Significant Improvements to the NMO-SCTT algorithm and its utilization to non-destructively detect very dense and weak stratigraphy

The so-called Normal Moveout Downhole Seismic Tomographic Testing (*NMO-SCTT*) (https://users.neo.registeredsite.com/1/4/2/21752241/assets/Baziw_and_Verbeek_CPT-18.pdf) was developed to facilitate two dimensional imaging of the sub-surface utilizing DST data sets and normal moveout of the horizontally polarized shear source wave (SH wave). There has been significant recent interest in the geotechnical *in-situ* site characterization for identifying lateral soil variations non-destructively. Particular interest is given to identifying very dense soils/rocks and very weak soils for foundation designs considerations.

The *NMO-SCTT* algorithm is an ideal candidate for non-destructively quantifying the lateral variations of stratigraphy. Extensive additions and modifications have been made to the *NMO-SCTT* algorithm since the original publication in 2018. The two main improvements are

- Increase maximum number of soil cells that can be estimated for each NMO source offset from 8 to 10.

- Significant improvement in estimated interval velocities by removing instabilities in search algorithm and introducing source wave raypaths known constraints into solution space.

The mathematical details of the improved *NMO-SCTT* will shortly be submitted to a journal or conference.

Below is outlined a very challenging test bed simulation demonstrating the impressive performance of the upgraded *NMO-SCTT* algorithm..

NMO-DSTT - Test Bed Simulation

Tables 1 and 2 below provide the working parameters for a very challenging *NMO-SCTT* test bed simulation with two source offsets (3 m and 6 m). The depth of analysis starts at 2 m and goes down to a depth of 24m at 2m depth increments. Column 4 of Table 1 outlines the interval velocities for the 3m offset for this test bed simulation. Column 3 of Table 1 shows the associated arrival times derived from the interval velocities specified in column 4 for the 3m offset and after implementing Fermat's principle of least time. Column 5 of Table 1 outlines the estimated interval velocities for a Straight Ray Assumption (SRA) for offset 3m. The percent differences between the SRA estimates and true interval velocities are given in column 6 of Table 1 for a 3m offset. As is outlined in column 6 the percent difference are relatively large down to a depth of 12m. Column 7 of Table 1 outlines the estimated *NMO- SCTT* algorithm interval velocities where Fermat's principle is taken into account. The *NMO- SCTT* algorithm and true interval velocities percent differences are outlined in column 8 of Table 1.

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]**	**SRA Estimated Interval Velocities [m/s]**	**SRA-True Velocity Percent Difference [%]**	***NMO-SCTT* Estimated Interval Velocity [m/s]**	***NMO-SCTT* True Percent Difference [%]**
2	3	40.062	90	90	N/A	90	0
4	3	40.518	180	7907	191.1	180	0
6	3	67.906	70	47	39.3	70	0
8	3	80.7047	140	118	17	140	0
10	3	87.2391	250	254	1.6	250	0
12	3	109.0857	90	80.	11.8	90	0
14	3	119.1872	190	178	6.5	190	0
16	3	127.1191	240	234	2.5	240	0
18	3	134.2198	270	266	1.5	270	0
20	3	141.011	285	281	1.4	285	0
22	3	147.0812	320	317	0.9	320	0
24	3	151.9237	400	400	0	300	0

Table 2 outlines the input parameters and output from both the SRA and *NMO- SCTT* algorithm for the 6m source offset. In the newly formulated *NMO- SCTT* algorithm the last seismic source wave recorded at deepest depth is not utilized (i.e., RMS minimization of the error residual between measured and synthetic arrival times). This due to the instability in the collapse of slant and horizontal planes which define the interval velocity cells. The last trace is only utilize to set the 2D space (i.e., inverted right triangle).

Column 4 of Table 2 outlines the interval velocities for the 6m offset for this test bed simulation. As is shown in column 4 there is a very high velocity cell of 1200 m/s between 2m and 4m. Column 3 of Table 2 shows the associated arrival times derived from the interval velocities specified in column 4 for the 6m offset and after implementing Fermat's principle of least time. Column 5 of Table 2 outlines the SRA estimated nonsensical interval velocities for offset 6m. SRA results outlined in column 5 clearly demonstrate that the arrival times from the 6m offset cannot be used for analysis with implementation of the SRA. The percent differences (rounded to first decimal place) between the SRA estimates and true interval velocities is given in column 6 of Table 2 for a 6m offset. As is outlined in column 6 the percent difference are very large down to a depth of 20m.

Column 7 of Table 2 outlines the estimated *NMO- SCTT* algorithm interval velocities for depths down to 16m. The *NMO- SCTT* assumes that there is minimal lateral variation in the velocities for 2 to 3 intervals before the last depth. This is due to the contraction of the solution space (inverted cone) as is shown in Fig. 1. The arrival times at these depths are still utilized within the estimation (i.e., RMS minimization of the error residual between measured and synthetic arrival times). This is due to that fact that these arrival times reduce the solution space for the optimally estimated interval velocities. Figure 1 also shows the *NMO- SCTT* algorithm source wave estimated raypaths for the 3m offset. Figure 2 illustrates the *NMO- SCTT* algorithm source wave estimated raypaths for the 6m offset down to a depth of 8m. As is expected, the source waves prefer to travel in the faster 1200m/s velocity cell according to Fermat's principle of lease time. The *NMO- SCTT* algorithm and true interval velocities percent differences are outlined in column 8 of Table 2.

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]**	**SRA Estimated Interval Velocities [m/s]**	**SRA-True Velocity Percent Difference [%]**	***NMO-SCTT* Estimated Interval Velocity [m/s]**	***NMO-SCTT* True Percent Difference [%]**
2	6	48.455	210	131	46.3	210	0
4	6	26.8546	1200	-41	214.2	1200	0
6	6	52.9328	160	49	106.2	160	0
8	6	45.1873	320	-196	832.3	320	0
10	6	42.9835	140	-754	291.2	153	-8.9
12	6	64.5095	150	82	58.6	148	1.3
14	6	74.2354	230	187	20.6	206	11.0
16	6	86.2158	240	155	43.0	243	-1.2
18	6	84.7395	270	-1277	307.2	270	N/A
20	6	91.4808	285	283	0.7	285	N/A
22	6	97.5782	320	315	1.6	320	N/A
24	6	N/A	400	N/A	N/A	N/A	N/A

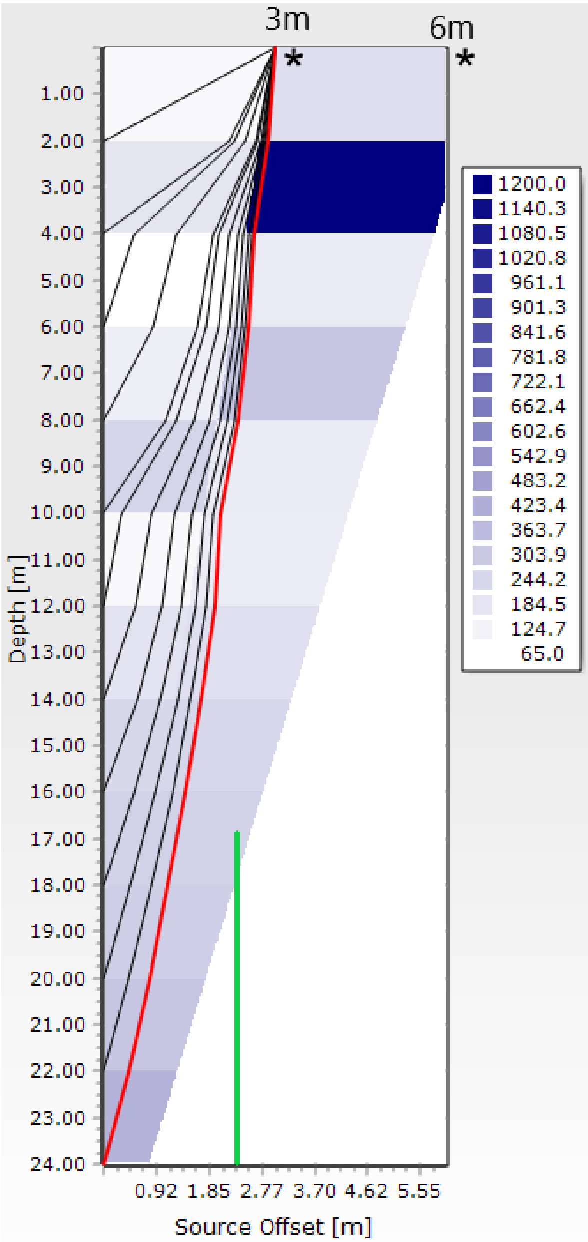

Figure 1. Output from the *NMO-SCTT* algorithm illustrating source wave travel paths for the 3m source offset and the collapse of the cells at greater depths (green line) due to inverted cone solution space.

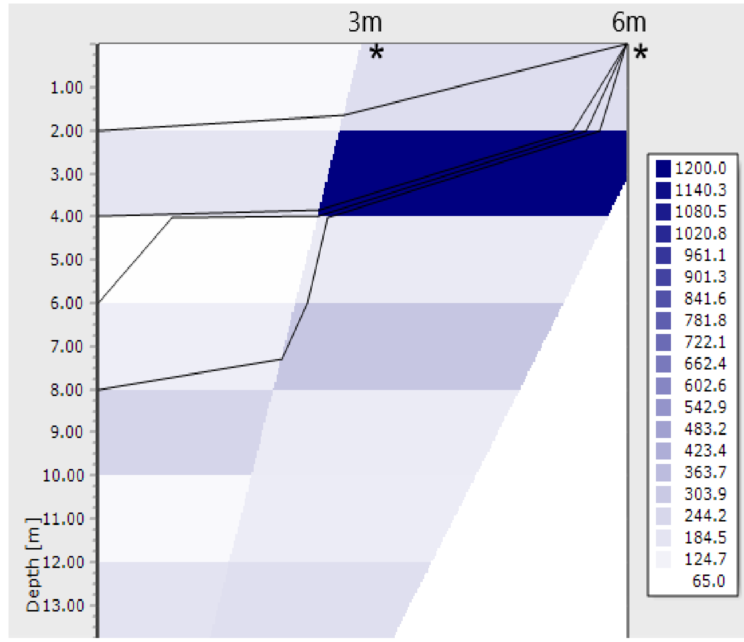

Figure 2. Output from the *NMO-SCTT* algorithm illustrating source wave travel paths for the 6m source offset for depths 2m to 8m.

Erick Baziw

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