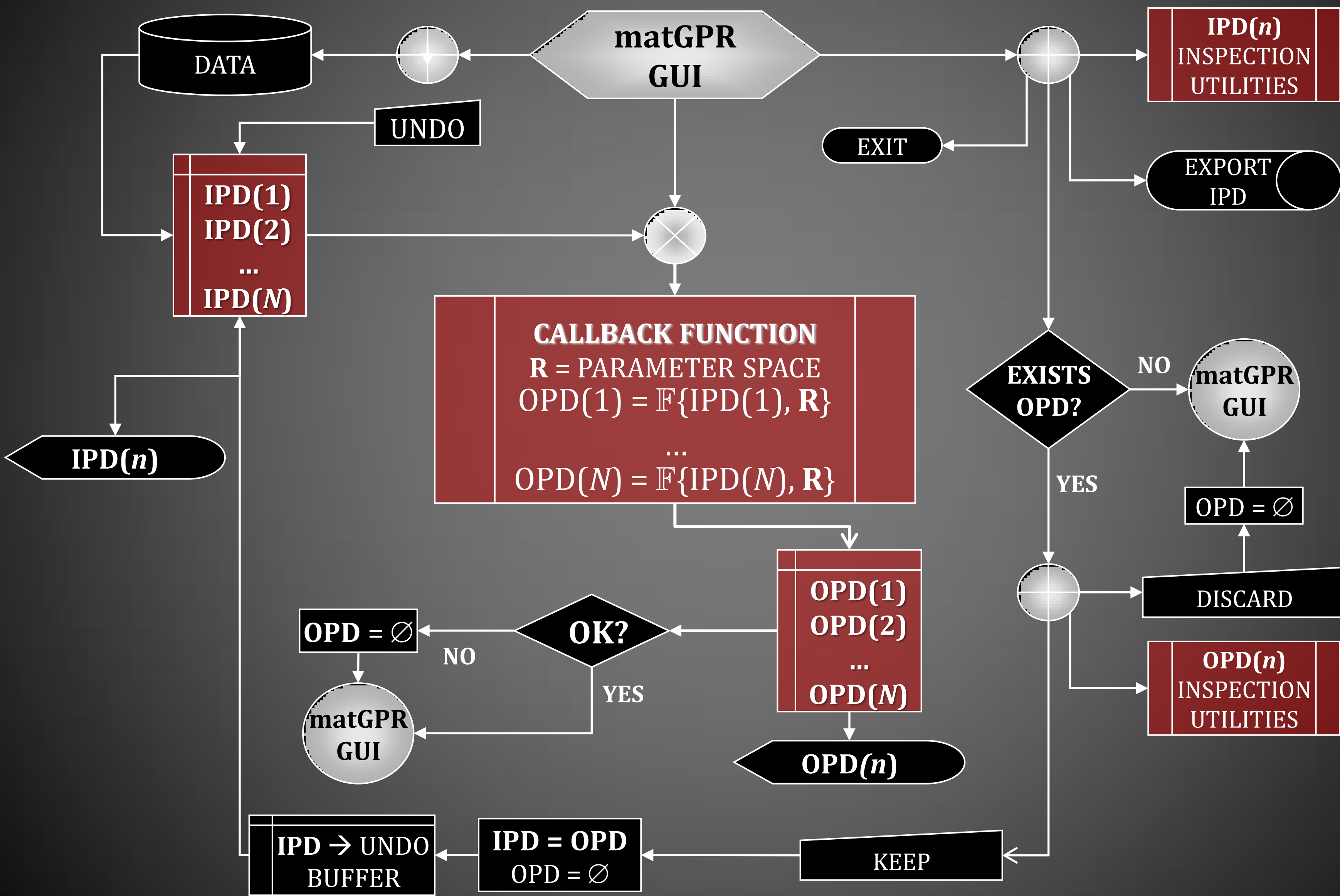
matGPR offers increased control of the analysis procedure and scrutiny into the data:



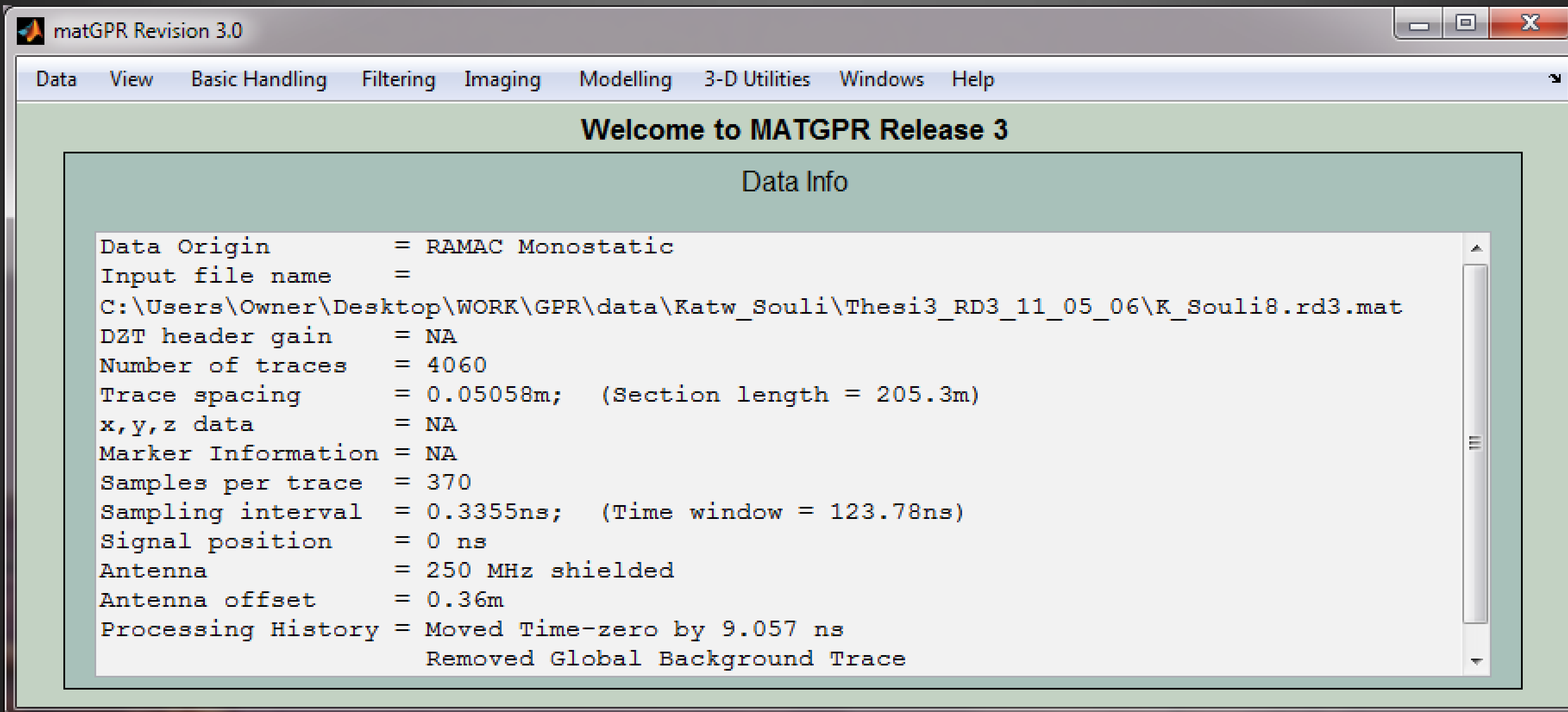
Productivity is not overlooked: Batch processing of large data sets



Architecture Extensible to Multi-static Data



The matGPR GUI

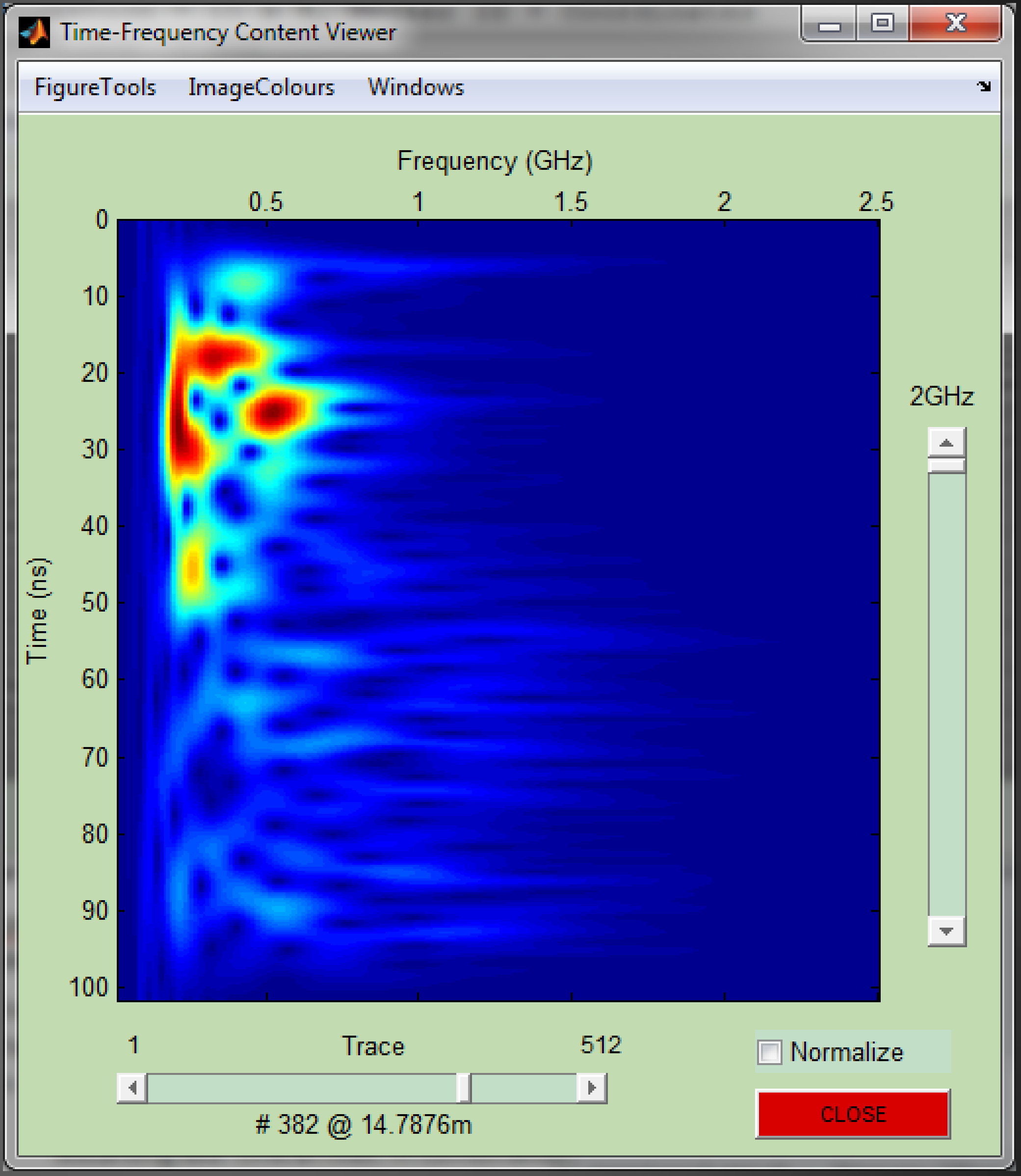


Data Properties and Visualization

- ✓ Image (colour-graded) displays, wiggle-trace displays, variable-area displays and combinatory displays
  - Colour scheme editing, zooming, panning, peeking, exporting to all standard graphics formats, printing, figure editing, axes editing, graph editing
- ✓ Individual traces and trace Fourier spectra
- ✓ **Time-frequency characteristics of traces**.
- ✓ **Attenuation characteristics** of the input and output radargrams
- ✓ The instantaneous attributes of the input radargram
- ✓ **Centroid frequency** of the input radargram
- ✓ **Curvature attributes** of the input radargram

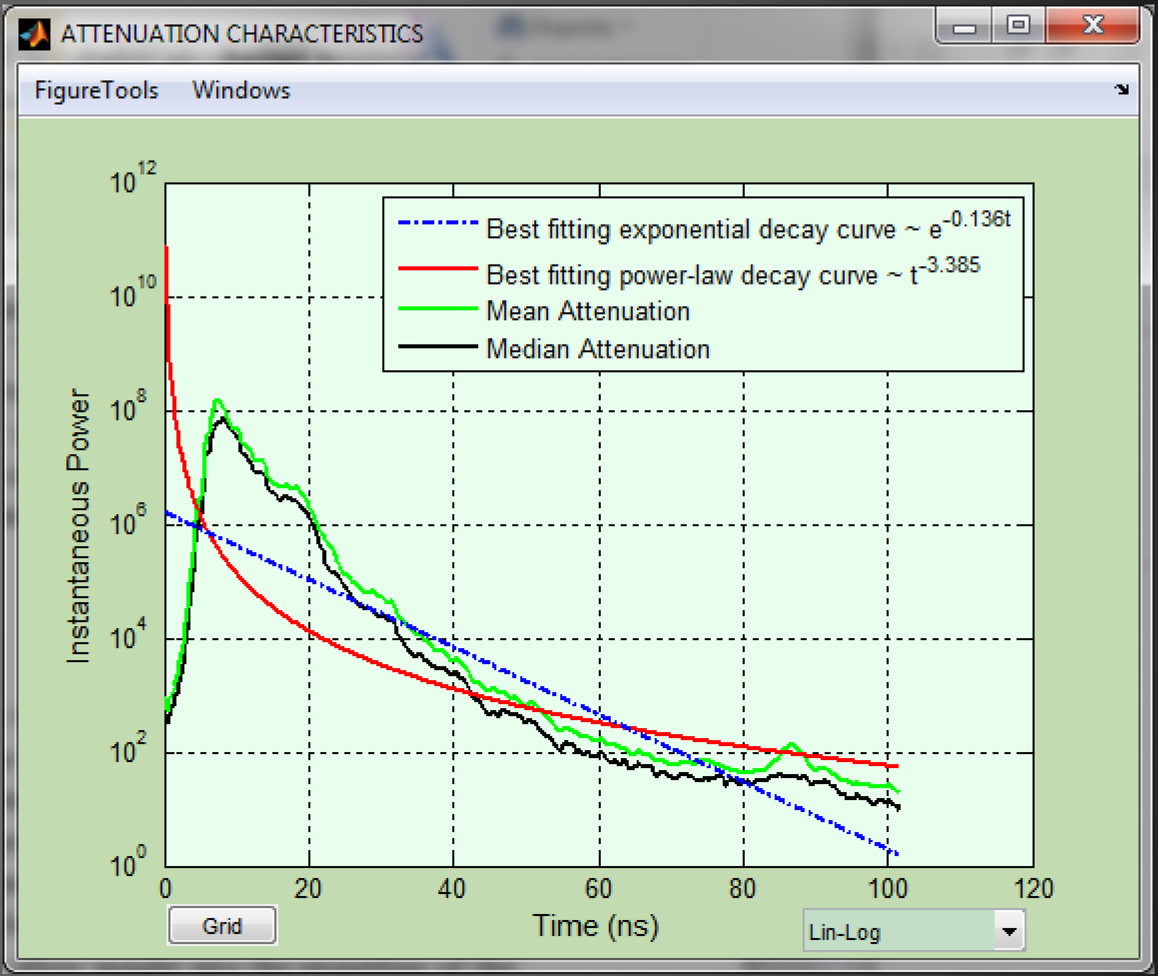
Time-Frequency analysis

- Intended for detailed study of the input or output data.
- Computes a *time-frequency representation* of individual traces using the ultra-high resolution S-transform (Stockwell et al. 1996)
- Helpful in assessing the characteristics of propagation in complex media



Attenuation Characteristics

- Allows insight into the properties of the propagation medium and facilitates gain manipulations
- Computes instantaneous power of all traces.
- Computes the median and mean instantaneous power of all traces in the section.
- Determines best fitting power-law and exponential attenuation models based on the median attenuation function.
- Displays attenuation functions and the best fitting power-law and exponential decay models.

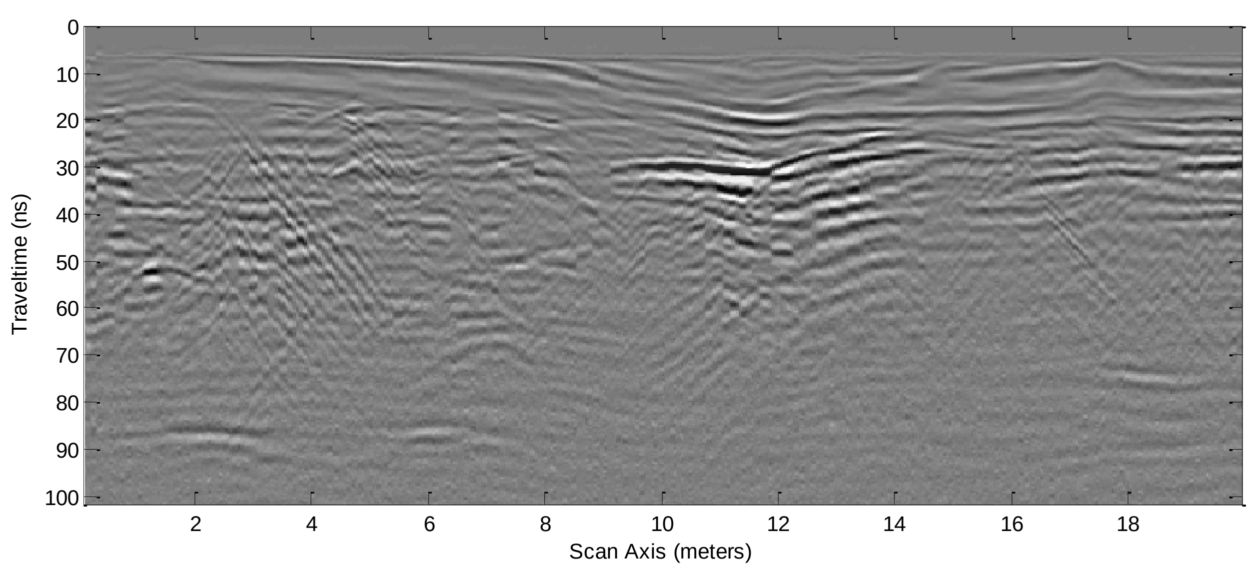


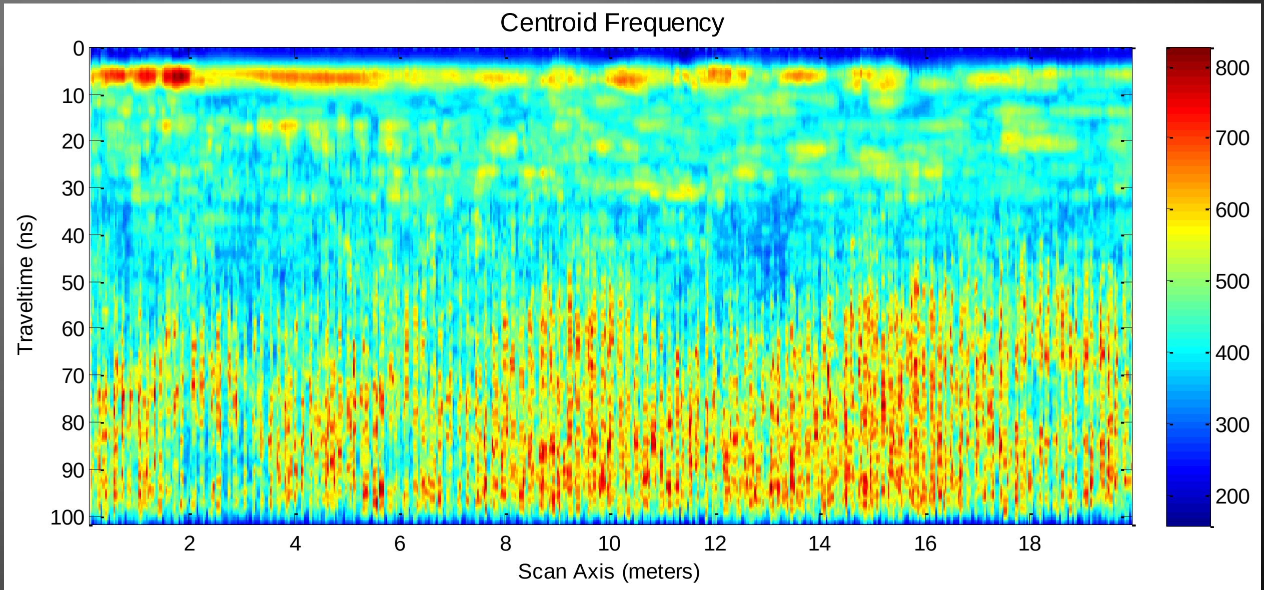
Centroid Frequency

- Computes and displays a map of the frequency of the *Spectral Centroid*:

$$f_c = \frac{\int_0^\infty fS(f)df}{\int_0^\infty S(f)df}$$

- Offers a synopsis of the location of the spectral content of the data, hence a measure of changes in propagation conditions.
  - The CF is expected to decrease (increase) with time, as the signal enters high (low) attenuation domains
  - Expected to exhibit consistent gradual downshift in cases of dispersive propagation
- Calculation based on an *ultra-high resolution* S-transform (Stockwell et al., 1996).

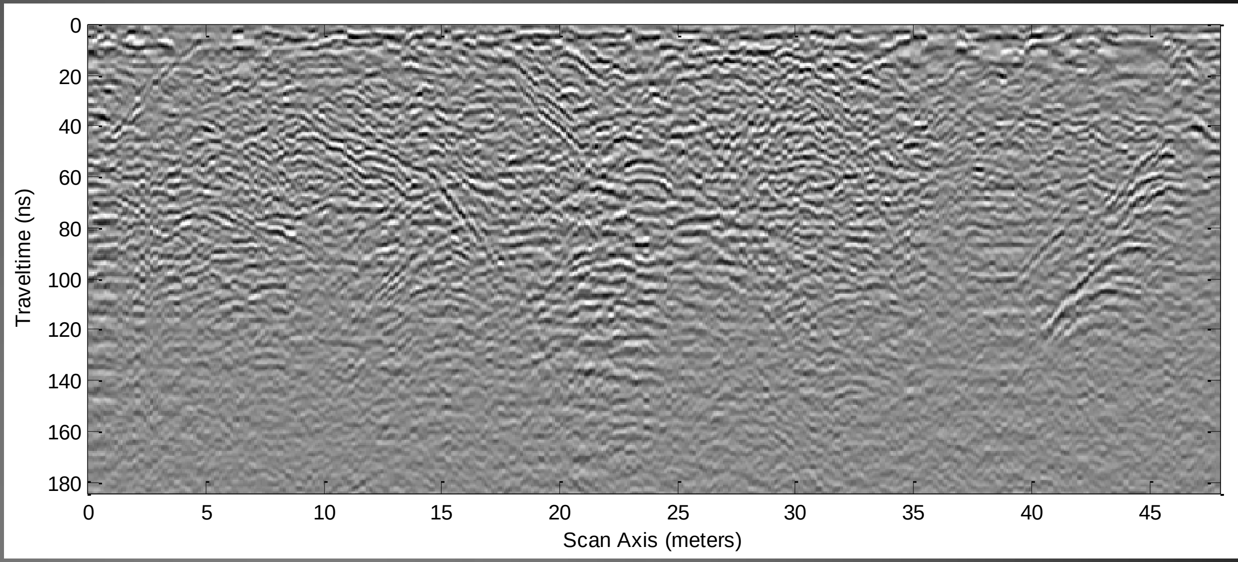


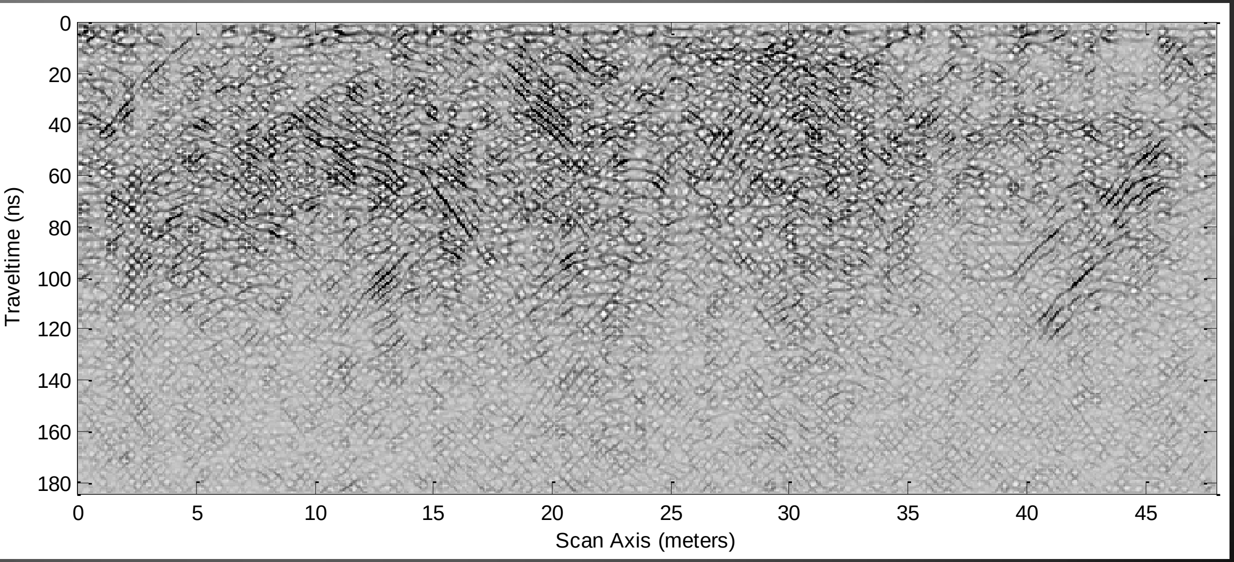


Curvature Attributes

Edge detection with Curvature Attributes suitable for 2-D profile data:

- ✓ Most Positive Curvature
- ✓ Most Negative curvature
- ✓ Maximum Curvature
- ✓ Minimum Curvature





Basic Processing

- ✓ Graphically assisted determination and adjustment of time-zero
- ✓ Graphically assisted Trace and Radargram Editing utilities: Time-Window Trimming, Scan-line trimming.
- ✓ Elimination of errant traces
- ✓ DC removal, Dewow
- ✓ Equalization
- ✓ Gain Manipulation:
  - Standard and Gaussian-tapered Automatic Gain Control (AGC)
  - **Inversion of Amplitude Decay**
  - Inversion of Power Decay
- ✓ Resampling in *time* and/or *space* with band limited sinc interpolation.
- ✓ Marker Interpolation and Trace Positioning
  - Editing and management of *marker traces* whose locations are *a priori* assigned with reference to a local coordinate frame.
  - Transformation of data collected in equal-time mode, to data at equal-spacing.
  - Assignment of x, y and z coordinates to traces by reference to the known coordinates of marker traces.

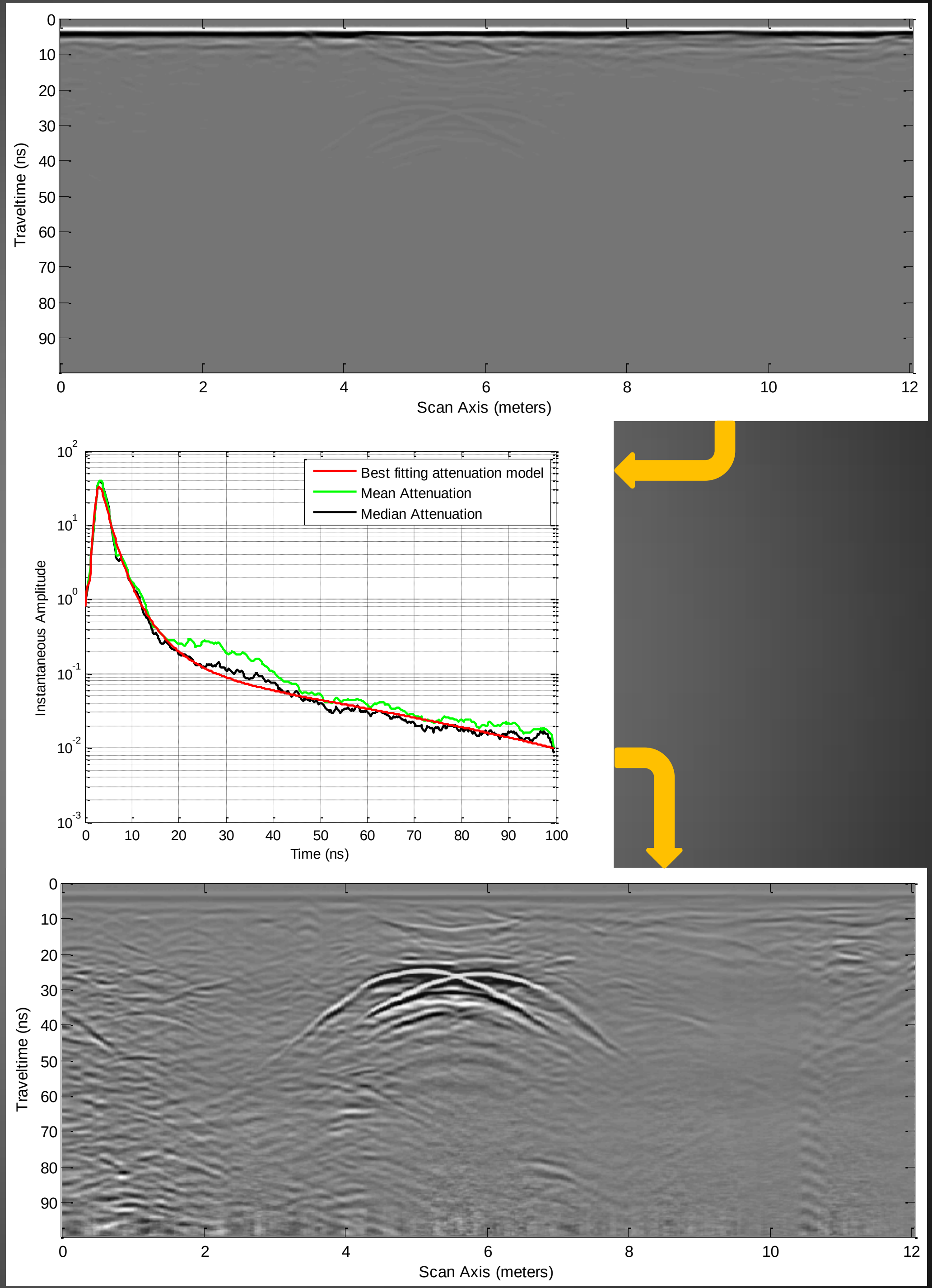
Inversion of Amplitude decay

Empirical gain function which almost exactly compensates the mean or median attenuation.

- Computes the median and a mean amplitude attenuation function from instantaneous amplitude of all traces
- Computes empirical best fitting attenuation models with a function of the form

$$A(t) = c_1\,\mathrm{e}^{-a_1 t} + c_2\,\mathrm{e}^{-a_2 t} + \cdots + c_N\,\mathrm{e}^{-a_N t}$$

- Displays the mean and median attenuation and best fitting model and allows for interactive optimization
- The gain function is the normalized inverse of the amplitude decay model



Filtering – Advanced Filtering

- ✓ Mean and median spatial filtering in one and two dimensions.
- ✓ Background (mean) trace subtraction to reduce source effects
- ✓ Removal of a sliding window's mean (background) trace to expose high-angle dipping reflections.
- ✓ Removal of a sliding-window's "foreground" traces to eliminate high-angle reflections and enhance horizontal (e.g. hydrogeologic features)
- ✓ **Karhunen–Loeve filtering** based on low-dimensional subspace approximation
- ✓ Graphically assisted design and implementation of zero-phase FIR filters in the frequency and wavenumber domains.
- ✓ Interactive, graphically assisted F-K filter design and implementation
- ✓ S/N enhancement and *orientation and scale-sensitive* information retrieval with
  - **Tuneable Directional B-spline and Gabor Wavelet Filters**
  - **Tuneable Multidirectional Scale-selective B-spline and Gabor Wavelet Filters**
  - **Multi-scale/Multidirectional *Curvelet* based Optimal Filtering.**
- ✓ Graphically assisted Tau-P domain modelling and filtering
- ✓ F-X Deconvolution to suppress random noise.
- ✓ **Predictive Deconvolution** to suppress reverberation
- ✓ Sparse Deconvolution to obtain a maximally parsimonious reflectivity structure

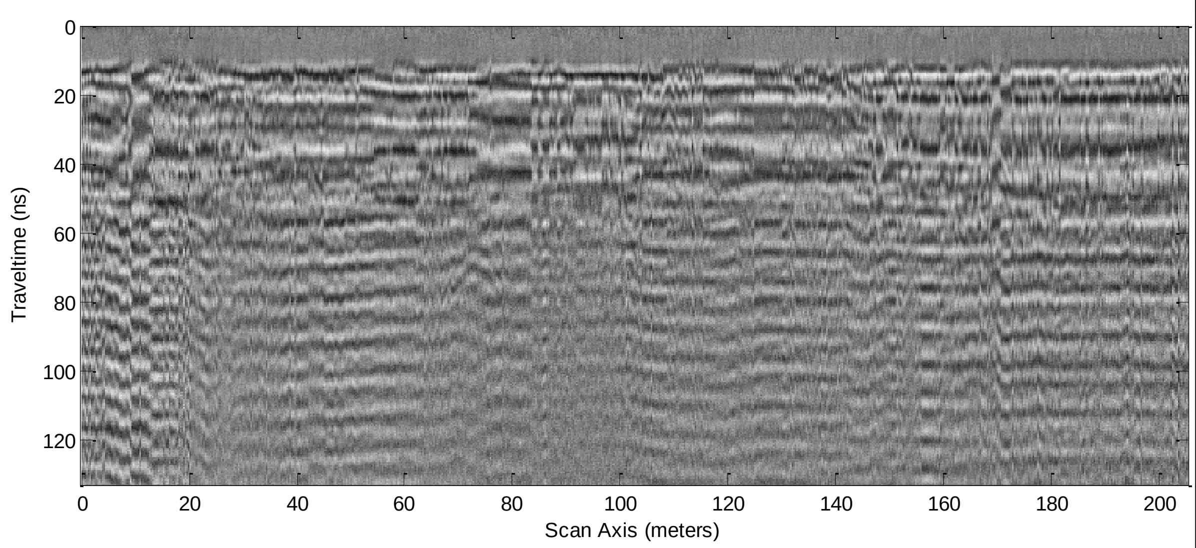
Karhunen – Loeve Filter

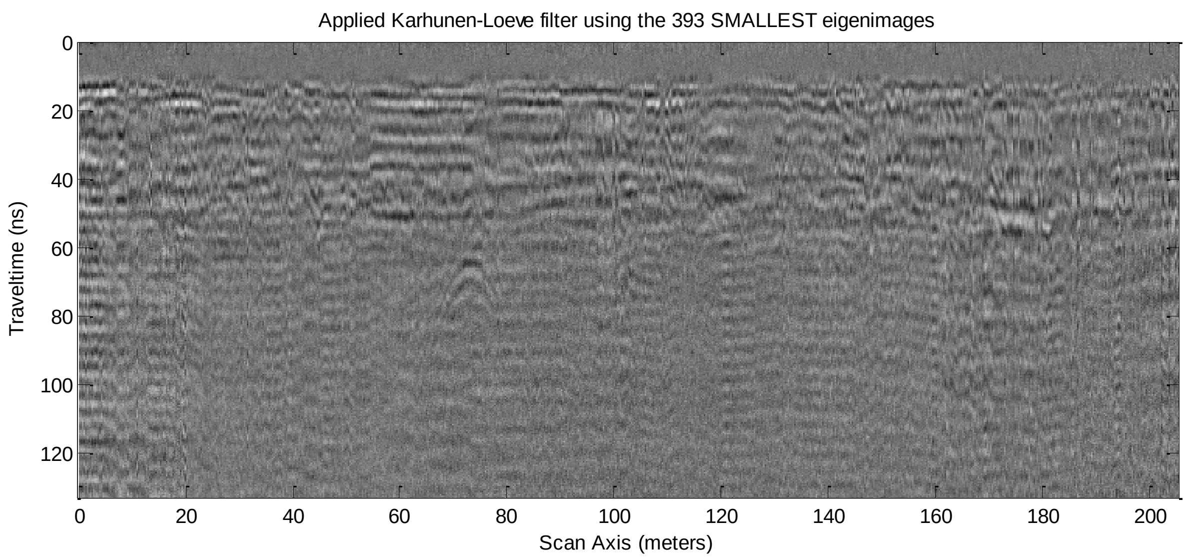
The Karhunen – Loeve transform is approximates a set of vectors or images by a with a low-dimensional subspace.

- The approximating subspace is defined in terms of the first (largest) N singular values and singular vectors (*eigenimages*) of the data.
- The appropriate value of N is unique for each data set and should be determined by experiment.

<u>Example</u>:

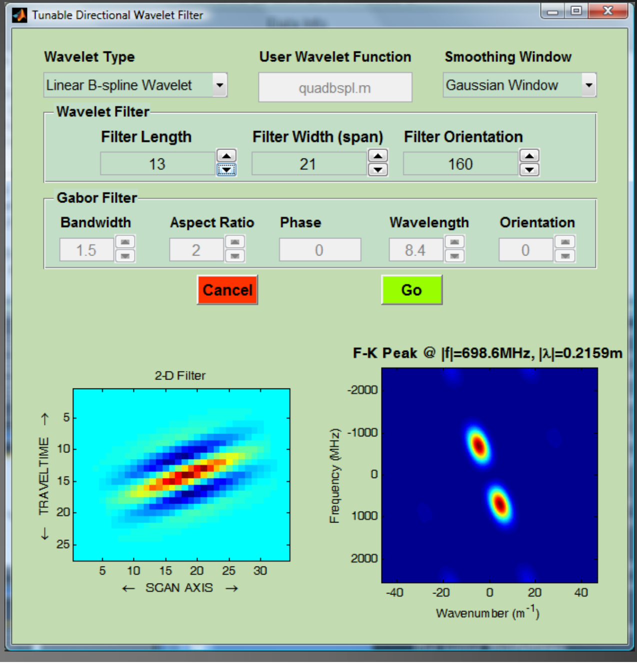
- **Top:** Full-space data comprising 397 eigenimages.
- **Bottom:** $N = 4$; complimentary low subspace approximation based on the 393 smallest eigenimage.
- Large scale interference is effectively removed.

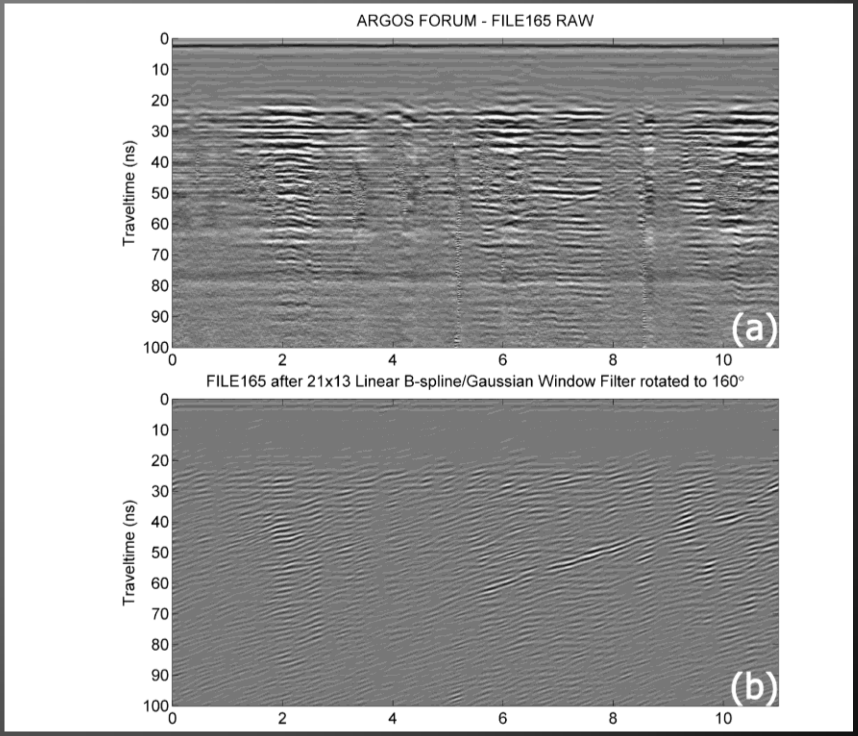




Tuneable directional B-spline and Gabor Wavelet Filters

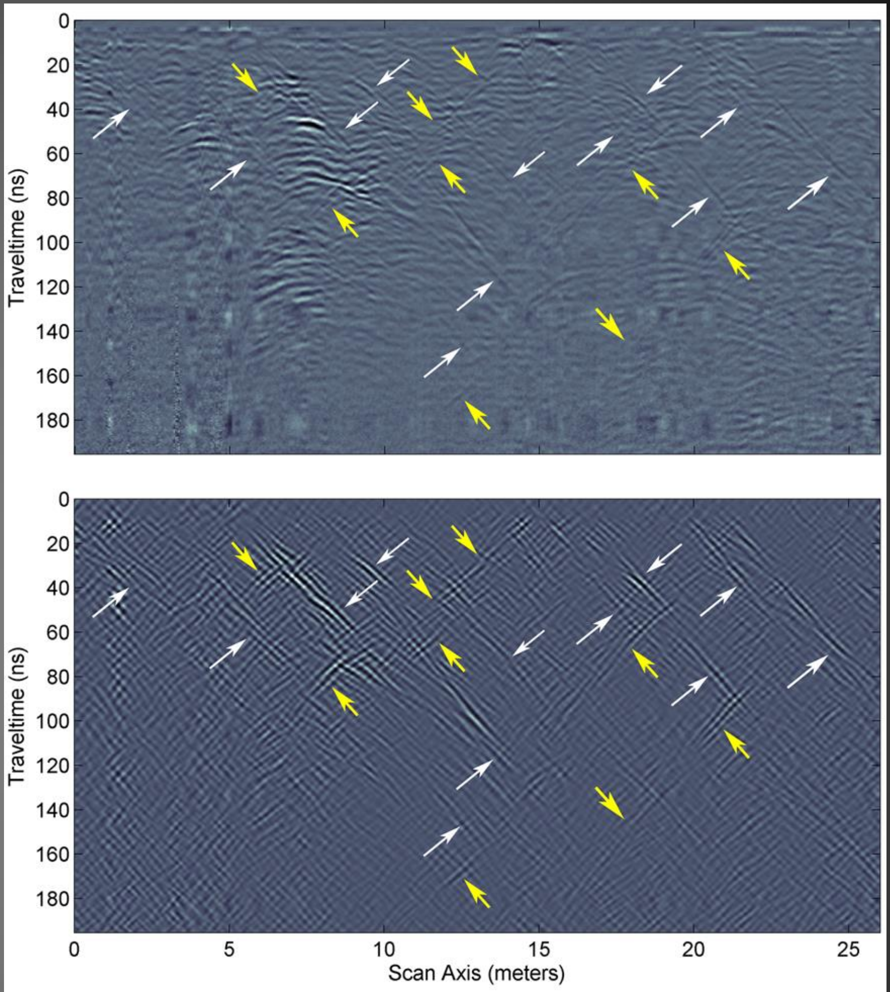
- A 2-D wavelet filter is built by sidewise arranging a number of identical 1-D B-spline wavelets, tapering the transverse direction with an orthogonal window and rotating the resulting matrix to the desired orientation.
  - The length of the wavelet determines the scale (frequency or wavenumber).
  - The number of parallel wavelets determines the degree of smoothing.
- The output contains information at a specific location, of features with scales matching the filter's bandwidth – each scale is coupled to a particular orientation.
- Scale and orientation can be varied so as to construct a matrix filter tuneable at any trait in the data
- The 2-D Gabor filter comprises of Gaussian kernel function modulated by a sinusoidal plane wave.
- The tuning of the Gabor filter follows the same guidelines





Tuneable *Multi-directional* Scale-selective B-Spline and Gabor Wavelet Filters

- Apply a Directional Filter rotated to different angles under adaptive control so as stay tuned at a given frequency or wavenumber.
- Stack the single-dip dependent outputs in the WLS sense. The stacking weight is a measure of the energy contained in the output data normalized by the same measure of energy contained in the input data.
  - Guarantees that output is not dominated by powerful spectral components and is a faithful representation of the scale-dependent information contained in the input data.
  - Smears dip-dependent noise eluding the filter at a given temporal or spatial scale.
- Filtering scheme facilitates combination of “partial” (same-scale-and-dip-dependent) data subsets into an image that is scale-dependent but dip-independent .
- The output image will account for any variation in the angle of dip, including the case of curved interfaces.



Fracture detection in massive fragmented limestone

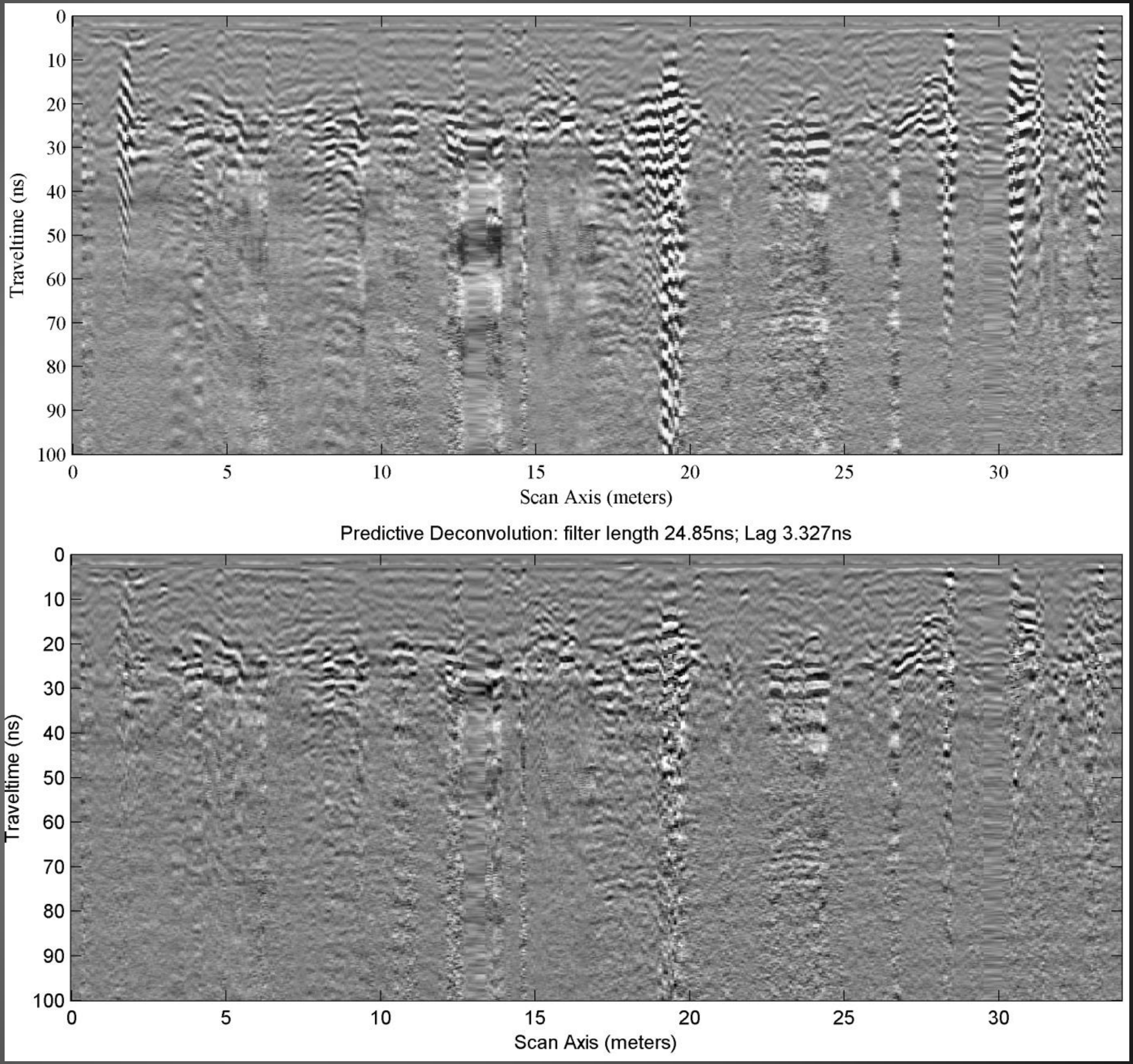
Top: Radargram collected with a Måla GPR system and 250MHz antenna at a levelled surface above massive fragmented limestone (Fig. 5). The white and yellow arrows point at faint down and up dipping reflections from synthetic (main) and antithetic fractures.

Bottom: Reflections from synthetic and antithetic fractures isolated by multidirectional application of Gabor filter tuned at k = 0.3m^{-1} over the arcs [50°, 65°] ∪ [115°, 130°]

Predictive Deconvolution

Assuming stationarity, use of information from the earlier part of a trace to predict and deconvolve repeating components from a later part of that trace

- ✓ Objective is to suppress multiples or other reverberations (e.g. ringing).
- ✓ An old dependable friend from the golden years of seismic exploration



Migration - Modelling

- ✓ Graphically assisted manual fitting of diffraction front hyperbolae on the premise of non-dispersive propagation in a uniform halfspace and targets comprising point diffractors, or finite objects with quasi-circular cross section

Imaging utilities include:

- ✓ **1-D Migration**: The required uniform or layered velocity model is supplied internally via the hyperbola fitting procedure, may be imported or may be entered via an appropriate UI.
  - ➢ **F-K Time Migration** (uses Stolt stretching to account for layered velocity structures)
  - ➢ **Phase-Shifting (Gazdag) Time Migration**.
  - ➢ **1-D Depth Migration**.
- ✓ **2-D Depth Migration.** The required 2-D velocity model may be read in, or be generated by a suitable utility on the basis of a synthetic structural model prepared by the in-house *Model Builder* utility.
  - ➢ **Phase-shift Plus Interpolation** (PSPI) migration for zero-offset data. Only the non-dispersive phase velocity term is used.
  - ➢ **Split-Step Migration**, augmented to account for frequency dependence of the phase velocity (dispersion).

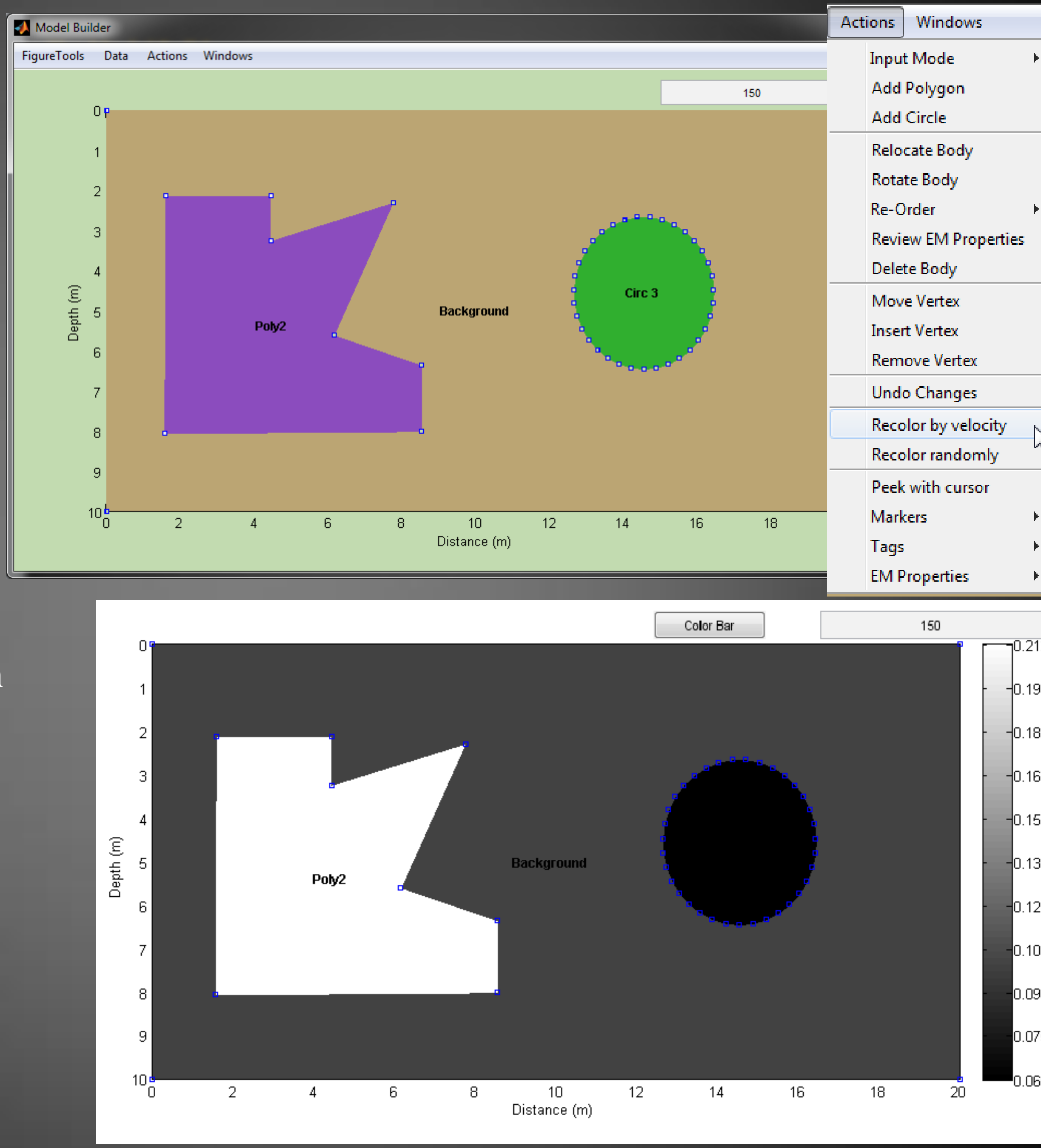
The Model Builder

Graphically assisted construction of 2-D structural models to be used with the 2-D Depth Migration and forward modelling methods.

- Models comprise an ensemble of objects with polygonal or circular cross-sections and may be edited, saved and modified indefinitely.

Editing utilities include:

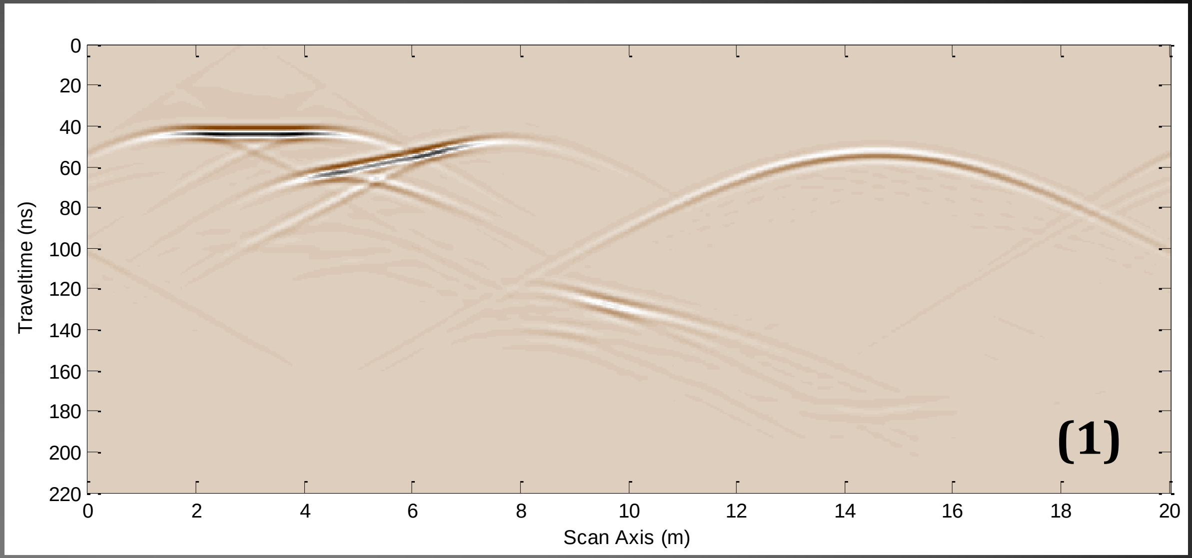
- Deletion of old and insertion of new objects.
- Graphically assisted modification of an object's position (by relocation or rotation) and an object's geometry (by relocation, deletion and/or insertion of vertices). All modifications can be undone.
- Modification of an object's dielectric constant, resistivity and magnetic permeability.
- Visualization enhancement utilities (e.g. colouring).

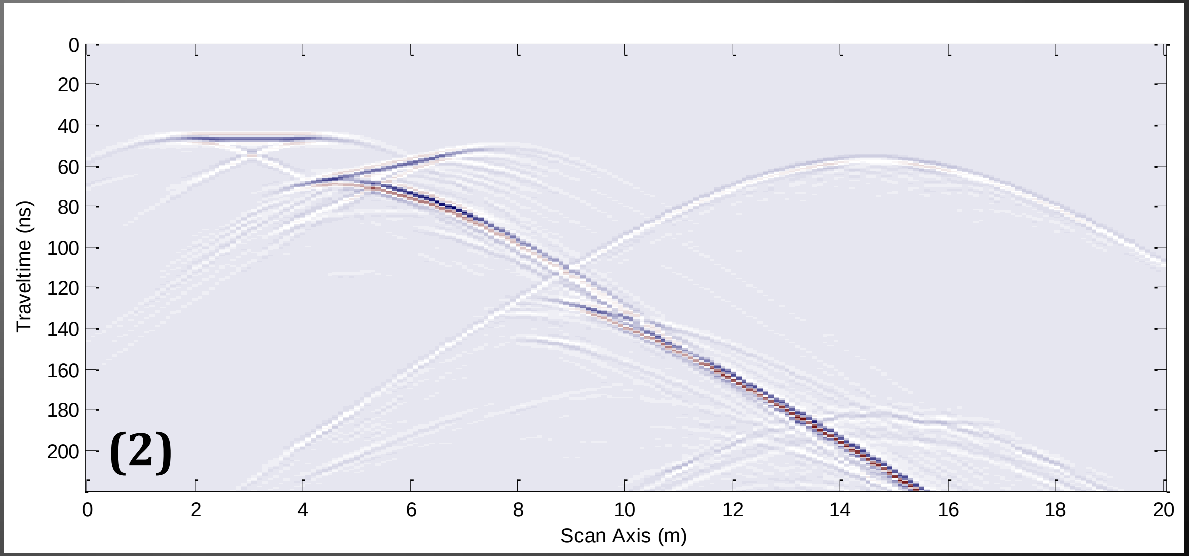


Forward Modelling

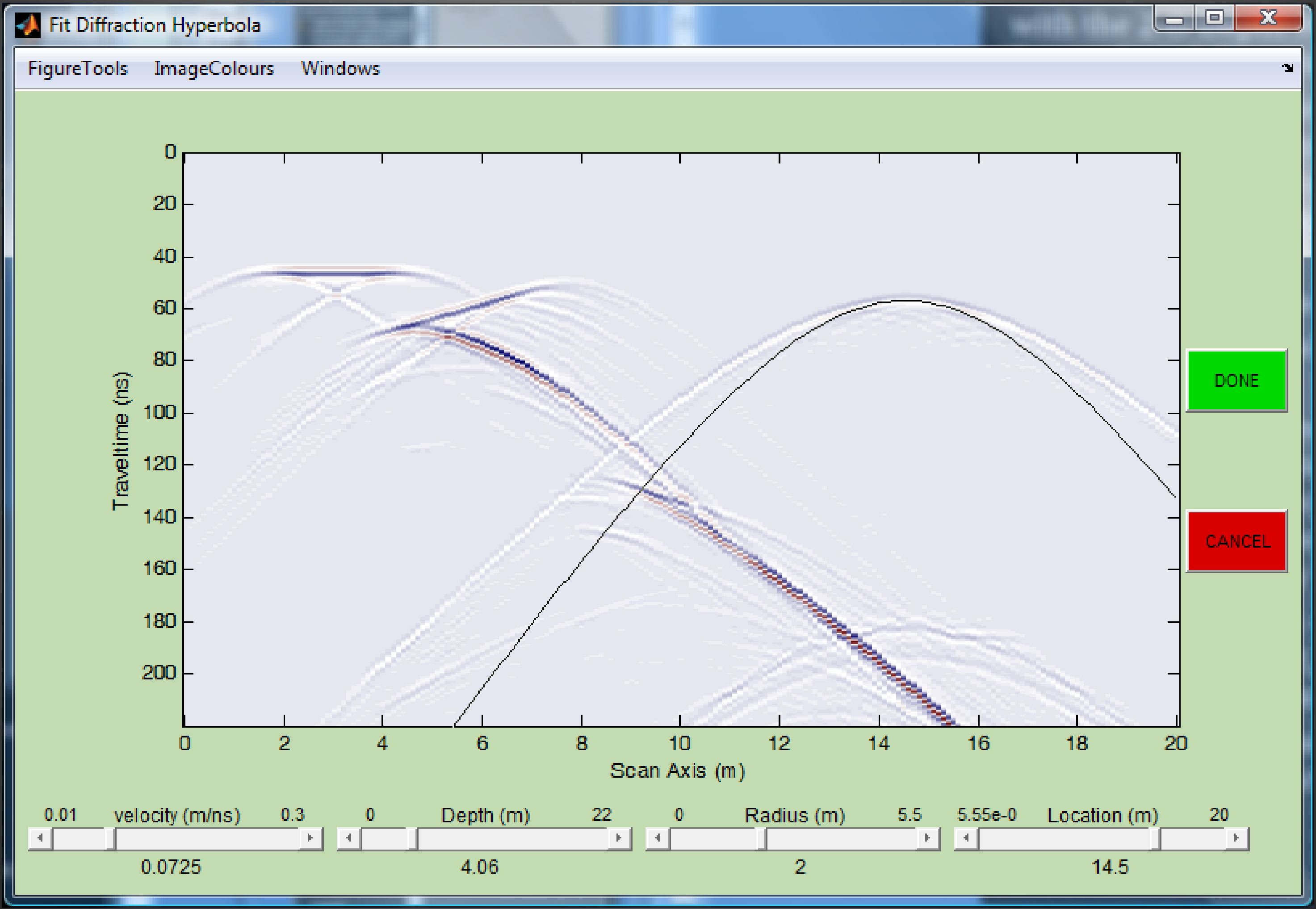
matGPR provides two modelling methods; both require synthetic structural models constructed with the Model Builder:

1. **Adjoint Split-Step method**:
   - Fast and dirty, lacking in detail (no secondary effects like multiples), and prone to artifacts if applied indiscriminately.
   - Efficient enough to effectively supplement the interpretation.
   - Modified and expanded from Bitri and Grandjean, Geophys. Prospecting, 46, 287-301, 1998).
2. **Finite Difference Time-Domain method**.
   - Irving and Knight, Computers & Geosciences, 32, 1247–1258, 2006.
   - Slow but accurate

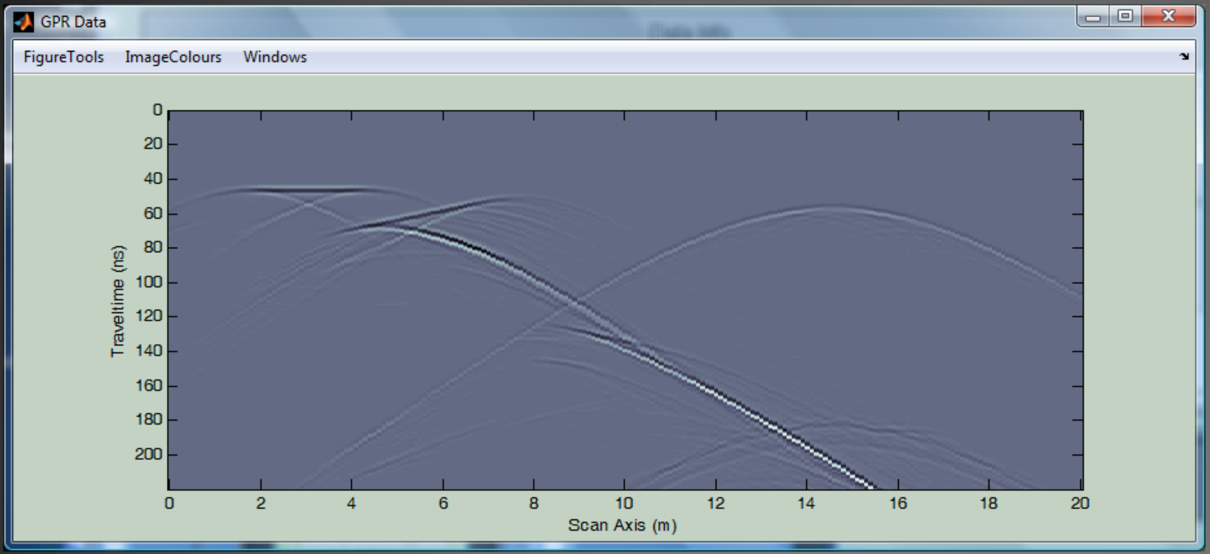


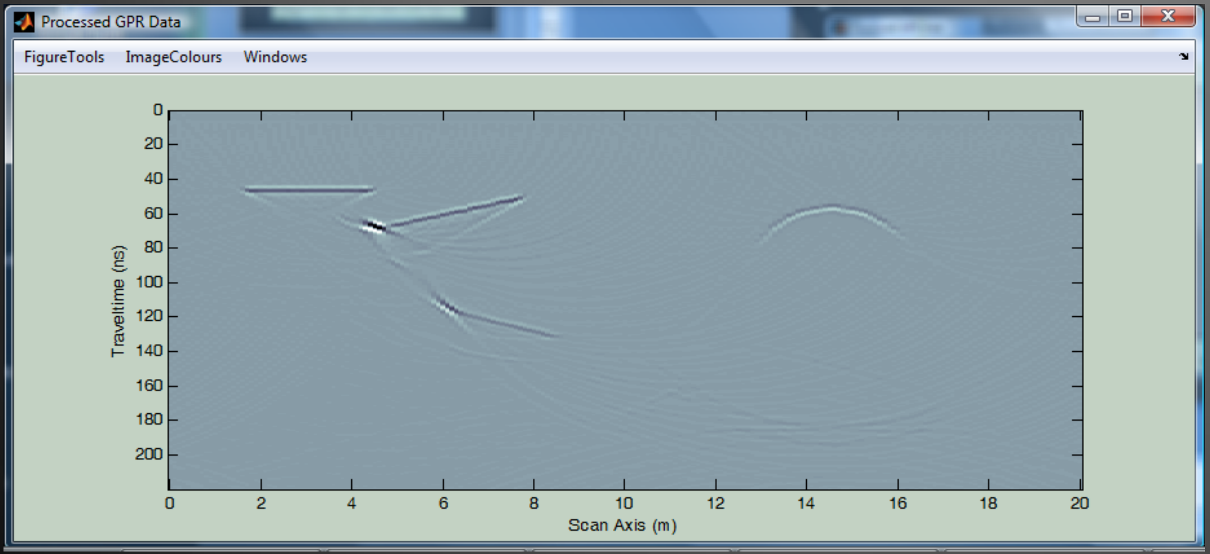


Interactive Fitting of Diffraction Hyperbolae



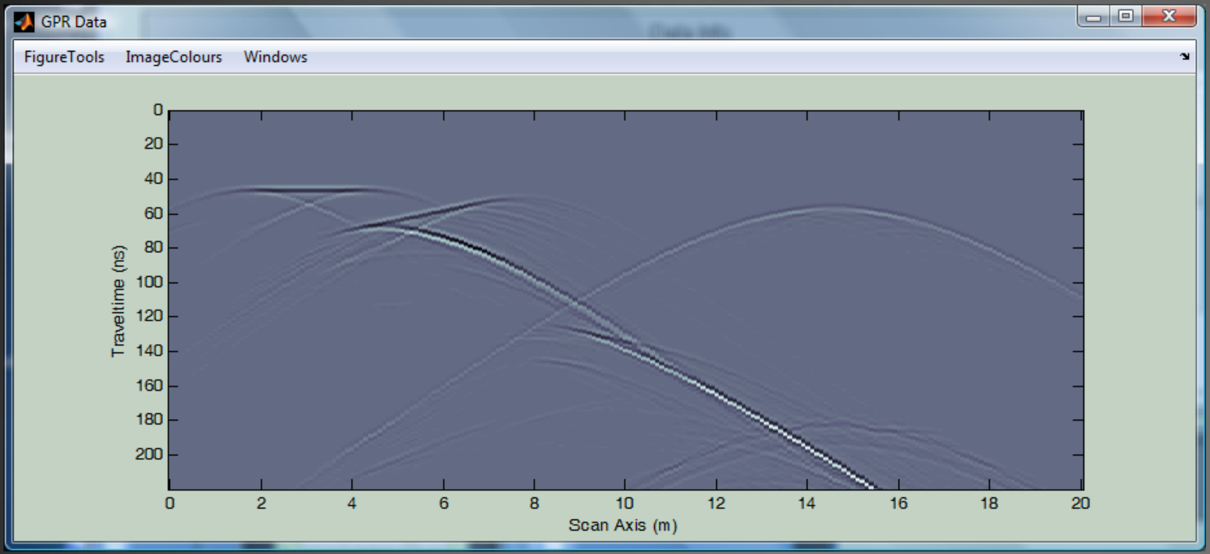
1-D F-K Migration

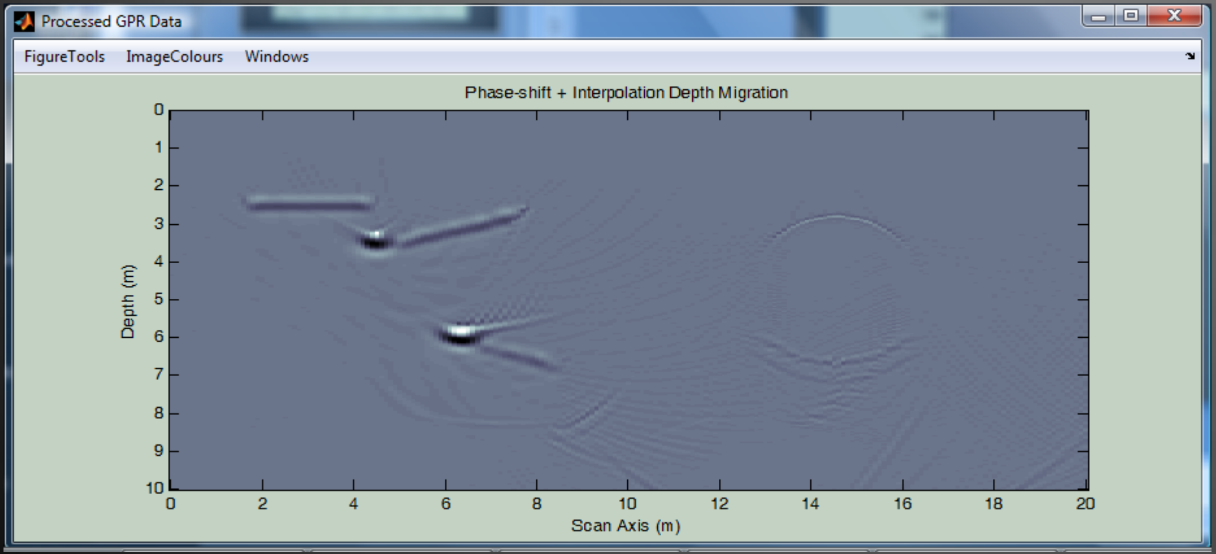




Uses layered velocity model constructed by direct measurements, or estimated by fitting diffraction front hyperbolae and trial and error.

2-D PSPI Depth Migration

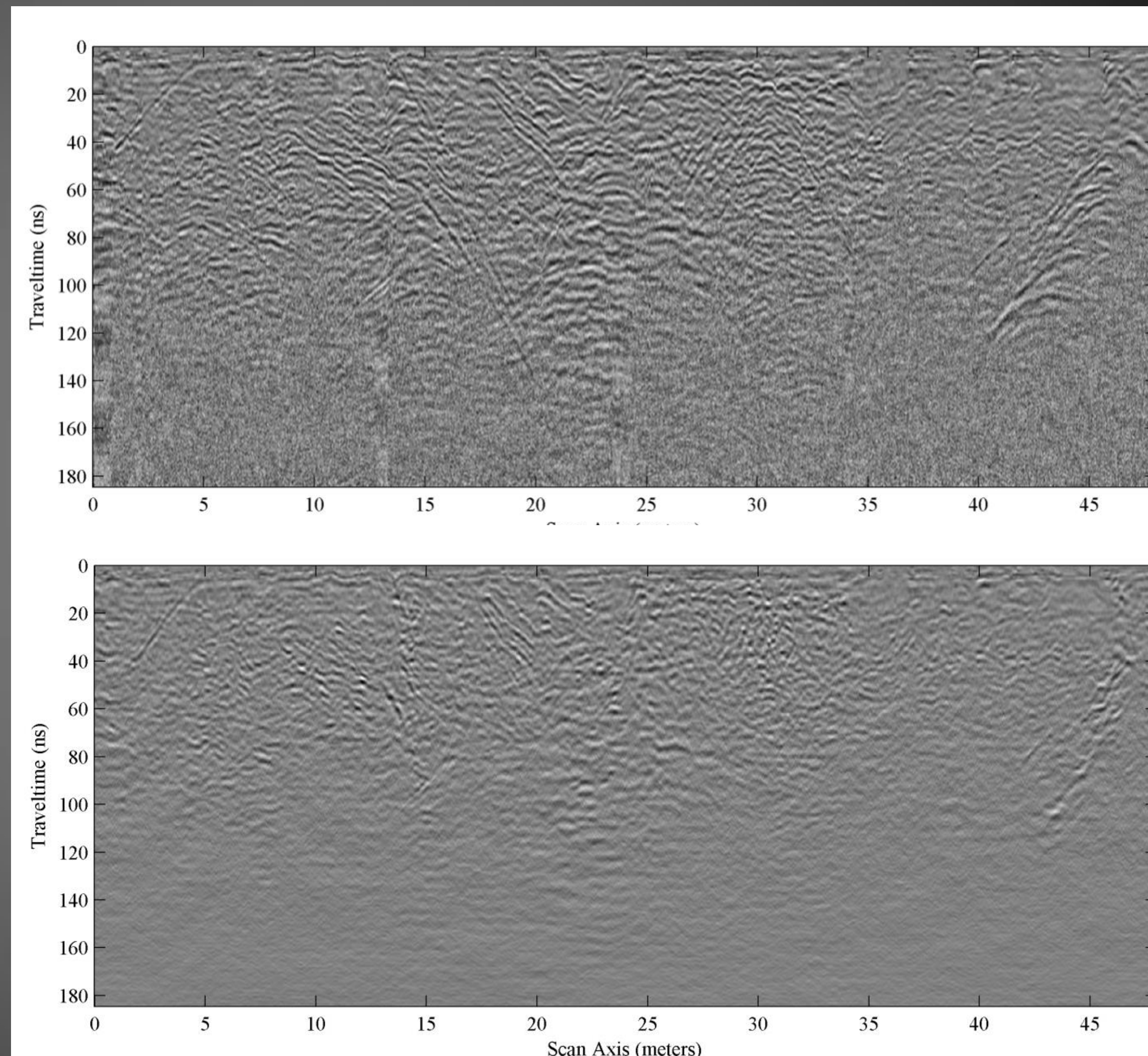




Uses 2-D velocity model constructed with the Model Builder.

Migration is frequently necessary in geotechnical work

Pre-migrated



Migrated

3-D Visualization

- ✓ 3-D data volume generation using a stacking technique

Visualization techniques include:

- ✓ The **GPR-slice** utility to generate orthographic opaque or translucent slices The user controls the azimuth and elevation of the viewing position, the aspect ratio, the axes limits and the colour saturation (contrast) of the display.
- ✓ **Isosurface displays**: Orthographic representations of the data in the form of lit isometric surfaces with equal signal amplitudes, or less rigorously stated lit surfaces of equal reflectivity. The user may manipulate the display by:
- ✓ The **3-D Slices** utility to visualize the *entire* data volume with orthographic opaque or translucent slices parallel to the *x*-axis.

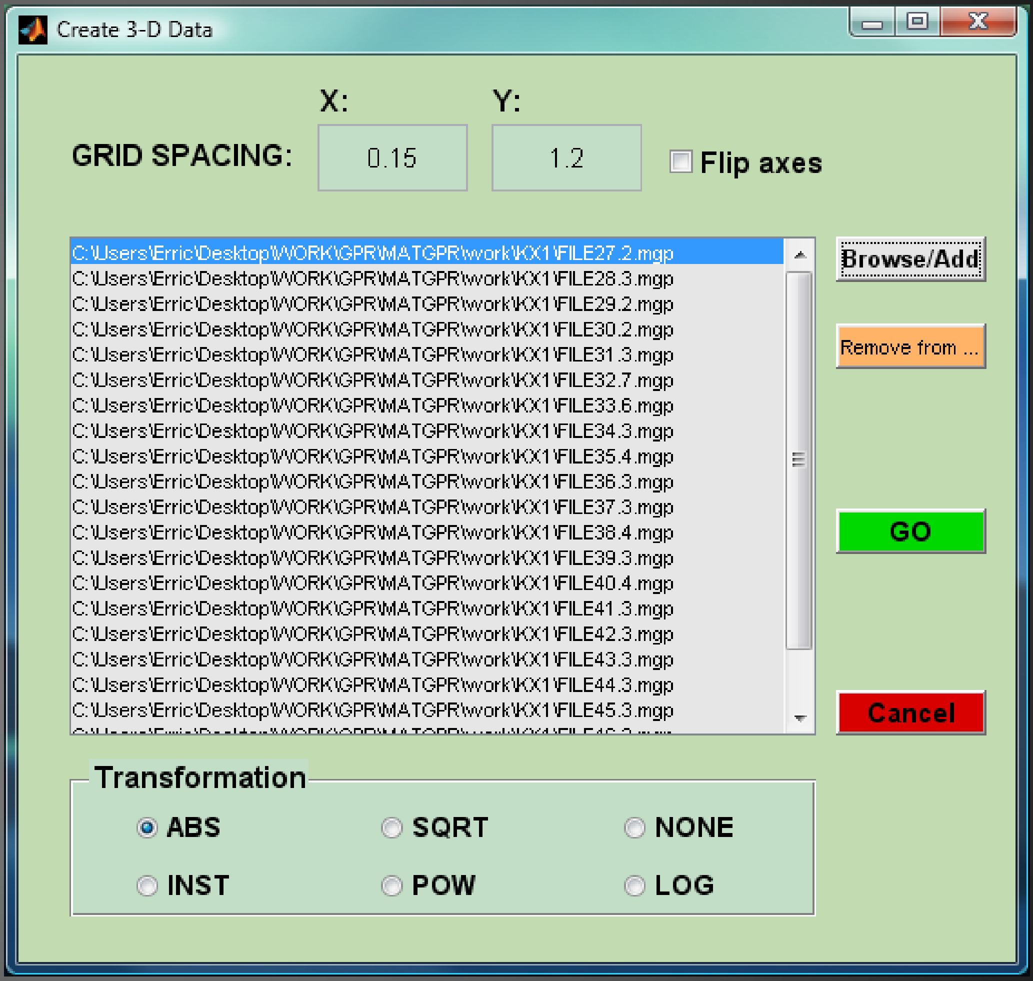
3-D Data Generation

Assumes local co-ordinate system :

- Radargrams can have any shape, length, orientation and trace spacing with respect to the coordinate axes.
- The vertical axis can be either time or depth.
  - Equal time window sizes or sampling rates, or depth window sizes, or depth spacing *not* required.
- Data transformations available are: *absolute* values, *squared* values, *log_{10}* values, *instantaneous amplitude* and *instantaneous power*.

Stacking procedure:

- Data files are read in.
- For each file, traces that fall within a 2-D horizontal search window around a volume cell are transformed and stacked.
- After all files have been processed, the final volume cell values are calculated by averaging all values added to them

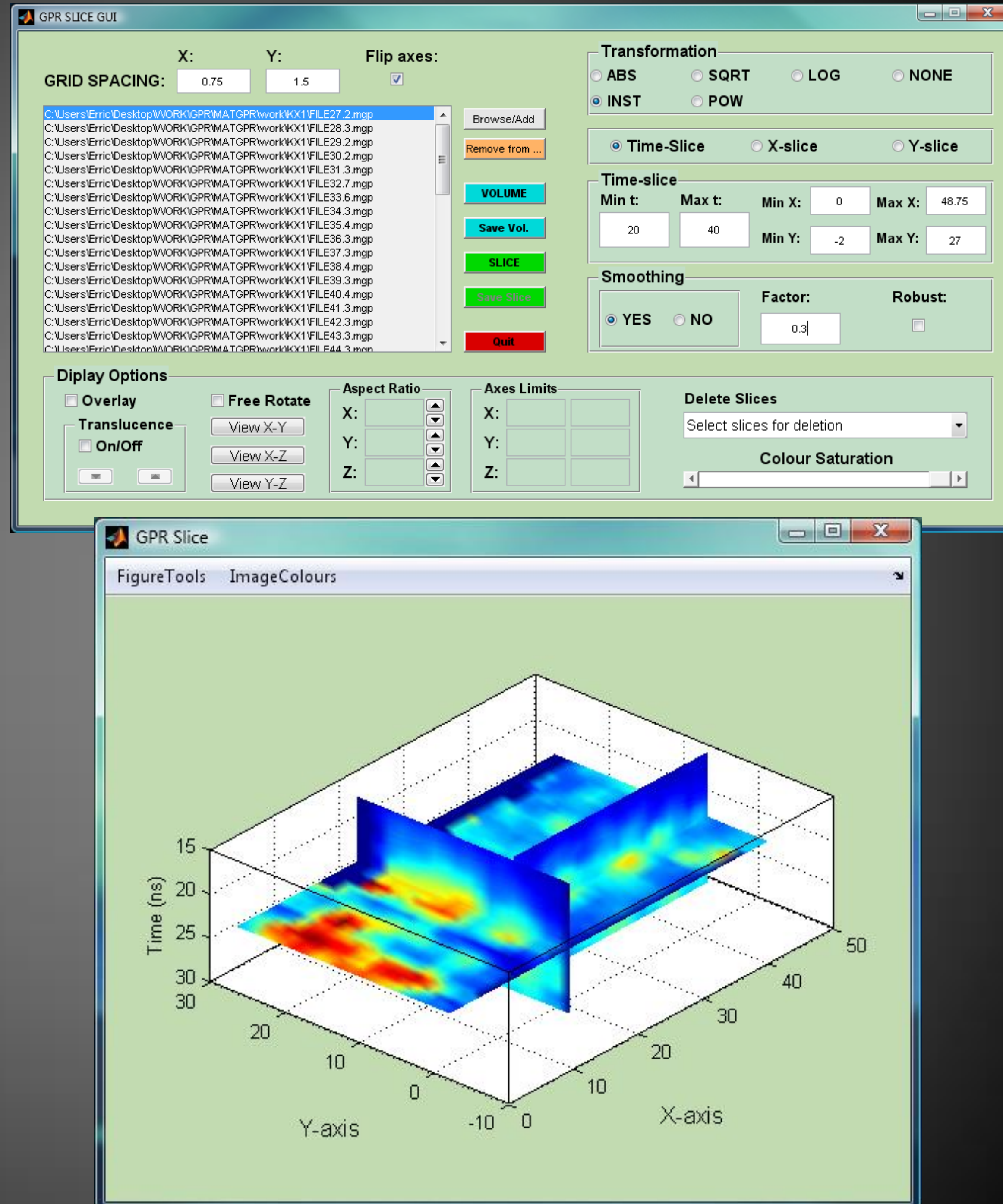


GPR-Slice

Orthographic, opaque or translucent slices that are:

- Horizontal and perpendicular to the vertical grid direction (*z*-axis).
- Vertical and perpendicular to the *x*-axis.
- Vertical and perpendicular to the y-axis

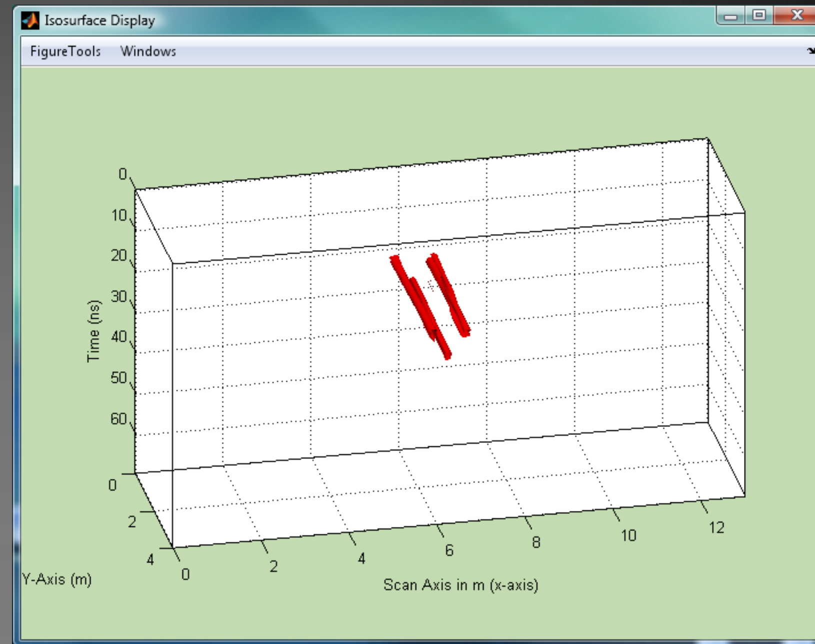
- Prior to displaying, each slice may be smoothed with a robust discretized smoothing spline technique.
- The horizontal and vertical size of the slices is controlled by the user.
- Slices may be added or removed from the display, thus enabling an arbitrarily complex and detailed visualization of the data volume.
- The user controls the azimuth and elevation of the viewing position, the aspect ratio, the axes limits and the colour saturation (contrast) of the display.

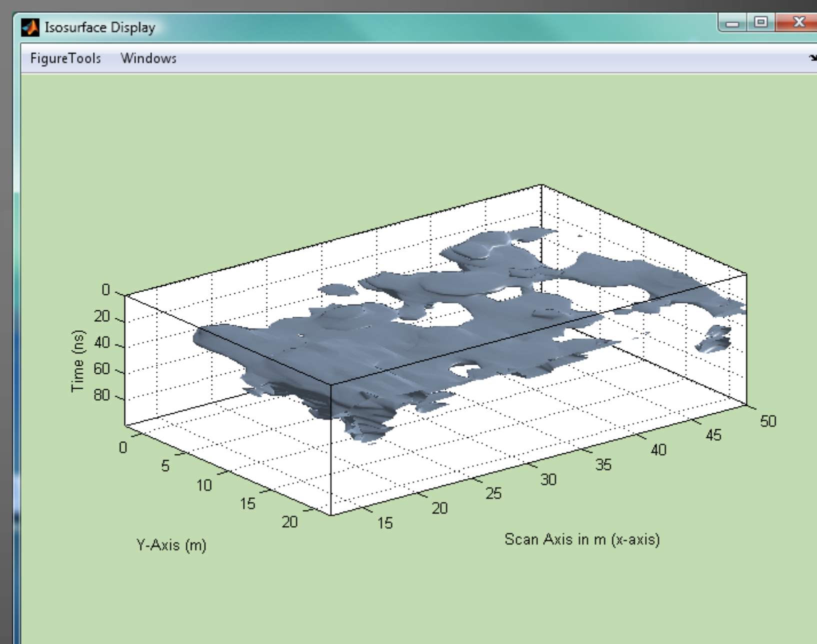


Isosurface displays

Orthographic representations of the data in the form of lit isometric surfaces with equal signal amplitudes

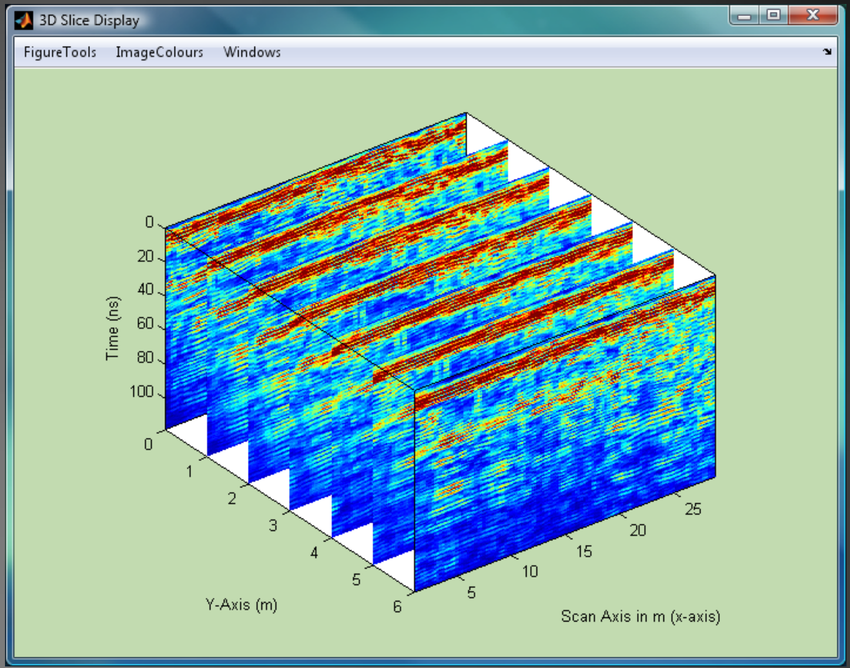
- The user may manipulate the display by:
  - Specifying the isosurface value (signal amplitude).
  - Specifying the azimuth and elevation of the viewer position.
  - Specifying the aspect ratio of the display and the direction of lighting (light position).
  - Specifying the colour of the iso-surface.

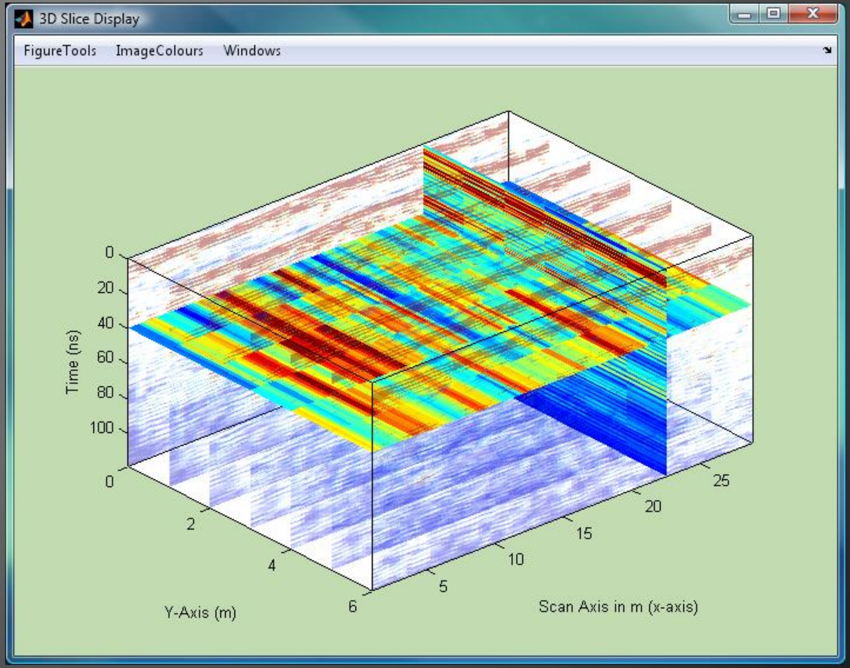




3-D Slices

- Visualize the *entire* data volume with orthographic opaque or translucent slices parallel to the *x*-axis.
- Horizontal slices perpendicular to the z-axis and vertical slices perpendicular to the y-axis can be overlaid .
- The user controls the azimuth and elevation of the viewing position, the aspect ratio and the colour saturation of the display.





Future Feats Feasible …

- ✓ Speed-up FDTD model computations – possibly use vector FORTRAN.
- ✓ Introduce multi-offset data analysis
- ✓ Improve 3-D visualization (imperative)!
- ✓ Correct for effects of dispersive propagation
- ✓ Automatically recognize diffraction patterns and estimate diffractor size.
- ✓ Consider *curvelet-based scale-sensitive* migration
- ✓ Consider multi-static data manipulation and tomography.
- ✓ … not necessarily in this order and the list does not end here …