Normal Moveout Downhole Seismic Tomographic Testing (NMO-DSTT) Algorithm

Seismic travel-time tomography (STTT) allows for two dimensional imaging of the sub-surface stratigraphy. In general terms, in STTT the velocity profile is derived by seismic data inversion or iterative forward modelling, while adhering to Fermat's principle of least time. This is a particularly challenging problem in that the seismic raypaths depends upon the unknown velocity structure.

A common application for STTT is Crosshole Seismic Tomography Testing (CSTT) as illustrated in Figure 1. However, the execution of CSTT requires a significant effort to create the various source and receiver boreholes. In addition, the CSTT analysis is unwieldy due to the fact that there are many velocity blocks with a limited number of source wave intersections, which more than likely will result in instability in the analysis equations.

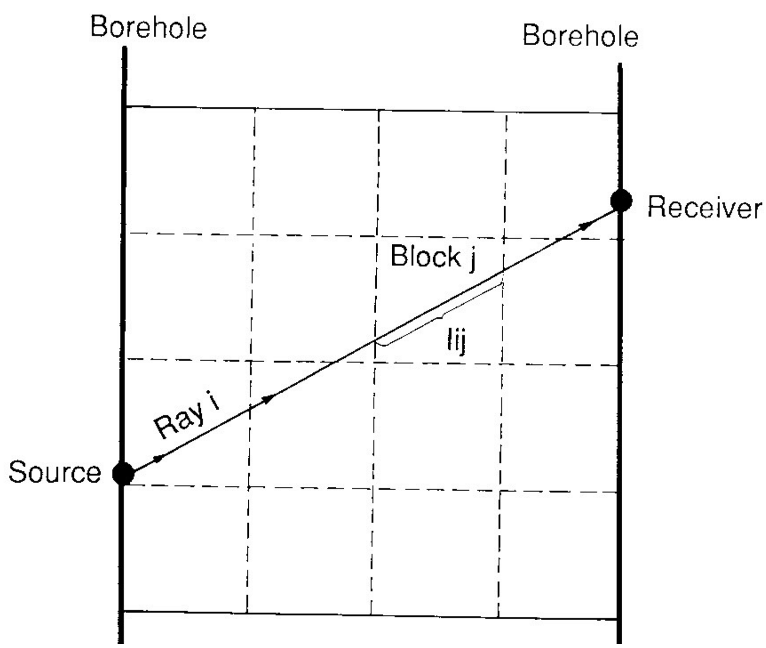


Figure 1. Schematic of a crosshole seismic tomographic testing and analysis configuration. In this illustration there is a linearized ray path between the source and receiver and its discretization into blocks. The *i*th ray travels the distance l_{ij} in the *j*th block (after, Gibowicz and Kijko (1994)).

Figure 2 illustrates a schematic of a Normal Moveout Downhole Seismic Tomographic Testing (NMO-DSTT) and analysis configuration. In *NMO-DSTT*, downhole seismic data sets are acquired at various radial source offsets, and since only receiver boreholes are required *NMO-DSTT* has significantly lower associated cost compared to CSTT. While analyzing the data sets 2D velocity models are derived for each subsequent offset resulting in a dramatic lowering of the unknowns since the previously established velocity values are used whenever the ray path travels through an area that was covered before. For example, the ray path for offset X2 and depth Z2 might travel through areas V2D[1,2], V2D[1,1] and V2D[1,2], in which case for the last two areas the velocity values obtained during the analysis of the data set for offset X1 are used and V2D[1,2] is estimated.

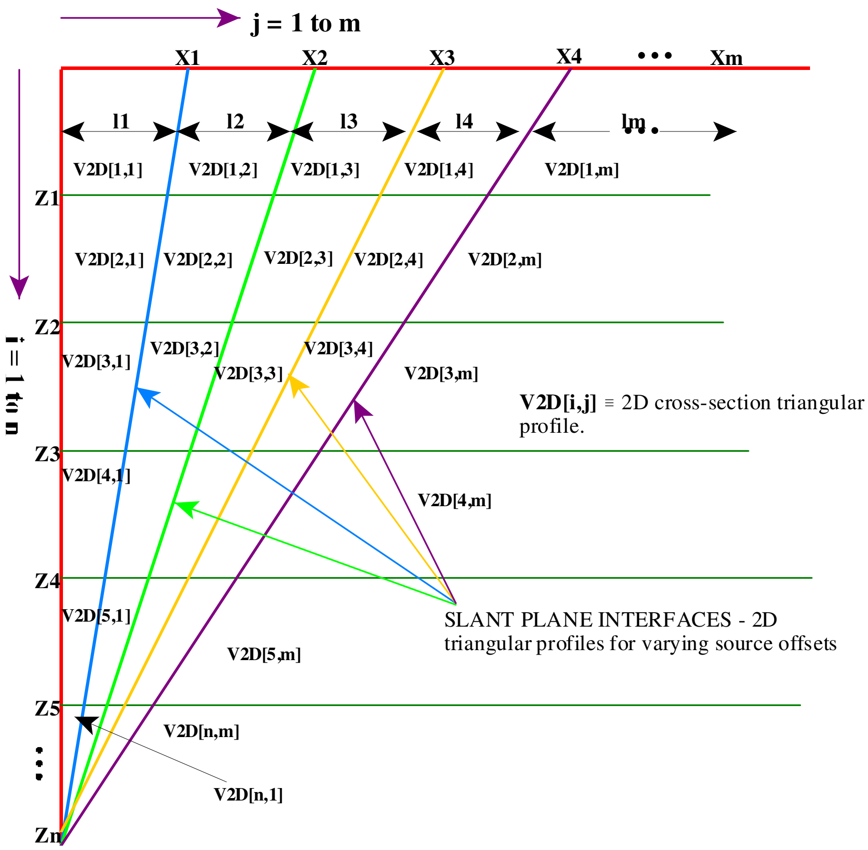


Figure 2. Schematic of a normal moveout downhole seismic tomographic testing and analysis configuration (after, Baziw (2004)).

In the 2016 release of BCE's downhole seismic data analysis software (*SC1,3-RAV™ 2016)* a powerful and unique *NMO-DSTT* algorithm has been introduced. This *NMO-DSTT* algorithm implements the same mathematical tools (e.g., Newton-Raphson technique and simplex iterative forward modeling) that are used in the single source offset Forward Modeling / Downhill Simplex Method (*FMDSM*) technique (Baziw, 2002), but with additional slant plane interfaces for each source offset as is illustrated in Fig. 2.

The *NMO-DSTT* algorithm allows for a maximum of seven consecutive depth 2D interval velocity estimations at a 2m depth resolution. This is typically reflected by analyzing the top seven depth intervals at a 2m resolution (e.g., 2m, 4m 6m, 8m, 10m, 12m, and 14m). Any arrival time information which exceeds this analysis depth window (e.g., 15m, 16m, 17m, 18m, …) is also inputted into the *NMO-DST* algorithm so that a greater density of source rays intersecting the velocity cells is utilized in the estimation algorithm. The 2D interval velocities which exceed the maximum analysis depth (e.g., 14 m) are assumed to be equal to the interval velocity estimation values derived from the first or closest offset FMDSM. There is very strong mathematical validity to this due to the cone nature of the *NMO-DSTT* 2D testing environment. As the DST depth increases 2D interval velocities collapse onto the first offset estimates (the apex of the analysis cone is readily approached with an increase in depth) as illustrated in Fig. 2.

The *NMO-DSTT* algorithm implements a Monte Carlo technique where numerous (100) searches are carried out when finding the optimal 2D interval velocities. The first search assumes that there is a Transverse Isotropic (TI) medium (i.e., no lateral variation). The subsequent 99 estimates use the Monte Carlo technique for specifying the initial simplex for the search grid. The interval velocity results which give a cost function minimum (RMS difference between true and synthetic arrival times) are used and stored within the *NMO-DSTT* tomography database. The Monte Carlo technique is implemented due to the fact that there are numerous local minimum present and it is necessary to search a large solution space for the interval velocities which give an overall minimized cost function. A parallel processing technique will be incorporated into a subsequent release of the *NMO-DSTT* algorithm. This is estimated to reduce processing time by 4x (for a quad core CPU) for each source offset.

NMO-DSTT - Test Bed Example

Table 1, 2, and 3 below provide the working parameters for a very challenging *NMO-DSTT* simulated example with three source offsets (3 m, 6 m and 9 m). The depth of analysis starts at 2 m and goes down to a depth of 20m at 2m depth increments. Table 1 shows arrival times derived for the true interval velocities specified for the 3m offset and after implementing Fermat's Principle of least time. As is shown in Table 1 and as is expected, the *NMO-DSTT* algorithm obtained the specified interval velocities for the first 3m offset. The NMO-DSTT residual arrival time errors (difference between true and synthetic arrival times) are 0 for all the estimated interval velocities for the first offset of 3m. Figure 3 outlines the source wave raypaths for the first offset of 3m and assuming a TI medium.

Table 2 shows arrival times derived for the true interval velocities specified for the 6m offset and after implementing Fermat's Principle of least time. There several examples where there are faster arrival times for deeper source waves (48.161 at 2m and 35.388 at 4m) and larger offsets (40.518 at a 3m offset and 4m depth versus 35.388 at a 6m offset and 4m depth) making the application of a straight ray analysis impossible. For the second offset, there are numerous possible ray paths for a variety of interval velocities which would result in local cost function minimums. This is why the Monte Carlo technique is utilized for 100 searches so that the global cost function minimum is found.

Table 2 outlines the estimated *NMO-DSTT* interval velocities and associated arrival time residuals for the 6m offset seismic dataset. As is illustrated, the estimated interval velocities are very close to the true interval velocities for the 6m offset with associated low error residuals. Larger variation in estimated and true interval velocities general occur when there raypaths have minimal intersections within a velocity cell under analysis or the raypaths equally enter and exit a set of cells without deviation giving an averaged interval velocity estimate for the cells intersected. This phenomenon is somewhat present for the depth increment 8m to 12m. Figure 4 outlines the source wave raypaths for the second offset of 6m. As is shown in Fig. 4, the raypaths for depths 14m, 16m, 18m and 20m equally enter the velocity cells for the depths 8m to 12m with minimal variations.

Table 3 shows arrival times derived for the true interval velocities specified for the 9m offset and after implementing Fermat's Principle of least time. Table 3 also outlines the estimated *NMO-DSTT* interval velocities and associated arrival time residuals for the 9m offset seismic dataset. As is illustrated, the estimated interval velocities are very close to the true interval velocities for the 9m offset with associated low error residuals. In general terms, it is expected that large NMO offsets will tend to have larger relative errors compared to smaller NMO offsets due to any errors from the smaller NMO offsets propagating to the larger NMO offsets. Figure 5 outlines the source wave raypaths for the third NMO offset of 9m.

As is shown in Figs. 3, 4 and 5 and according to Fermat's Principle, the seismic waves prefer travelling in the faster velocity blocks and spending a minimal amount of time in the slower velocity blocks. As a result there can be (in this case there are) so-called negative relative arrival times in certain instances.

Table 1. NMO-DST Test Bed Example Parameters and Estimated Interval Velocities (3m Offset)

Depth [m]	Offset [m]	Arrival Time [ms]	True Interval Velocity [m/s]	Estimated Interval Velocity [m/s]	*NMO-DSTT* Residual Error [ms]
2	3	40.062	90	90	0
4	3	40.518	180	180	0
6	3	67.906	70	70	0
8	3	80.705	140	140	0
10	3	87.245	250	250	0
12	3	109.088	90	90	0
14	3	119.191	190	190	0
16	3	127.132	240	240	0
18	3	134.244	270	270	0
20	3	141.045	285	285	0

Table 2. NMO-DST Test Bed Example Parameters and Estimated Interval Velocities (6m Offset)

Depth [m]	Offset [m]	Arrival Time [ms]	True Interval Velocity [m/s]	Estimated Interval Velocity [m/s]	NMO-DST Residual Error [ms]
2	6	48.161	210	210	-0.0002
4	6	35.388	262	262	1.61e-5
6	6	61.864	160	159.8	1.8e-5
8	6	52.715	320	320.9	6.3e-5
10	6	51.004	140	144.9	-0.0028
12	6	72.569	150	144.7	0.0027
14	6	79.825	230	230	5e-5
16	6	85.610	240	240	0.00036
18	6	92.371	270	270	-4e-5
20	6	98.890	285	285	-0.00034

Table 3. NMO-DST Test Bed Example Parameters and Estimated Interval Velocities (9m Offset)

Depth [m]	Offset [m]	Arrival Time [ms]	True Interval Velocity [m/s]	Estimated Interval Velocity [m/s]	NMO-DST Residual Error [ms]
2	9	78.139	100	100	-0.0001
4	9	65.041	120	120.1	-1.9e-5
6	9	95.514	220	219.4	-0.006
8	9	83.912	240	238.1	0.009
10	9	77.163	200	202.5	0.0006
12	9	98.771	230	228.7	-9.6e-5
14	9	96.598	210	210	0.0002
16	9	101.719	240	240	-0.0023
18	9	108.454	270	270	-0.0004
20	9	114.214	285	285	0.0016

Figure 3. 2m Radial Offset Ray Paths:

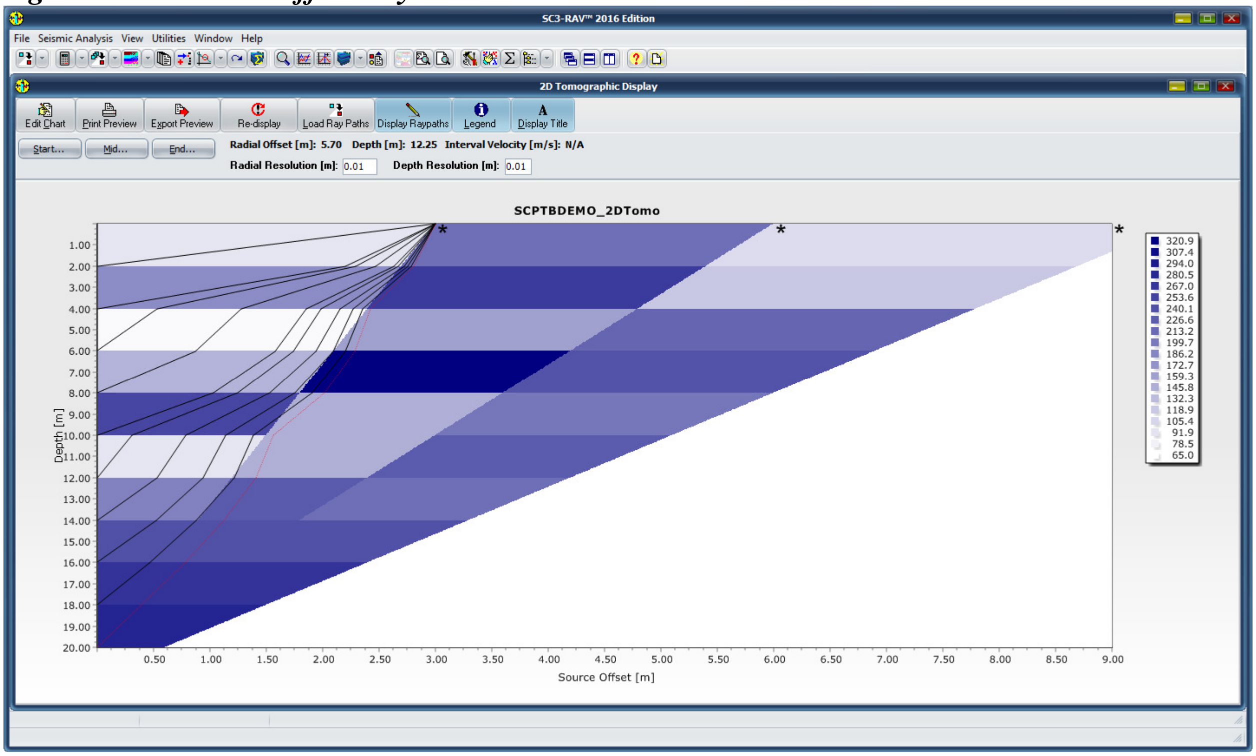


Figure 4. 6m Radial Offset Ray Paths:

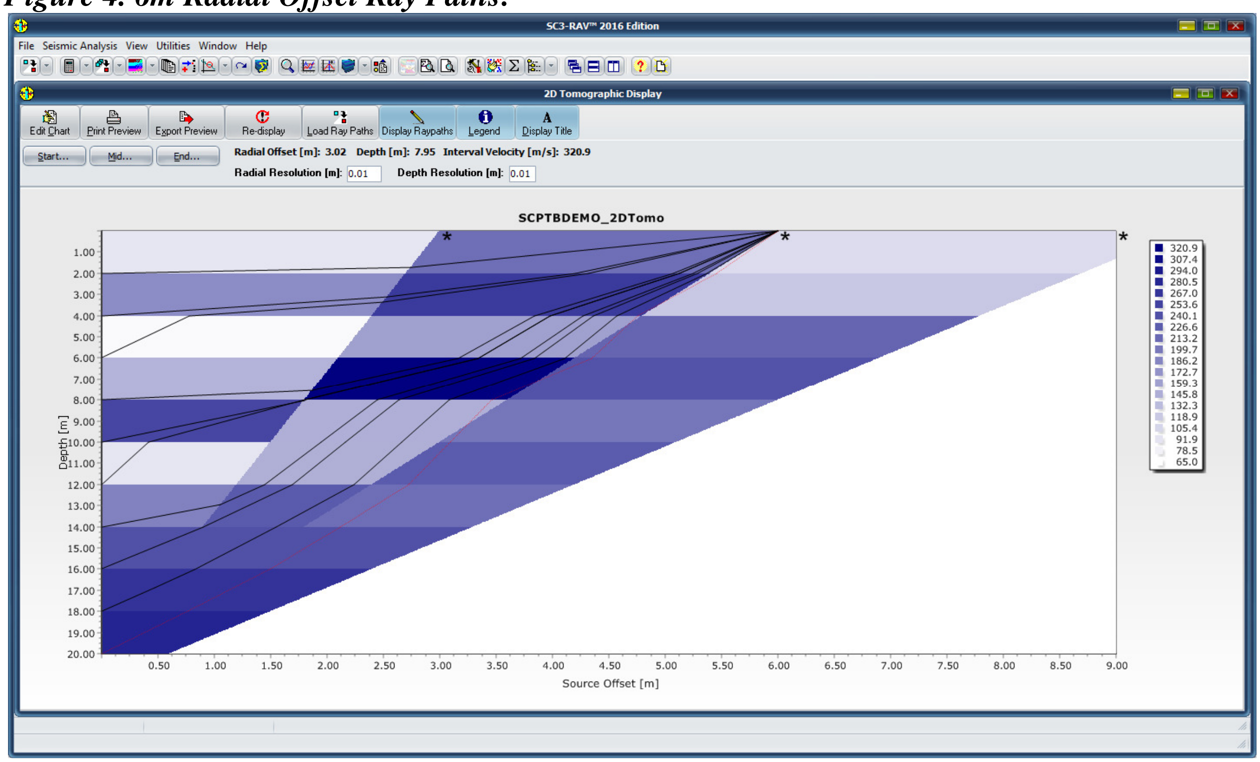
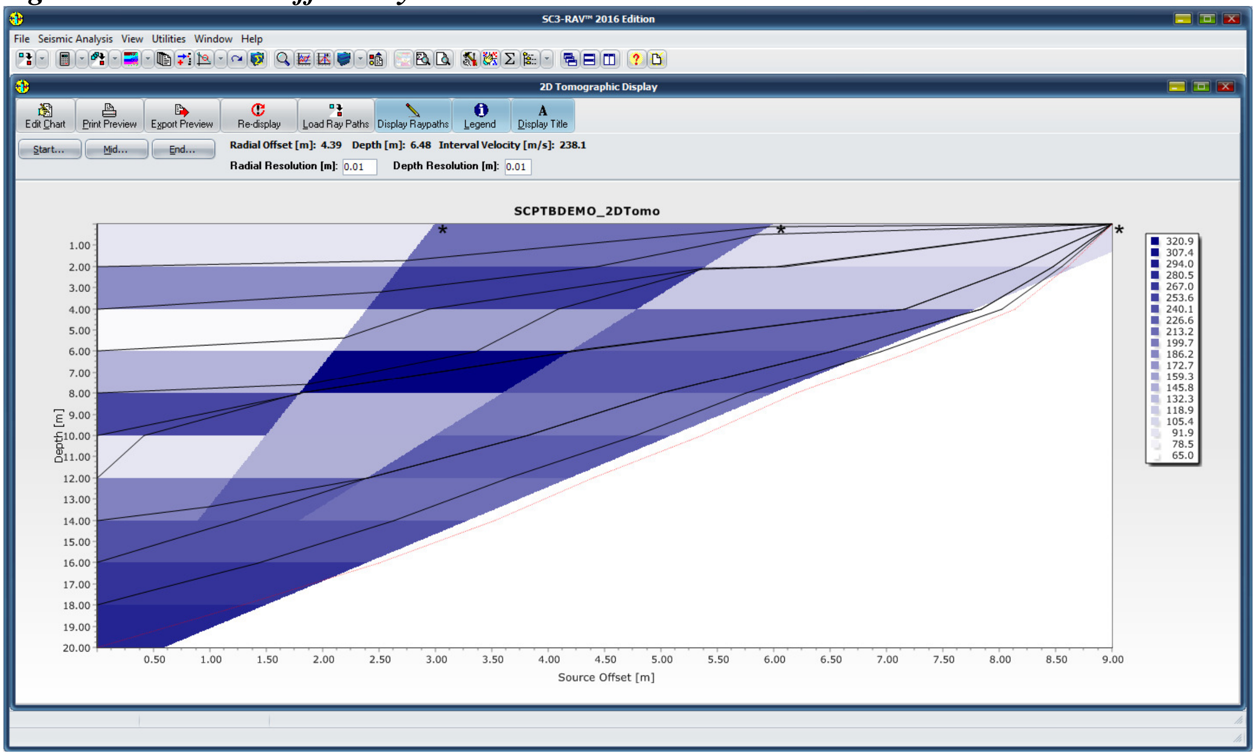


Figure 5. 9m Radial Offset Ray Paths:



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