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Seismic Approach to Quality Management of HMA

NRRA INTELLIGENT CONSTRUCTION TECHNOLOGIES TEAM

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16. Abstract (Limit: 250 words)

We provide a final summary report of the project executed during last 2.5-year period (January 2020 - June 2022). The project tasks are summarized in the following scope of work (SOW):

- Task #1: Project Management and Administration
- Task #2: Hardware Development (Seismic Data Acquisition System) & Testing
- Task #3: Software Development & Testing
- Task #4: Delivery and Demonstration of Seismic Data Acquisition System and Software
- Task #5: Final Report

Initial project development and its progress in tasks #1 - #3 have been summarized in the quarterly reports and updated every month on the dedicated website until the end of December 2021. This final report focuses on the delivery of the completed system and subsequent demonstration surveys (tasks # 4 and #5). Associated details are presented in Appendix I (delivery) and Appendix II (demonstration surveys). Background theories and historical development that led to this particular system are described in an expanded abstract submitted to Geo-Congress 2022 at Charlotte, NC, March 20-23, 2022, which is attached in Appendix III. The developed system is named "TAPPER 64", and it consists of four (4) 16-channel receiver arrays that are transversely arranged to survey a certain width of the pavement (e.g., 0.5-m) simultaneously. Detailed technical and operational contents in hardware and software components of TAPPER 64 are presented in the "TAPPER 64-User's Manual" attached in Appendix IV.

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TABLE OF CONTENTS

Page

1. SUMMARY

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The main objective of the project is to develop a seismic system that one can routinely use in the field for the quality management of Hot Mix Asphalt (HMA) pavement by evaluating seismic shear-wave velocity (Vs) of HMA layer. Vs is considered one of the most direct indicator of pavement stiffness. Despite reduced accuracy in comparison to the Vs evaluation, thickness (H) evaluation was also included in the objective. Background theories and historical development that led to this particular system are described in an expanded abstract submitted to Geo-Congress 2022 at Charlotte, NC, March 20-23, 2022, which is attached in Appendix III.

The developed system is named "TAPPER 64", and it consists of four (4) 16-channel receiver arrays that are transversely arranged to survey a certain width of the pavement (e.g., 0.5-m) simultaneously. Each array has 16 micro-electro mechanical sensor (MEMS) microphones linearly arranged with a 2.25-cm separation. The arrays record seismic surface waves generated when a small cap bolt taps on the pavement surface. The acquisition-control and data-process software package, called ParkSEIS (PS)-HMA, which is installed in an onboard laptop computer analyzes acquired seismic data in a fully automated way and displays output results in a pseudo-real-time mode as survey vehicle travels. Detailed technical and operational contents in hardware and software components of TAPPER 64 are presented in the "TAPPER 64-User's Manual" attached in Appendix IV.

The completed system was delivered to MnDOT Materials Lab in St Paul, MN, on June 10, 2022. Principal Investigator (PI) (Choon Park) and a staff (Jin Park) from Park Seismic LLC assembled the system during the morning of June 15. The PI presented about technical, operational, and maintenance aspects of the system in the afternoon. Topics covered can be found in the presentation file (Appendix I). On the following day (June 16), field demonstration surveys were conducted at MnROAD Low Volume Road (LVR) in Otsego, MN, by two Park Seismic participants and MnDOT personnel. A video illustration of the demo survey is posted on YouTube. A separate summary report of all three demo surveys is presented in Appendix II.

Results from the demo surveys are examined in this report for the purpose of evaluating the overall performance of the system in its accuracy and potential for improvement. Three demo surveys were conducted (surveys #1-#3) about 30-min apart, with survey #1 starting at 10:16 AM, over about 450-m distances between cell #188 and cell #728 on the MnROAD LVR. The first two surveys (#1 and #2) were conducted almost at the same part of the road, while the last survey (#3) was conducted on the other side of the road starting from the end of survey #2, travelling in the opposite direction. Average measured temperatures of pavement surface were 23.75 °C (#1), 25.80 °C (#2), and 27.50 °C (#3). Average velocities (Vs) evaluated by the PS-HMA are 1680 m/s (#1), 1664 m/s (#2), and 1625 m/s (#3), slightly decreasing with survey #. This is believed mainly due to the pavement surface temperature increasing with survey #. Average Young's (E) and shear (μ) moduli are calculated from the average velocities (Vs) by using a Poisson's ratio of 0.3 and density of 2300 kg/m^3. They are E=16.89 (GPa) and μ =6.49 (GPa) for survey #1, E=16.57 (GPa) and μ =6.37 (GPa) for survey #2, and E=15.81 (GPa) and μ =6.08 (GPa) for survey #3. Average thickness (H) from surveys #1 and #2 are 6.2 (cm) and 6.1 (cm), respectively. Average H from survey #3 is 5.9 (cm). According to the design profile last updated in 2017, the entire area of surveyed road is listed as having a 3.5" thickness (= 8.89 cm). If it represents the ground truth, then the evaluated values from the 3 surveys represent about 70% of accuracy. The reduced accuracy in H evaluation has always been anticipated from the earliest stage of project execution. The main focus has always been in the accurate evaluation of seismic velocity (Vs). The results of modeling experiments executed throughout the entire project execution period consistently indicated the overall accuracy in H evaluation can be 20-30% lower than that in the Vs evaluation. In this sense, velocity (Vs) results are expected to have a much higher accuracy (e.g., ≥ 95%).

A systematic variation is observed between the average Vs values from all 4 arrays (#1-#4) from all 3 surveys (#1-#3). The Vs value increases from array #1 (Vs1) to #4 (Vs4). For example, Vs1=1617 (m/s), Vs2=1647 (m/s), Vs3=1723 (m/s), and Vs4=1731 (m/s) for survey #1. The differences between Vs1 and Vs4 were 7% for survey #1, 4% for survey #2, and 8% for survey #3. It is believed that this systematic variation was caused by the cross slope of the road, which was not compensated during the leveling process of array panel that aimed only at the "horizontal" leveling. A similar variation is also observed between the average H values. For example, H1=5.9 (cm), H2=6.1 (cm), H3=6.3 (cm), and H4=6.4 (cm) for survey #1. The differences between H1 and H4 were 8% for survey #1, 7% for survey #2, and 5% for survey #3. It is believed that this variation in H is caused by the algorithmic link between the two methods of Vs and H evaluations.

Velocity (Vs) and thickness (H) results of survey #1 obtained from the "In-Office" process method are presented in comparison to those from the "In-Field" method obtained during the survey. Despite a more-rigorous and therefore more-advanced algorithm, the results are less reliable, especially for thickness (H) evaluation, which showed a high degree of unrealistic variation. It seems more thorough examination of the in-office method using more field data sets may be advisable in the future.

The report concludes with a section that provides recommendations aimed at helping to make the system more robust and convenient in field operations.

2. BRIEF DESCRIPTION OF BACKGROUND THEORY

In the process of pavement construction, it is important to achieve a stiffness level of pavement materials that can sustain expected load stress. In this sense, quality management can be regarded as being analogous to in-situ stiffness measurement. Previous research has established seismic shear-wave velocity (Vs) as one of the most direct indicators of a material's stiffness (Sheriff, 2002). The multichannel analysis of surface waves (MASW) method (Park et al., 1999) has been widely used to measure shear-wave velocity (Vs) of the near-surface materials (e.g., < 30 m). The method employs a multichannel seismic exploration technique that uses a highly mobile impact source (e.g., sledge hammer) and geophone-array receivers to record seismic surface waves in relatively low frequency range (e.g., 1-100 Hz) for the most-common application of soil-bedrock characterization. Recent applications also focus on the very-shallow depths to characterize the pavement layer. To use the seismic approach as a practical pavement quality management tool, multiple conditions must be met. First, the field measurement and the subsequent data-analysis steps should be able to handle very-high-frequency (VHF) surface waves (e.g., 0-30 kHz) to focus on the microscopic scale of investigation depth (e.g., ≤ 0.1 m). Second, the survey speed has to be fast enough to measure a wide area as quickly as possible, while minimizing the interference with existing traffic. Third, considering the high data volume, the subsequent data-analysis steps must be fully automated. Furthermore, if the analysis speed can be fast enough and the results can be available on site, it would be even more ideal.

Ryden et al. (2001; 2004) first applied the multichannel principles to accurately characterize surface waves generated in the top pavement layer (Figure 2.1). It used one stationary accelerometer receiver and a source array with a small carpenter hammer (e.g., 12 oz). The impact source generated surface waves at progressively different locations to accomplish the multichannel acquisition through the source-receiver reciprocity. The results showed the type of surface waves generated in the pavement layer is highly analogous to the Lamb wave (Lamb, 1917) that, in theory, has unique dispersion curves in both asymmetric (A) and symmetric (S) modes (Ryden et al., 2003). The results also indicated that the fundamental-mode asymmetric (A0) dispersion is the one usually dominates (Figure 2.1). The field procedure was labor intensive and time consuming, taking at least 30-min to complete measurements for one data point. Subsequent data-analysis stage required a tedious procedure that would take at least 30-min even for a highly-experienced operator. To avoid the cumbersome procedure that was required to ensure a reliable coupling of accelerometer with pavement surface, Ryden et al. (2006) successfully used a microphone hanging in the air by about 10 cm above the pavement surface to record the leaky-mode Lamb waves (Figure 2.2). Ryden et al. (2019) later used a small steel ball (e.g., 1 cm) hanging down from the receiver array that bounced up and down spontaneously making impacts when the system is in forward motion, opening up true rolling measurement (Figure 2.3). This approach presented a practical survey that can continuously move at a moderate speed (e.g., 10 MPH – 30 MPH). Data acquisition by this approach can record multiple data points per second (e.g., 1-3 data points per second). Technical details of the recording hardware system for this rolling approach are presented in Starkhammar et al. (2007). More detailed description of theories and historical development of seismic approach for pavement evaluation can be found in Appendix III.

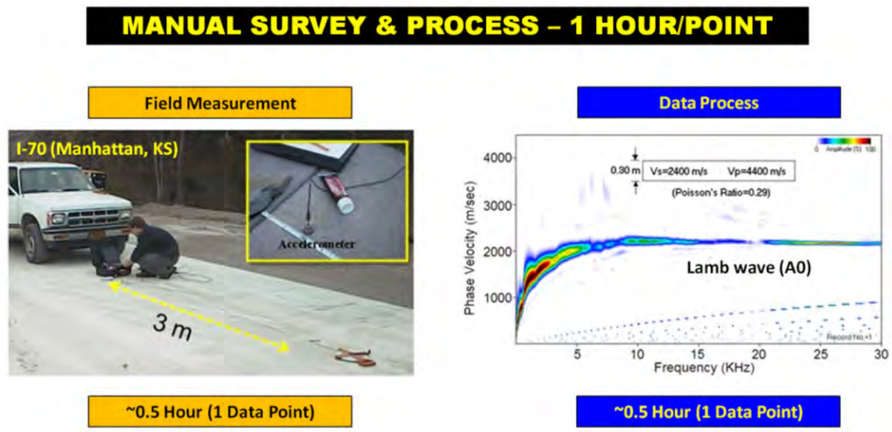


Figure 2.1 Early stage seismic pavement evaluation method that took at least 1 hour to produce one data-point result (Ryden et al., 2001).

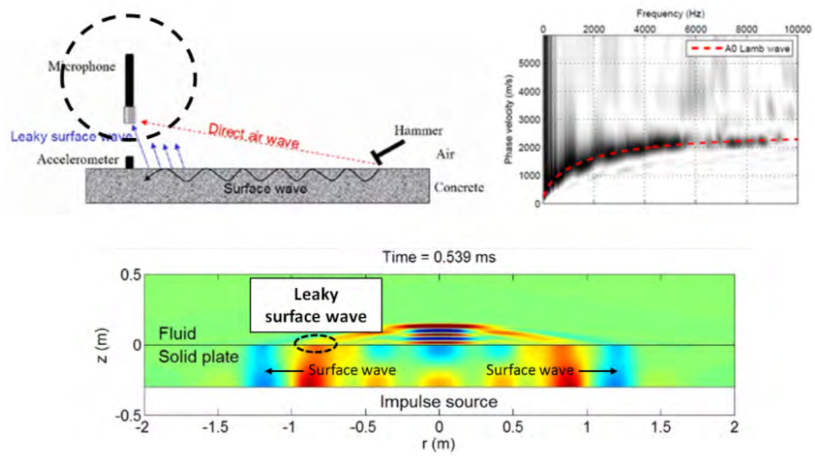


Figure 2.2 Non-contact measurement of leaky-mode seismic surface (Lamb) waves by using a microphone (Ryden et al., 2006).

Figure 2.3 Rolling seismic pavement method that can yield multiple (1-3) data-point results per second (Ryden et al., 2019).

3. SYSTEM DEVELOPED - "TAPPER 64"

TAPPER 64 is a 64-channel seismic system that collects seismic data in a rolling mode along the hot-mix-asphalt (HMA) road by using four (4) MEMS microphone arrays (16-channel each) (Figure 3.1). The four (4) arrays are transversely arranged to cover a certain width of HMA pavement simultaneously (adjustable approximately within 0.5 m - 1.0 m). The onboard laptop computer analyzes incoming seismic data automatically and displays output results of shear-wave velocity (Vs), thickness (H), Young's (E), and shear (μ) moduli, and temperature of HMA pavement with respect to distance (m) and GPS coordinates in plan view maps. The system records the leaky-mode seismic (Lamb) surface waves generated from an impact source located at equidistance from all arrays. The Lamb waves initially travelling horizontally along the pavement surface are transmitted into the air above the pavement surface ("leaked") in the form of sound waves, which are then detected by the MEMS microphones. TAPPER 64 represents a technical realization of the two-decade-long studies (Appendix III). Operational details are presented in the "TAPPER 64-User's Manual" attached in Appendix IV.

The 64-channel acquisition system (ACQ-64) is designed and built at Norrfee Tech AB in Lund, Sweden, by expanding the 1D system previously developed (Ryden et al., 2019). The ParkSEIS-HMA (PS-HMA) software package is developed by expanding its parent package of ParkSEIS AUTO (v. 3.0) first released in September 2017. The overall architecture of TAPPER 64 is presented in a schematic displayed in Figure 3.2.

The most sensitive part of the acquisition system is the impact source that can directly influence on the quality of acquired data. It is a small bolt with cap nut tightened in a zip tie, which is attached to a vertical rod installed in front of the arrays. It is hanging down on the pavement surface in a slant angle. The receiver-array panel is harnessed on the back of a survey vehicle into a 2-in hitch receiver (Figure 3.1). When the vehicle starts moving, the impact source will initially drag on the pavement surface. Then, it will soon start bouncing up and down to generate impacts as soon as the vehicle reaches at a cruising speed (10 MPH – 30 MPH). Each impact-generated high-pitched sound is detected by channel #1, which will then make the PXI recording system record a 64-channel 5-ms seismic data with 1.5-ms pre- and 3.5-ms post-trigger times, respectively. Each record will also include temperature (°C) and GPS (LAT/LON) data measured near the impact point. When 20 of such records are stored in the memory, they are saved as one TDMS file in a folder of PXI, which is also a stand-alone Windows computer.

Whenever a new TDMS file is saved, the ParkSEIS-HMA (PS-HMA) software package installed on an onboard laptop computer will start processing it immediately. The laptop computer communicates with the PXI via Wi-Fi connection and therefore can "view" the PXI computer whenever necessary through the remote desktop connection from the onboard laptop computer. Pushing the switch once will turn on the PXI system, which is a stand-alone Windows computer that automatically runs the acquisition control software as a startup program. A separate laptop computer has the ParkSEIS-HMA (PS-HMA) software package installed, which controls several key features of PXI system (e.g., recording parameters, initiation and termination of recording) and performs all steps of data analysis and display of the results. To start a new survey, the PXI must be turned on first and then laptop. When first booted, it usually takes about two minutes until both computers fully establish the wireless communication. Then, launch the PS-HMA program on the laptop.

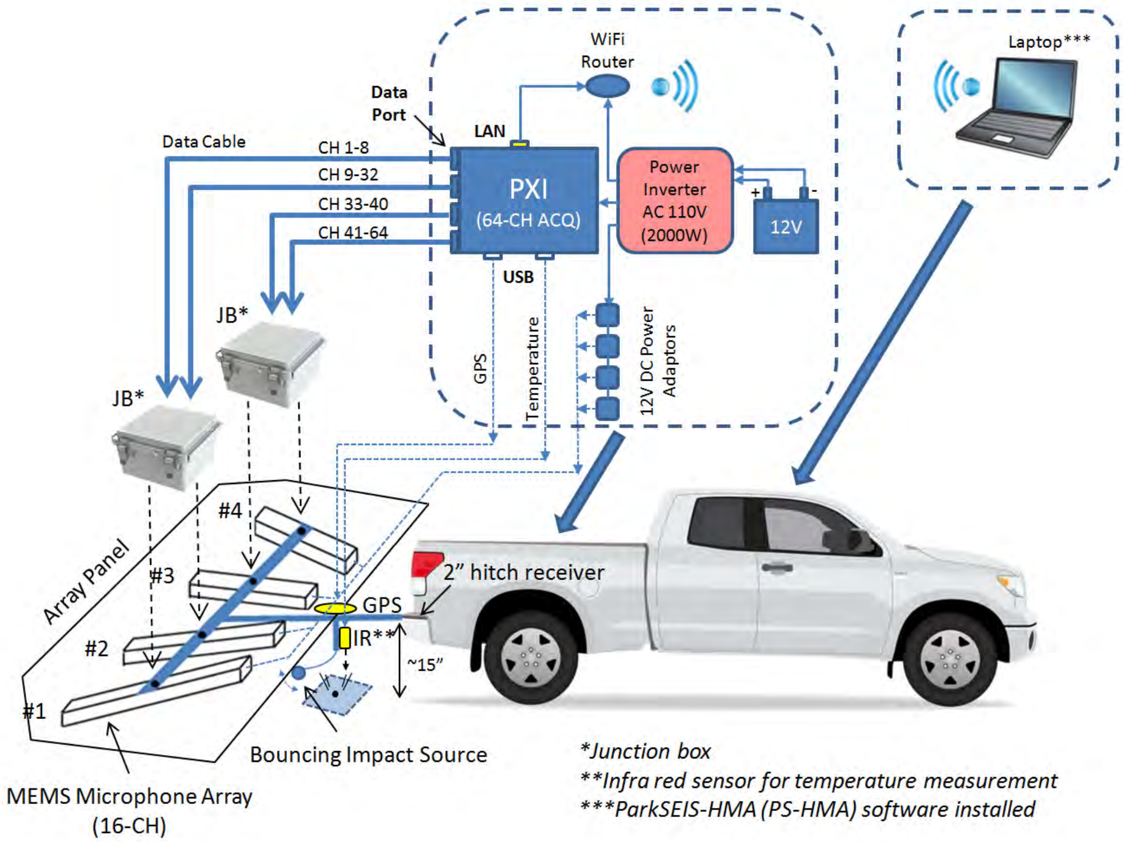


Figure 3.1 Overall schematic of "TAPPER 64" system.

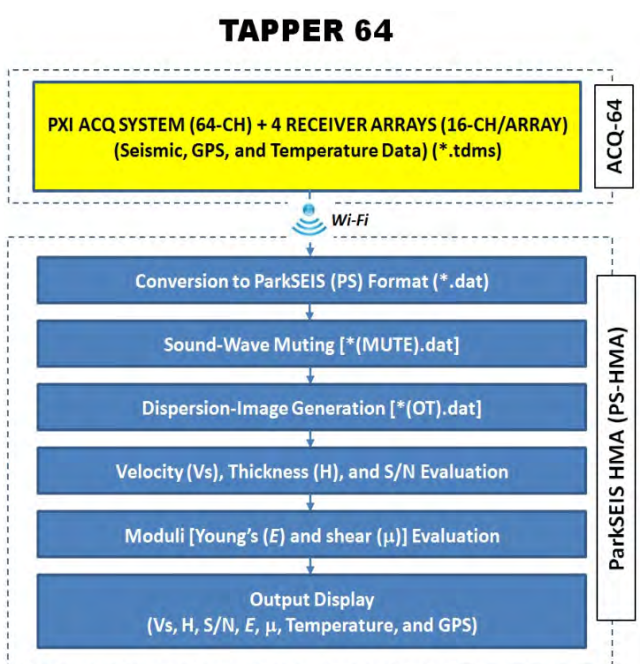


Figure 3.2 Overall architecture of "TAPPER 64" system.

4. SYSTEM DELIVERY AND BRIEFING AT MnDOT

Norrfee Tech, the subcontractor developing and building the hardware system, shipped the completed system to Park Seismic on February 14, 2022. Park Seismic started building the frame to install all (4) MEMS microphone arrays properly. Subsequent addition of peripheral components, such as cargo carrier, cable junction boxes, power inverter, extension cables, and rearrangement of components were made at Park Seismic by the end of April 2022. During this period, the ParkSEIS (PS)-HMA software package was modified in its data-acquisition control parts mostly through lab tests. Several field tests were also conducted at a parking of Trumbull high school, Trumbull, CT, about 10 miles from Park Seismic. These field tests critically helped fine tune the hardware configuration as well as the ParkSEIS (PS)-HMA software package. The finalized system was packaged into two boxes (Figure 4.1). All key electronic components, such as PXI unit, MEMS microphone arrays, and laptop computer, were placed in a big Pelican box. All other components such as array frame and hitch cargo-carrier frame, were placed into a crate. The two packages were delivered to MnDOT Materials Lab in St Paul, MN, on June 10, 2022. Principal Investigator (PI) (Choon Park) and a staff (Jin Park) from Park Seismic assembled the system during the morning of June 15 in a conference room. In the afternoon, the PI presented about technical, operational, and maintenance aspects of the system to MnDOT personnel attending onsite and remotely (Figure 4.2). Presentation file is attached in Appendix I that shows topics covered during the meeting. Figure 4.3 shows all items delivered, most of which were bagged separately.

Figure 4.1 Finalized TAPPER 64 system packaged into two boxes before shipping to MnDOT.

Figure 4.2 System briefing after delivery at MnDOT on June 15, 2022.

Figure 4.3 Display of itemized system components delivered.

5. DEMONSTRATION SURVEYS

The field demonstration surveys were conducted at MnROAD Low Volume Road (LVR) (Otsego, MN) (Figure 5.1) between 10 am and 12 pm on June 16, 2022, by Principal Investigator (Choon Park) and administration staff (Jin Park) from Park Seismic LLC as well as personnel from MnDOT. Three surveys were conducted with about 30-min intervals (surveys #1 – #3). Key survey attributes are summarized in Table 1. A video illustrating the process of demo surveys is posted on YouTube. Figure 5.2 shows the receiver array panel hooked on the back of survey truck that was horizontally leveled by using the two yellow tie-down straps. This section focuses on the general aspects of all 3 surveys, including output results. Complete display of results as appearing in the onboard laptop computer during the surveys and associated discussions are presented in a separate summary report in Appendix II.

Table 1: Summary table of key survey attributes

Survey #	NTDMS	NRCD	NTDMS^p	NRCD^p	Begin Time*	End Time*	Complete Time**	Distance(m)[1] (ADD[2])	Note
1	28	560	28	560	10:05:33	10:16:56	10:20:28	448 (0.80)	About 9 min pause at around the center of the survey line
2	30	600	29	580	10:42:19	10:46:18	10:54:38	444 (0.77)	One TDMS (*_5.tdms) copy error
3	36	720	36	720	11:19:33	11:20:59	11:31:11	456 (0.63)	Opposite direction survey on the other side of the road

NTDMS: # of TDMS files collected [1 TDMS = 20 records (RCD's)], NRCD: # of records collected, NTDMS^p: # of TDMS files processed, NRCD^p: # of records processed, *Survey begin ("armed") and end ("disarmed") times (AM) on June 16, 2022, **Completed time (AM) of entire process on June 16, 2022, [1]Distance between the first and last data points, [2]Average distance (m) per data point

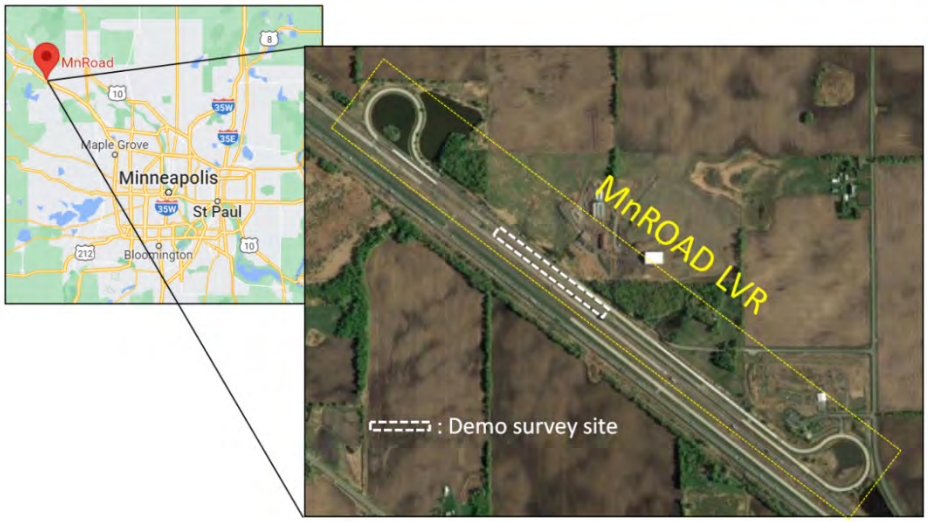


Figure 5.1 Site map of MnROAD Low Volume Road (LVR) where three demonstration surveys were conducted on June 16, 2022.

Figure 5.2 MEMS microphone array panel attached to the 2" hitch receiver on the back of survey truck.

5.1 Surveyed Cells

The surveys were conducted on the section between cell 188 and 728 on the MnROAD LVR as indicated in a profile map (Figure 5.1.1). The three surveys were conducted over 448-m (560 data points) (for survey #1), 444-m (580) (#2), and 456-m (720) (#3) distances by driving a pickup truck equipped with TAPPER 64 array panel on the back at about 15-Knot (17 MPH) speed. Surveys #1 and #2 were conducted on the same side of the road travelling toward SE with survey #2 starting about 15-m (about 20 data points) ahead of the survey #1 starting point and ending about 5-m pass the end of survey #1. Survey #3 started from the end of survey #2 on the other side of the road travelling in opposite direction toward NW and ended about 5-m pass the start of survey #2. Data points from all surveys are marked on Google satellite maps by using the GPS coordinates recorded with the seismic data (see Appendix II).

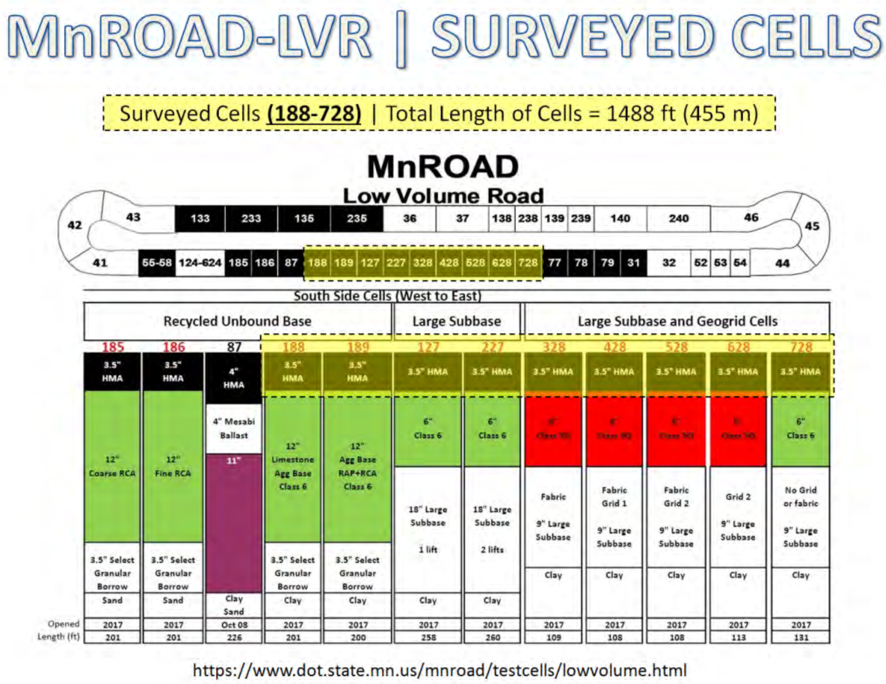


Figure 5.1.1 Profile map showing specifications for the surveyed cells (188-728) in MnROAD Low Volume Road (LVR) located in Otsego, MN.

5.2 Survey Results

Displays of complete output results for survey #1 are presented in Figure 5.2.1 for 1D graphs, Figure 5.2.2 for 2D graphs, and Figure 5.2.3 for GPS data points to illustrate the mode of output displays as appearing in the onboard computer screen during the survey.

The average, over all data points, velocity (Vs) and thickness (H) results from individual microphone arrays (array #1-#4) are summarized in Tables 2-4 for all three surveys. Average temperatures of the pavement surface during each survey were 23.75 °C (survey #1), 25.80 °C (survey #2), and 27.50 °C (survey #3), increasing gradually after the first survey that started at 10:05 AM.

Average Vs from survey #1 was 1680 (m/s) (Table 2), that of survey #2 was 1664 (m/s) (Table 3), and that of survey #3 was 1625 (m/s) (Table 4). Average Vs values from the two consecutive surveys (#1 and #2) match each other within less than 1% of margin. Considering the two surveys were conducted almost at the same part of the road with about 95% overlap, the results indicate a high degree of survey consistency (99%). Average Vs from the other side of the road from survey #3 (1625 m/s) is close to the previous two values. Vs decreases between consecutive surveys that were conducted about 30-min apart with about 2°C temperature increase. In this sense, the systematic change in average Vs between successive surveys can be mainly due to temperature change.

Average Young's (E) and shear (μ) moduli are calculated from the average velocities (Vs) by using a Poisson's ratio of 0.3 and density of 2300 kg/m^3. They are E=16.89 (GPa) and μ =6.49 (GPa) for survey #1, E=16.57 (GPa) and μ =6.37 (GPa) for survey #2, and E=15.81 (GPa) and μ =6.08 (GPa) for survey #3.

At this moment, it is not possible to assess how much of these differences in Vs and moduli represent changes in physical properties of pavements and how much represents inherent margin of error arising from the method itself. It seems obvious, however, the temperature change played a key role. Nonetheless, the overall differences between different surveys are fairly small.

Average thickness of HMA pavement (H) evaluated from surveys #1 and #2 are 6.2 (cm) and 6.1 (cm) (Tables 2 and 3), respectively. Average H from #3 is 5.9 (cm) (Table 4). According to the design profile last updated in 2017 (Figure 5.1.1), the entire area of surveyed road is listed as having a 3.5" HMA thickness (= 8.89 cm). If it represents the ground truth, then the evaluated values represent only about 70% of accuracy. The reduced accuracy in H evaluation has always been anticipated from the earliest stage of project execution. The main focus has always been in the accurate evaluation of seismic velocity (Vs). The results of modeling experiments executed throughout the entire project execution period consistently indicated the overall accuracy in H evaluation can be 20-30% lower than that in the Vs evaluation. In this sense, velocity (Vs) results are expected to have a much higher accuracy (e.g., ≥ 95%).

Average signal-to-noise ratio (S/N) (%) values for Vs evaluation are 95%, 96%, and 92% for surveys #1, #2, and #3, respectively (Tables 2-4). Those in H evaluation are 89%, 91%, and 87%, respectively, for the 3 surveys. S/N values higher than 80%, in general, indicate the surface wavefields are strong enough to be used for the reliable analysis.

Table 2: Summary of results from survey #1 (Average Temperature = 23.75 °C ± 0.22 °C)

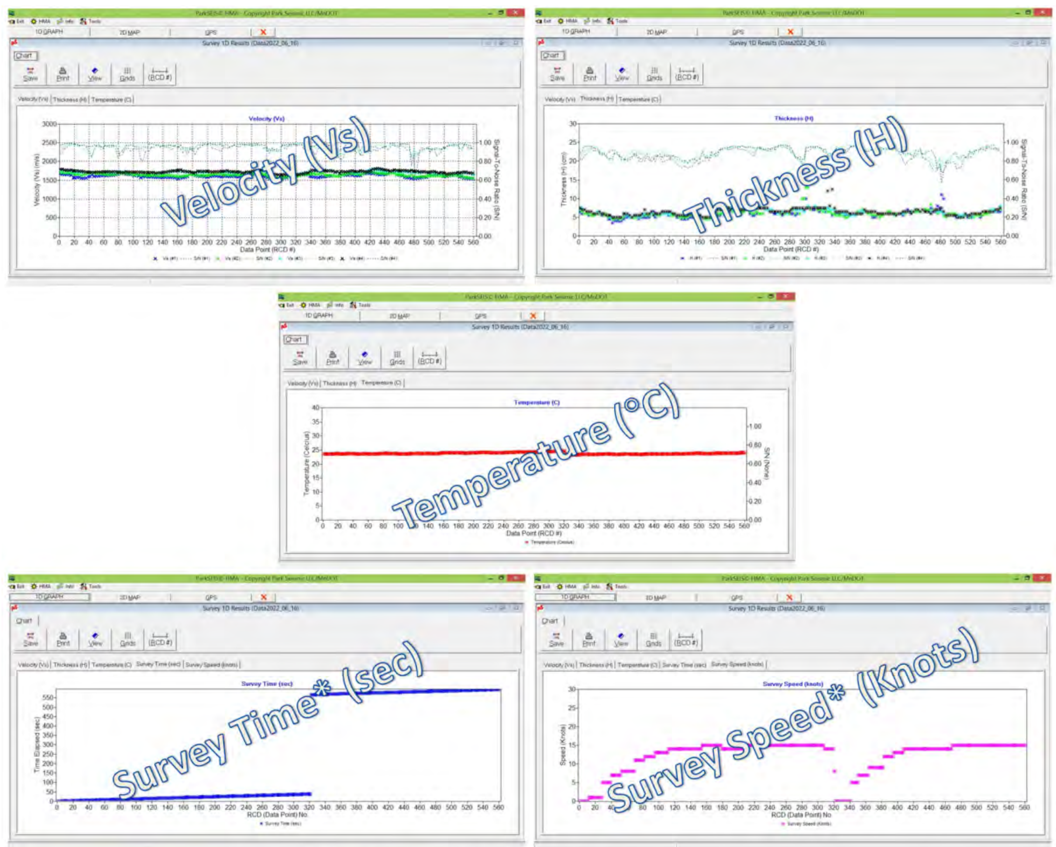
Array #	Velocity (Vs)				Modulus		Thickness (H)			
	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)	Young's (GPa)	Shear (GPa)	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)
1	1617	32	95	3	15.66	6.01	5.9	0.7	87	6
2	1647	30	95	3	16.22	6.24	6.1	0.7	89	5
3	1723	23	96	2	17.76	6.83	6.3	0.7	89	4
4	1731	26	95	3	17.92	6.89	6.4	0.7	89	5
Mean	**1680**	**28**	**95**	**3**	**16.89**	**6.49**	**6.2**	**0.7**	**89**	**5**

Table 3: Summary of results from survey #2 (Average Temperature = 25.80 °C ± 0.59 °C)

Array #	Velocity (Vs)				Modulus		Thickness (H)			
	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)	Young's (GPa)	Shear (GPa)	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)
1	1628	33	94	3	15.85	6.10	6.0	0.7	89	4
2	1668	28	96	2	16.64	6.40	6.0	0.6	92	3
3	1668	28	96	2	16.64	6.40	6.0	0.6	92	3
4	1693	27	96	2	17.14	6.59	6.4	0.8	91	3
Mean	**1664**	**29**	**96**	**2**	**16.57**	**6.37**	**6.1**	**0.7**	**91**	**3**

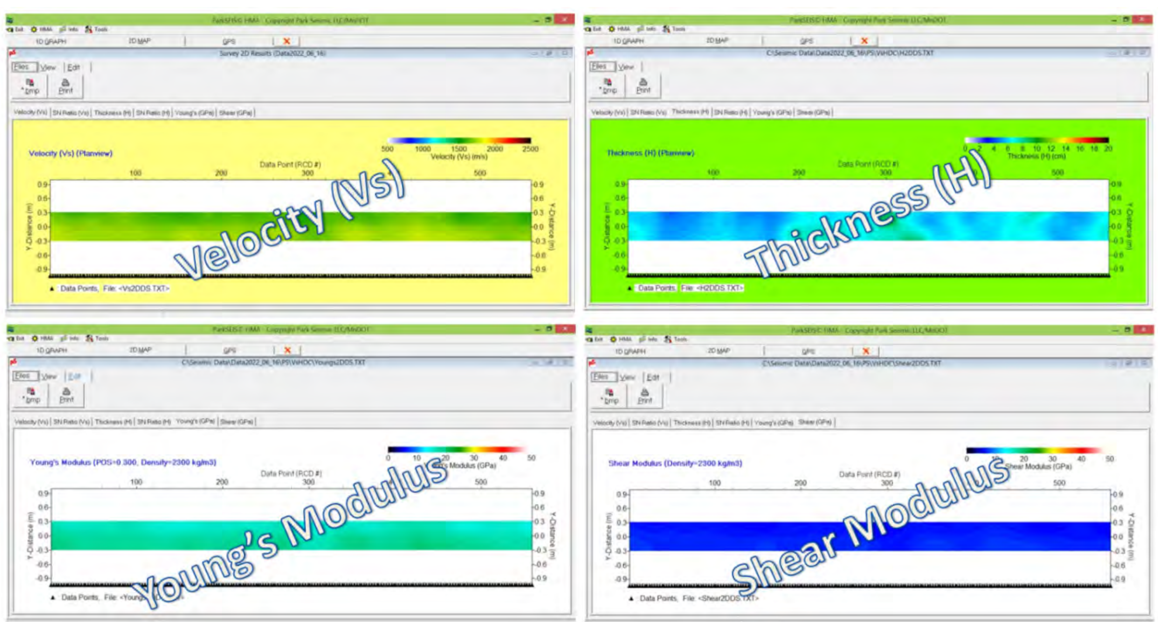
Table 4: Summary of results from survey #3 (Average Temperature = 27.50 °C ± 0.13 °C)

Array #	Velocity (Vs)				Modulus		Thickness (H)			
	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)	Young's (GPa)	Shear (GPa)	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)
1	1551	76	90	6	14.39	5.53	5.7	0.9	83	7
2	1615	55	91	5	15.60	6.00	5.9	0.9	86	6
3	1666	30	94	4	16.60	6.38	6.0	0.8	89	5
4	1668	36	94	4	16.64	6.40	6.0	0.6	89	6
Mean	**1625**	**49**	**92**	**5**	**15.81**	**6.08**	**5.9**	**0.8**	**87**	**6**



Display modules added after demo surveys

5.2.1 Results in 1D graphs as being displayed in onboard laptop computer during survey #1.



5.2.2 Results in 2D graphs as being displayed in onboard laptop computer during survey #1.

5.2.3 GPS data points as being displayed in onboard laptop computer during survey #1.

6. DISCUSSIONS

It is important to discuss, at least, two topics as listed below.

6.1 Over/Under Estimation of Velocity (Vs)

It is important to make each microphone array leveled with pavement surface within a few millimeters of difference (e.g., < ±5 mm) between the heights of the begin (closest to the impact point) and the end (furthest from the impact point) points of the array. A small difference (e.g., +/- 10 mm) can result in a significant over or under estimation of Vs (e.g., -/+ 10%) (Figure 6.1.1). For this reason, it is always necessary to ensure leveling of the array panel, longitudinally and transversely, after its installation on the back of the survey vehicle. Because of the weight that makes the back end of the array panel sag, the installation procedure tends to focus more on the longitudinal leveling. The most strict way would be to measure the heights manually by using a small hand-held ruler. For the demo surveys, a bubble leveling device was used to ensure the horizontal leveling of the array panel, which was then put in place by using two straps tied down on both sides of the panel (Figure 6.1.2). The length adjustment of these straps can control the panel orientation longitudinally and transversely.

A systematic variation is observed between the average Vs values from all 4 arrays (#1-#4) for all three surveys (#1-#3) (Tables 2-4). The Vs value increases from array #1 (Vs1) to #4 (Vs4). For example, Vs1=1617 (m/s), Vs2=1647 (m/s), Vs3=1723 (m/s), and Vs4=1731 (m/s) for survey #1. The differences between Vs1 and Vs4 were 7% for survey #1, 4% for survey #2, and 8% for survey #3. It is believed that this systematic variation was caused by the cross slope of the road (Figure 6.1.3), which was not compensated for during the leveling process of the array panel that aimed at the “horizontal” leveling. The effect of cross slope on the velocity (Vs) evaluation from different arrays is illustrated in Figure 6.1.3. It shows the first two arrays (#1 and #2) result in under (-) estimation because of the higher array end

(+dz). The extent of under estimation is greater for array #1 because of the steeper slope. The other two arrays (#3 and #4) are shown to result in over (+) estimation because of the lower array end (-dz) with the #4 causing a greater over estimation. Then, the evaluated velocities from all four arrays (Vs1, Vs2, Vs3, and Vs4) will have increasing values like Vs1 < Vs2 < Vs3 < Vs4.

A similar variation is also observed between the average H values. For example, H1=5.9 (cm), H2=6.1 (cm), H3=6.3 (cm), and H4=6.4 (cm) for survey #1. The differences between H1 and H4 were 8% for survey #1, 7% for survey #2, and 5% for survey #3. It is believed that this variation in H is caused by the algorithmic link between the two methods of Vs and H evaluations.

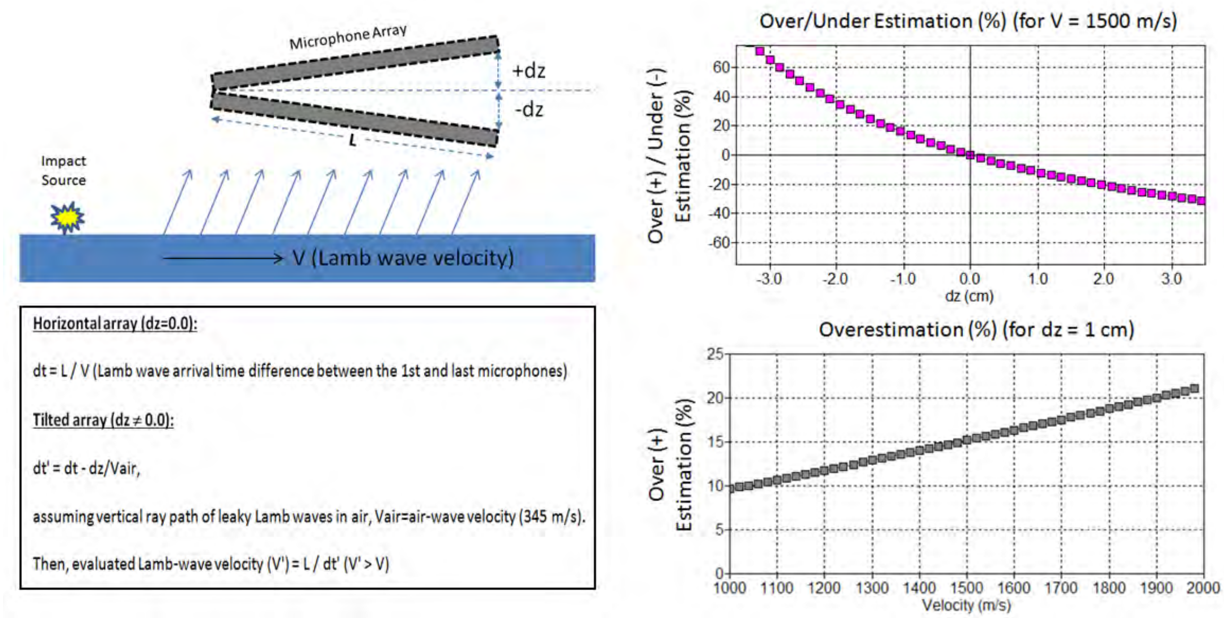


Figure 6.1.1 Calculation of over/under estimation of velocity (Vs) due to the tilting of the receiver array with respect to the pavement surface. Calculated values are graphically displayed for different tilting extent (dz) with a given velocity (Vs=1500 m/s)(top right), and also for different velocities with a given tilt (dz= -1 cm) (bottom right).

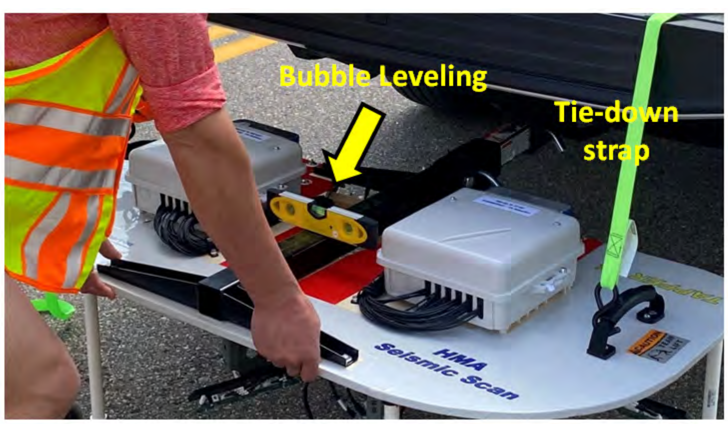


Figure 6.1.2 Procedure of leveling the receiver array frame by using a bubble-level device.

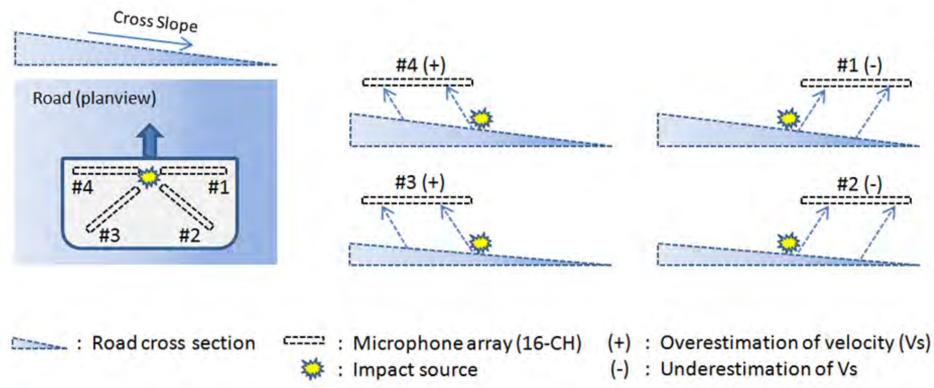


Figure 6.1.3 Schematics illustrating different degree of over/under estimation of velocity (Vs) due to unleveling with different slopes underneath each array, all of which are caused by the road cross slope.

6.2 In-Office Processing Results

Slightly different methods are used for velocity (Vs) and thickness (H) evaluations between the "In-Field (Approximate)" and "In-Office (Advanced)" processes. The former method determines the velocity (Vs) from asymptotic trend of the Lamb-wave dispersion image processed from the field seismic data. Then, the thickness (H) is determined by scanning through different values of H by using the evaluated Vs within a preset range (e.g., 1 cm - 20 cm) with a small increment (e.g., 0.1 cm) against the wavefield energy in the processed dispersion image. The H value that provides the highest match value between the scanned Lamb-wave dispersion curve (A0) and background energy is then selected as the final H value. On the other hand, the advanced method repeats this thickness scanning for different velocity values centered at the value (Vs') determined from the asymptotic trend (e.g., Vs'±0.1Vs'). Then, the combination of Vs and H that provides the highest match value is selected as the final values for Vs and H. Naturally, it takes a longer time. It was concluded based on limited modeling experiments that this "advanced" method can provide more accurate results in Vs and H.

The data set from demo survey #1 has been processed by the advanced ("In-Office") method after the survey. Results of Vs and H are displayed in Figure 6.2.1 for 1D graphs and Figure 6.2.2 for 2D graphs in comparison to those processed by approximate method (i.e., results obtained during the survey). Both figures indicate the advanced-method results have a higher degree of fluctuation in both Vs and H, which appears to be more numeric than real. Abrupt changes (e.g., > 10%) are observed in velocity (Vs) and even more abrupt changes (e.g., > 100%) are observed in thickness (H) results. Average values of Vs and H from all four arrays are compared in Tables 5 and 6, respectively. Velocity (Vs) values are alike (e.g., ≥ 99%). Thickness (H) values, however, are higher in the advanced-method results. The mean H value of 8.80 cm is almost the same as the value listed in the profile map (8.89 cm). This value, however, must have been affected largely by many outliers observed in the 1D graph (Figure 6.2.1) that are mostly overestimated values (e.g., > 15 cm).

At least for this particular data set, it seems the advanced method is less reliable. More thorough examination with more field data sets is necessary for more accurate evaluation of the two methods.

Table 5: Velocity (Vs) results from survey #1 by In-Field (Approximate) and In-Office (Advanced) Methods

Array #	In-Field Process (Approximate Method)				In-Office Process (Advanced Method)			
	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)
1	1617	32	95	3	1616	101	89	5
2	1647	30	95	3	1654	99	90	4
3	1723	23	96	2	1709	99	91	4
4	1731	26	95	3	1723	96	91	4
Mean	**1680**	**28**	**95**	**3**	**1676**	**99**	**90**	**4**

Table 6: Thickness (H) results from survey #1 by In-Field (Approximate) and In-Office (Advanced) Methods

Array #	In-Field Process (Approximate Method)				In-Office Process (Advanced Method)			
	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)
1	5.9	0.7	87	6	8.3	3.4	89	5
2	6.1	0.7	89	5	8.4	3.5	90	4
3	6.3	0.7	89	4	9.4	3.8	91	4
4	6.4	0.7	89	5	9.1	3.5	91	4
Mean	**6.2**	**0.7**	**89**	**5**	**8.8**	**3.5**	**90**	**4**

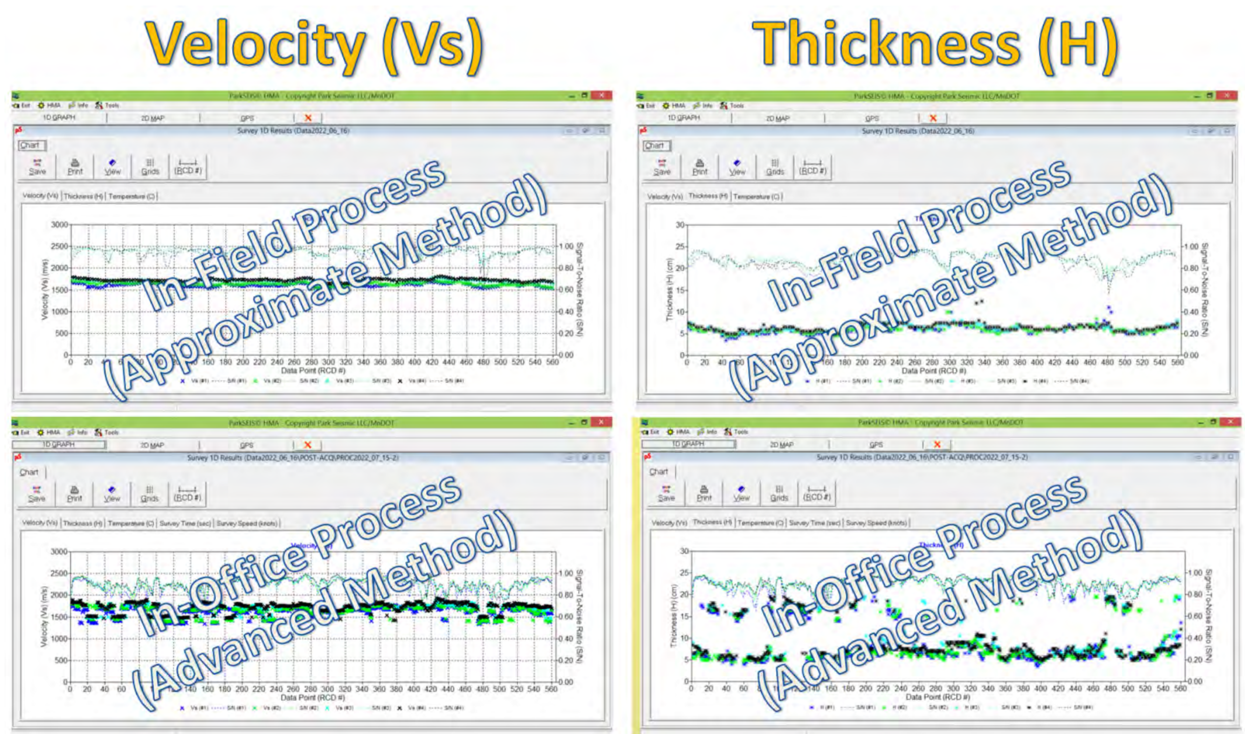


Figure 6.2.1 Comparison of velocity (Vs) and thickness (H) evaluation results in 1D graphs obtained from survey #1 processed with the "In-Field" (top) and "In-Office" (bottom) methods.

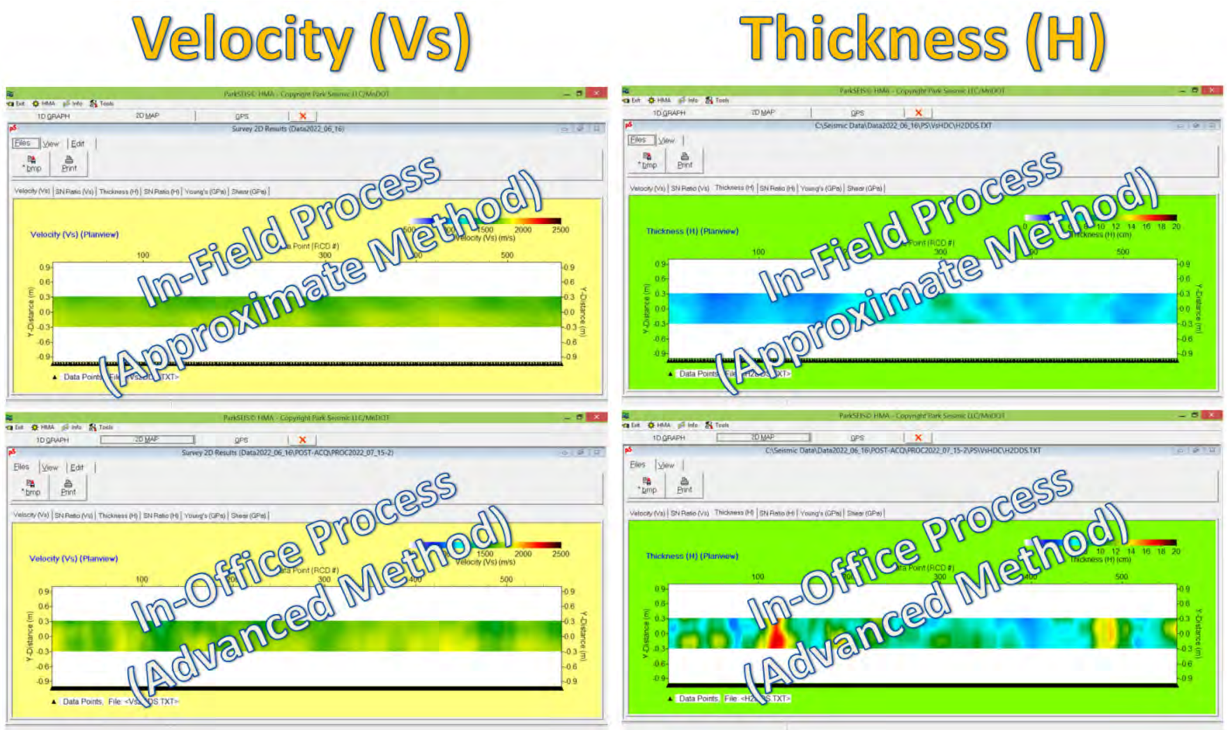


Figure 6.2.2 Comparison of velocity (Vs) and thickness (H) evaluation results in 2D graphs obtained from survey #1 processed with the “In-Field” (top) and “In-Office” (bottom) methods.

7. RECOMMENDATIONS

We would like to make following recommendations:

- To validate the evaluation results of velocity (Vs) and thickness (H) from the demo surveys, separate measurements by using different approach should be made at one or more representative locations within the surveyed cells.
- There are three (3) noisy channels. They are the 12^{th}, 32^{nd}, and 37^{th} channels existing in array #1, #2, and #3, respectively. They are functioning properly at relatively low frequencies (e.g., < 20 kHz) (see Appendix I). They are noisy only at higher frequencies influenced by unknown cause(s), which are believed to exist inside corresponding MEMS microphones. In consequence, they currently result in seismic data with slightly reduced signal-to-noise ratio (S/N) in the corresponding channel data. However, results of experiments executed by excluding them completely from the subsequent data analysis indicated no noticeable reduction of S/N in the processed dispersion images, not causing any harmful effect. In this sense, they do not need to be replaced at this moment by the new array boards (supplied in the “Spare Parts” box) unless other more serious issues develop.
- The leveling of receiver-array panel is critically important to ensure the reliability of velocity (Vs) results. The current frame installation method by using the hitch receiver will have limitations in securing the necessary degree of strict leveling. It seems necessary to make it a stand-alone unit with four (4) wheels so that the leveling is always maintained with road surface (Figure 7.1). This 4-wheel unit will protect MEMS microphone arrays more effectively as it will not be

affected by the orientation of the parent survey vehicle. It can also become a stationary measurement device that can be operated with manual impacts at precise locations of interest on the road.

- The accuracy of thickness (H) evaluation can be improved through further methodological refinement. For example, an inversion approach based on the comparison of dispersion images, rather than dispersion curves, may yield more reliable result at the expense of significantly elevated computation time (e.g., 100 times). It can then be used as an "In-Office" process approach that can run overnight.
- The impact source can be further studied to control key source attributes such as the spectral contents of impact, how often and when the impact is made, etc. For example, a heavier impact source may generate more surface wave energy at relatively low frequencies (e.g., < 10 kHz) that can help improve the evaluation accuracy in the thickness (H) evaluation. This can also lead to the possibility of velocity (Vs) evaluation of base materials below the pavement layer if the dispersion-image inversion (DII) method is adopted. The ability to control when and how often the impact is made can make the survey proceed at a faster speed (e.g., ≥ 50 MPH) with controlled survey intervals (e.g., measurements made every 1 km while driving at 60 MPH).
- Attenuation properties of HMA layer can be analyzed from the same seismic data used for the velocity (Vs) evaluation. The attenuation property may reflect micro-crack conditions (and possibly other related features) developed inside the pavement layer. The results of attenuation coefficients (α) can be displayed in the same way current velocity (Vs) and thickness (H) results are displayed in1D and 2D graphs.
- The system needs to be used under diverse conditions such as old vs. new roads, cold vs. warm roads, etc. Operational information, seismic data sets collected, and subsequent evaluation results will help understand the scope of the system in a more precise and specific manner.
- The system may be open to public for continued research and developments to be contributed by academia as well as practitioners.

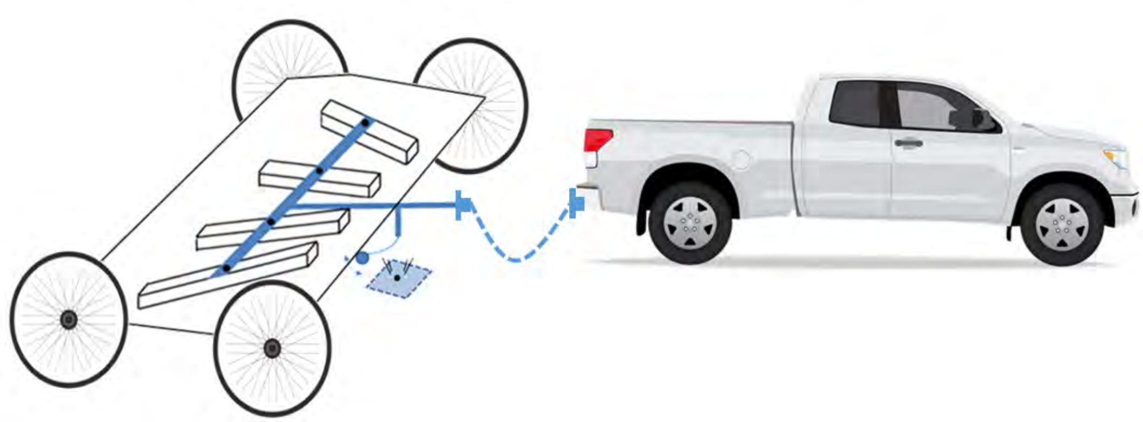


Figure 7.1 A conceptual design of the receiver array frame with four (4) wheels.

8. ACKNOWLEDGMENTS

This system has been developed under MnDOT Contract No. 1034287, "Seismic Approach to Quality Management of HMA", during January 2020 – June 2022. It is a project funded by National Road Research Alliance (NRRA). We acknowledge NRRA for the opportunity we had that led to building this unique seismic system for HMA evaluation.

We would like to express our special thanks of gratitude to Jason Richter at MnDOT who played highly effective and positive role as technical liaison during the entire period of project execution. We also would like to give our sincere appreciation to John Siekmeier and Rebecca Embacher at MnDOT, as well as other Technical Advisory Panel (TAP) members, for their continued support and productive guidance.

We thank Jason Richter, John Siekmeier, Joe Hudak, Micah Holzbauer, and Beth Lanzon at MnDOT for their highly professional contribution during the preparation and execution of the field demonstration surveys.

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Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Final Report - Appendices

Park Seismic LLC
2 Balsam Circle
Shelton, Connecticut

July 29, 2022

Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Final Report – APPENDIX I

Park Seismic LLC
2 Balsam Circle
Shelton, Connecticut

July 29, 2022

TAPPER 64

HMA Seismic Scan

Seismic System Developed Under
MnDOT Contract No. 1034287
"Seismic Approach to Quality
Management of HMA"
January 2020 - June 2022

Park Seismic

Norrfee
Tech

Choon Park, Ph.D.

Principal Geophysicist
Park Seismic LLC

Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287
Federal Project Number: TPF-5 (341)
Execution: January, 2020 - June, 2022

Principal Investigator (PI): **Choon Park, Ph.D.,** *Founder/Principal Geophysicist, Park Seismic LLC**

Co Investigator (CI): **Nils Ryden, Ph.D.,** *Research Director Norrfee Tech AB, Lund, Sweden***

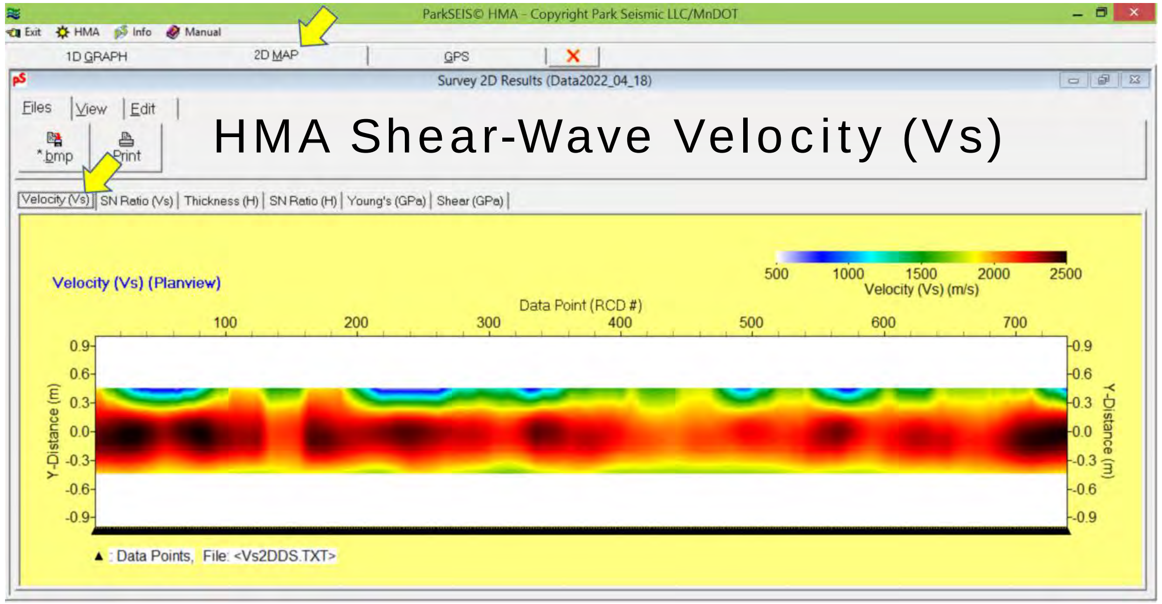
Co Investigator (CI): **Josefin Starkhammar, Ph.D.**, *Founder Norrfee Tech AB, Lund, Sweden***

Administration Staff: **Jin Park, Ph.D.**, *Operations Manager/Financial Coordinator, Park Seismic LLC**

**Prime Contractor:* *Project Oversight, Development of Software Package*

***Sub Contractor:* *Development of Hardware System*

WHAT IS IT?



ParkSEIS© HMA - Copyright Park Seismic LLC/MnDOT
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1D GRAPH 2D MAP GPS
Survey 2D Results (Data2022_04_18)
Files View Edit
bmp Print
HMA Shear-Wave Velocity (Vs)
Velocity (Vs) | SN Ratio (Vs) | Thickness (H) | SN Ratio (H) | Young's (GPa) | Shear (GPa)
Velocity (Vs) (Planview)
500 1000 1500 2000 2500
Velocity (Vs) (m/s)
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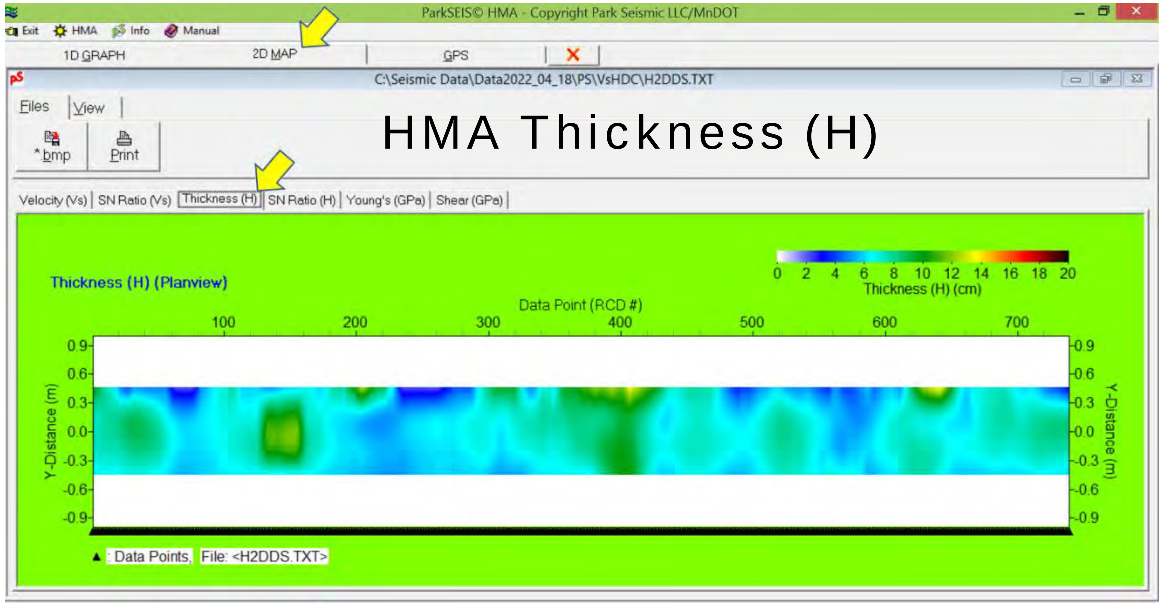

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Exit HMA Info Manual
1D GRAPH 2D MAP GPS
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HMA Thickness (H)
Velocity (Vs) | SN Ratio (Vs) | Thickness (H) | SN Ratio (H) | Young's (GPa) | Shear (GPa)
Thickness (H) (Planview)
0 2 4 6 8 10 12 14 16 18 20
Thickness (H) (cm)
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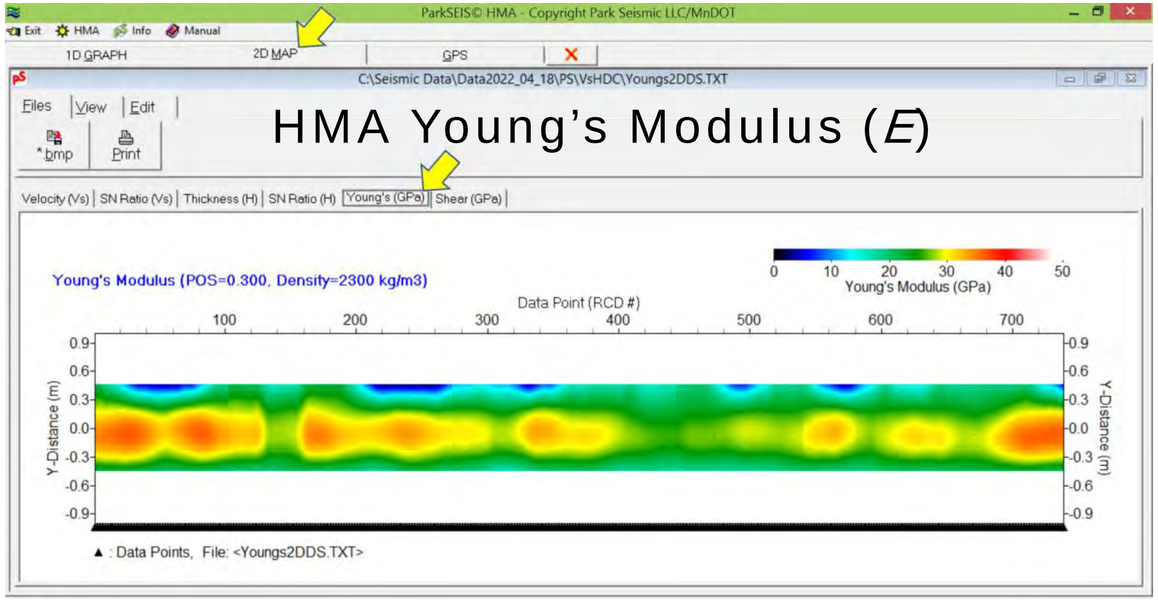

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bmp Print
HMA Young's Modulus (E)
Velocity (Vs) | SN Ratio (Vs) | Thickness (H) | SN Ratio (H) | Young's (GPa) | Shear (GPa)
Young's Modulus (POS=0.300, Density=2300 kg/m3)
0 10 20 30 40 50
Young's Modulus (GPa)
Data Point (RCD #)
100 200 300 400 500 600 700
Y-Distance (m)
0.9 0.6 0.3 0.0 -0.3 -0.6 -0.9
▲ : Data Points, File: <Youngs2DDS.TXT>

ParkSEIS© HMA - Copyright Park Seismic LLC/MnDOT
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1D GRAPH 2D MAP GPS
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Files View Edit
bmp Print
HMA Shear Modulus (μ)
Velocity (Vs) | SN Ratio (Vs) | Thickness (H) | SN Ratio (H) | Young's (GPa) | Shear (GPa)
Shear Modulus (Density=2300 kg/m3)
0 10 20 30 40 50
Shear Modulus (GPa)
Data Point (RCD #)
100 200 300 400 500 600 700
Y-Distance (m)
0.9 0.6 0.3 0.0 -0.3 -0.6 -0.9
▲ : Data Points, File: <Shear2DDS.TXT>

Pavement MASW (Ryden et al., 2004)

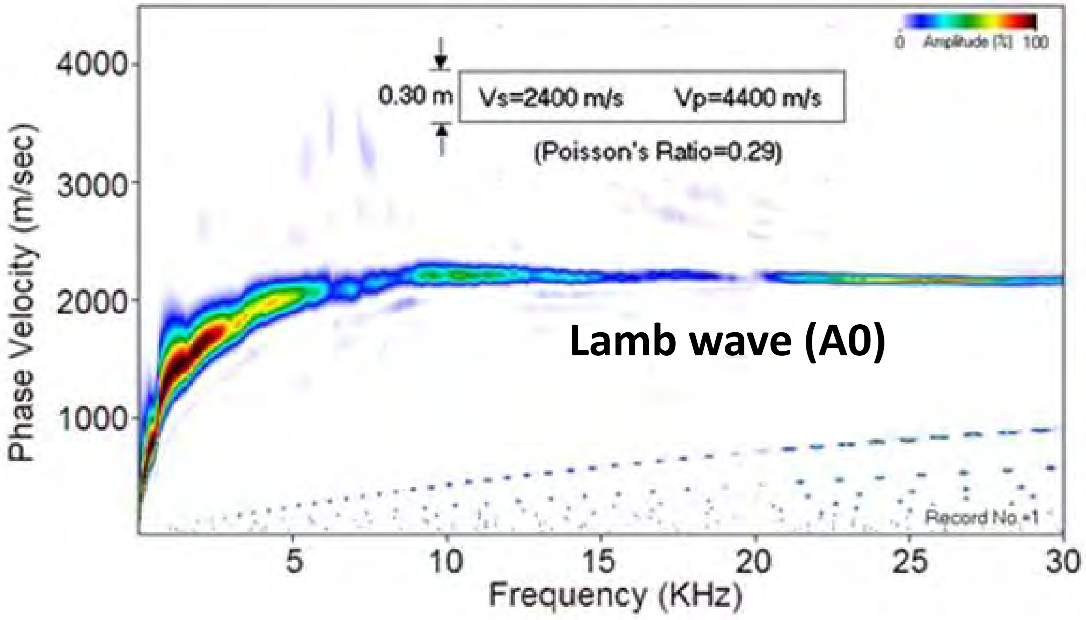
- Contact measurements with accelerometer and a small hammer.

MANUAL SURVEY & PROCESS – 1 HOUR/POINT

Field Measurement

~0.5 Hour (1 Data Point)

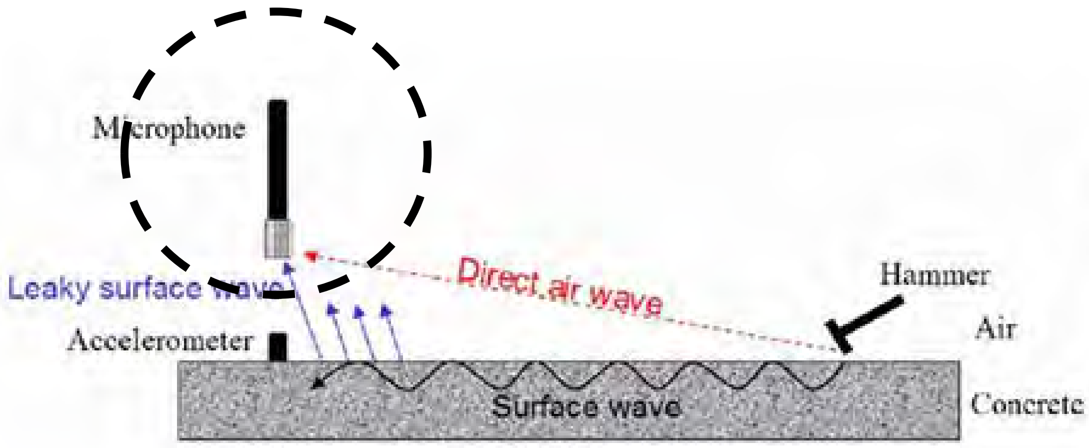
Data Process

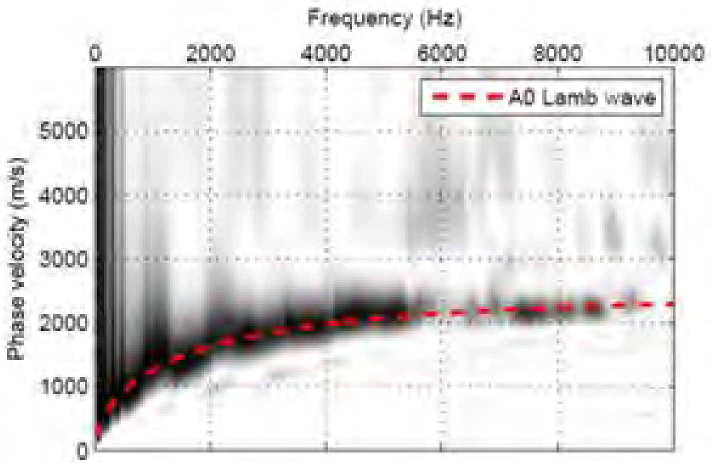


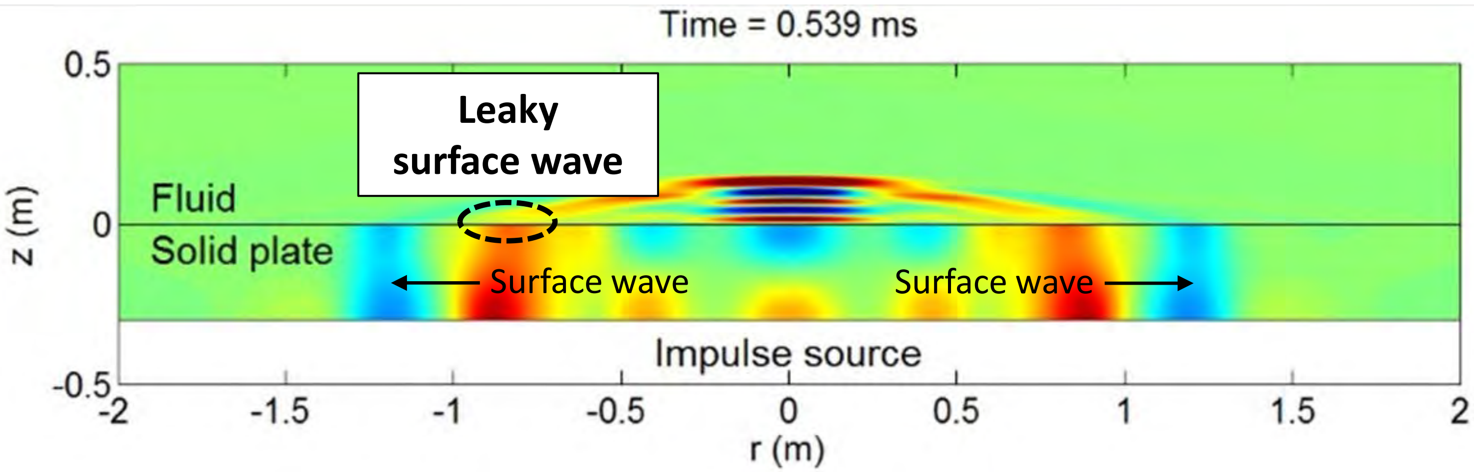
~0.5 Hour (1 Data Point)

Non-Contact Pavement MASW

(Ryden et al., 2006)



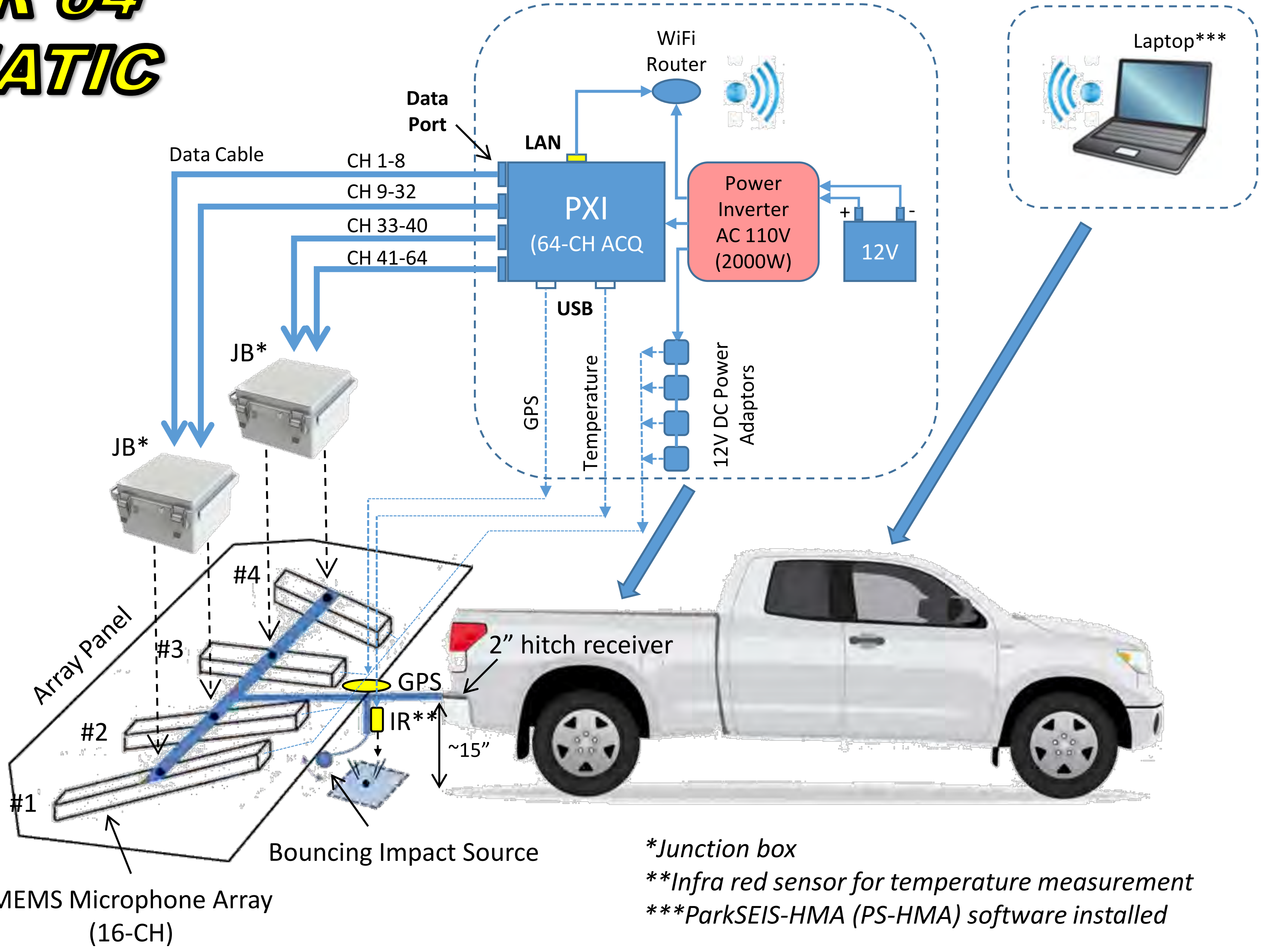




TAPPER 64 (2022)

FULL-AUTO SURVEY & PROCESS – 0.5 S/POINT

TAPPER 64 SCHEMATIC

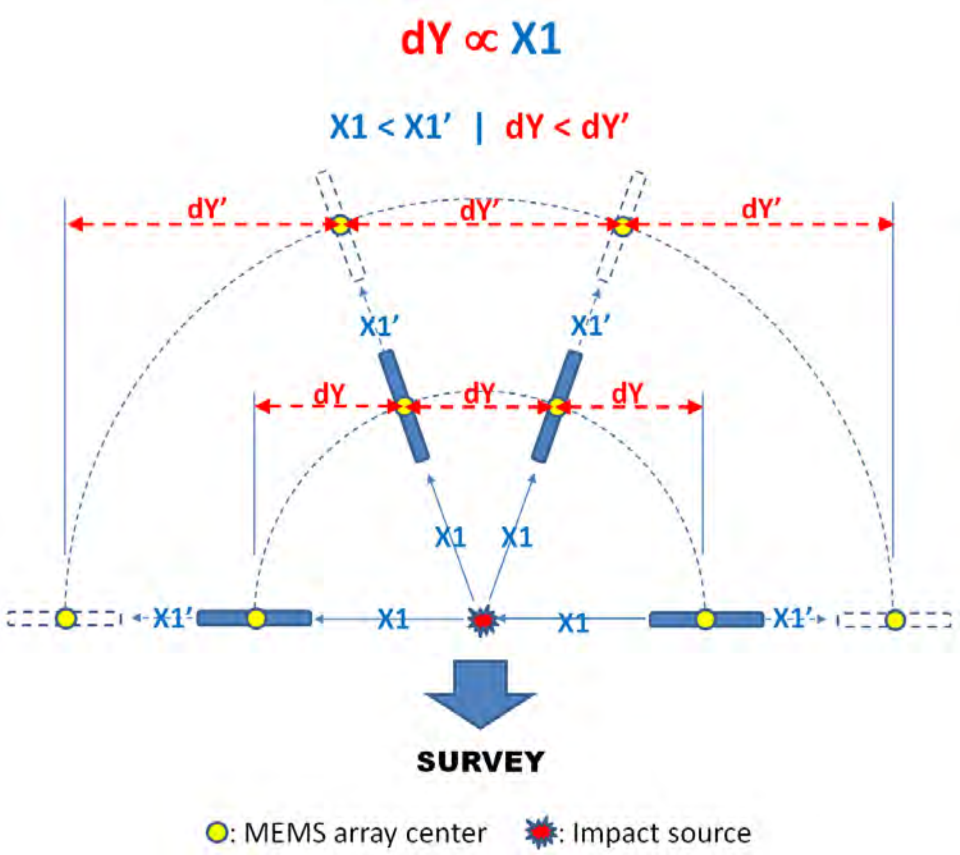


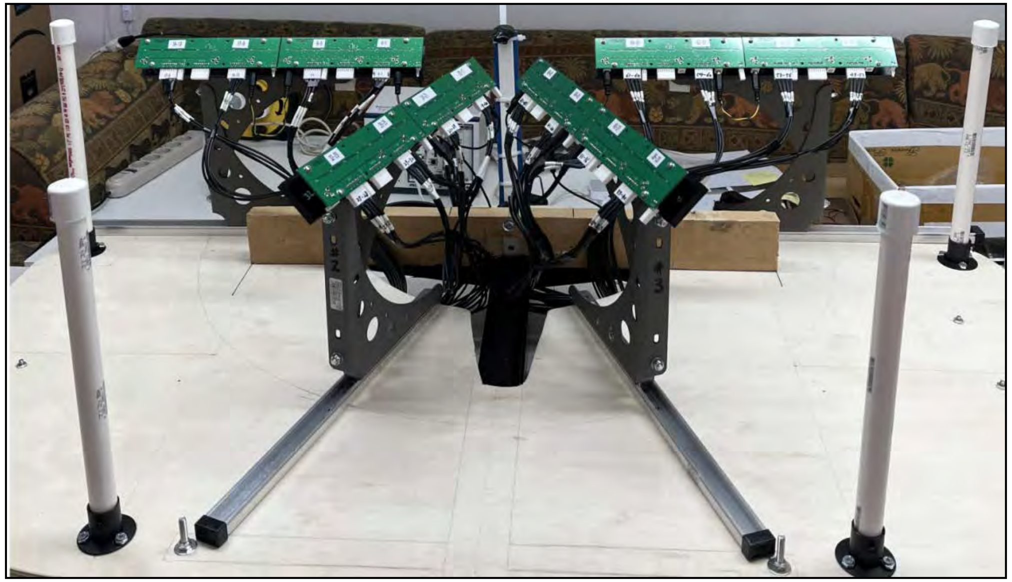
*Junction box

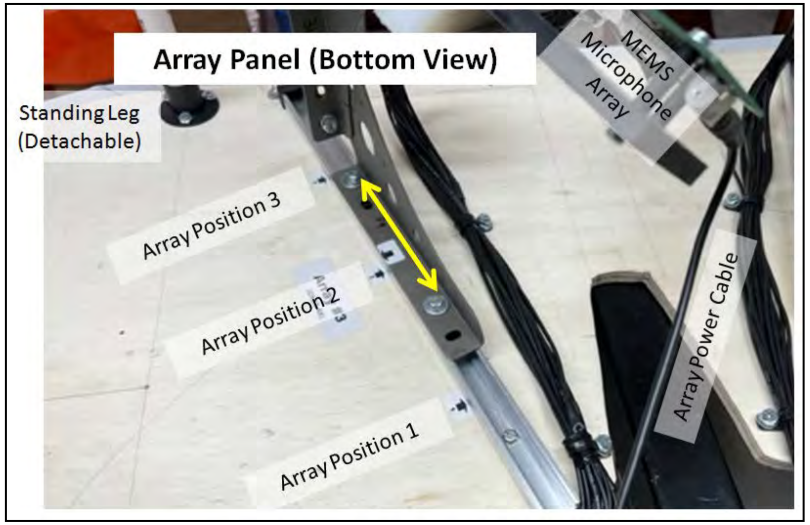
**Infra red sensor for temperature measurement

***ParkSEIS-HMA (PS-HMA) software installed

2D System – Common Source with Radial Arrays







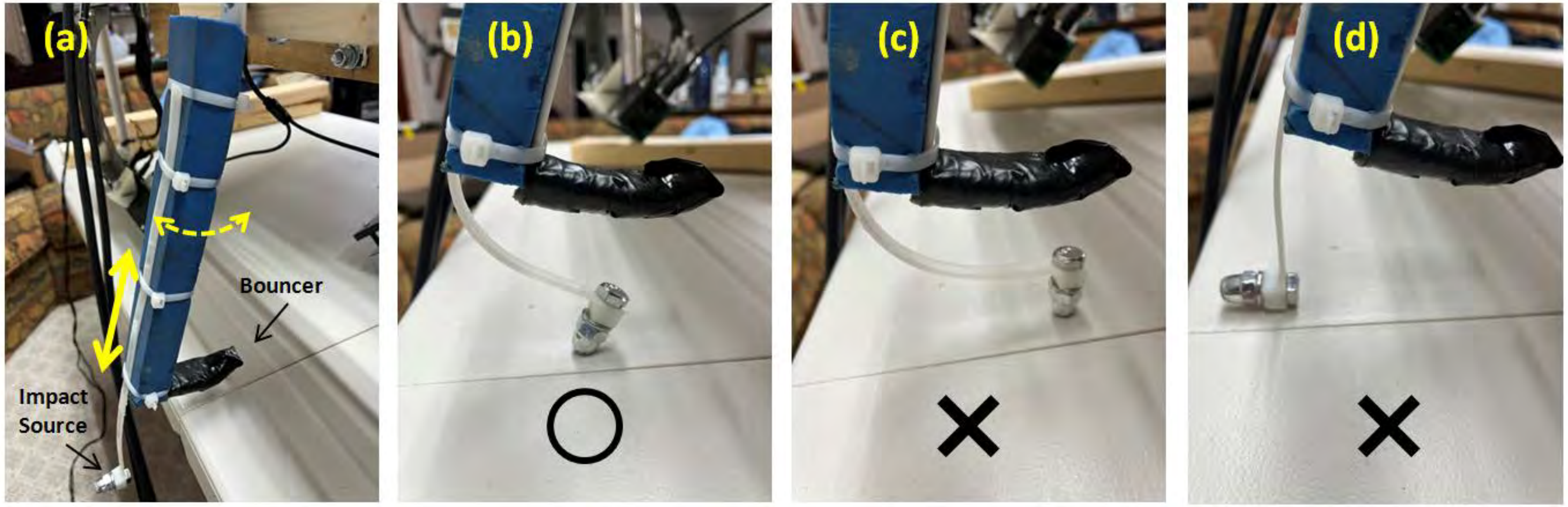
Items Delivered

: *ParkSEIS-HMA (PS-HMA) Software Package Installed, User's Manual, Quick Guide for New Survey*


IMPACT SOURCE IN MOTION

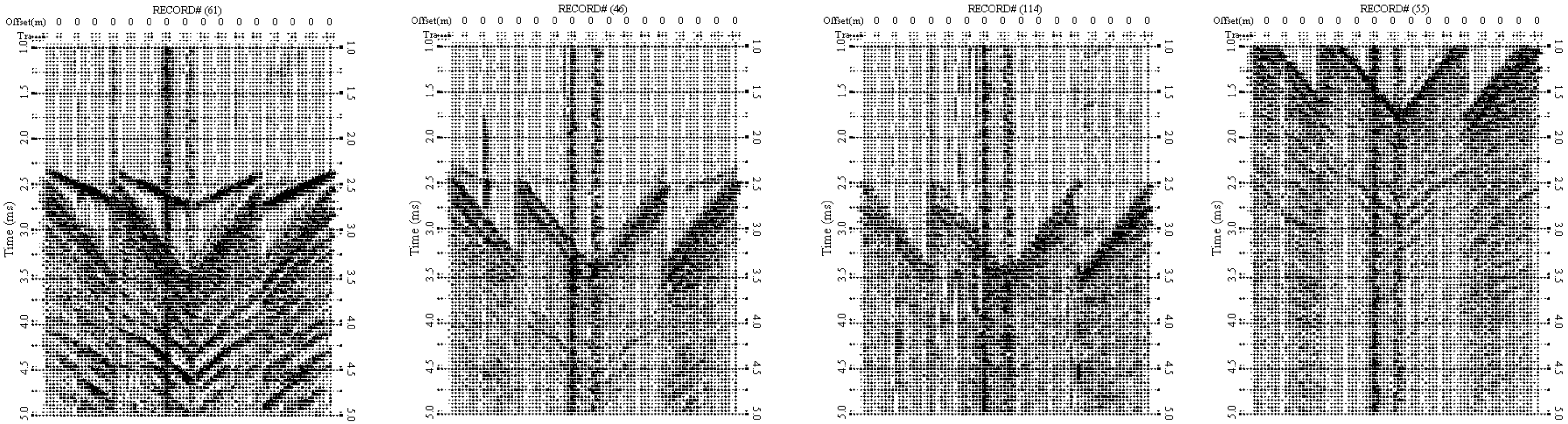
Impact Source

No Impact, No Data!



Data Quality

EXCELLENT GOOD FAIR POOR

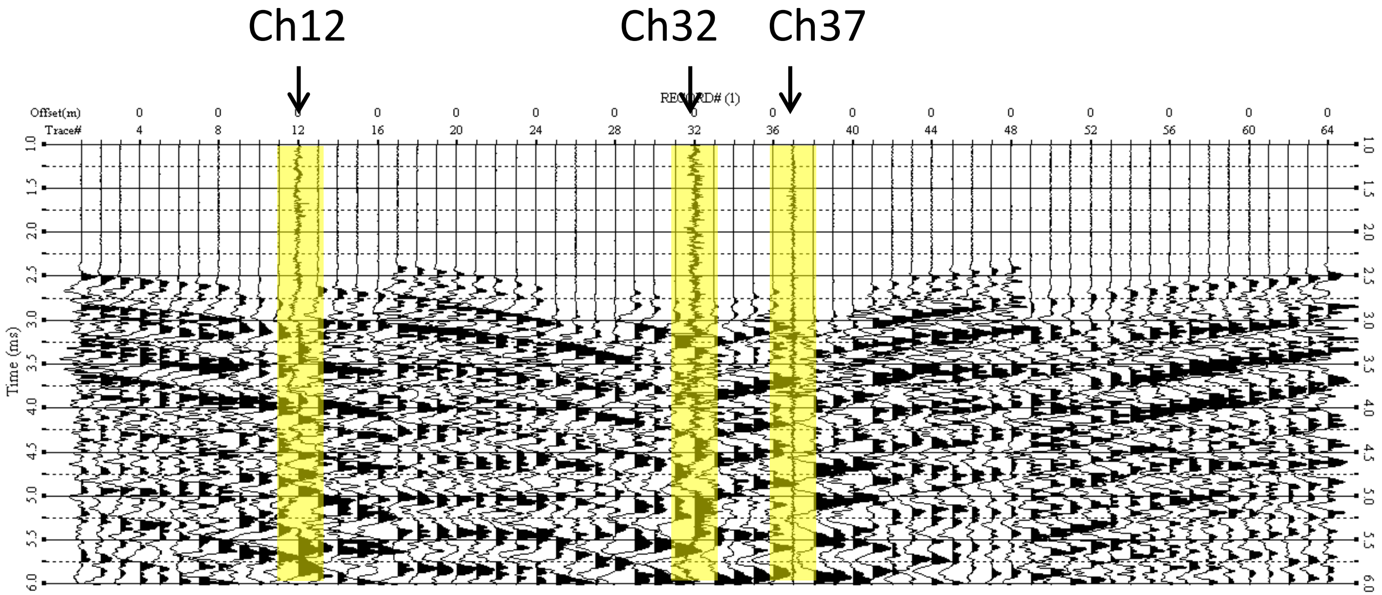


95%

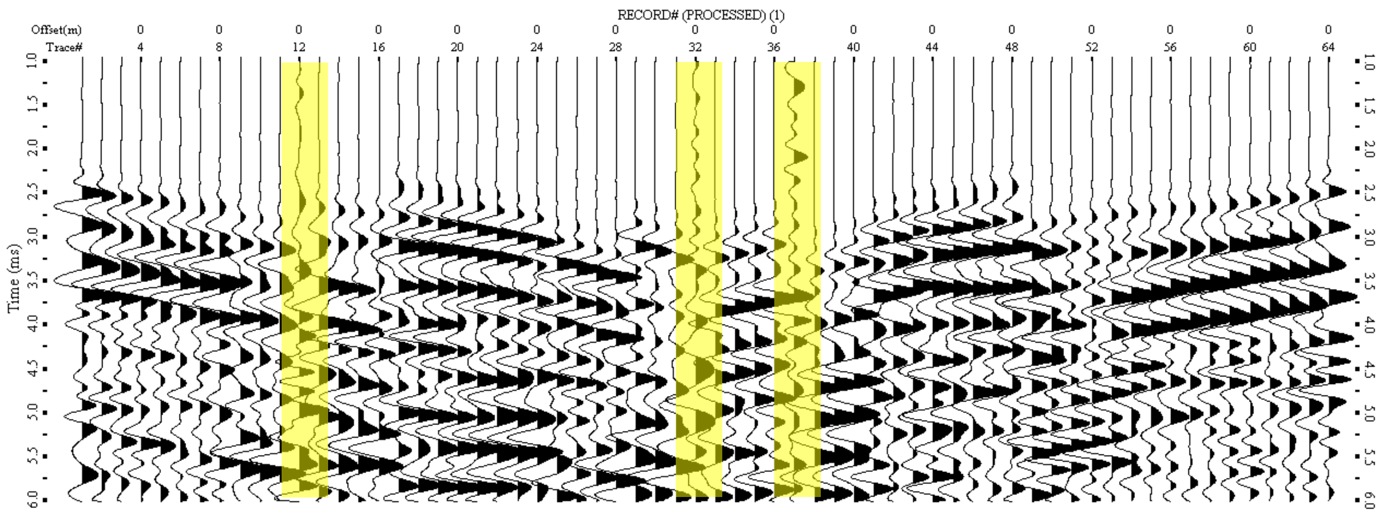
5%

NOISY CHANNELS (12, 32, AND 37)

RAW

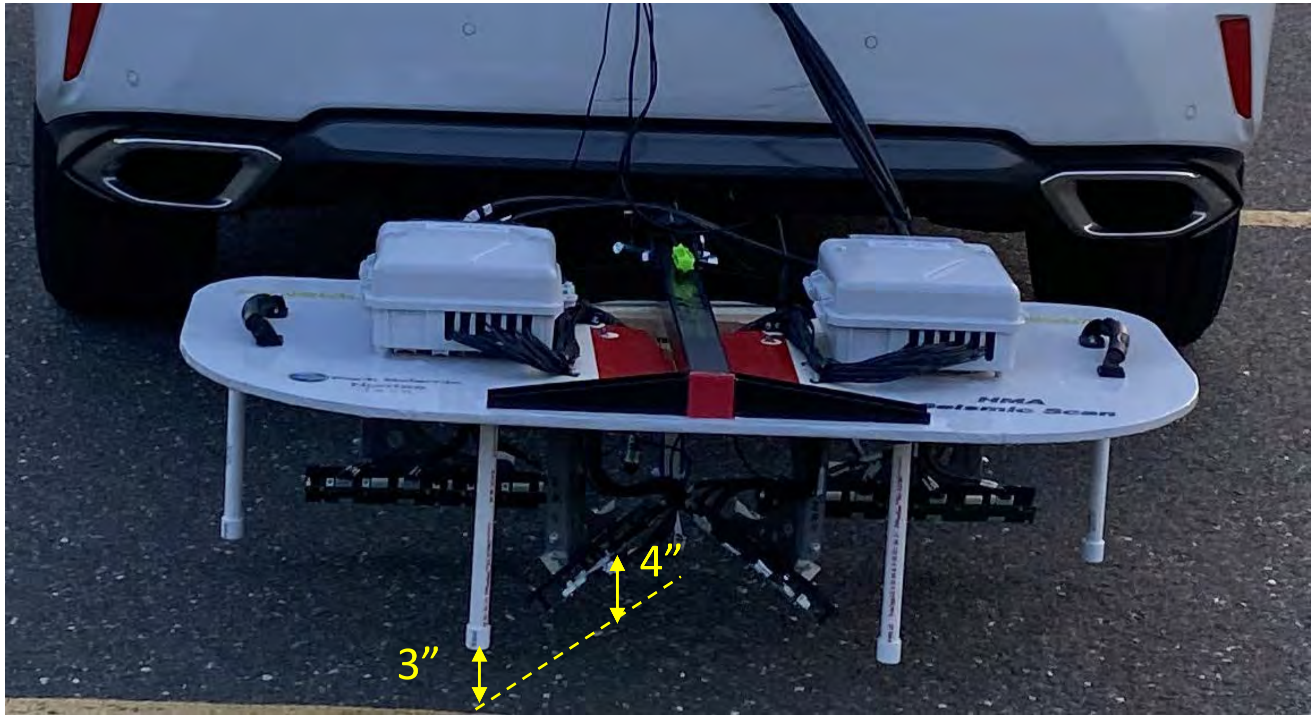


LOW-PASS
FILTERED



CAUTION!

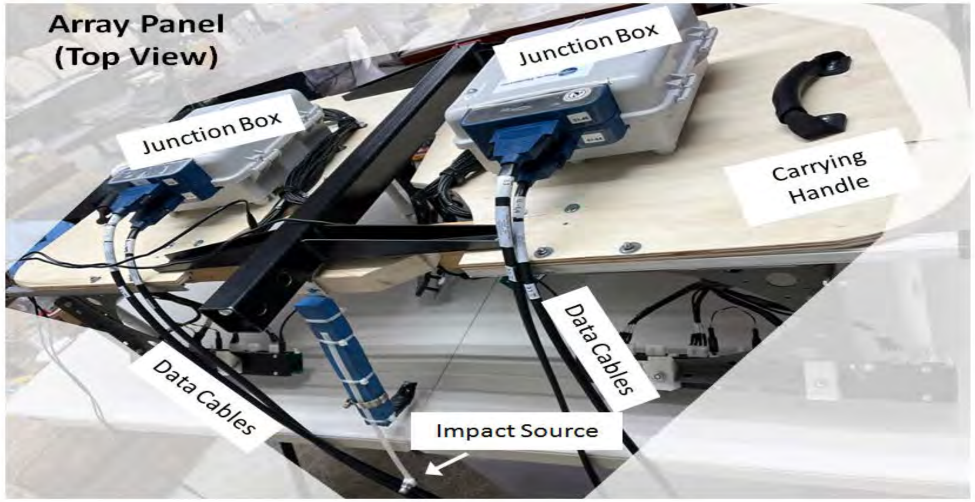
- Drive around the survey site (“flat” and no surface “objects”)
- Harness array panel with legs and slowly drive around (no “touching” sound)
- Survey at a cruising speed (~20 MPH)

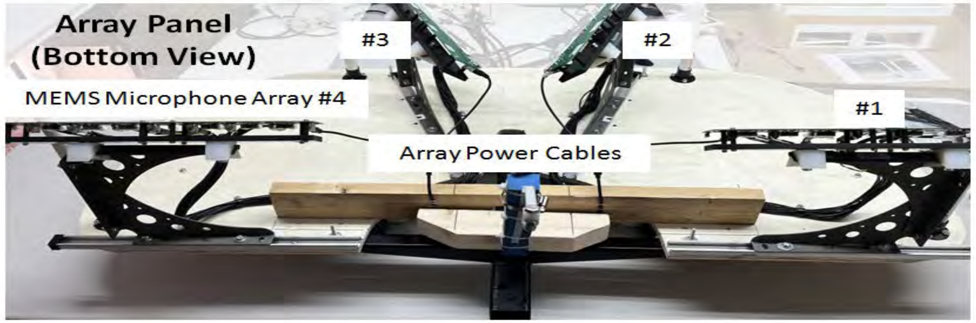


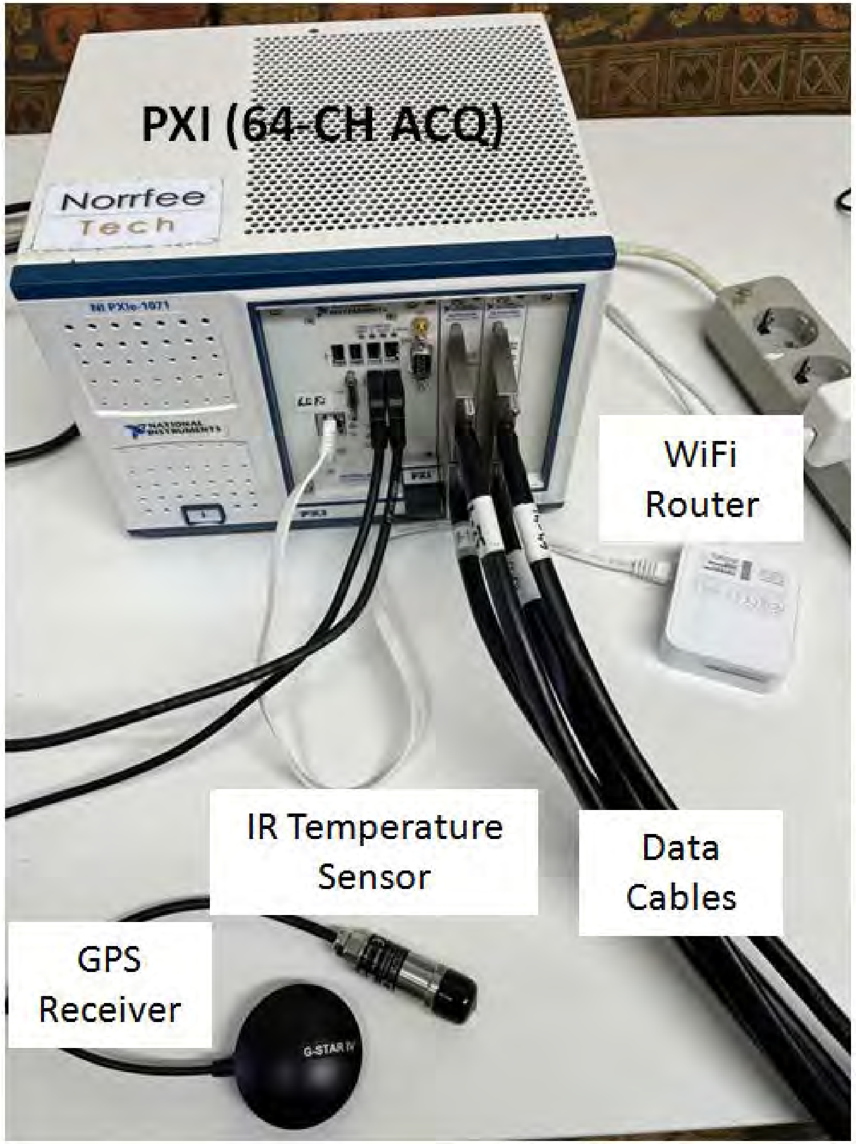
ITEM PHOTOS

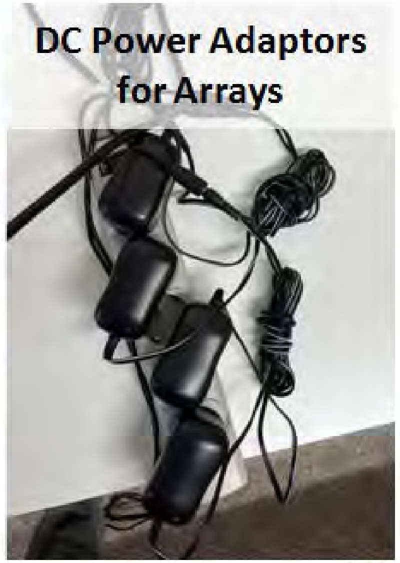

Array Panel Connected to 2" Hitch Receiver


Array Panel Connected to 2" Hitch Receiver


Array Panel
(Top View)
Junction Box
Junction Box
Carrying Handle
Data Cables
Data Cables
Impact Source


Array Panel
(Bottom View)
#3
#2
#1
MEMS Microphone Array #4
Array Power Cables


PXI (64-CH ACQ)
Norrfee
Tech
WiFi
Router
IR Temperature
Sensor
Data
Cables
GPS
Receiver

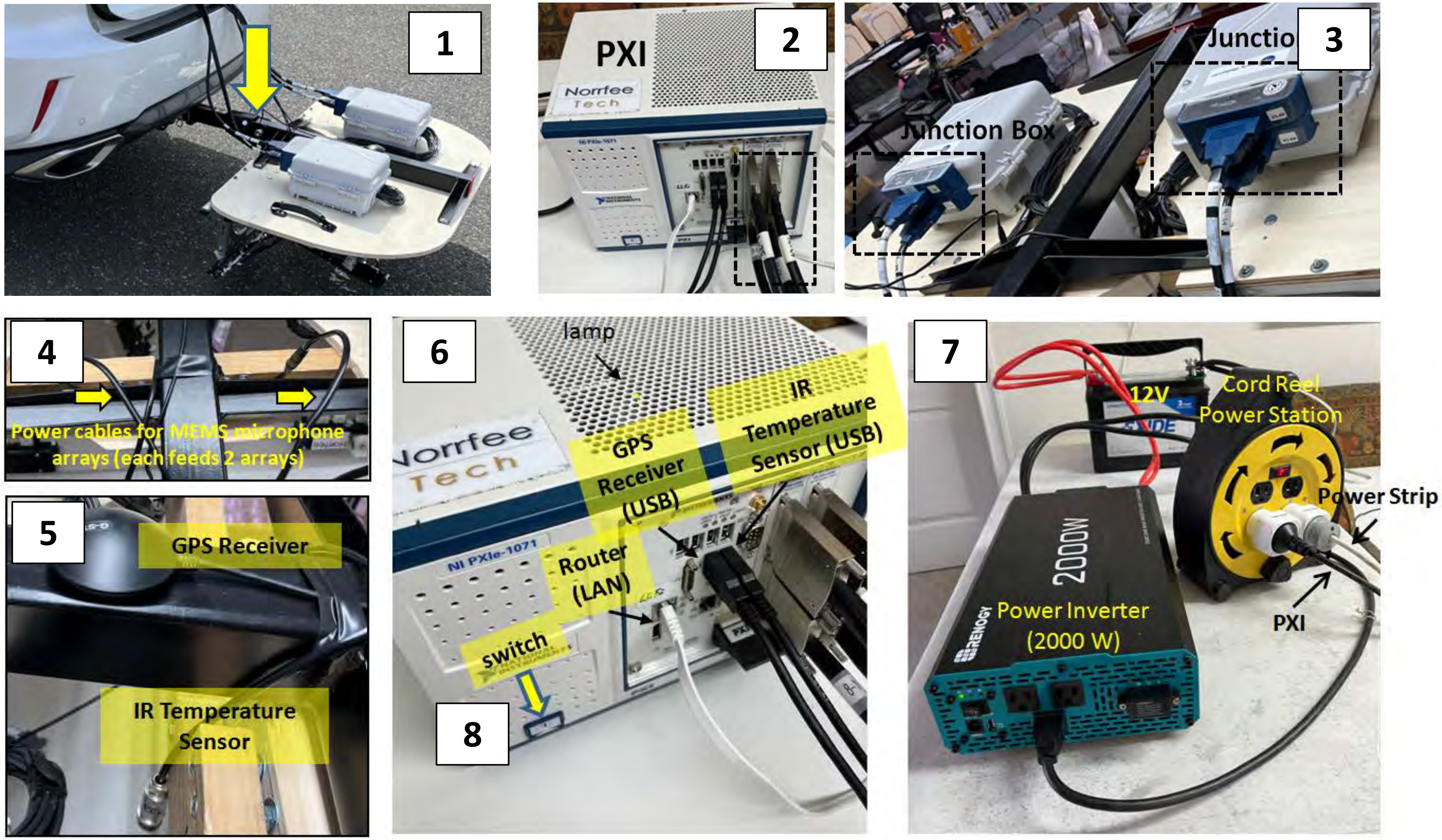

DC Power Adaptors
for Arrays


Power Inverter
2000W


Laptop

QUICK GUIDE FOR NEW SURVEY

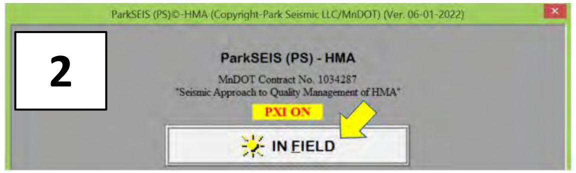
A. HARDWARE SETUP

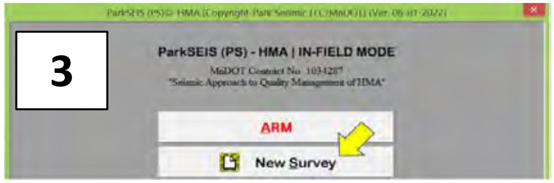


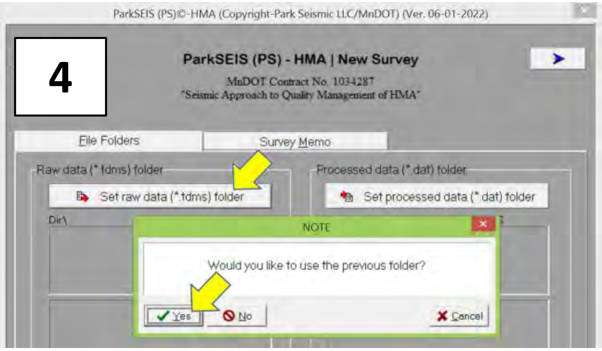
QUICK GUIDE FOR NEW SURVEY

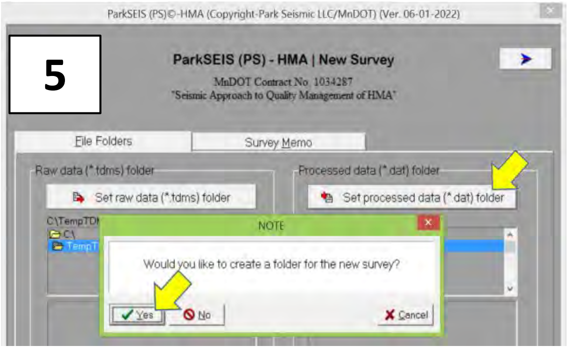
B. SOFTWARE SETUP

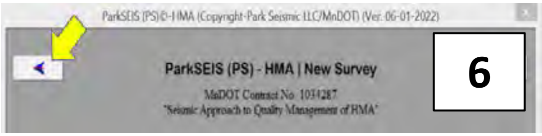
2 min



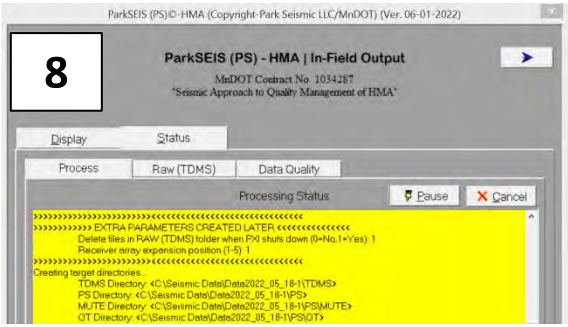


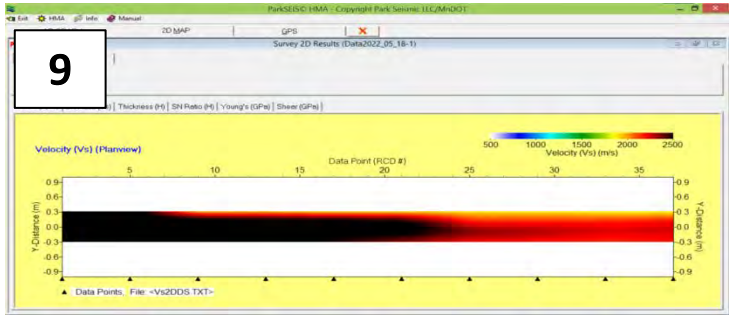


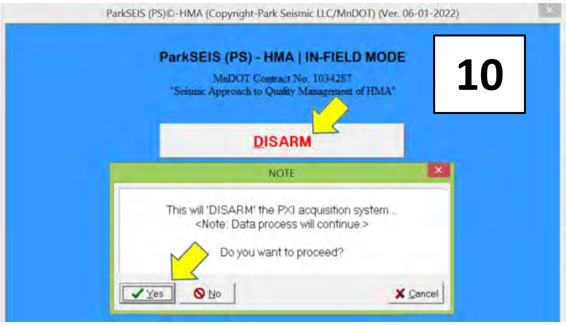




Drive ~1000'



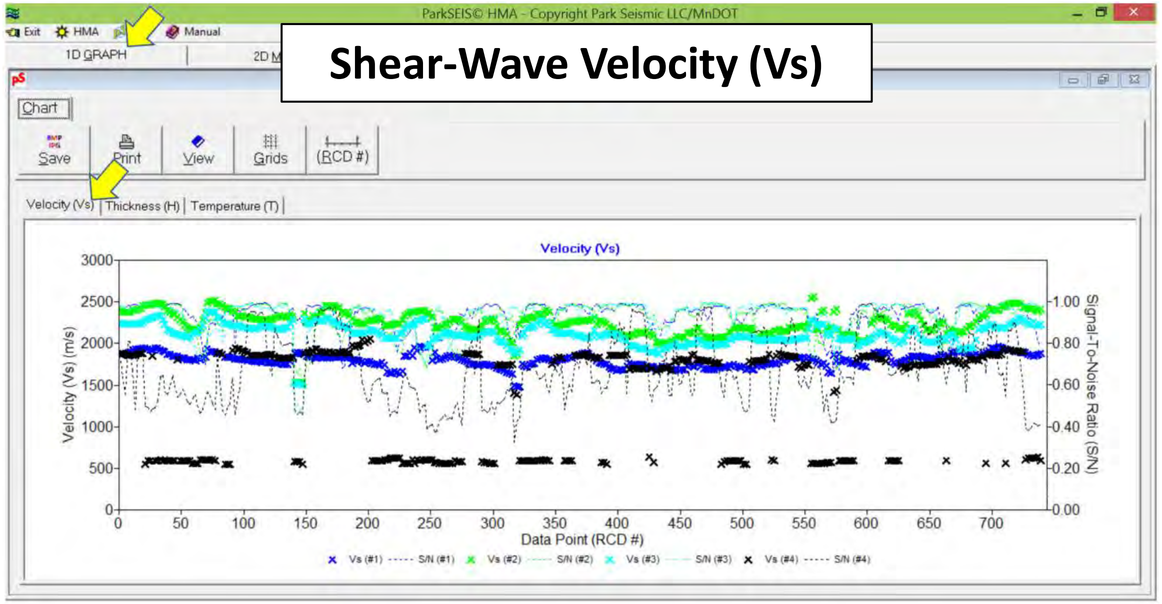


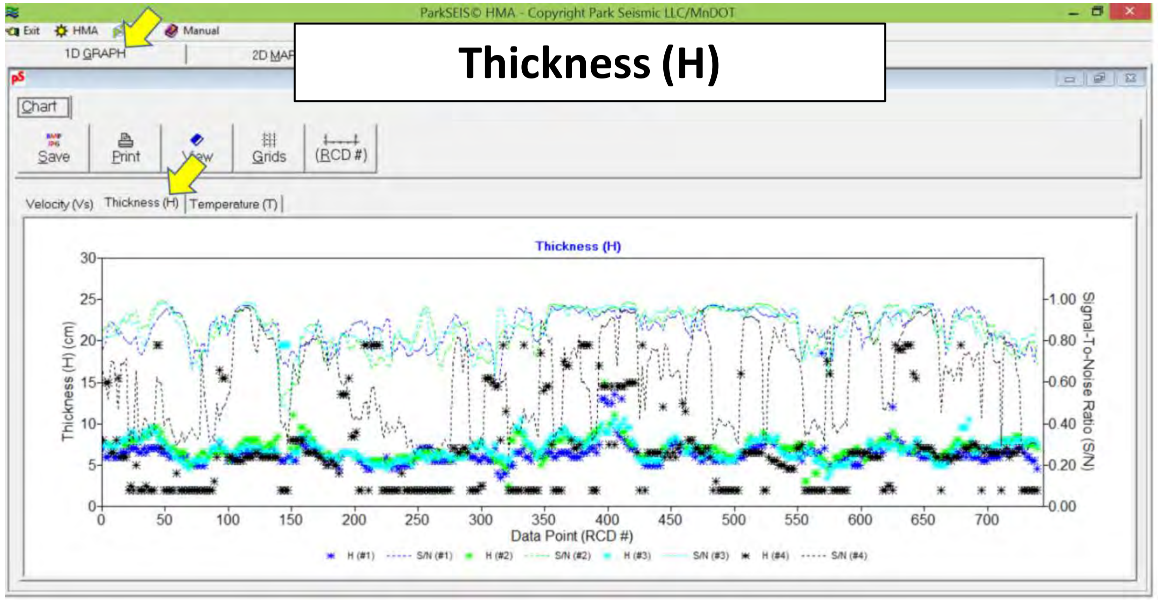


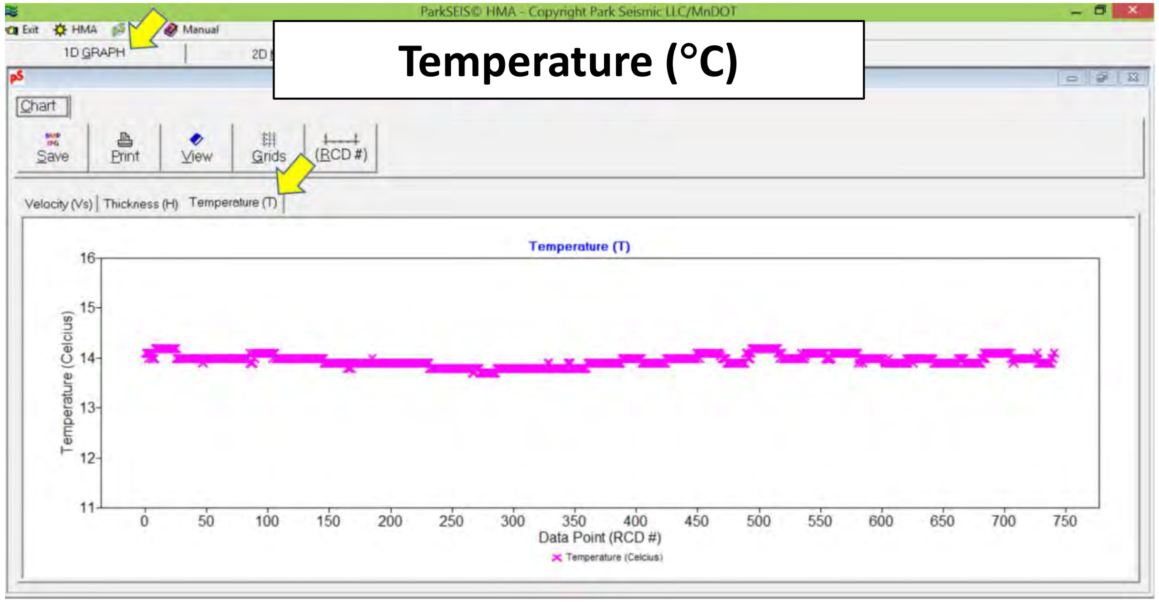
FULL OUTPUT RESULTS

Type	Availability		
	Graphical		Text (*.txt)
	1D	2D	
Shear Velocity (Vs)	√	√	√
Signal-To-Noise Ratio (S/N) (Vs)	√	√	
Thickness (H)	√	√	√
Signal-To-Noise Ratio (S/N) (H)	√	√	
Young's Modulus (GPa)		√	√
Shear Modulus (GPa)		√	√
Temperature	√		√
GPS (LAT/LON)		√	√
Log (Survey Memo, Process Memo)			√

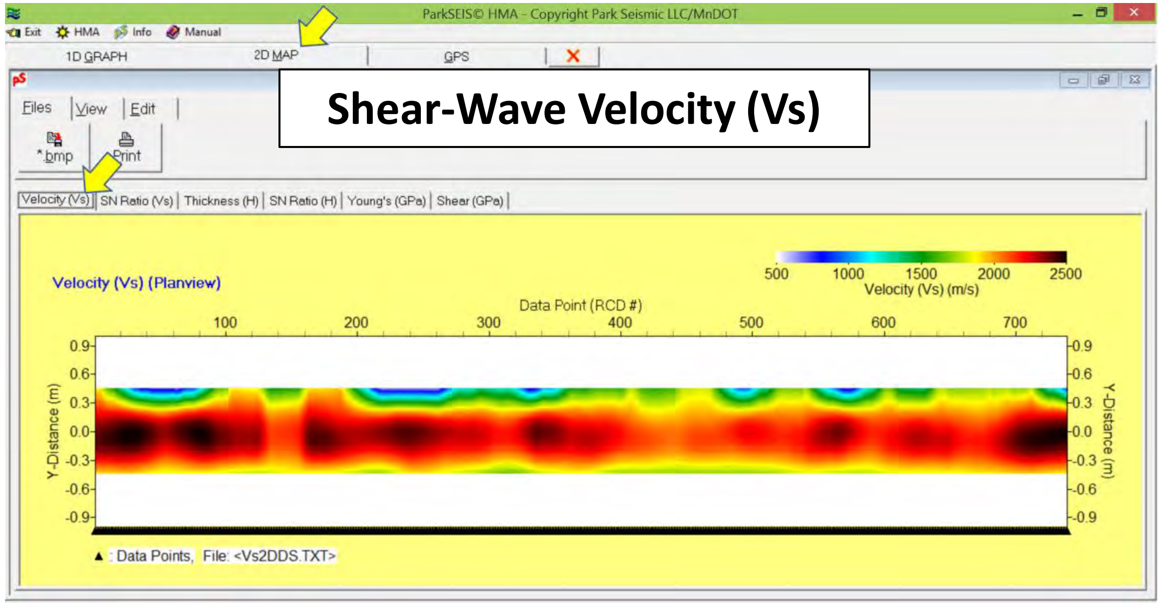
FULL OUTPUT RESULTS (1D)

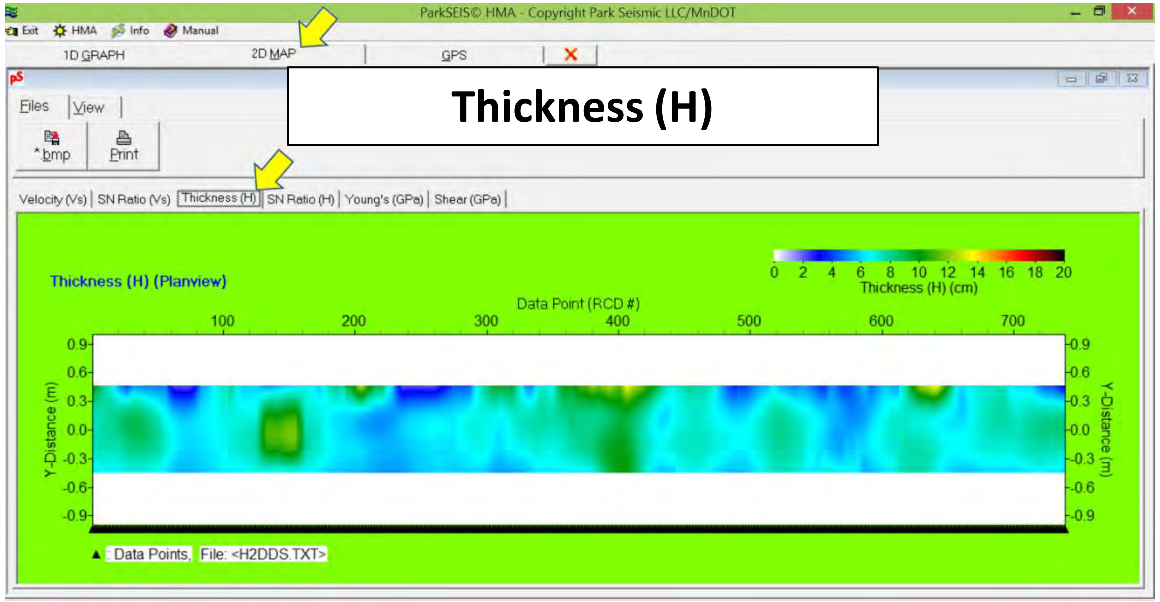


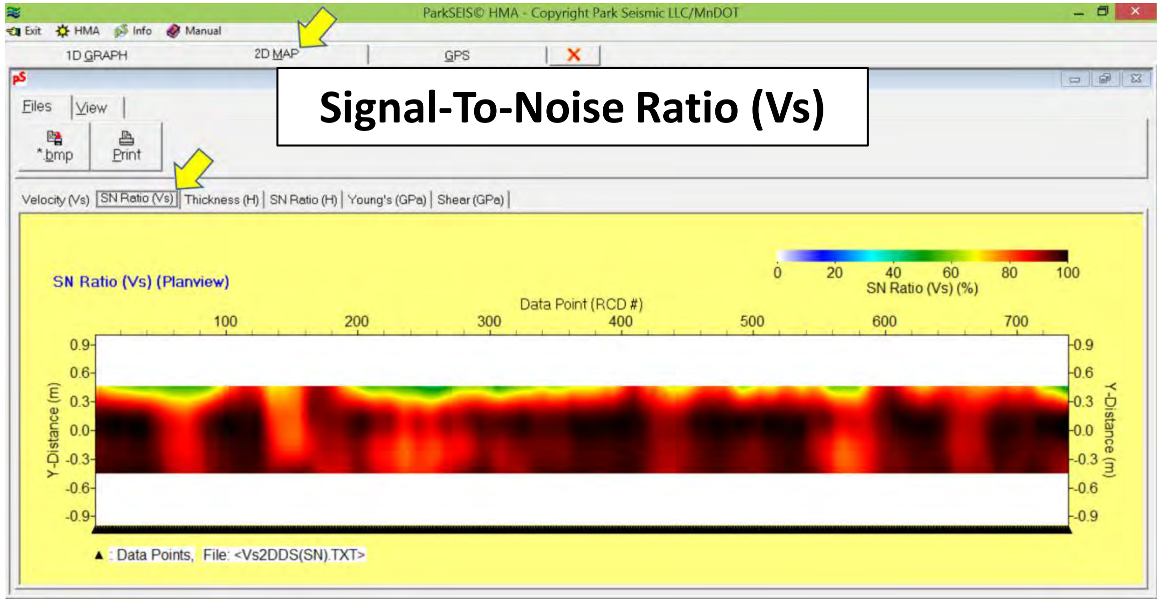


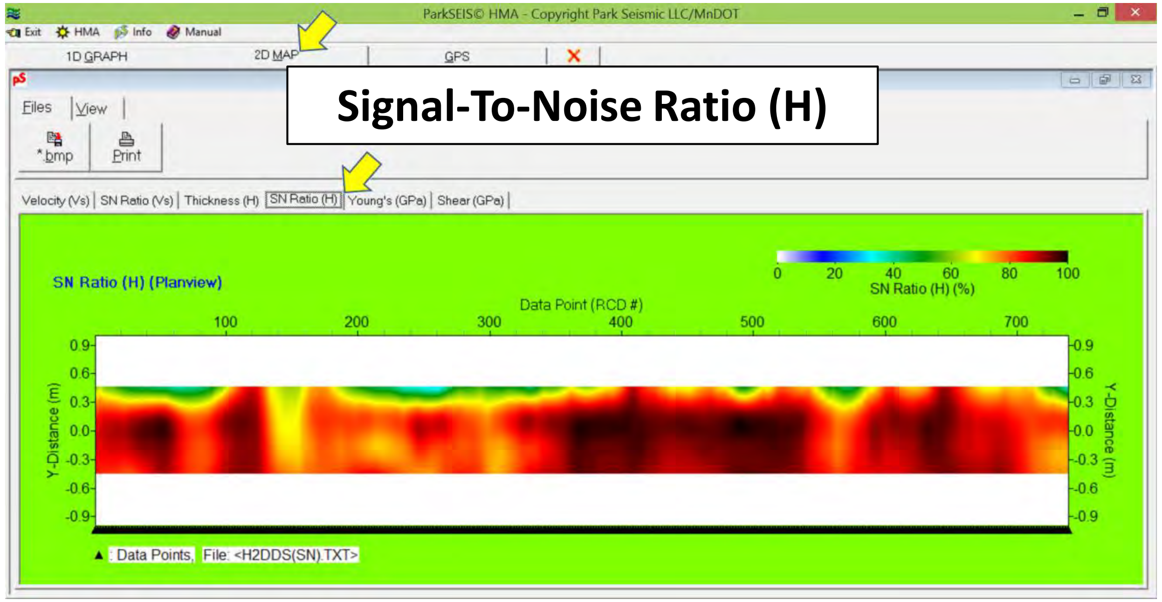


FULL OUTPUT RESULTS (2D)

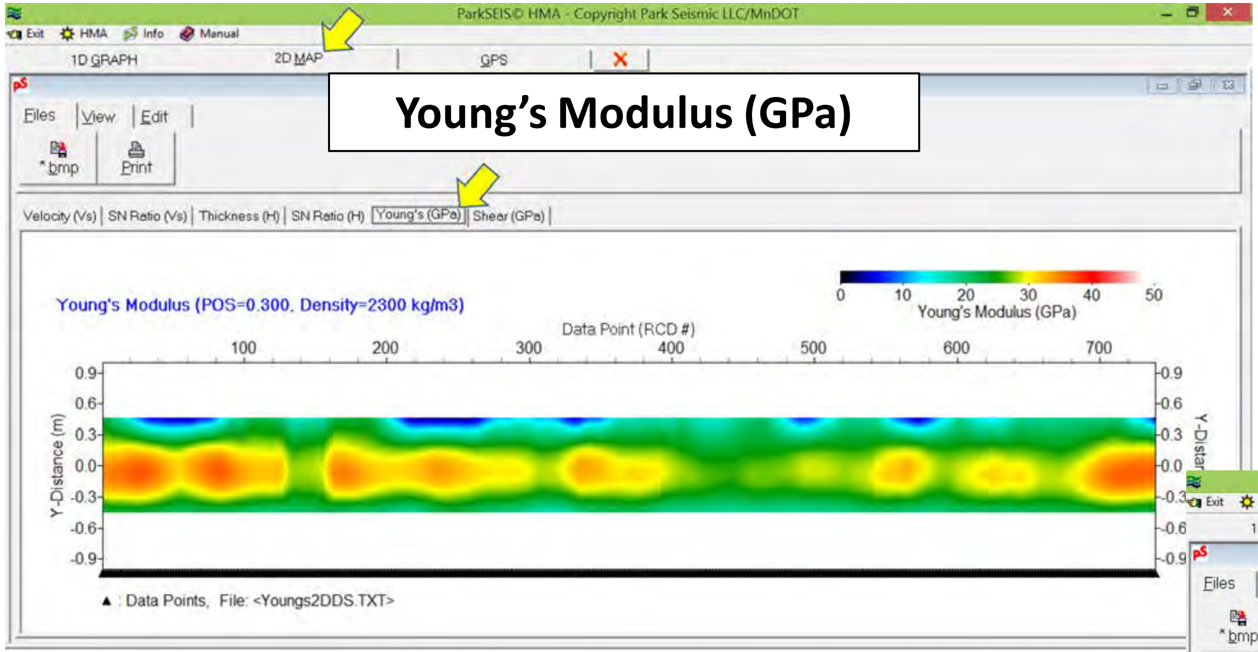


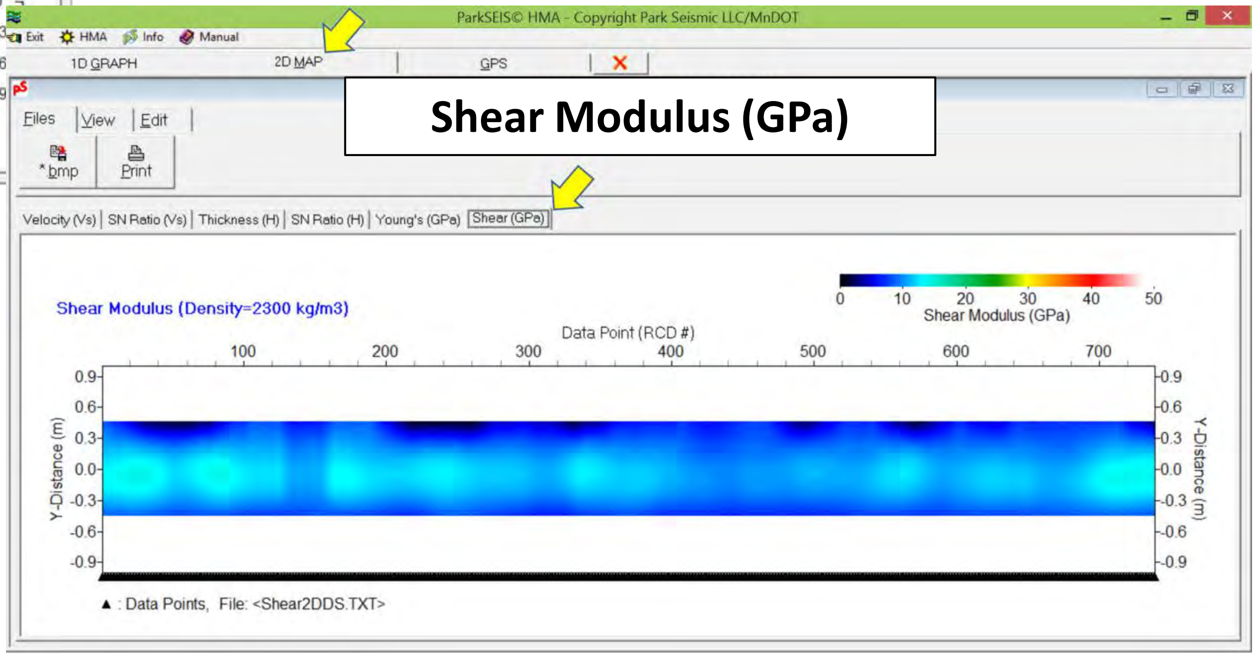




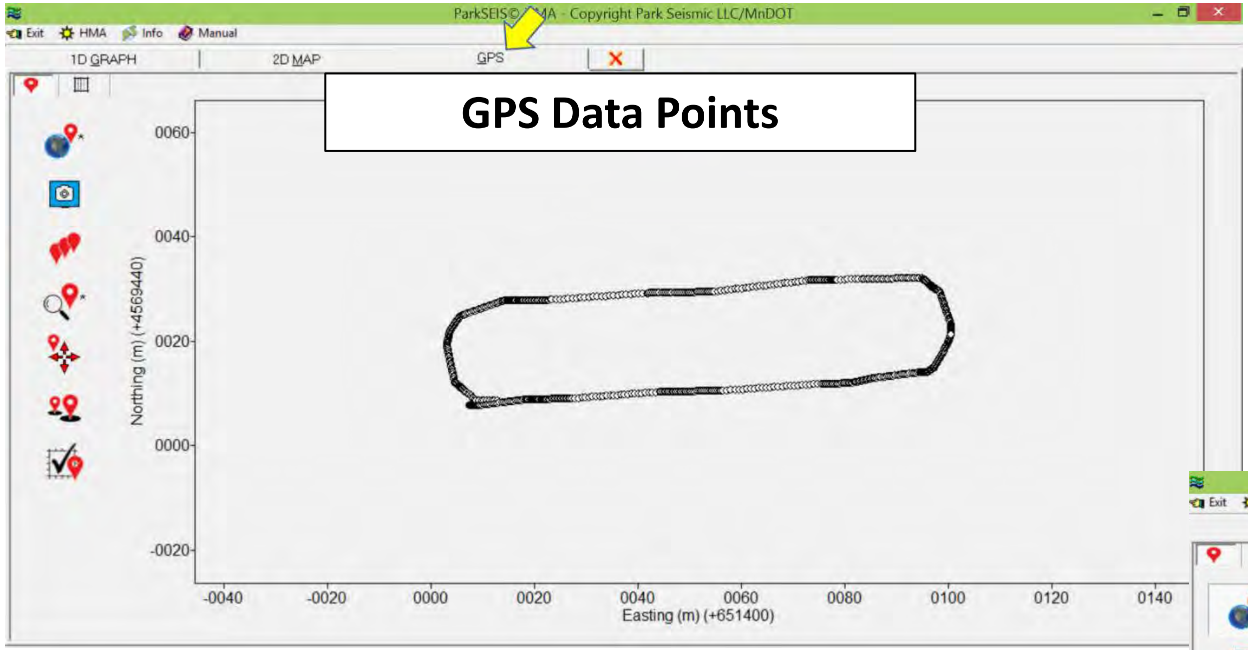


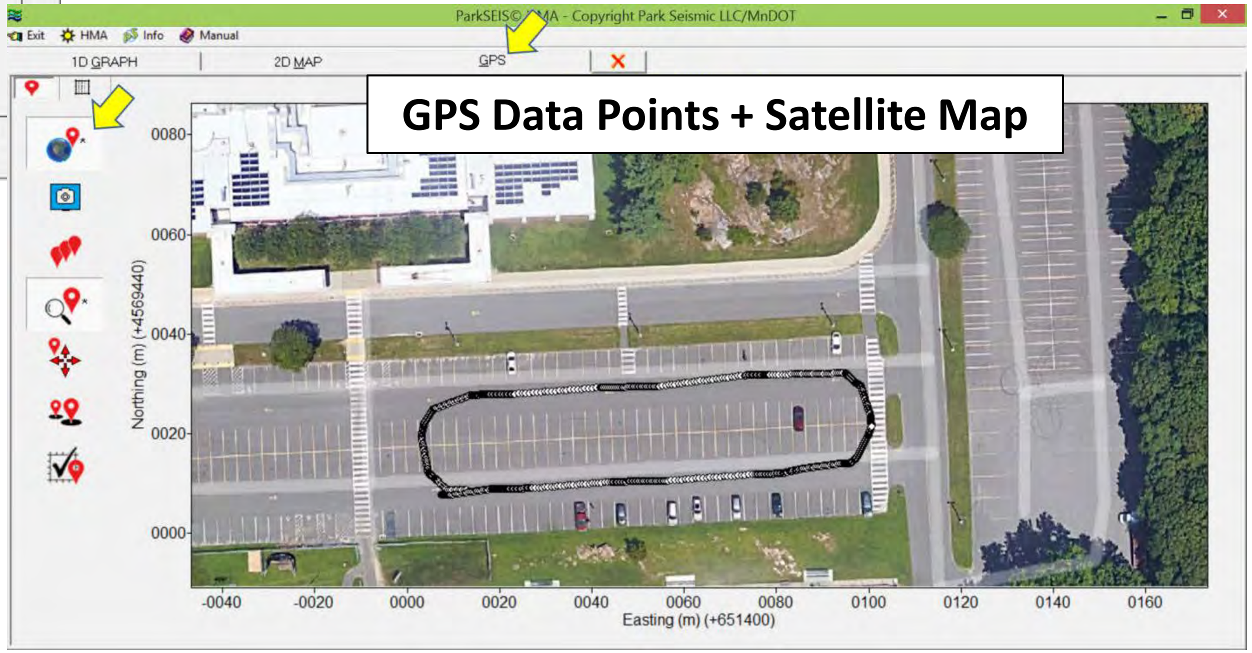
FULL OUTPUT RESULTS (2D)





FULL OUTPUT RESULTS (2D)





FULL OUTPUT RESULTS (TEXT)

Velocity (Vs) and Thickness (H)

Velocity (Vs) and Thickness (H) Data

Print Save

S-Velocity (Vs) and Thickness (H) Output Data
Project Name: Data2022_05_12
RCD: Record number, X (m): Distance from 1st data point (=0.0 m), TdegC: Temperature in Celcius
Vs: Velocity from each array in m/s (e.g., Vs1=Vs from array #1), VsAve: Average of all (4) Vs values
H: Thickness from each array in cm (e.g., H1=H from array #1), HAve: Average of all (4) H values

RCD	LAT	LON		X(m)	TdegC	Vs1	Vs2		Vs3	Vs
1	41.2622639973958	-73.1924886067708	0.00	14.5	2621.8	2632.8	2632.8	2621.8	2627.3	8.5
3	41.2622644147302	-73.1924877721020	0.08	14.5	2610.8	2610.8	2610.8	2621.8	2613.6	8.5
5	41.2622648320646	-73.1924869374332	0.17	14.5	2632.8	2632.8	2632.8	2643.9	2635.6	8.5
7	41.2622652493990	-73.1924861027644	0.25	14.5	2621.8	2632.8	2632.8	2632.8	2630.1	8.5
9	41.2622656667334	-73.1924852680956	0.34	14.5	2621.8	2621.8	2621.8	2621.8	2621.8	8.0
11	41.2622660840678	-73.1924844334268	0.42	14.3	2610.8	2610.8	2610.8	2610.8	2610.8	5.
13	41.2622665014022	-73.1924835987580	0.50	14.3	2610.8	2610.8	2610.8	2621.8	2613.6	6.
15	41.2622669187366	-73.1924827640892	0.59	14.4	2599.8	2610.8	2610.8	2621.8	2610.8	6.
17	41.2622673360710	-73.1924819294204	0.67	14.4	2577.8	2588.8	2588.8	2599.8	2588.8	5.
19	41.2622677534054	-73.1924810947516	0.76	14.4	2566.7	2577.8	2577.8	2588.8	2577.8	5.
21	41.2622681707399	-73.1924802600828	0.84	14.4	2544.7	2544.7	2544.7	2555.7	2547.5	5.
23	41.2622685880742	-73.1924794254140	0.92	14.4	2511.7	2522.7	2522.7	2533.7	2522.7	5.
25	41.2622690054087	-73.1924785907452	1.01	14.4	2489.6	2489.6	2489.6	2500.6	2492.4	5.
27	41.2622694227431	-73.1924777560764	1.09	14.4	2412.5	2423.5	2423.5	2445.6	2426.3	5.
29	41.2622698400775	-73.1924769214076	1.17	14.5	2379.5	2379.5	2379.5	2412.5	2387.7	5.
31	41.2622702574119	-73.1924760867388	1.26	14.5	2335.4	2335.4	2335.4	2379.5	2346.4	5.

Young's and Shear Moduli

Young's and Shear Moduli Data

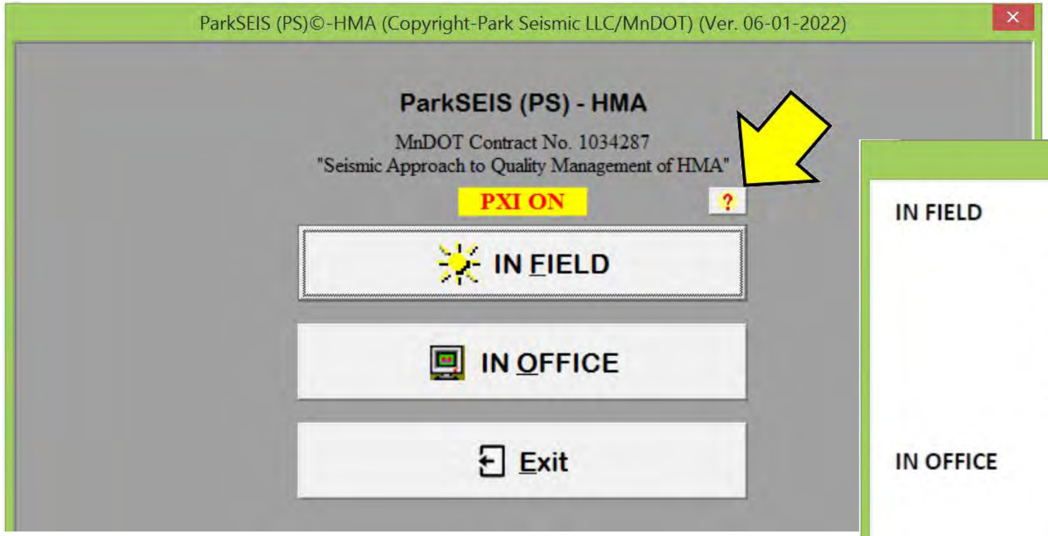
Print Save

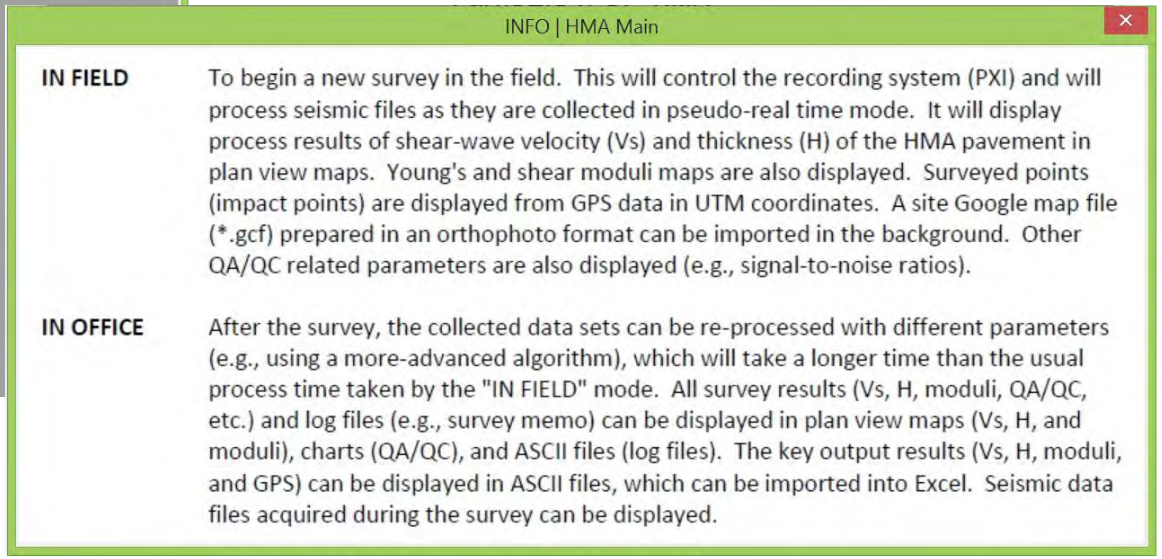
Young's (E) and Shear (U) Modulus Output Data
Project Name: Data2022_05_12
RCD: Record number, X (m): Distance from 1st data point (=0.0 m), TdegC: Temperature in Celcius
E: Young's modulus from each array in GPa (e.g., E1=E from array #1), EAve: Average of all (4) E values
U: Shear modulus from each array in GPa (e.g., U1=U from array #1), UAve: Average of all (4) U values

RCD	LAT	LON		X(m)	TdegC	E1		E2	E3	E4
1	41.2622639973958	-73.1924886067708	0.00	14.5	41.1	41.5	41.5	41.1	41.3	15.8	15
3	41.2622644147302	-73.1924877721020	0.08	14.5	40.8	40.8	40.8	41.1	40.8	15.7	15
5	41.2622648320646	-73.1924869374332	0.17	14.5	41.5	41.5	41.5	41.8	41.5	15.9	15
7	41.2622652493990	-73.1924861027644	0.25	14.5	41.1	41.5	41.5	41.5	41.4	15.8	15
9	41.2622656667334	-73.1924852680956	0.34	14.5	41.1	41.1	41.1	41.1	41.1	15.8	15
11	41.2622660840678	-73.1924844334268	0.42	14.3	40.8	40.8	40.8	40.8	40.8	15.7	1
13	41.2622665014022	-73.1924835987580	0.50	14.3	40.8	40.8	40.8	41.1	40.8	15.7	1
15	41.2622669187366	-73.1924827640892	0.59	14.4	40.4	40.8	40.8	41.1	40.8	15.5	1
17	41.2622673360710	-73.1924819294204	0.67	14.4	39.7	40.1	40.1	40.4	40.1	15.3	1
19	41.2622677534054	-73.1924810947516	0.76	14.4	39.4	39.7	39.7	40.1	39.7	15.2	1
21	41.2622681707399	-73.1924802600828	0.84	14.4	38.7	38.7	38.7	39.1	38.8	14.9	1
23	41.2622685880742	-73.1924794254140	0.92	14.4	37.7	38.1	38.1	38.4	38.1	14.5	1
25	41.2622690054087	-73.1924785907452	1.01	14.4	37.1	37.1	37.1	37.4	37.1	14.3	1
27	41.2622694227431	-73.1924777560764	1.09	14.4	34.8	35.1	35.1	35.8	35.2	13.4	1
29	41.2622698400775	-73.1924769214076	1.18	14.5	33.9	33.9	33.9	34.8	34.1	13.0	1
31	41.2622702574119	-73.1924760867388	1.26	14.5	32.6	32.6	32.6	33.9	32.9	12.5	1

ParkSEIS-HMA (PS-HMA) SOFTWARE

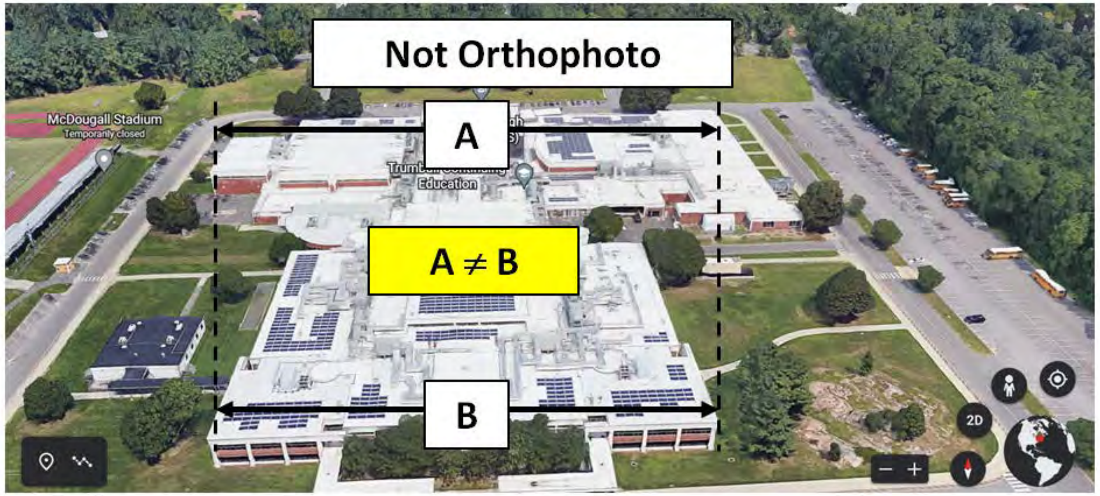
- User's Manual
- Quick Guide for New Survey
- Spot Info

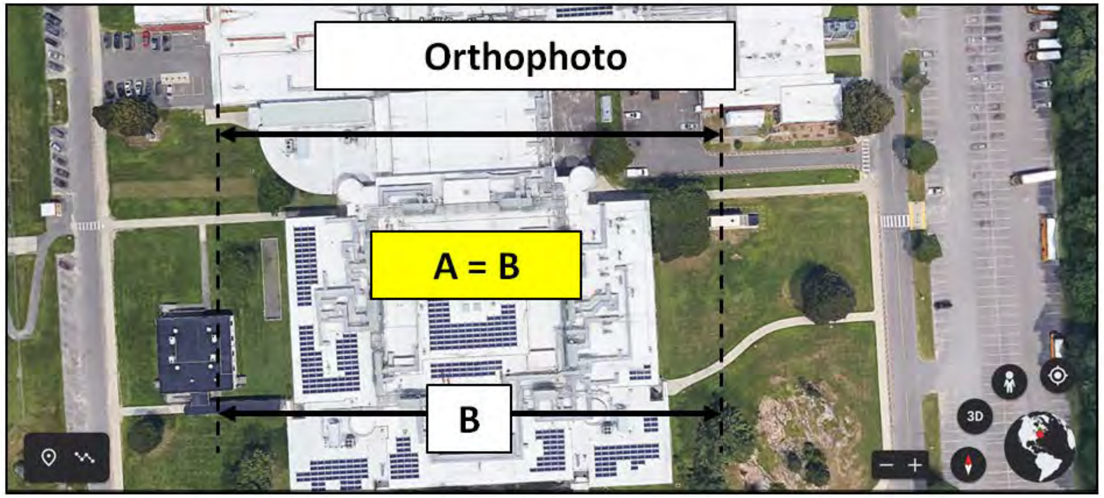




USING GPS DISPLAY

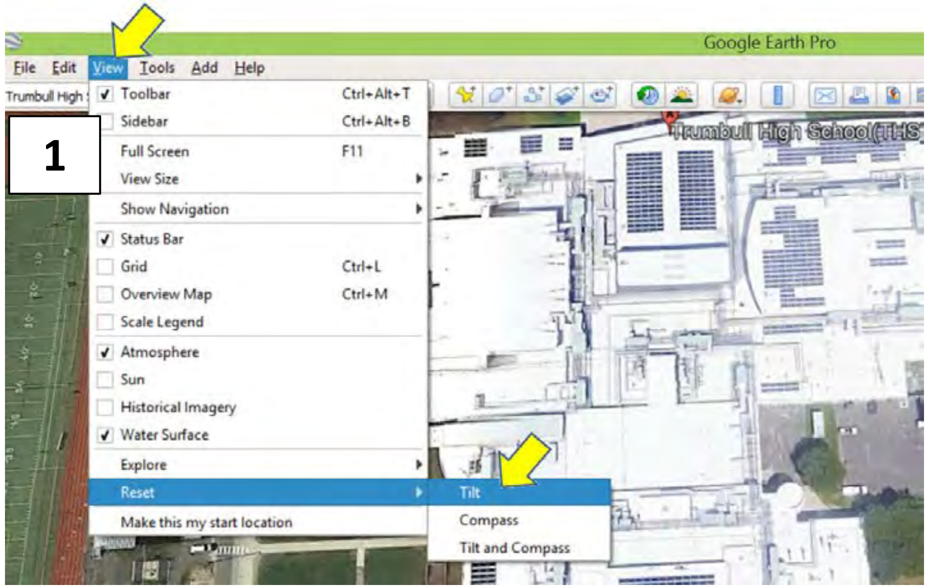
Preparing Orthophoto

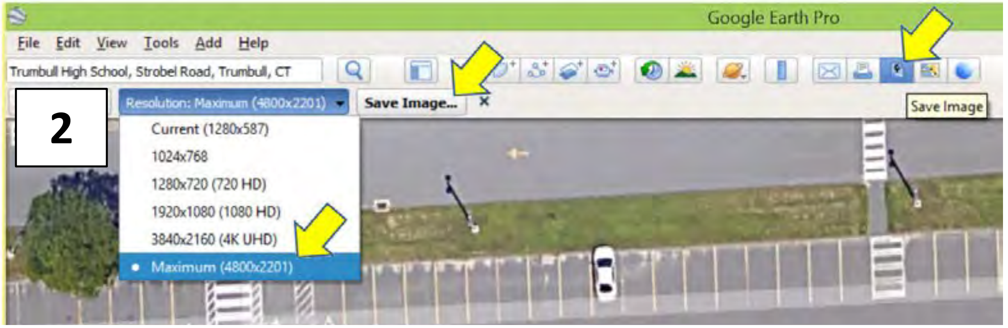


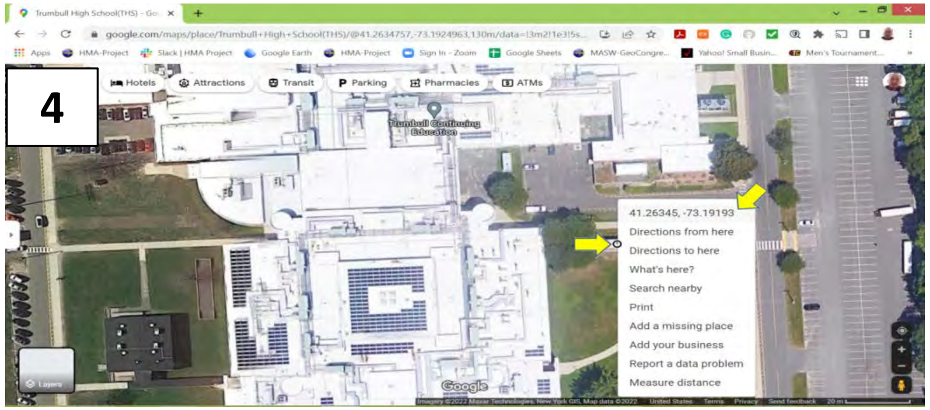


USING GPS DISPLAY

Preparing Orthophoto with LAT/LON (*.GCF) by Using "Google Earth Pro"

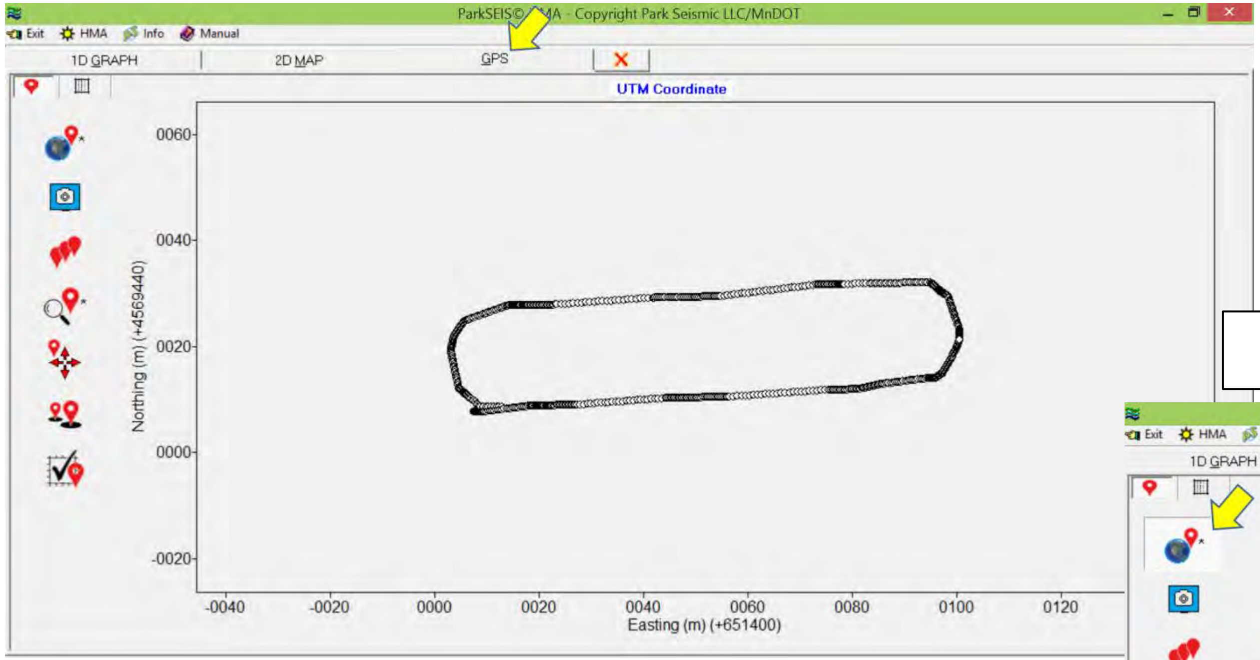




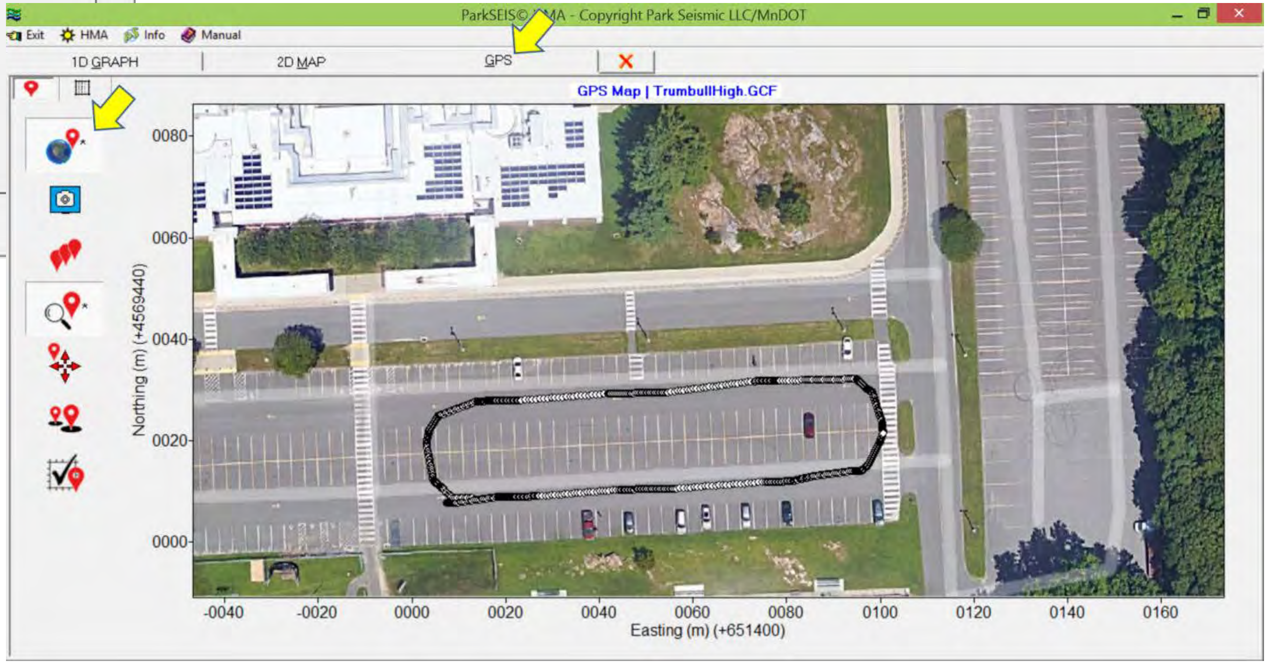


USING GPS DISPLAY

GPS Display (No *.GCF)

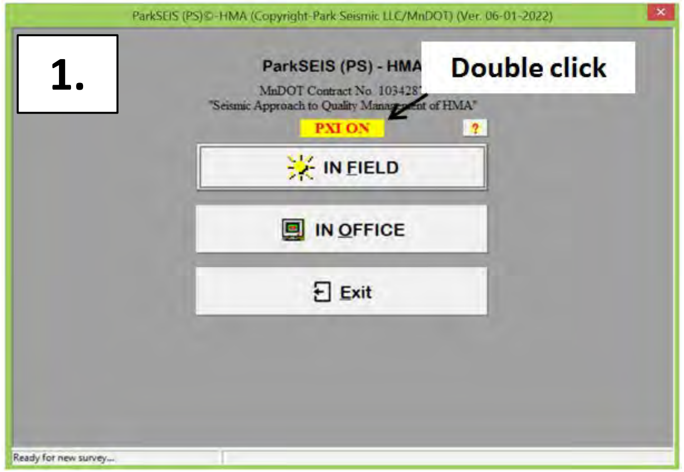


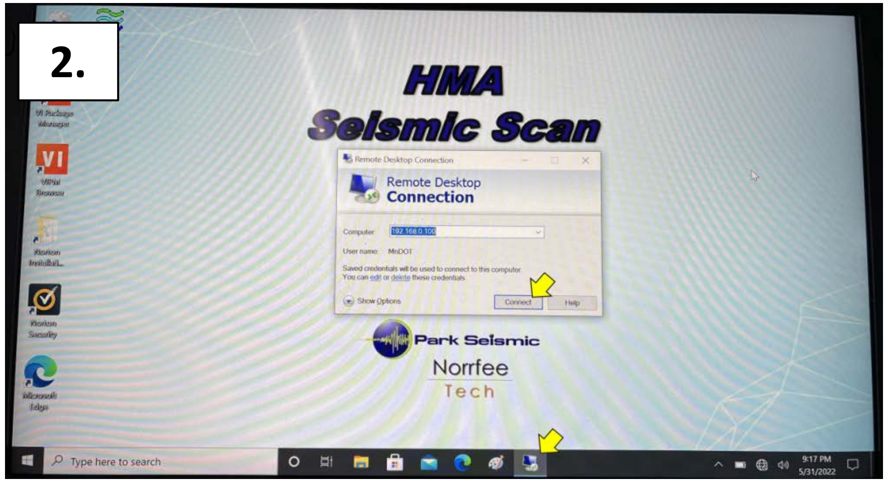
GPS Display With Graphic Combined File (*.GCF)

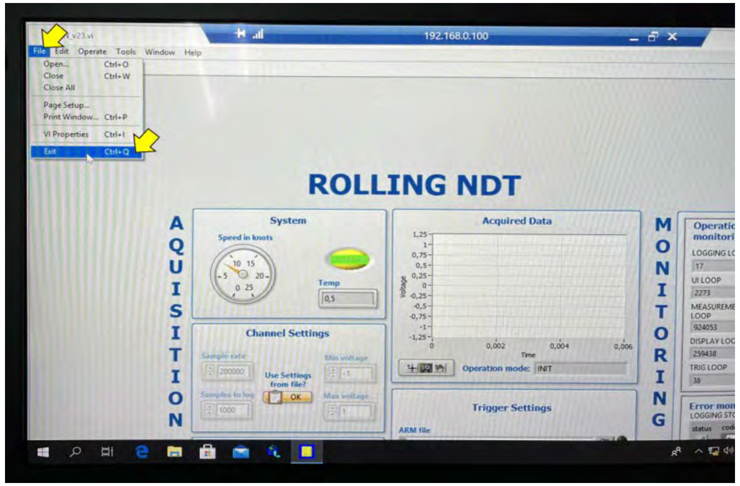


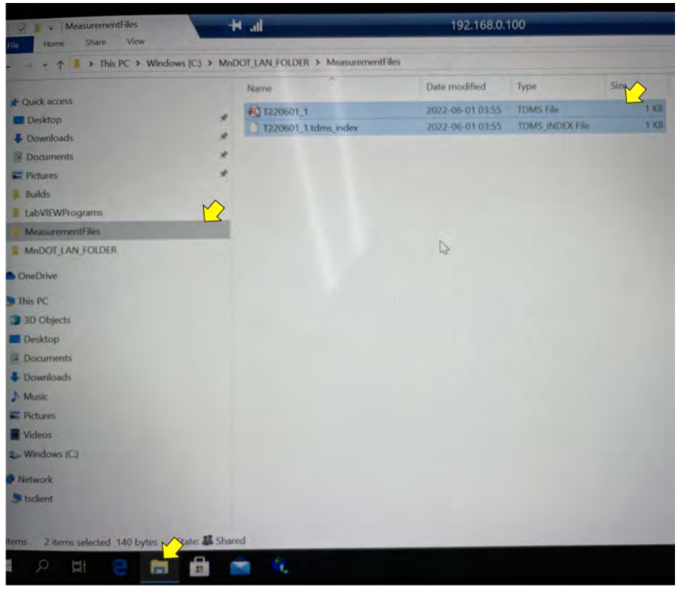
TROUBLESHOOTING

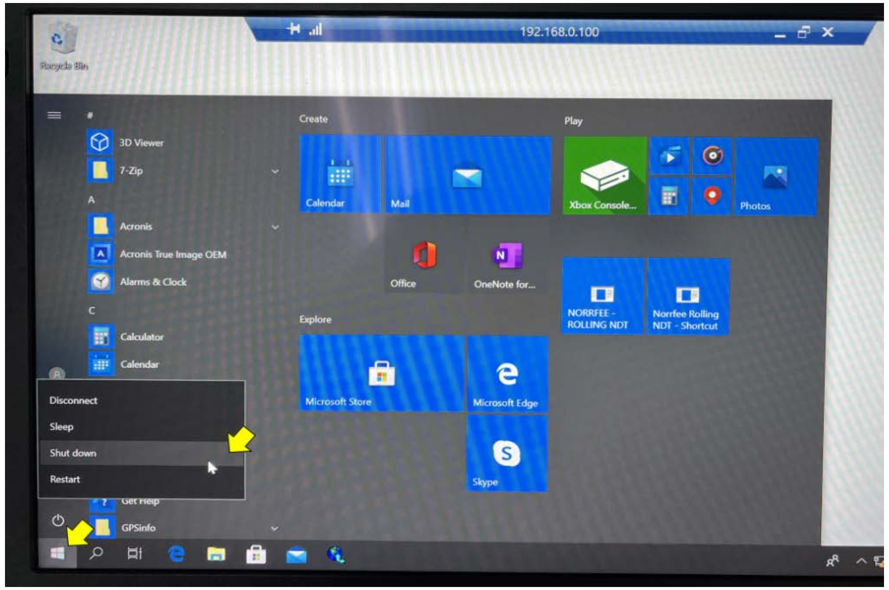
Shutting down PXI (1. or 2.)





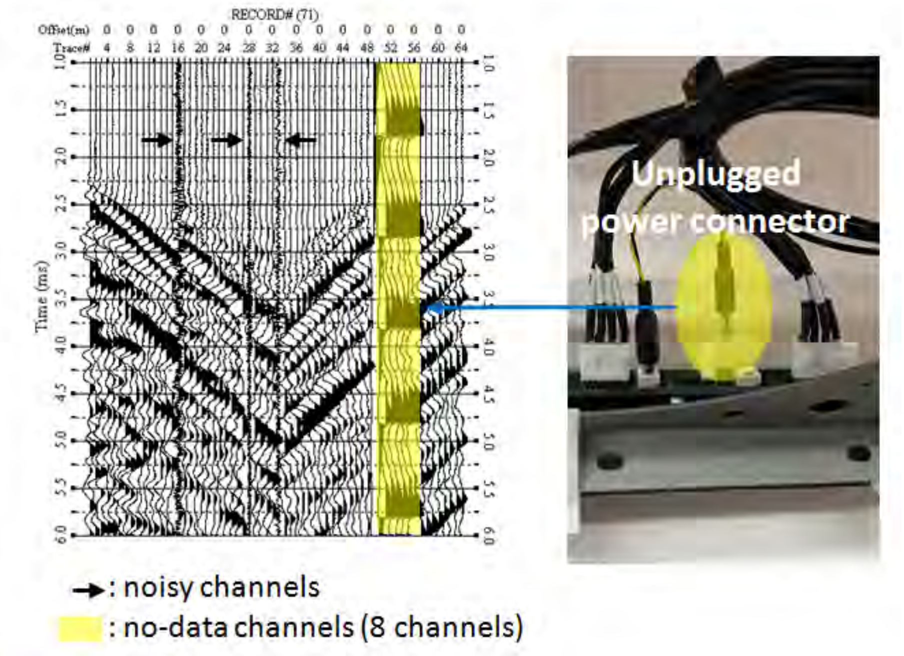






TROUBLESHOOTING

- PXI shutdown accidentally
- No triggering
- Noisy or no-data channels
- ParkSEIS-HMA (PS-HMA) closed abnormally



KNOWN ISSUES

- HARDWARE
  - Nosy channels (12, 32, 37)
- SOFTWARE
  - GPS point click for measurement info – incorrect

MODIFICATION / IMPROVEMENT

- 4-wheel-cart array station
  - Leveling
  - Stationary Measurements
- Inversion analysis for lower layers
  - More accurate Vs and H evaluation
  - Vs and H for base layer
- Attenuation analysis
  - Micro-crack detection

DEMO SURVEY PLAN

- Thursday, June 16th
  - TH36 & MnROAD – Morning (?)
  - Post-ACQ Meeting (Discussions and Q&A) – Afternoon (?)

INDOOR DEMONSTRATION

- IN-FIELD SURVEY MODE
  - Hardware Setup
  - Software Setup
  - ARM/DISARM
  - Manual Tapping
- IN-OFFICE MODE
  - DISPLAY
  - PROCESS

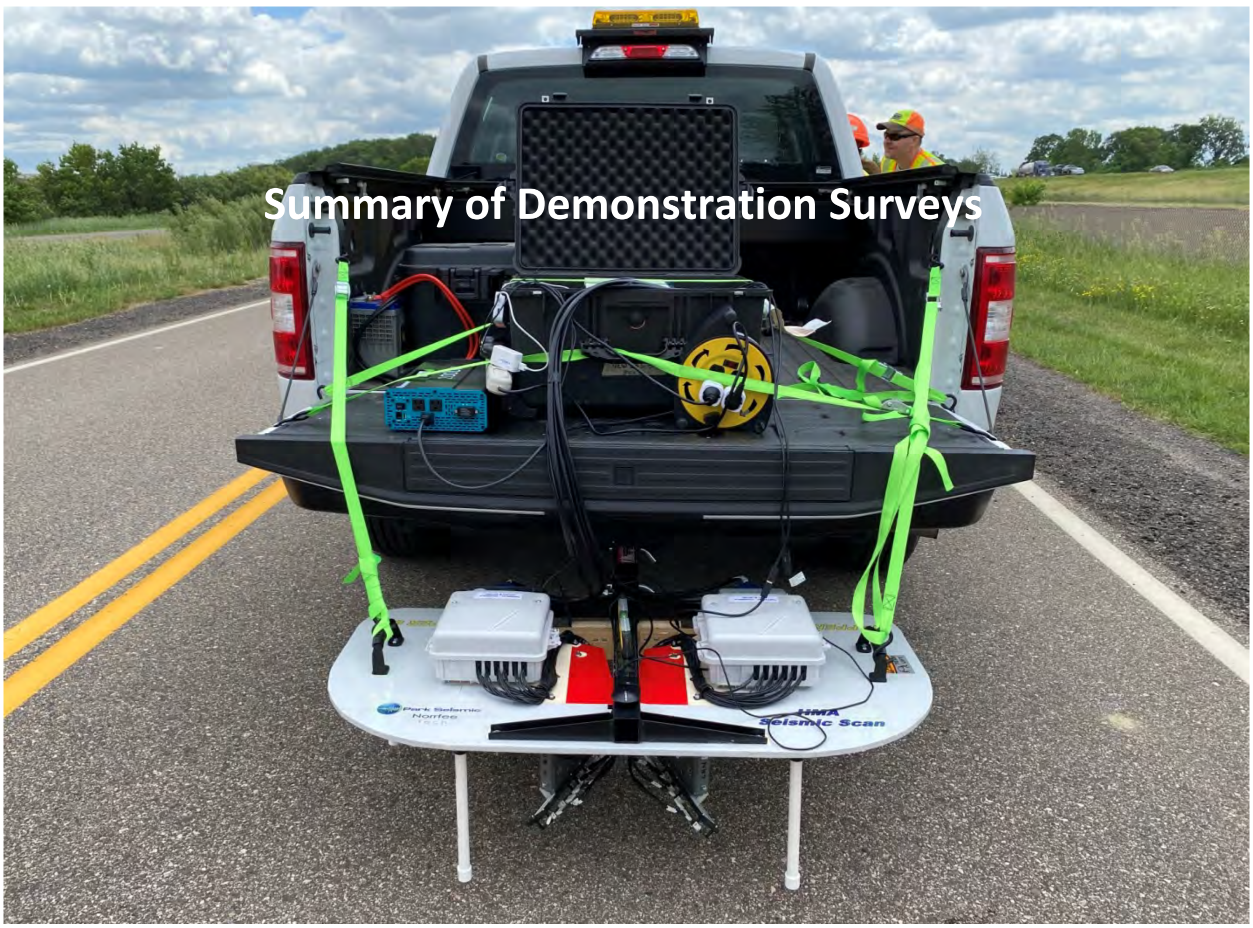
DISCUSSIONS

Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Final Report – APPENDIX II

Summary of Demonstration Surveys



Park Seismic LLC
2 Balsam Circle
Shelton, Connecticut

July 29, 2022

TAPPER 64

Pavement Seismic Scan

Seismic System Developed Under
MnDOT Contract No. 1034287
"Seismic Approach to Quality Management of HMA"
January 2020 - June 2022

TAPPER 64 Field Demonstration

MnROAD

Low Volume Road (LVR)

10 am – 12 pm

June 16, 2022

SUMMARY

- “TAPPER 64” is a seismic scan system consisting of four (4) linear 16-channel microphone arrays transversely arranged to evaluate the seismic shear-wave velocity (Vs) and thickness (H) of HMA pavement. It is developed by Park Seismic LLC (Shelton, Connecticut, USA) as prime contractor and Norrfee Tech AB (Lund, Sweden) as subcontractor. The project has been funded by National Road Research Alliances (NRRA) under MnDOT contract no. 1034287 “Seismic Approach to Quality Management of HMA” during the period of January 2020 – June 2022. The completed system has been delivered to MnDOT Materials Testing Lab (St Paul, MN) in June 2022. The field demonstration surveys were conducted on June 16, 2022, at MnROAD Low Volume Road (LVR) (Otsego, MN) by Principal Investigator (Choon Park) and administration staff (Jin Park) from Park Seismic LLC as well as personnel from MnDOT. Description of the delivered system and how to maintain and operate it were presented during a meeting on the previous day.
- This report summarizes key attributes of all three (3) demo surveys including outputs displayed in the onboard laptop computer during each survey. A video illustrating the process of demo surveys is posted on YouTube.
- The surveys were conducted on the section between cell 188 and 728 on the MnROAD LVR as indicated in a profile map presented in this report. Three surveys were conducted (surveys #1 – #3) with about 30-min intervals over 448-m (560 data points) (for survey #1), 444-m (580) (#2), and 456-m (720) (#3) distances by driving a survey pickup truck equipped with TAPPER 64 array panel on the back at about 15-Knot (17 MPH) speed. Surveys #1 and #2 were conducted on the same side of the road travelling toward SE with #2 starting about 15-m (about 20 data points) ahead of the #1 starting point and ending about 5-m pass the end of #1. Survey #3 started from the end of survey #2 on the other side of the road travelling in opposite direction toward NW and ended about 5-m pass the start of survey #2. Data points from all surveys are marked on Google satellite maps presented in this report by using the GPS coordinates recorded with the seismic data. Key survey attributes are summarized in Table 1. The velocity (Vs) and thickness (H) results from individual microphone arrays (array #1-#4) for all surveys are summarized in Tables 2-4.
- Average temperatures of the pavement surface during each survey were 23.75 °C (survey #1), 25.80 °C (survey #2), and 27.50 °C (survey #3). Temperature for each survey increased by about 2 °C after the first survey that started at 10:20 AM.

SUMMARY (Cont'd)

- Average Vs from survey #1 was 1680 (m/s), that of survey #2 was 1664 (m/s), and that of survey #3 was 1625 (m/s). Average Vs values from the two consecutive surveys (#1 and #2) match each other within less than 1% of margin. Considering the two surveys were conducted almost at the same part of the road with a 95% overlap, the results indicate a high degree of survey consistency (99%). Average Vs from the other side of the road from survey #3 (1625 m/s) is close to the previous two values. It should be noted here that Vs decreases between consecutive surveys that were about 30-min apart with about 2°C temperature increase. Therefore, the change in average Vs between surveys can be mainly due to temperature change.
- Average Young's (E) and shear (μ) moduli are calculated from the average velocities (Vs) by using a Poisson's ratio of 0.3 and density of 2300 kg/m^3. They are E=16.89 (GPa) and μ =6.49 (GPa) for survey #1, E=16.57 (GPa) and μ =6.37 (GPa) for survey #2, and E=15.81 (GPa) and μ =6.08 (GPa) for survey #3.
- At this moment, it is not possible to assess how much of these differences in Vs represent changes in the physical properties of pavements and how much represents the inherent margin of error arising from the method itself. It seems, however, reasonable to assume the temperature changes played the main role. Nonetheless, the overall differences are fairly small.
- Average thickness (H) from surveys #1 and #2 are 6.2 (cm) and 6.1 (cm), respectively. Average H from #3 is 5.9 (cm). According to the design profile last updated in 2017, the entire area of surveyed road is listed as having a 3.5" thickness (= 8.89 cm). If it represents the ground truth, then the evaluated values from the 3 surveys represent about 70% of accuracy. The reduced accuracy in H evaluation has always been anticipated from the earliest stage of project execution. The main focus has always been in the accurate evaluation of seismic velocity (Vs). The results of modeling experiments executed throughout the entire project execution period consistently indicated the overall accuracy in H evaluation can be 20-30% lower than that in the Vs evaluation.
- Average signal-to-noise ratio (S/N) values for Vs evaluation are 95%, 96%, and 92% for surveys #1, #2, and #3, respectively. Those in H evaluation are 89%, 91%, and 87%, respectively, for the 3 surveys. S/N values higher than 80%, in general, indicate the surface wavefields are strong enough to be used for the reliable analysis.

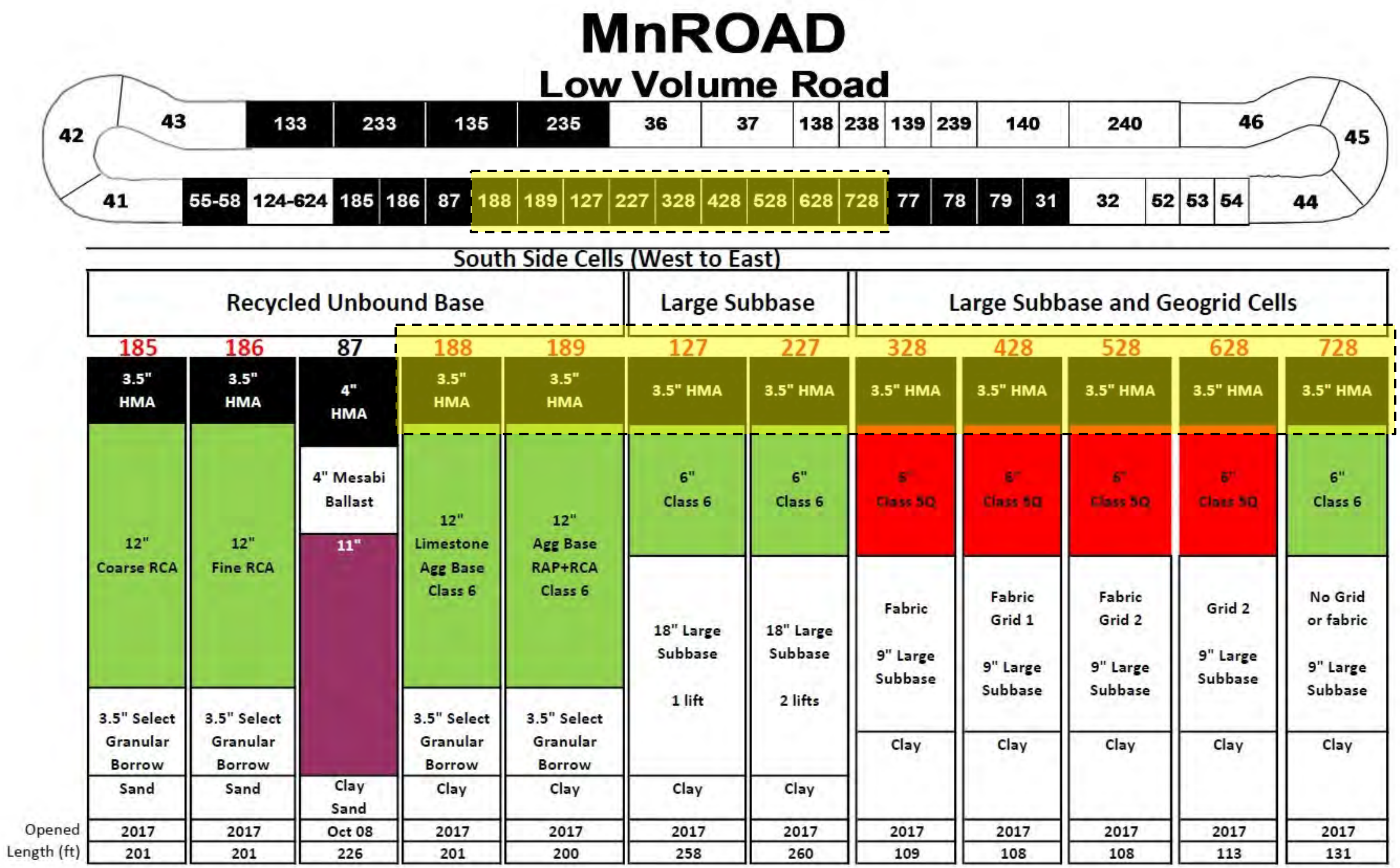
SUMMARY (cont'd)

- It is important to make each microphone array leveled with pavement surface within a few millimeters (e.g., < 5 mm) of difference between the heights of the begin (closest to the impact point) and the end (furthest from the impact point) points of the array. A small difference (e.g., +/-10 mm) can result in a significant over or under estimation of Vs (e.g., -/+ 10%). For this reason, it is always necessary to ensure leveling of the array panel, longitudinally and transversely, after its installation on the back of the survey vehicle. The most strict way would be to measure the heights manually by using a small hand-held ruler. For the demo surveys, however, a bubble leveling device was used to measure the horizontal leveling of the array panel, which was then put in place by using two straps tied down on both sides of the panel. The length adjustment of these straps could control the panel orientation longitudinally and transversely.
- A systematic variation is observed between the average Vs values from all 4 arrays (#1-#4) fro all 3 surveys (#1-#3). The Vs value increases from array #1 (Vs1) to #4 (Vs4). For example, Vs1=1617 (m/s), Vs2=1647 (m/s), Vs3=1723 (m/s), and Vs4=1731 (m/s) for survey #1. The differences between Vs1 and Vs4 were 7% for survey #1, 4% for survey #2, and 8% for survey #3. It is believed that this systematic variation in Vs was caused by the cross slope of the road, which was not compensated during the leveling process of array panel that aimed at the "horizontal" leveling.
- A similar variation is also observed between the average H values. For example, H1=5.9 (cm), H2=6.1 (cm), H3=6.3 (cm), and H4=6.4 (cm) for survey #1. The differences between H1 and H4 were 8% for survey #1, 7% for survey #2, and 5% for survey #3. It is believed that this variation in H is caused by the algorithmic link between the two methods of Vs and H evaluations.

MnROAD – Low Volume Road (LVR)

MnROAD-LVR | SURVEYED CELLS

Surveyed Cells **(188-728)** | Total Length of Cells = 1488 ft (455 m)



https://www.dot.state.mn.us/mnroad/testcells/lowvolume.html

TABLE OF SURVEY ATTRIBUTES

Table 1: Summary table of key survey attributes

Survey #	NTDMS	NRCD	$NTDMS^p$	$NRCD^p$	Begin Time*	End Time*	Complete Time**	Distance(m)[1] (ADD^2)	Note
1	28	560	28	560	10:05:33	10:16:56	10:20:28	448 (0.80)	About 9 min pause at around the center of the survey line
2	30	600	29	580	10:42:19	10:46:18	10:54:38	444 (0.77)	One TDMS (*_5.tdms) copy error
3	36	720	36	720	11:19:33	11:20:59	11:31:11	456 (0.63)	Opposite direction survey on the other side of the road

NTDMS: # of TDMS files collected [1 TDMS = 20 records (RCD's)], NRCD: # of records collected, $NTDMS^p$: # of TDMS files processed, $NRCD^p$: # of records processed, *Survey begin ("armed") and end (“disarmed”) times (AM) on June 16, 2022, **Completed time (AM) of entire process on June 16, 2022, [1]Distance between the first and last data points, [2]Average distance (m) per data point

TABLE OF SURVEY RESULTS

Table 2: Summary of results from survey #1 (Average Temperature = 23.75 °C ± 0.22 °C)

Array #	Velocity (Vs)				Modulus		Thickness (H)			
	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)	Young's (GPa)	Shear (GPa)	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)
1	1617	32	95	3	15.66	6.01	5.9	0.7	87	6
2	1647	30	95	3	16.22	6.24	6.1	0.7	89	5
3	1723	23	96	2	17.76	6.83	6.3	0.7	89	4
4	1731	26	95	3	17.92	6.89	6.4	0.7	89	5
Mean	**1680**	**28**	**95**	**3**	**16.89**	**6.49**	**6.2**	**0.7**	**89**	**5**

Table 3: Summary of results from survey #2 (Average Temperature = 25.80 °C ± 0.59 °C)

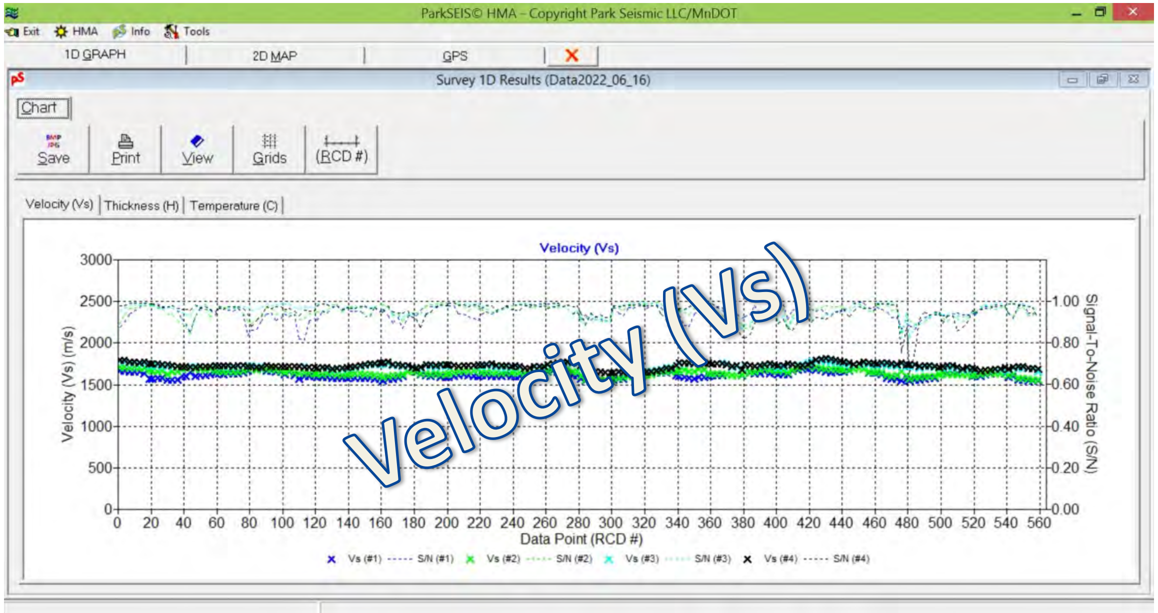
Array #	Velocity (Vs)				Modulus		Thickness (H)			
	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)	Young's (GPa)	Shear (GPa)	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)
1	1628	33	94	3	15.85	6.10	6.0	0.7	89	4
2	1668	28	96	2	16.64	6.40	6.0	0.6	92	3
3	1668	28	96	2	16.64	6.40	6.0	0.6	92	3
4	1693	27	96	2	17.14	6.59	6.4	0.8	91	3
Mean	**1664**	**29**	**96**	**2**	**16.57**	**6.37**	**6.1**	**0.7**	**91**	**3**

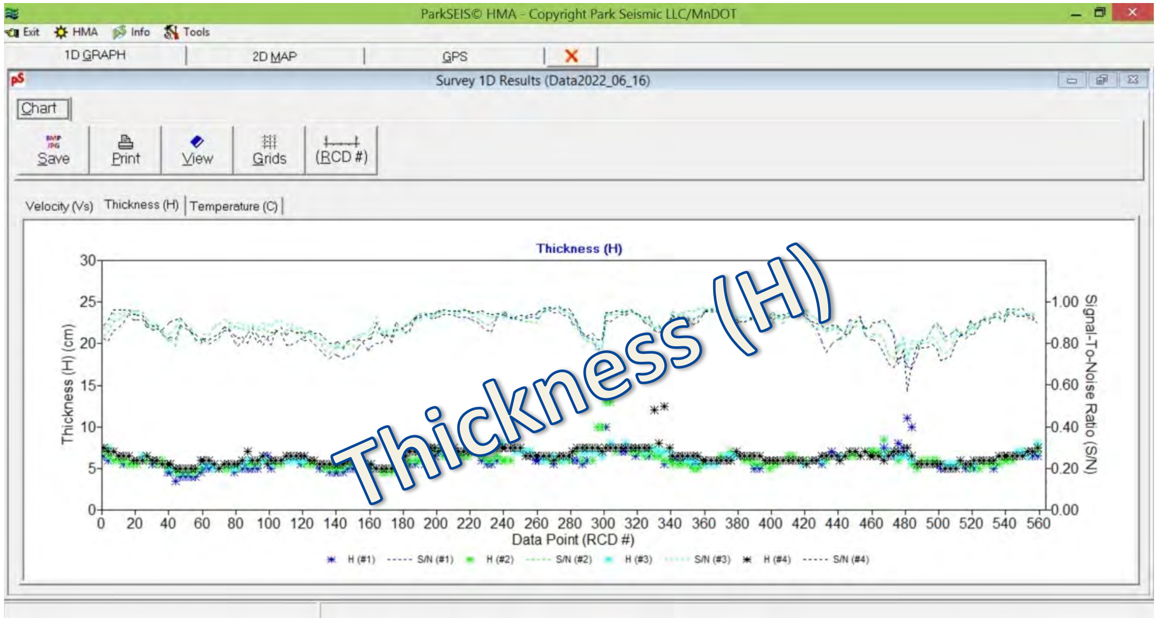
Table 4: Summary of results from survey #3 (Average Temperature = 27.50 °C ± 0.13 °C)

Array #	Velocity (Vs)				Modulus		Thickness (H)			
	Vs (m/s)	±dVs (m/s)	SN (Vs) (%)	±dSN (Vs) (%)	Young's (GPa)	Shear (GPa)	H (cm)	±dH (cm)	SN (H) (%)	±dSN (H) (%)
1	1551	76	90	6	14.39	5.53	5.7	0.9	83	7
2	1615	55	91	5	15.60	6.00	5.9	0.9	86	6
3	1666	30	94	4	16.60	6.38	6.0	0.8	89	5
4	1668	36	94	4	16.64	6.40	6.0	0.6	89	6
Mean	**1625**	**49**	**92**	**5**	**15.81**	**6.08**	**5.9**	**0.8**	**87**	**6**

DEMO SURVEY (#1)

OUTPUT (#1 Survey) | 1D GRAPH





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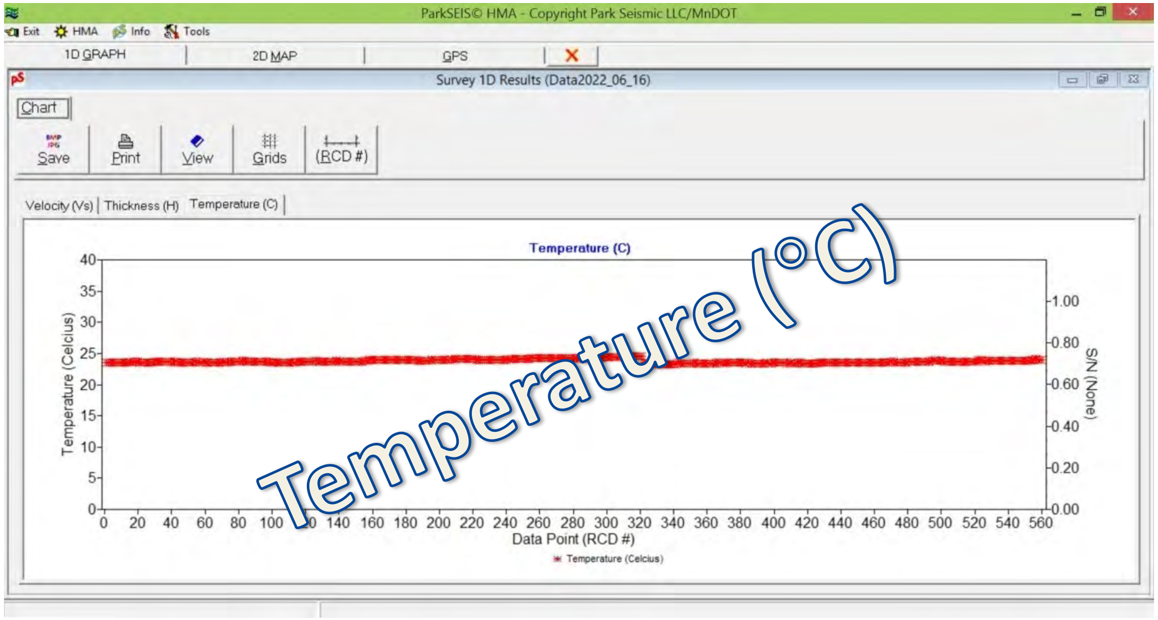

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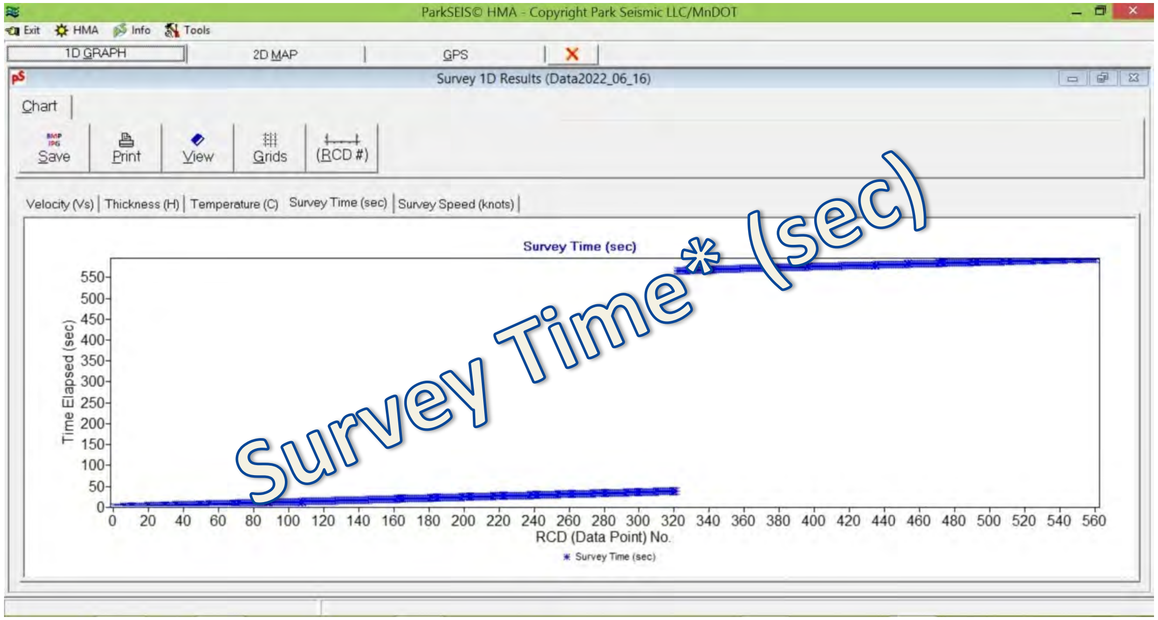
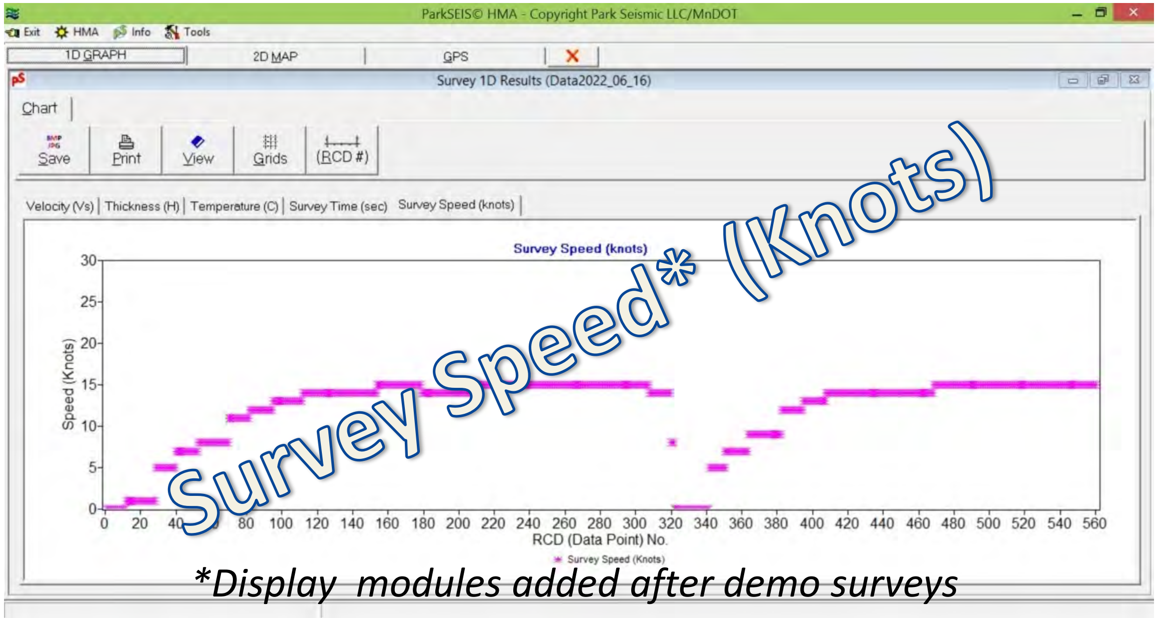
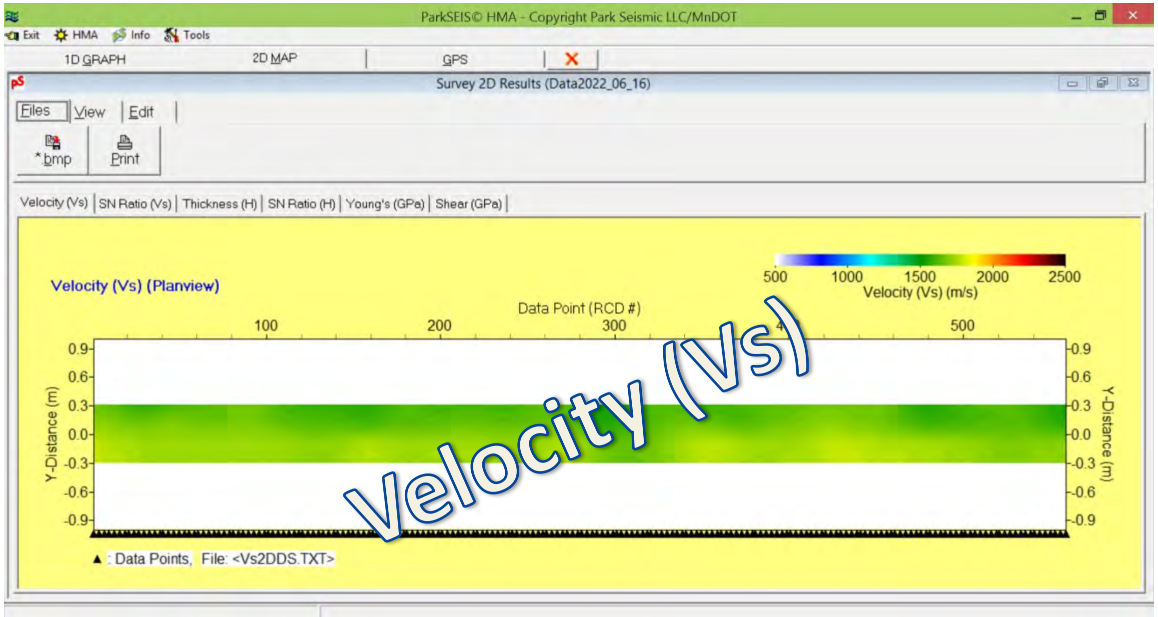
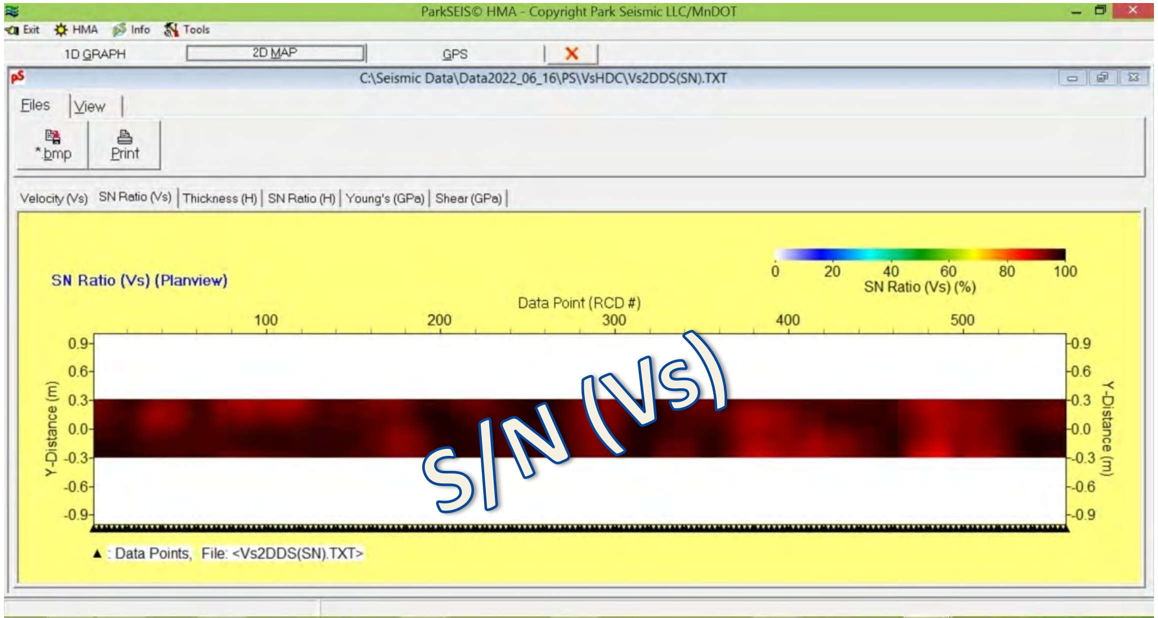




*Display modules added after demo surveys

OUTPUT (#1 Survey) | 2D GRAPH





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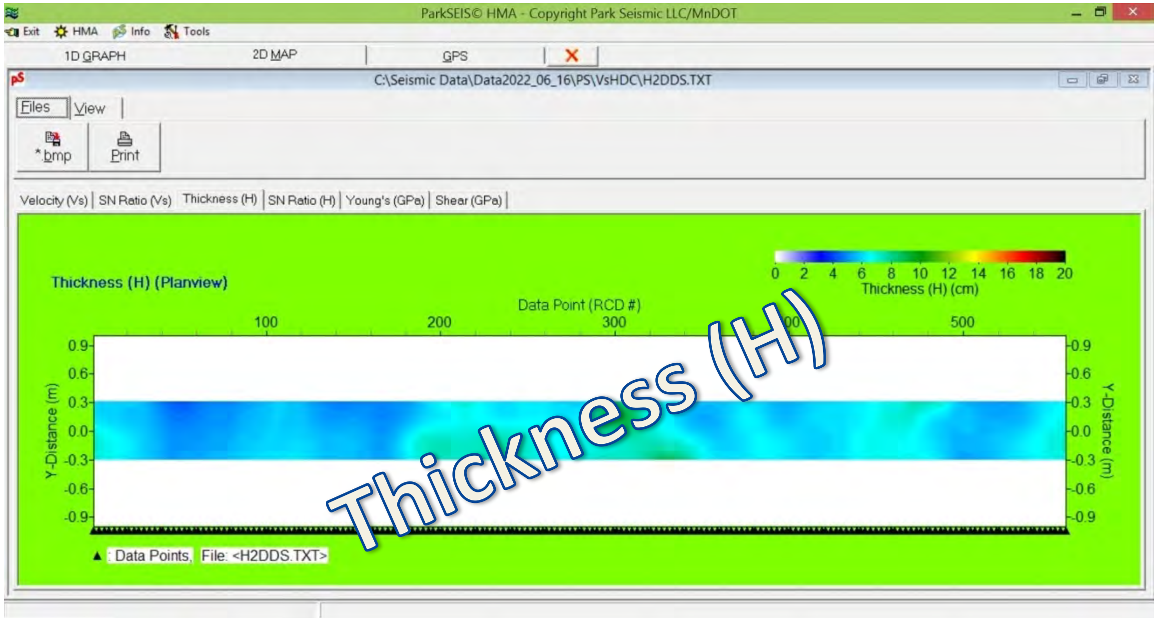
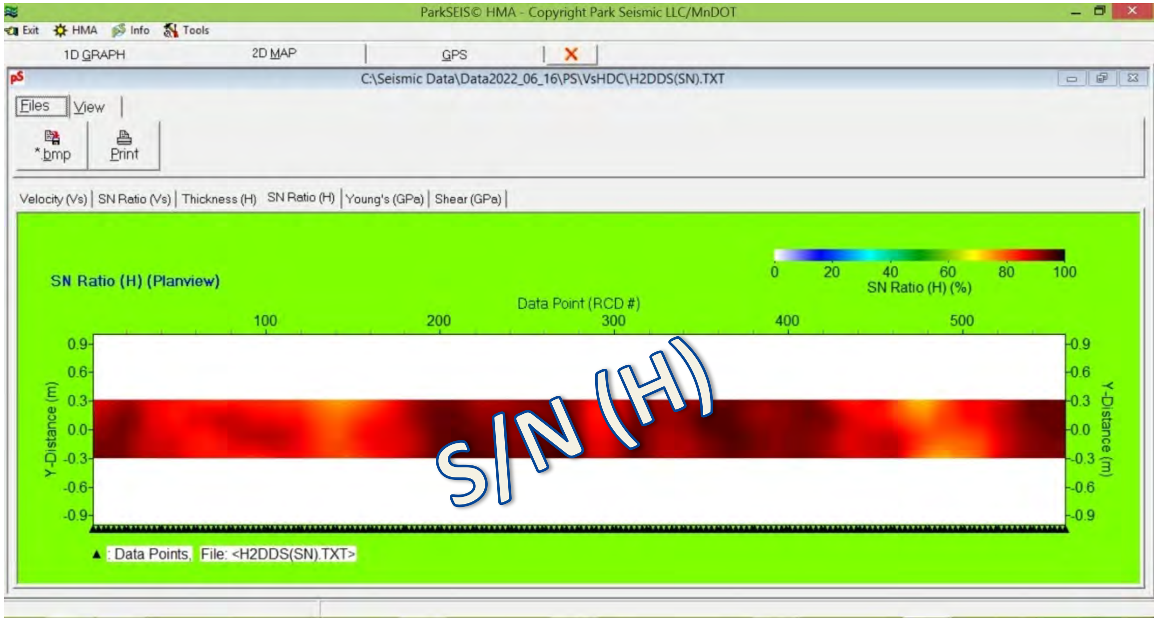
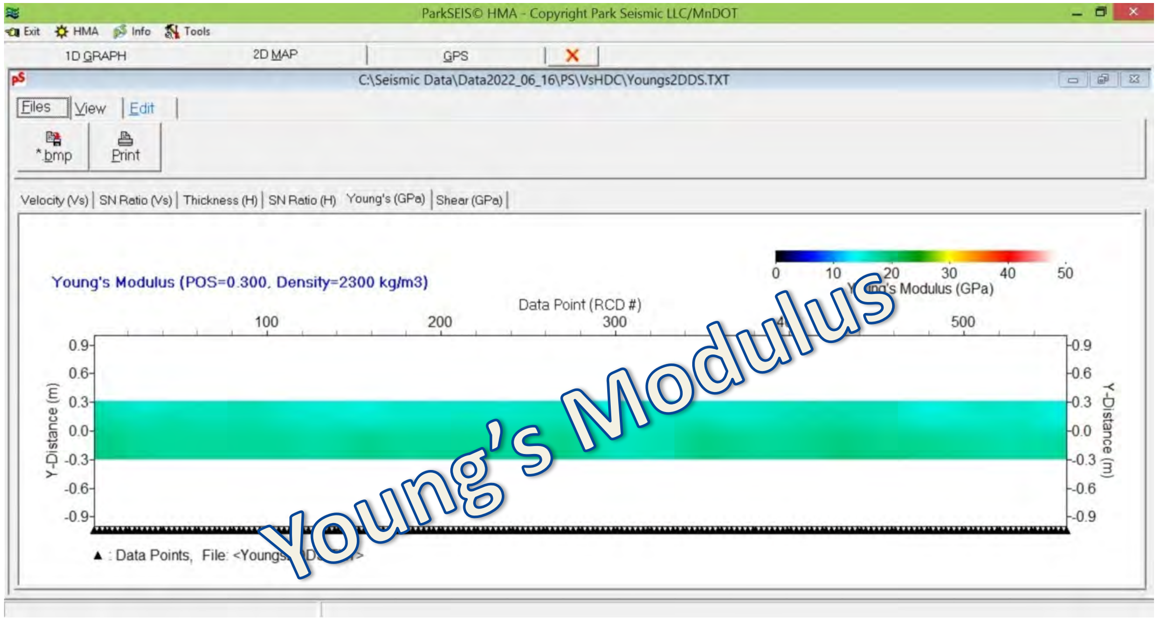
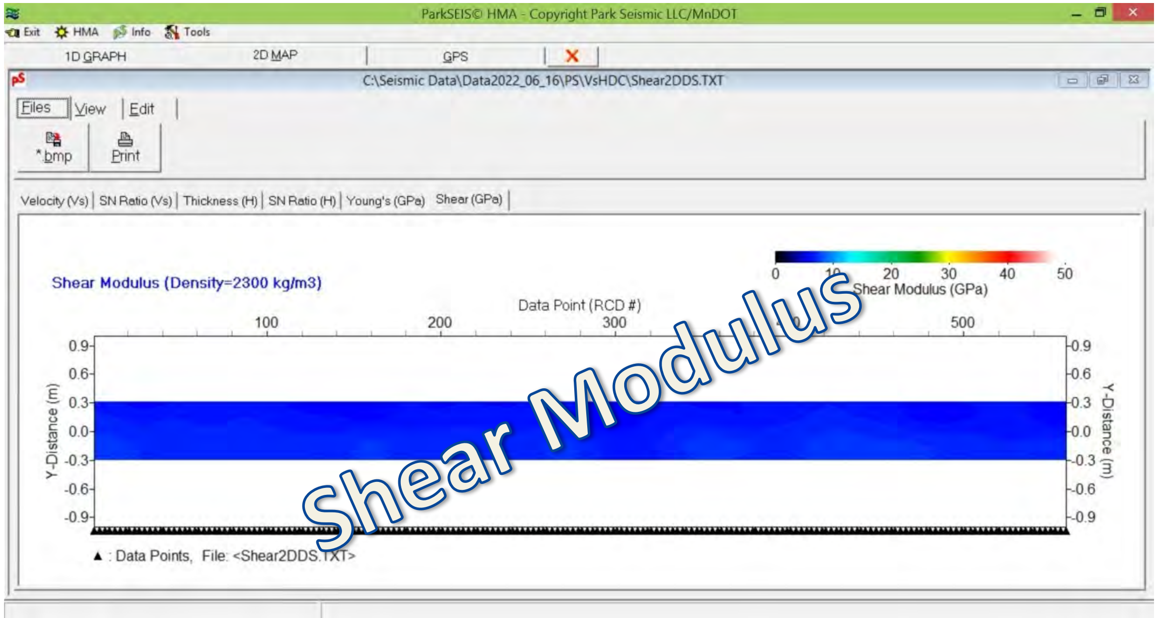




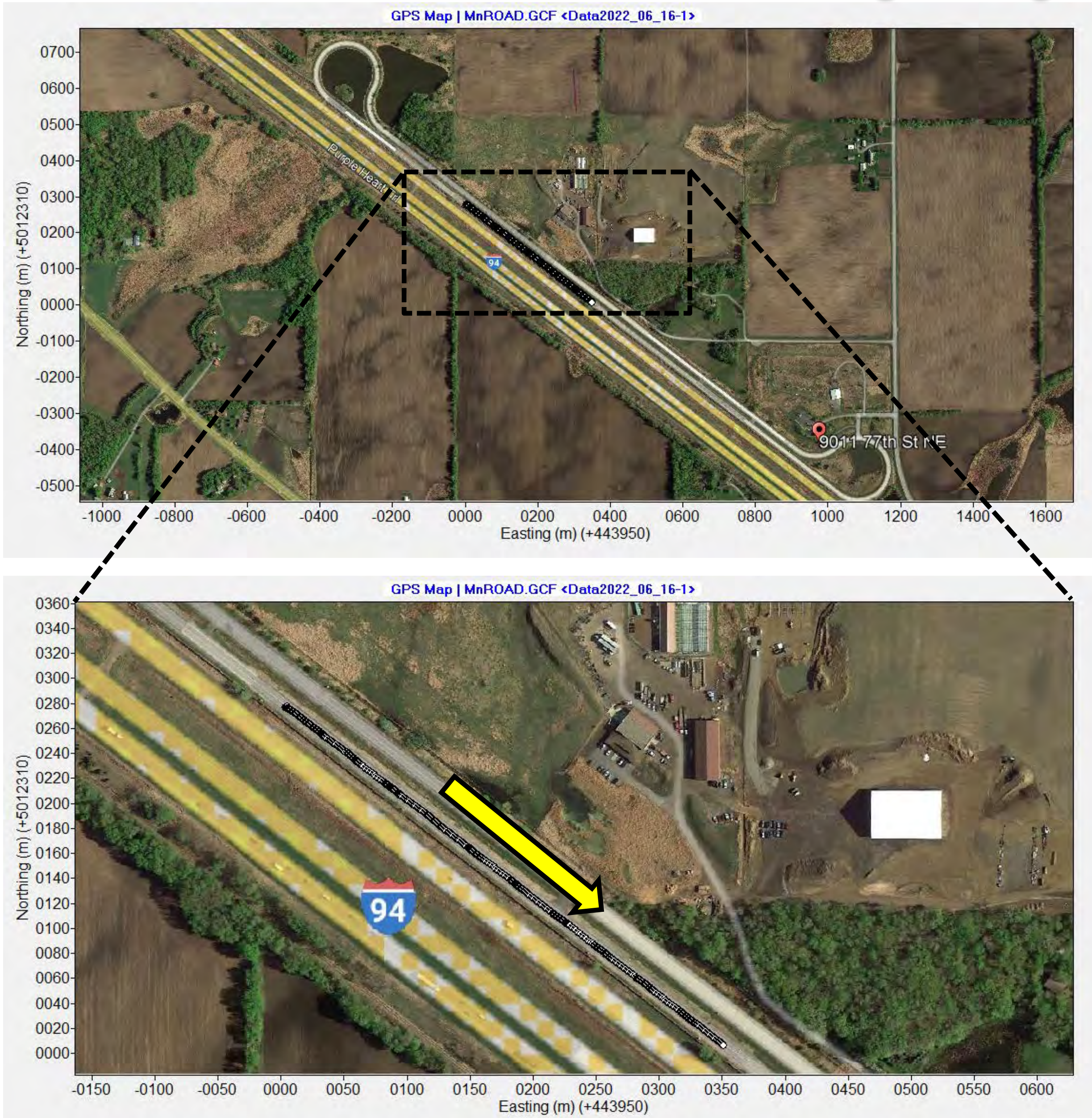
OUTPUT (#1 Survey) | 2D GRAPH





OUTPUT (#1 Survey) | GPS

DEMO SURVEY (#2)



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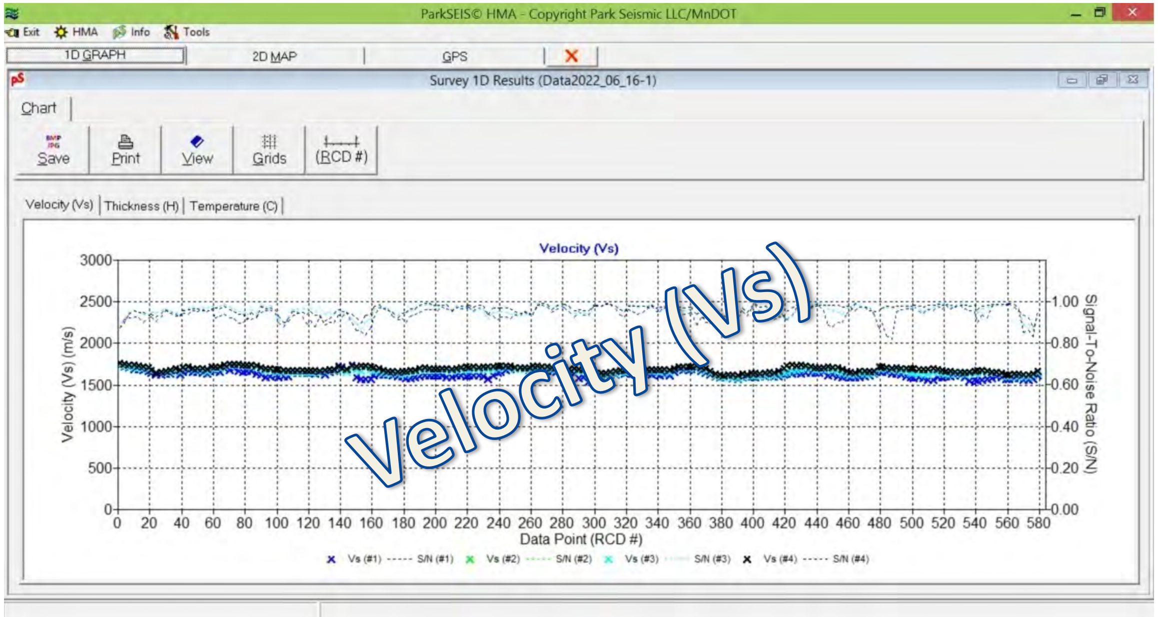

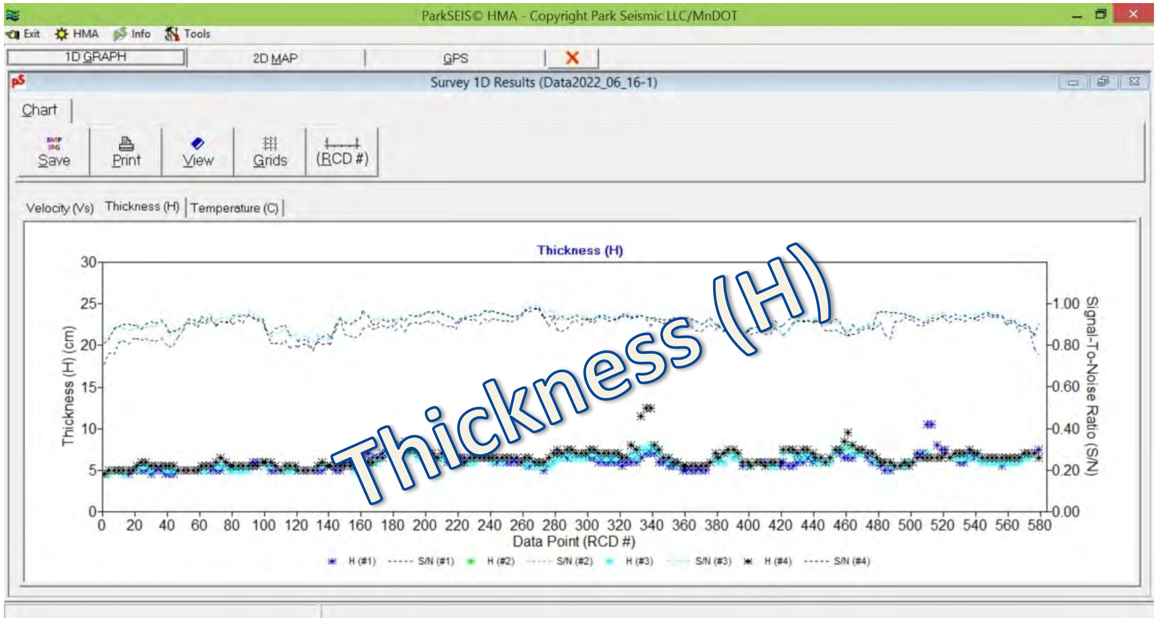

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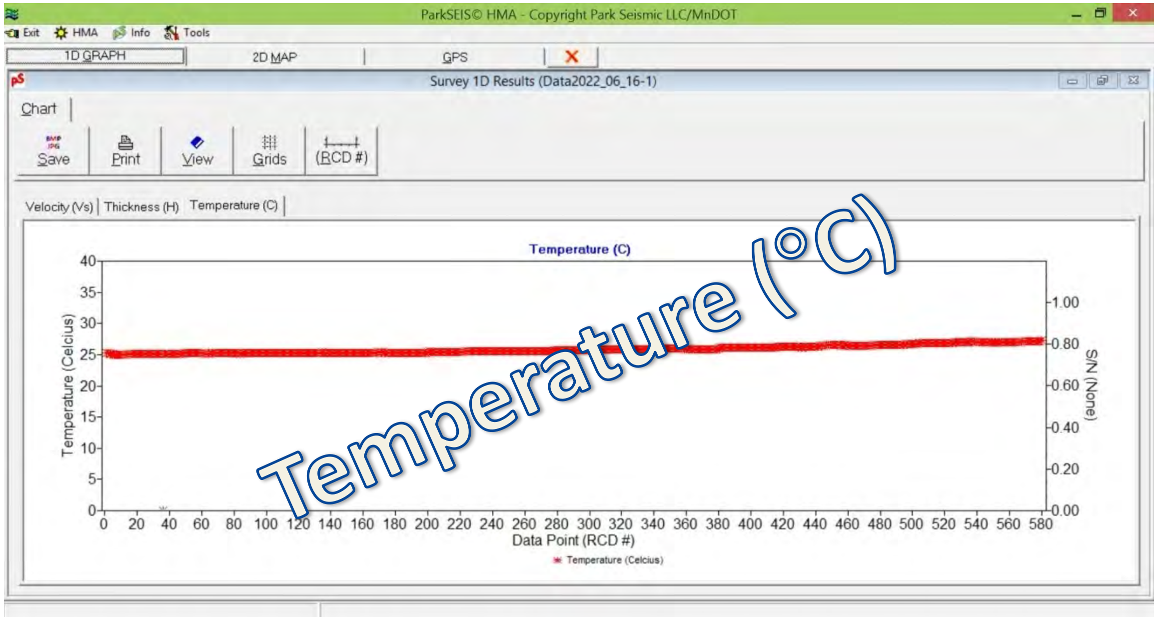

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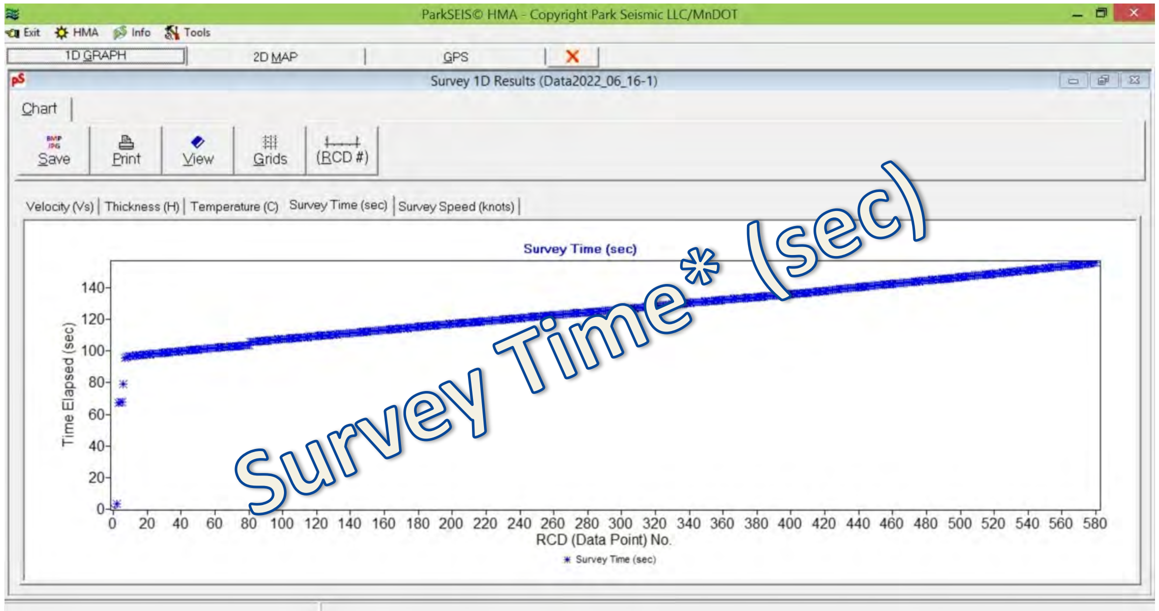
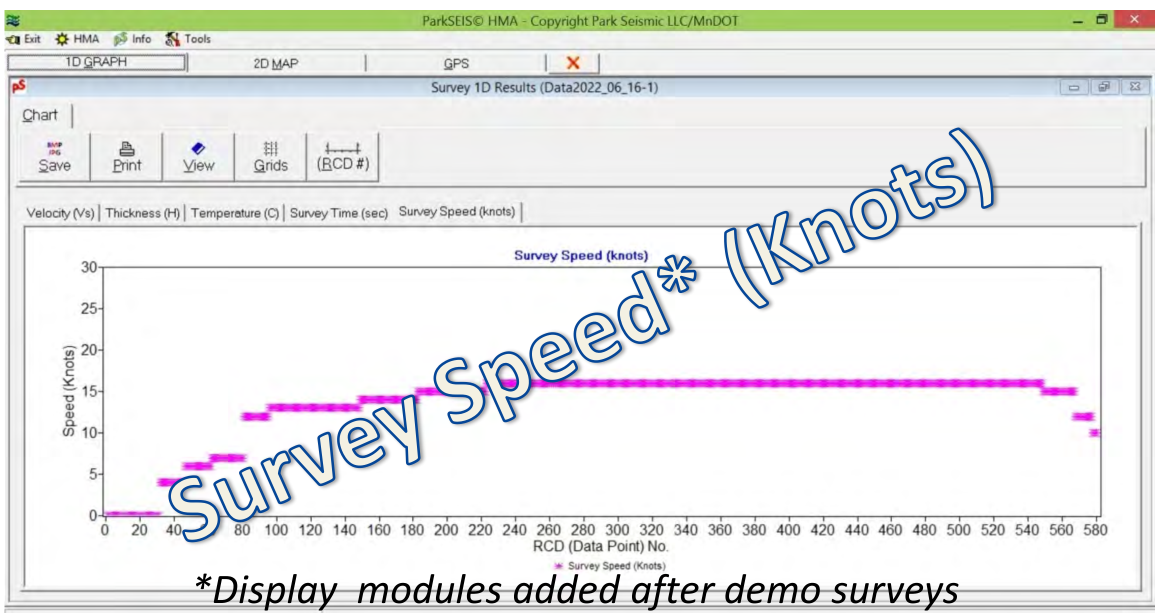
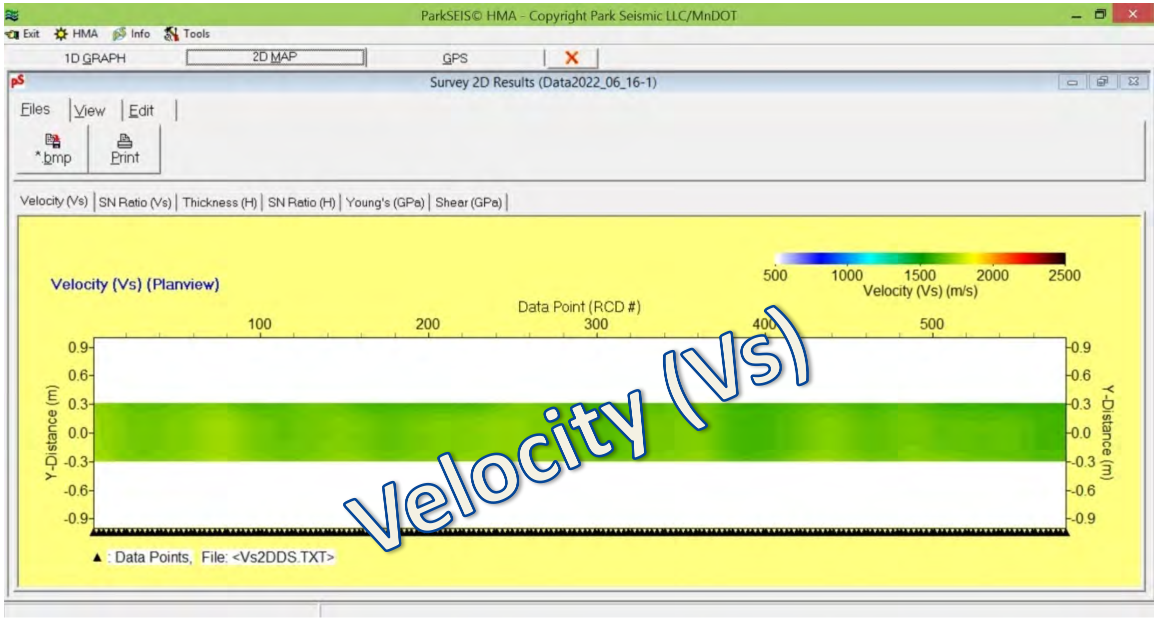
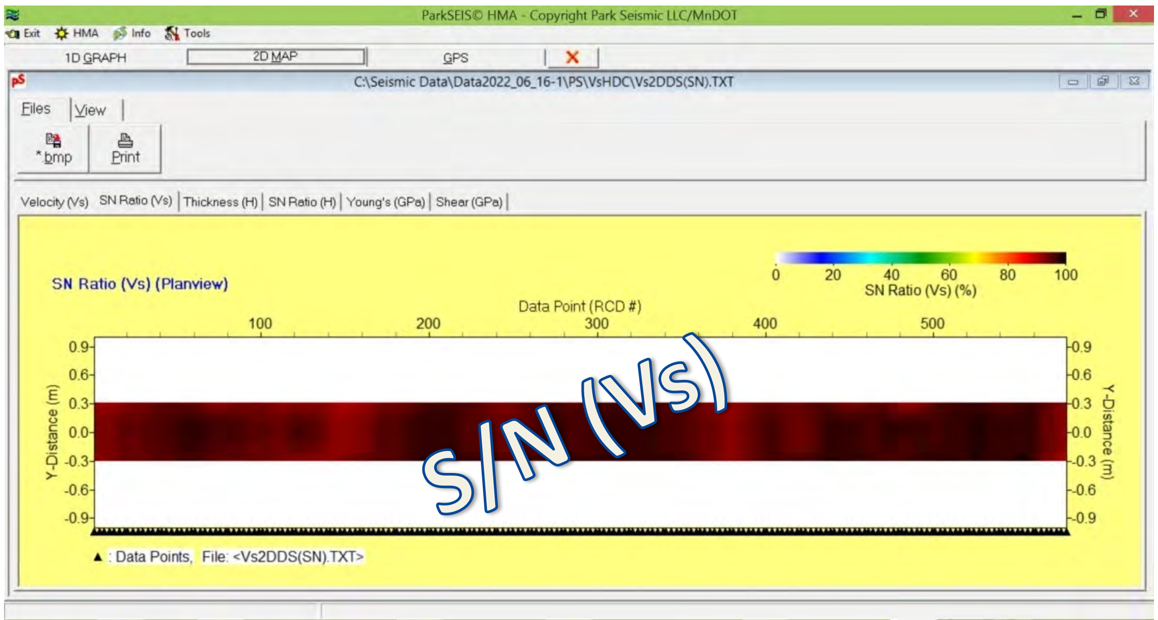




*Display modules added after demo surveys

OUTPUT (#2 Survey) | 2D GRAPH





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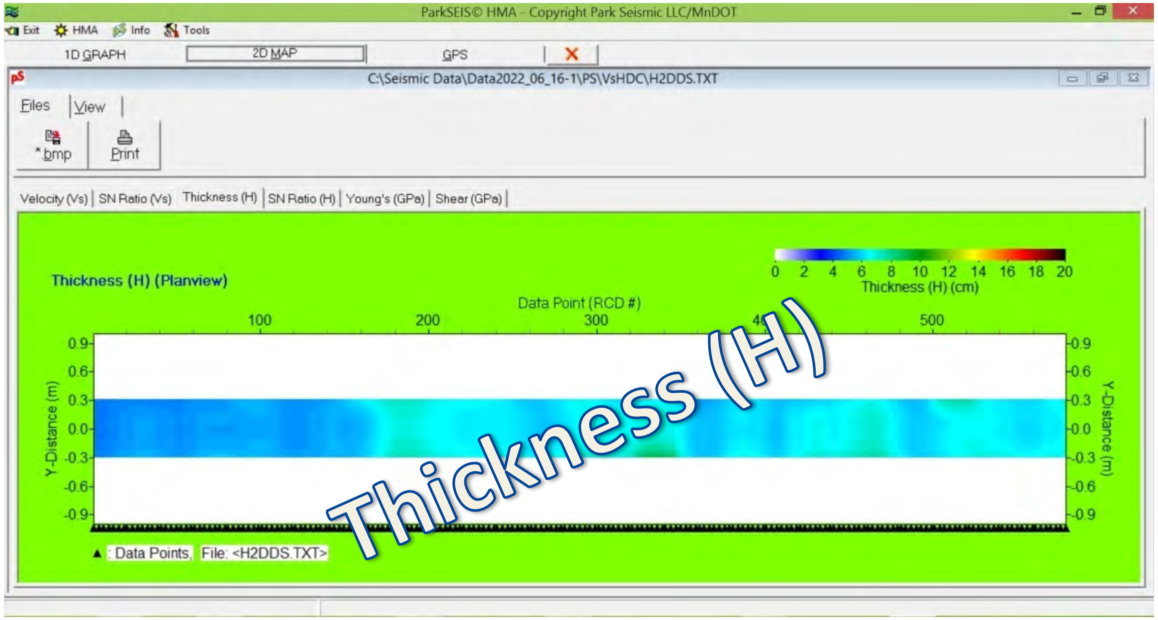

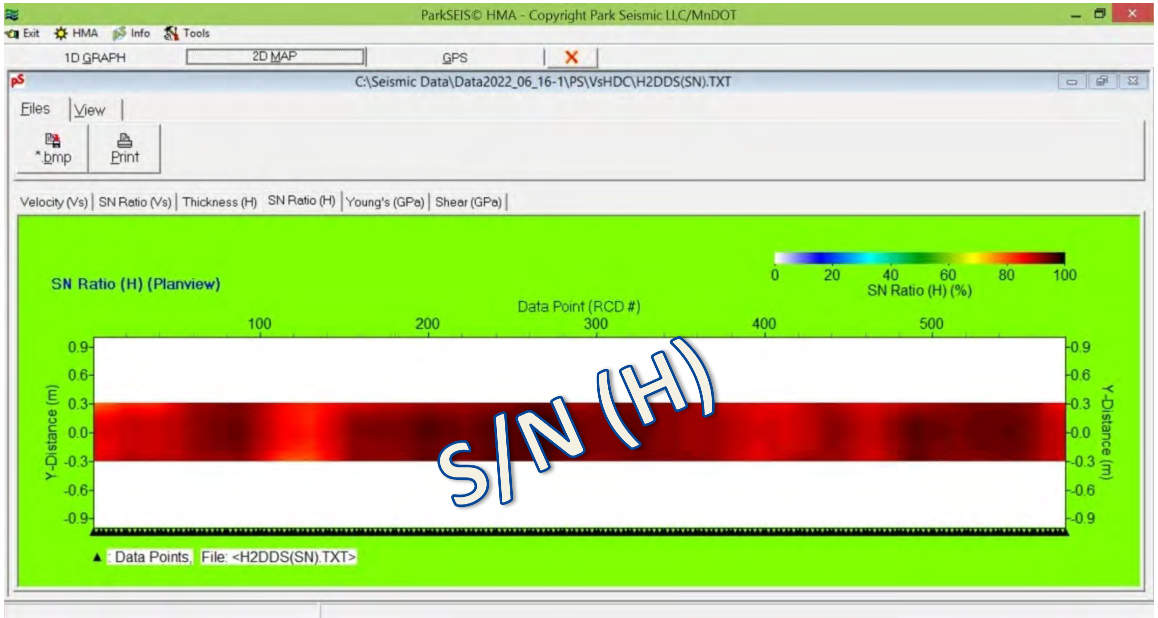

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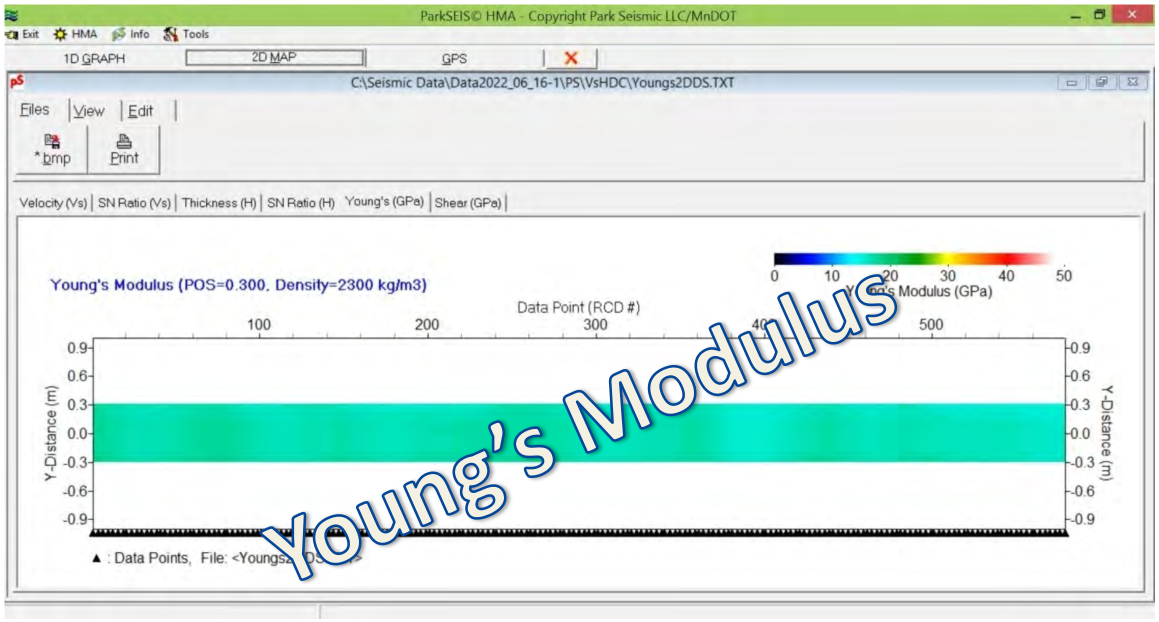
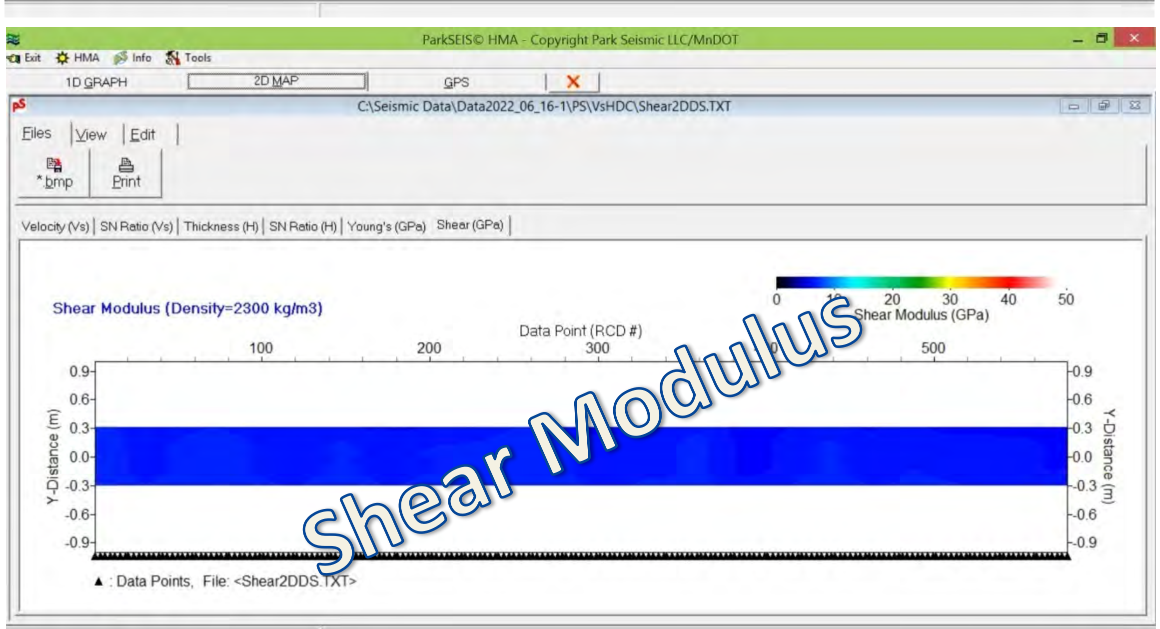
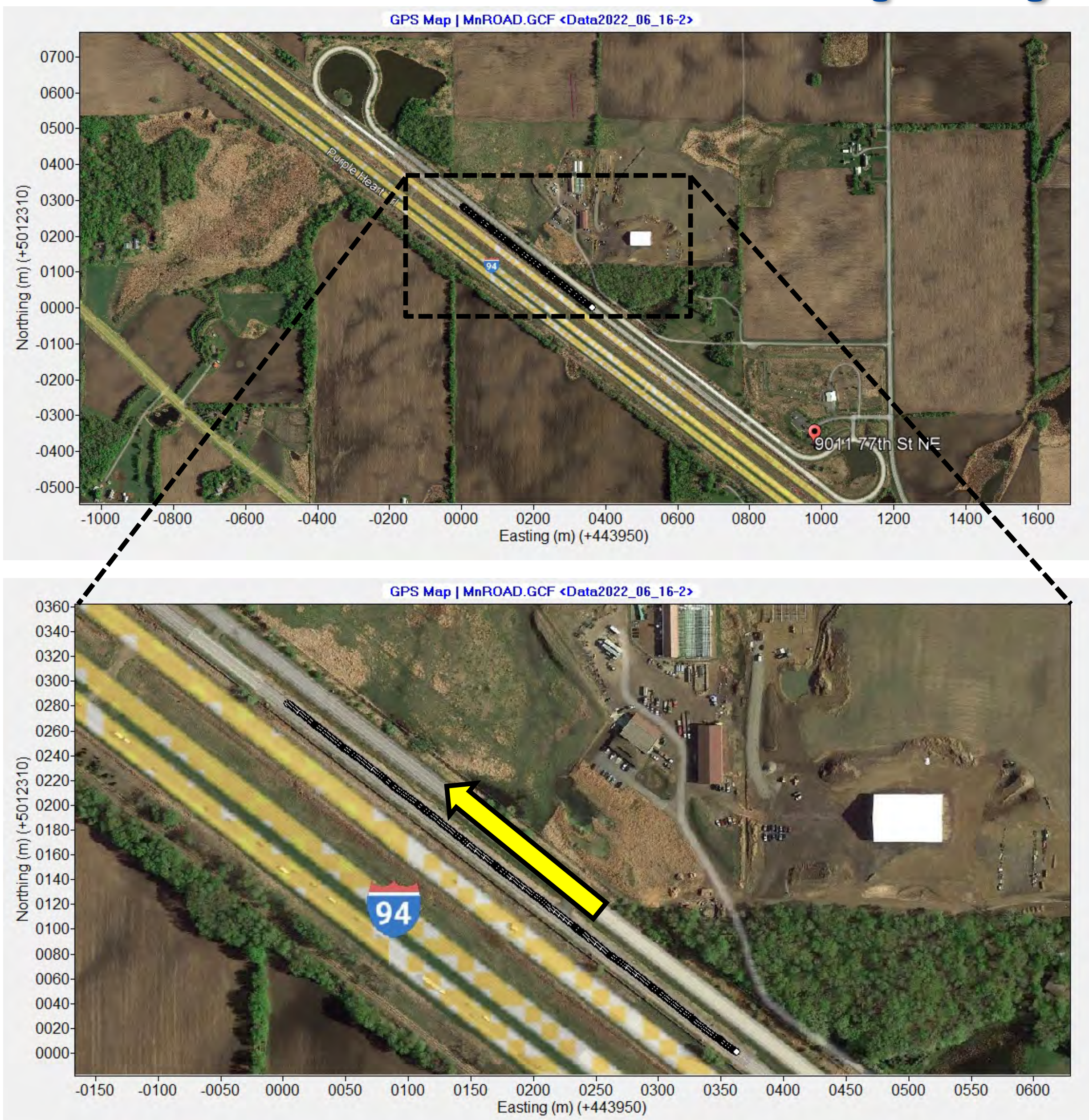


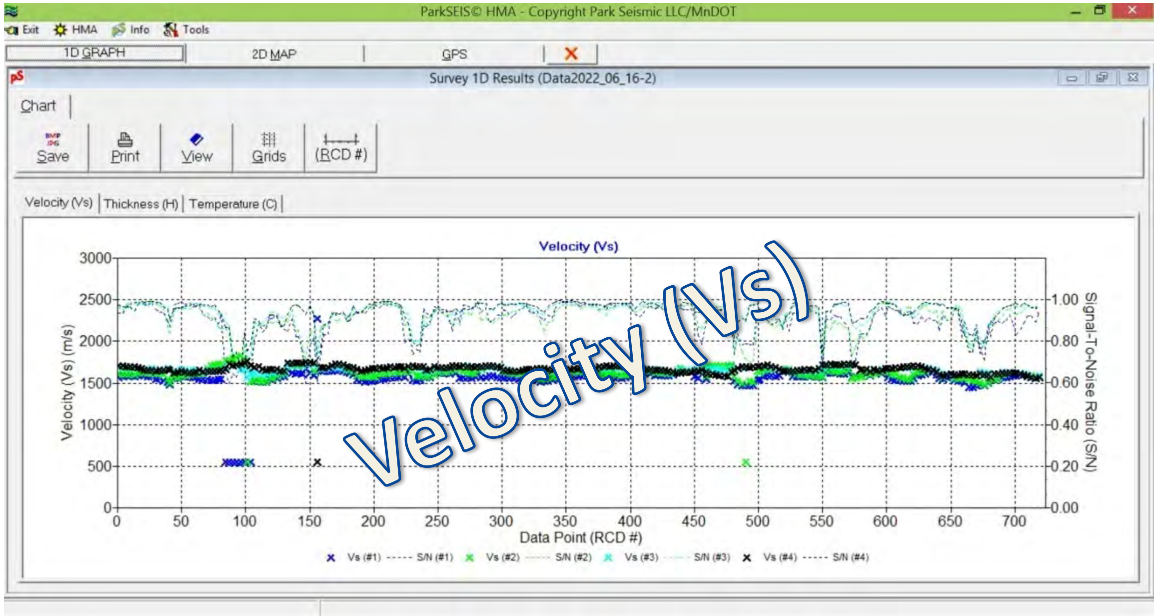


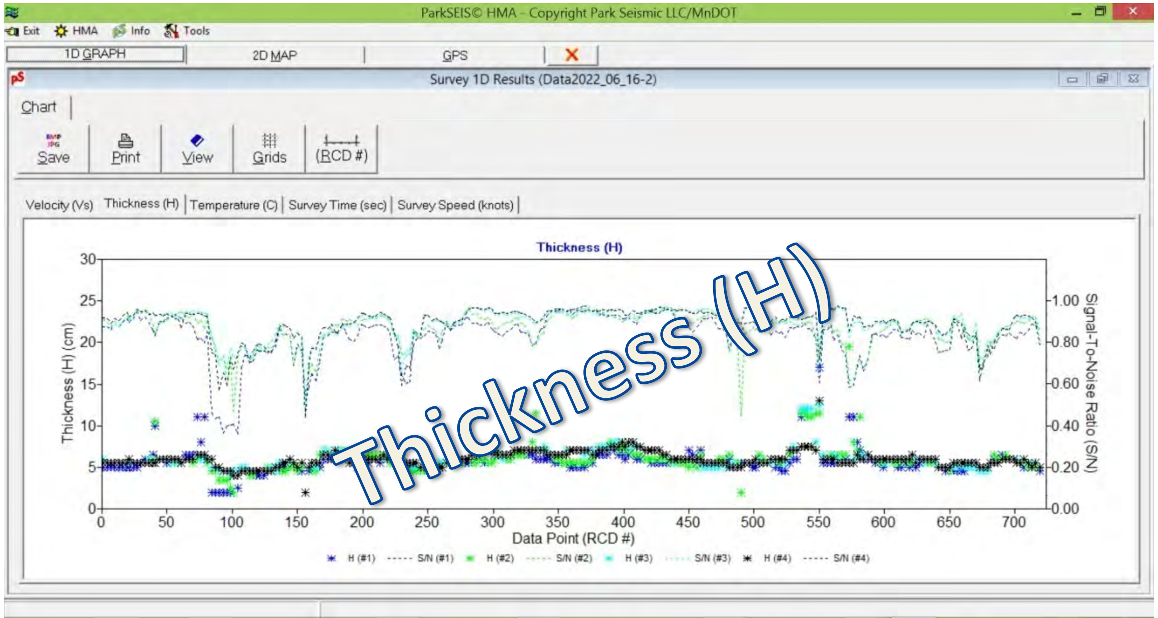
OUTPUT (#2 Survey) | GPS

DEMO SURVEY (#3)



OUTPUT (#3 Survey) | 1D GRAPH





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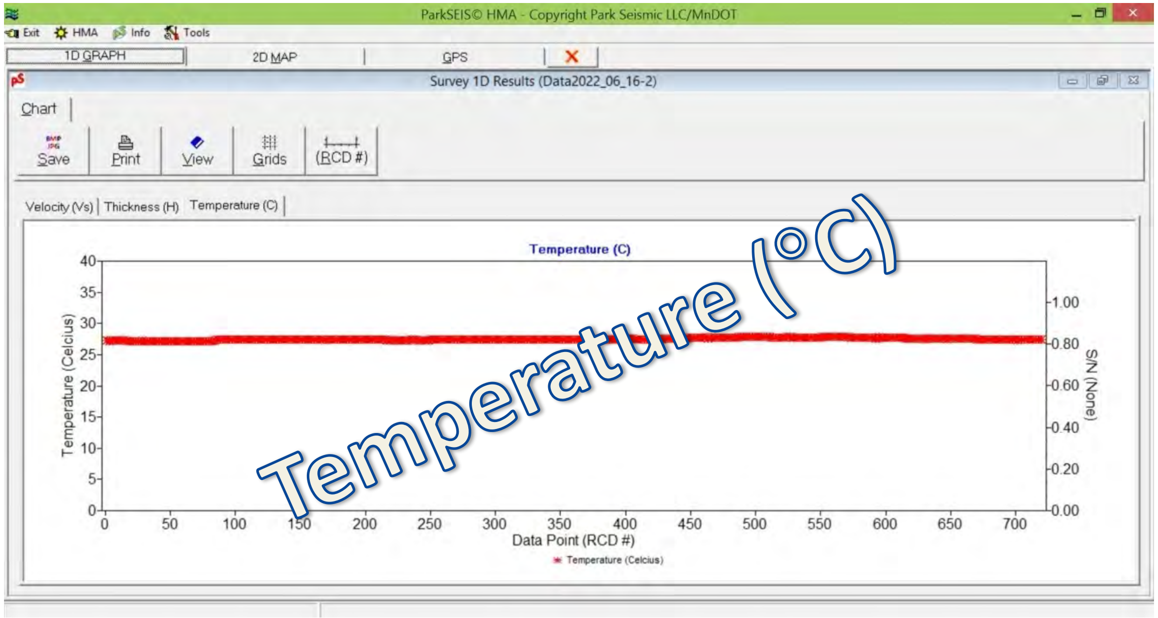

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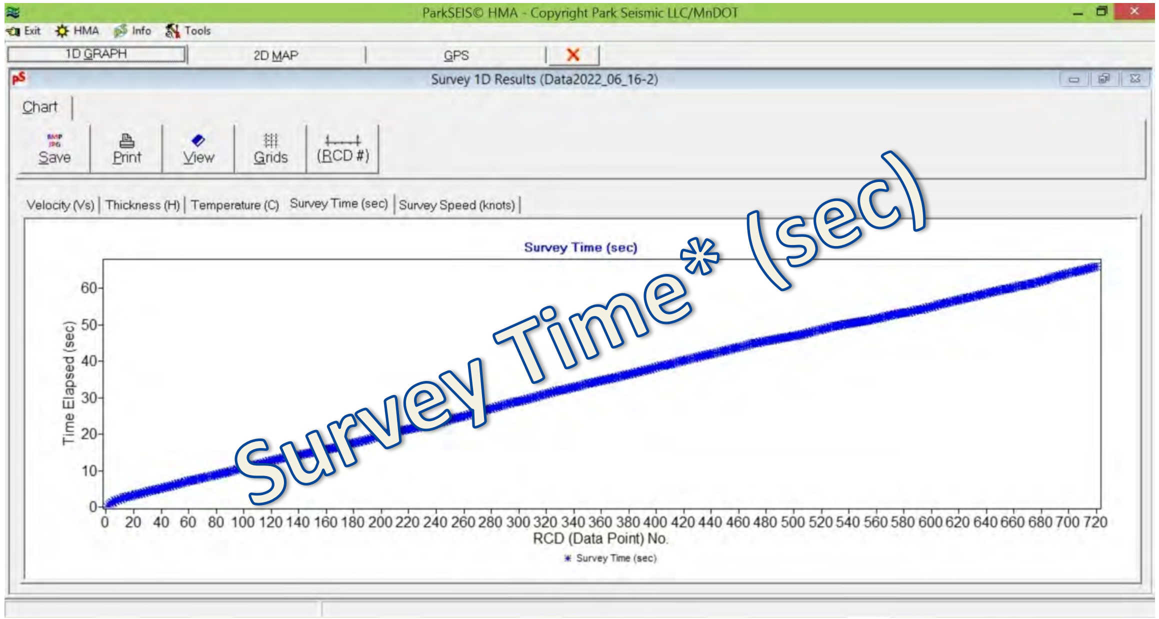
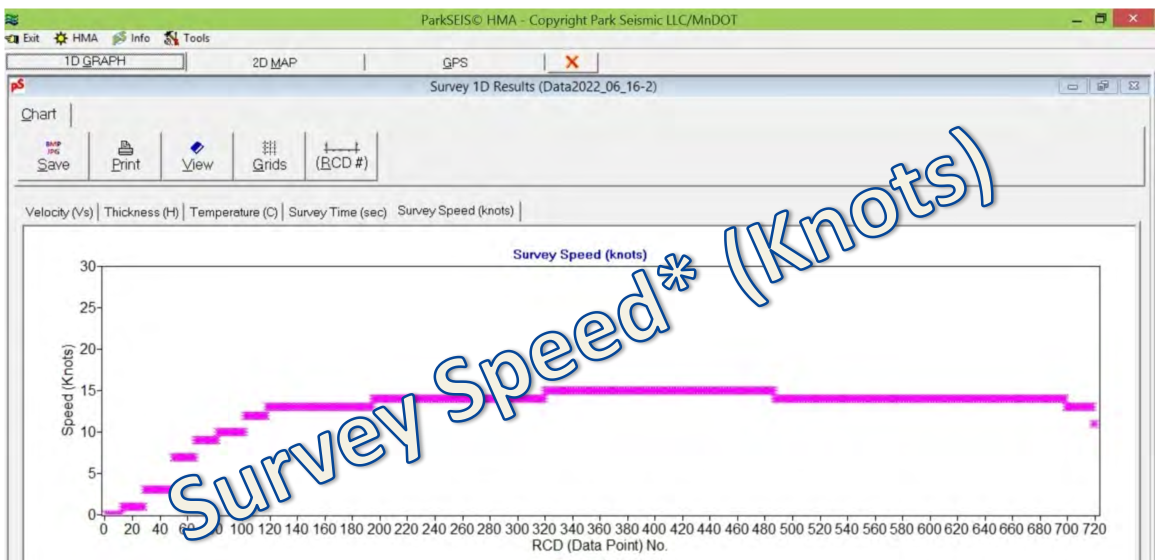
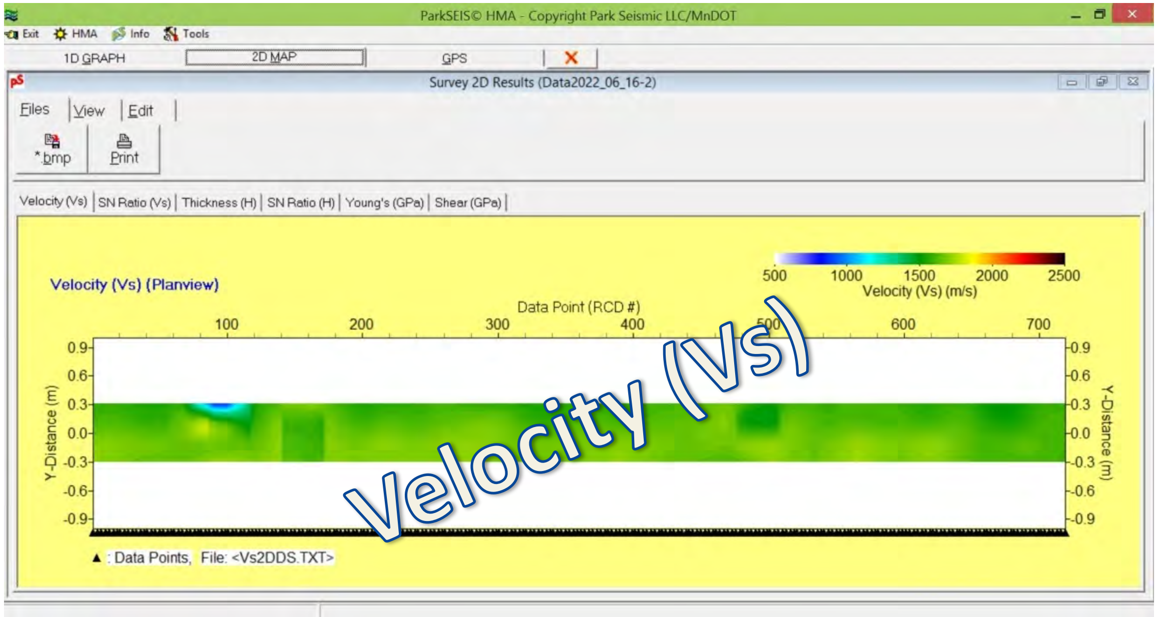
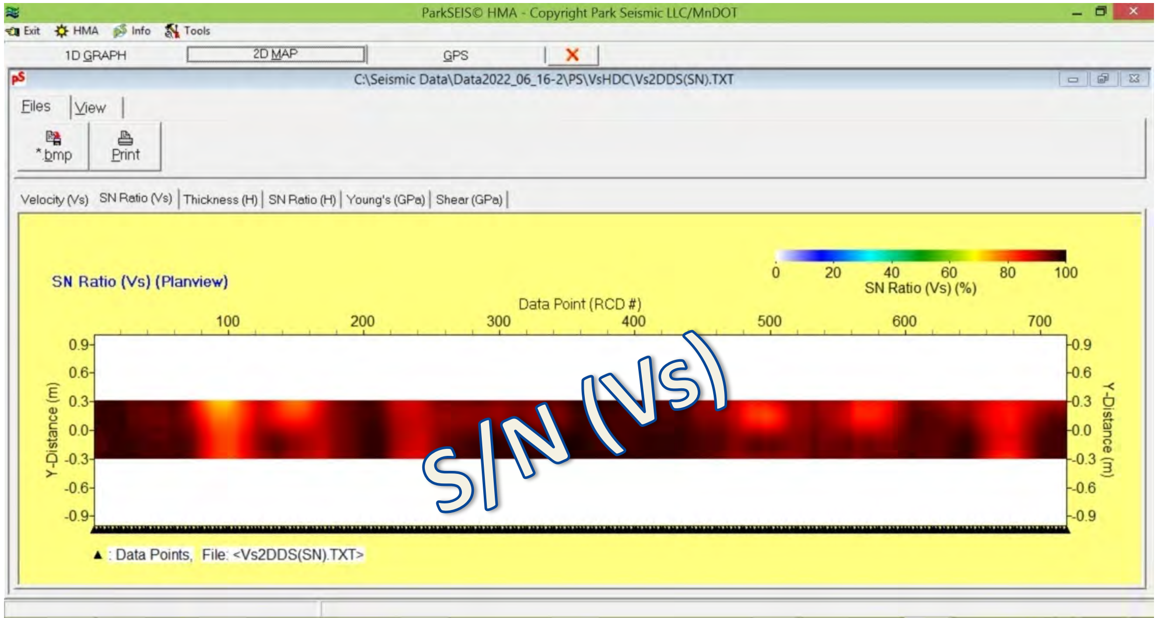




**Display modules added after demo surveys*

OUTPUT (#3 Survey) | 2D GRAPH





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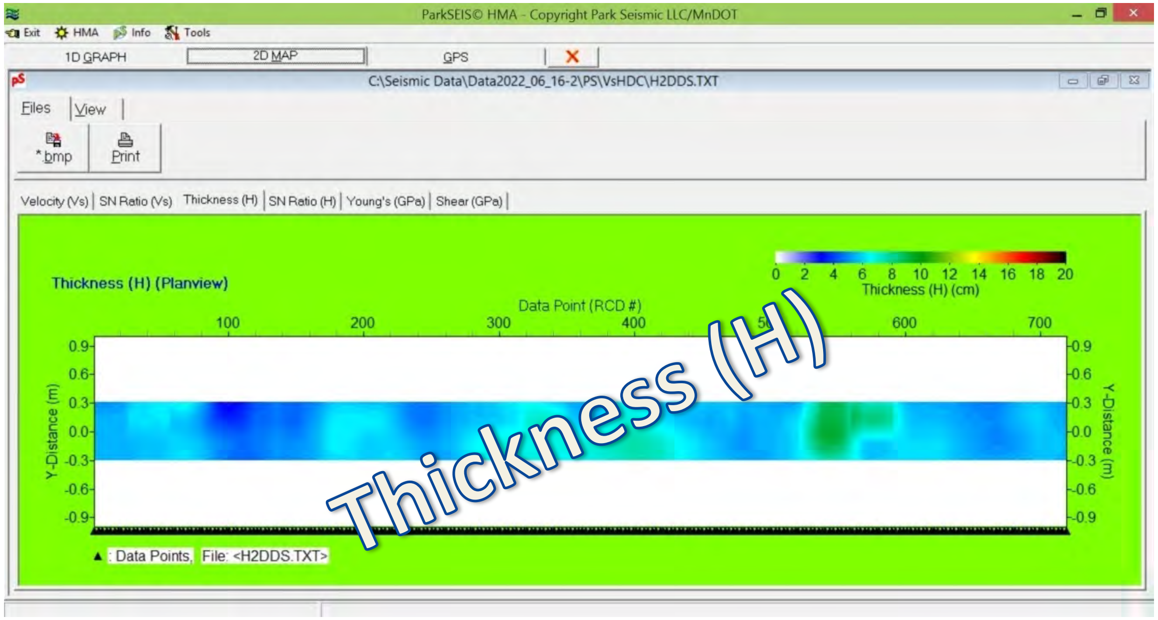
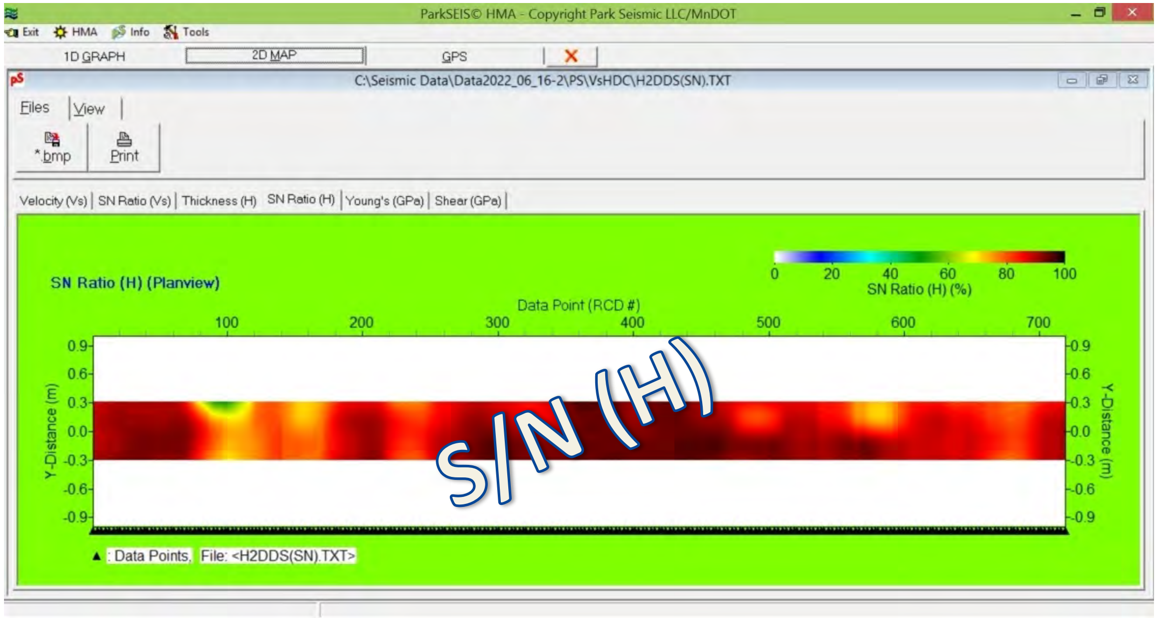
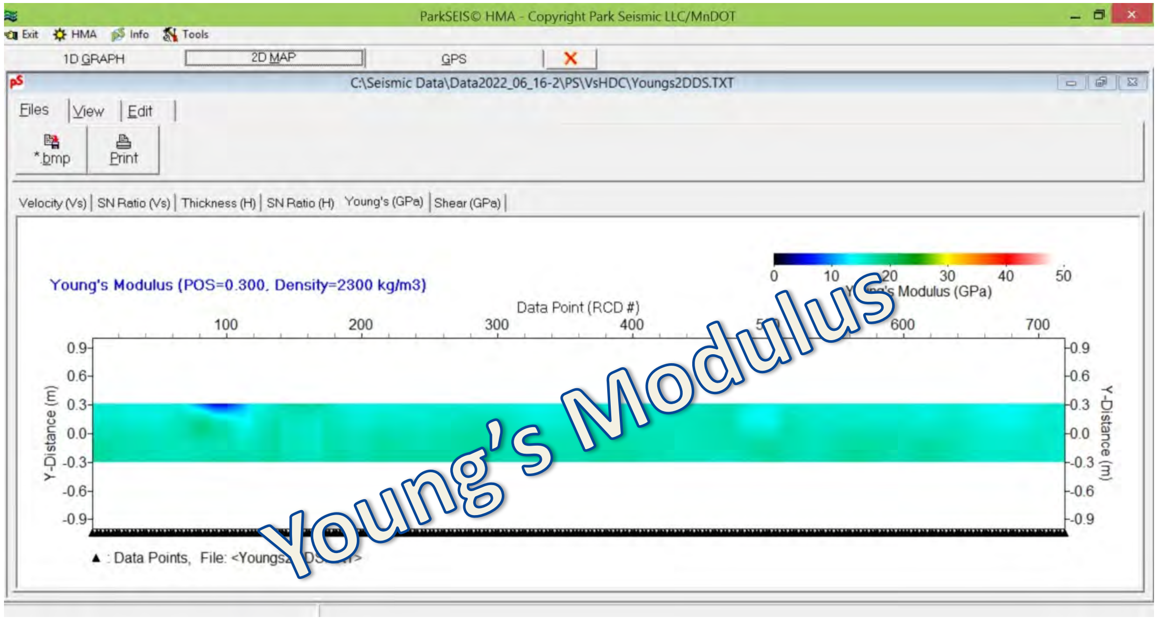
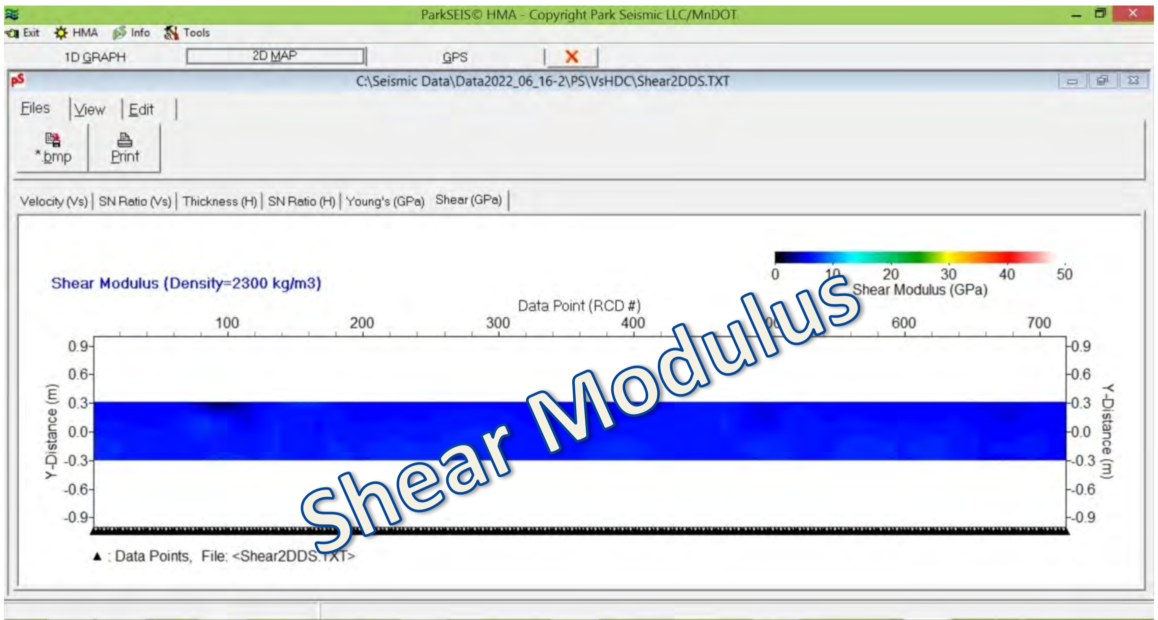




OUTPUT (#3 Survey) | 2D GRAPH





OUTPUT (#3 Survey) | GPS

Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Park Seismic
Geotechnical Seismic Investigation

Final Report – APPENDIX III

Park Seismic LLC
2 Balsam Circle
Shelton, Connecticut

July 29, 2022

Stiffness and Thickness Measurement of HMA Pavement with Flying Microphone Arrays

Choon Park, Ph.D.,[1] Josefin Starkhammar, Ph.D.,[2] and Nils Ryden, Ph.D.[2]

[1]Park Seismic LLC, Shelton, CT, USA
[2]Norrfee Tech AB, Lund, Sweden

ABSTRACT

In January 2020, the Minnesota Department of Transportation (MnDOT) launched a project to build a seismic system that one can routinely use in the field for quality management of Hot Mix Asphalt (HMA) pavement. The system measures the shear-wave velocity (Vs) and thickness of the pavement. When fully completed, it will be a 2D receiver-array system consisting of four (4) 1D arrays arranged transversely to measure a certain width of pavement with a high spatial resolution (e.g., 2 ft x 1 ft). The system can be easily harnessed on a bicycle rack on the back of a car, which can travel at a speed of 10-30 MPH making rolling measurements. The on-board GPS and IR sensors record the location and temperature data for geo-referencing and temperature-referencing of the final results. The on-board software package analyzes incoming data in a fully automated mode to display results on a computer screen almost in real time. At the time of paper preparation, building and testing of the 1D 16-channel MEMS microphone array system has been completed. It includes a rolling impact source, recording device, and the on-board software package. The field test performed along a 1.2-km HMA road produced highly reasonable Vs and H values.

INTRODUCTION

In the process of road construction, it is important to achieve a level of stiffness and thickness of road materials that can sustain expected load stress. In this sense, quality management can be regarded as being analogous to in-situ stiffness and thickness (H) measurement of road beds. Previous research has established seismic shear-wave velocity (Vs) as one of the most direct indicators of a material's stiffness (Sheriff, 2002).

The multichannel analysis of surface waves (MASW) method (Park et al., 1999) has been widely used to measure shear-wave velocity (Vs) and layering information of the near-surface materials (e.g., < 30 m). The method employs a multichannel seismic exploration technique that uses a highly mobile impact source (e.g., sledge hammer) and geophone-array receivers to record seismic surface waves in relatively low frequency range (e.g., 1-100 Hz) for the most-common application of soil-bedrock characterization. Recent applications also focus on the very-shallow depths to characterize the road beds (e.g., ≤ 0.3 m). To use the seismic approach as a practical road quality management tool, multiple conditions must be met. First, the field measurement and the subsequent data-analysis steps should be able to handle very-high-frequency (VHF) surface waves to focus on the microscopic scale of investigation depth (e.g., 0-30 kHz). Second, the survey speed has to be fast enough to measure a wide area as quickly as possible, while minimizing the interference with existing traffic. Third, considering the high data volume, the subsequent data-analysis steps must be fully automated. Furthermore, if the analysis speed can be fast enough and the results can be available on site, it would be even more ideal.

Park and Richter (2017) used the conventional MASW approach with geophones on quadruple land streamers to evaluate seismic velocities (Vs's) of road structure during a Full Depth Reclamation (FDR) construction of an HMA road (Figure 1). The evaluation of the top pavement (HMA) layer, however, was beyond the ability at the time because of the microscopic depth range that would require measurements of VHF surface waves, which is far beyond what the conventional geophones can record (e.g., 1 Hz – 300 Hz). Although Ryden et al. (2004) first applied the multichannel seismic approach to record the pavement surface waves in 1-30 kHz by using an accelerometer (Figure 2), it was impractical because of the slow measurement speed (e.g., half hour to make one measurement). The most recent development of non-contact rolling measurement by using micro-electro-mechanical sensor (MEMS) microphones opened up a completely practical approach that can continuously survey at a speed of 10-30 MPH while recording the leaky-mode surface waves radiated from the pavement surface (Ryden et al., 2019) (Figure 3).

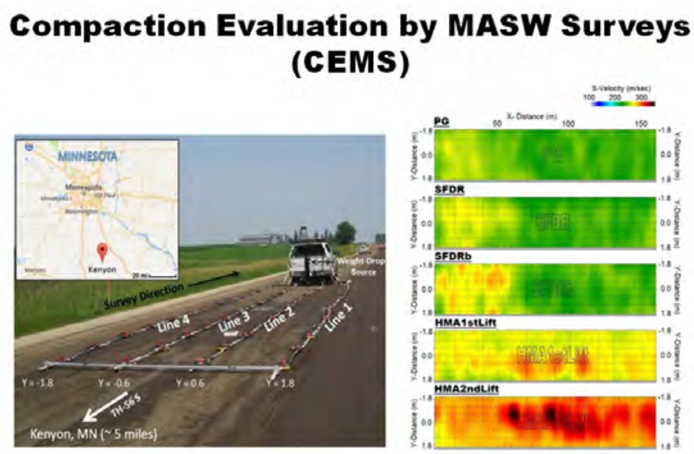


Figure 1. MASW surveys with quadruple land streamers (left) and shear-wave velocity (Vs) depth-slice maps at 5 stages during FDR road construction (right) (Park and Richter, 2017).

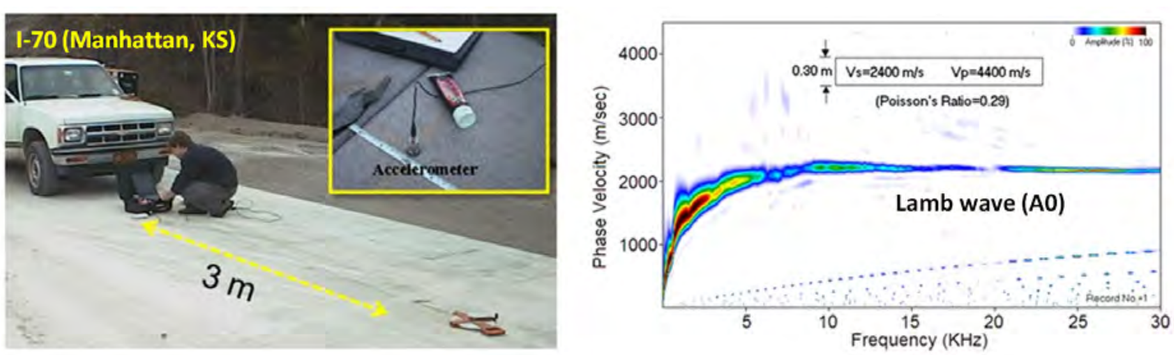


Figure 2. Seismic pavement measurement with one accelerometer (left) and analyzed Lamb dispersion image (right) (Ryden et al., 2004).

This paper describes the development of a system that can be harnessed on the back of a car by using a simple apparatus: for example, a bicycle rack. The system, when completed, will have a 2D receiver array consisting of four 1D arrays of MEMS microphones arranged transversely with relatively small separation to cover a certain width (e.g., 4 ft) of HMA pavement simultaneously (Figure 4). The survey vehicle travels at a moderate speed (e.g., 10-30 MPH) while a small steel object (e.g., 1 cm) hanging down from one end of the system frame spontaneously makes repeated impacts on the pavement surface. The system takes GPS and temperature measurements during the survey for geo- and temperature-referencing of the final results. The on-board laptop computer equipped with a dedicated software package continuously analyzes the incoming data and displays output results (Vs and H) on the screen almost in real time. Historical development of the seismic approach for road evaluation is described. Procedures to build a 1D MEMS microphone array and the corresponding data analysis and visualization software package, completed at the time of the paper preparation, are also described. The results from the subsequent field test that collected 2000 production records of 16-channel acquisition along a 1.2-km long HMA road are presented. This development was launched as a 2-year project in January 2020 at the Minnesota Department of Transportation (MnDOT) funded by National Road Research Alliance (NRRA).

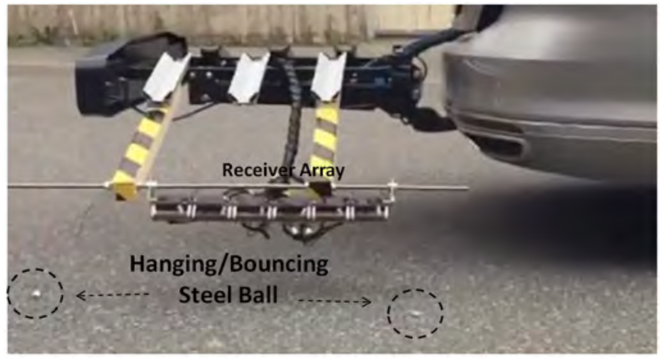


Figure 3. Flying non-contact measurement of seismic surface waves by using 48-channel MEMS microphones (Ryden et al., 2019).

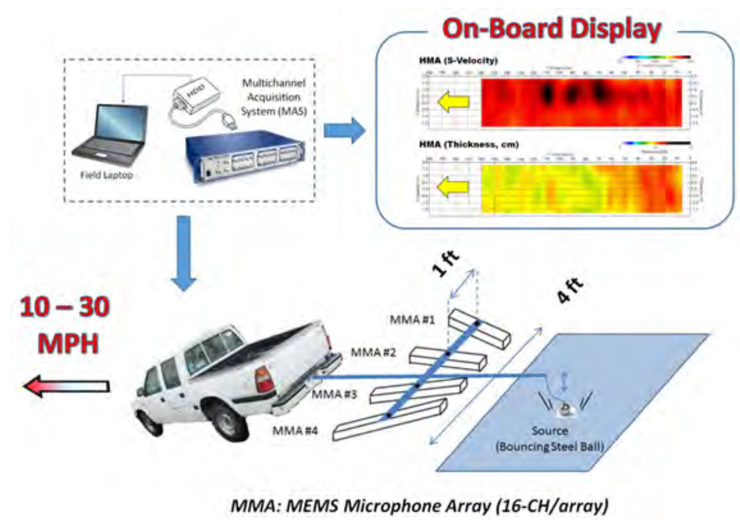


Figure 4. Schematic of the overall configuration of the final 2D system this project aims to develop.

SEISMIC APPROACH

Shear-Wave Velocity (Vs) and Stiffness. A material's stiffness property represents its resistance to deformation from an external force. To precisely describe it, three elastic moduli have been used (Sheriff, 2002). The Young's modulus (E) represents a resistance to the longitudinal deformation, the shear modulus (μ) to the transverse deformation, and the bulk modulus (β) to the volume change (Figure 5). In geotechnical materials, the bulk modulus can be often ignored because there is little volume change involved. The defining equations for the two moduli (E and μ) include three terms; density (ρ), Poisson's ratio (σ), and shear-wave velocity (Vs). The P-wave velocity (Vp) is linked with Poisson's ratio through Vs. Vs is included as a square term in both equations, indicating the most sensitive and therefore the most contributing term. In addition, for the other two terms of density and Poisson's ratio, approximate values are always available. For example, ρ can be considered a constant value of 2.0 gm/cc for most geotechnical materials, and σ can be set to 0.35 for most asphalt materials. On the other hand, Vs can vary significantly; for example, it can be lower than 50 m/s for highly soft soil and exceed 2500 m/s for highly competent bedrock. This is why the Vs evaluation is often considered the same as the stiffness measurement of a material.

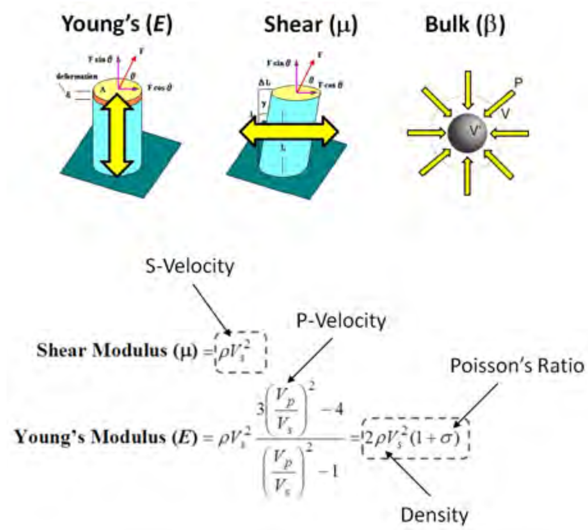


Figure 5. Graphical definition of the elastic moduli (*E*, μ, and β) and defining equations for *E* and μ.

Compaction Evaluation by MASW Surveys (CEMS) for Road Bed Evaluation. In 2013, Minnesota Department of Transportation (MnDOT) performed a series of MASW surveys over a test segment of the HMA road (500 ft x 12 ft) during a full depth reclamation (FDR) construction (Figure 1). The surveys used the conventional geophones mounted on the quadruple land streamers that covered the 12-ft wide area of the road simultaneously with a 3-ft transverse resolution. The surveys generated the velocity (Vs) depth-slice maps (0-2 meters) at five different stages during the construction that showed the stiffness (Vs) variations not only within the test area but also, more clearly, through different stages of road construction (Park and Richter, 2017). Because of the relatively low-frequency nature of surface waves measured by using geophones (e.g., < 300 Hz), the survey results were correlated with the stiffness properties of top about 2-m depth as a whole, and the top pavement (HMA) layer could not be evaluated independently.

Historical Development of Seismic Approach for Pavement Evaluation. Ryden et al. (2001; 2003) first applied the multichannel principles to accurately characterize surface waves generated in the top pavement layer (Figure 2). It used one stationary accelerometer receiver and a source array with a small carpenter hammer (e.g., 12 oz). The impact source generated surface waves at progressively different locations to accomplish the multichannel acquisition through the source-receiver reciprocity (Ryden et al., 2001). The results showed the type of surface waves generated in the pavement layer is highly analogous to the Lamb wave (Lamb, 1917) that, in theory, has unique dispersion curves in both asymmetric (A) and symmetric (S) modes (Ryden et al., 2003). The results also indicated that the fundamental-mode asymmetric (A0) dispersion is the one usually dominates (Figure 2). Details about the field approach and subsequent data-analysis procedures are presented in Ryden et al. (2004). To avoid the cumbersome procedure that was required to ensure a reliable coupling of accelerometer with pavement surface, Ryden et al. (2006) successfully used a microphone hanging in the air by about 10 cm above the pavement surface to record the leaky-mode Lamb waves (Figure 6). This was the first non-contact measurement of seismic waves on pavement,

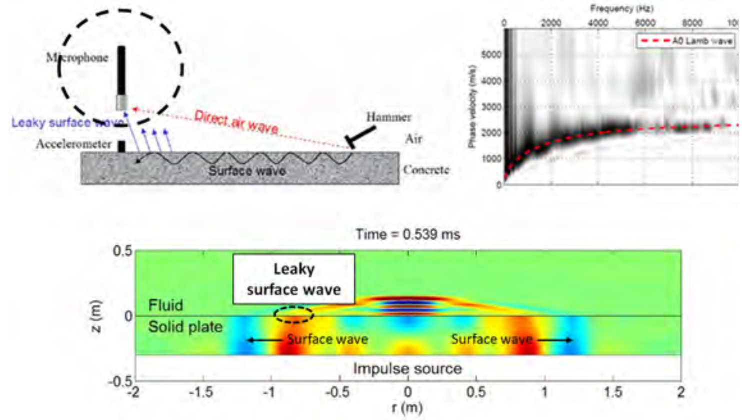


Figure 6. Schematic illustration of the microphone measurement of leaky-mode surface waves (top left), measured dispersion image (top right), and a snap shot of numerical modeling to show the leaky-mode generation (bottom) (Ryden et la., 2006).

opening up the possibility of rolling measurement. Bjurström and Ryden (2017) used a true multichannel (48-channel) system harnessed on a pulling cart (Figure 7) to record the leaky-mode Lamb waves by using a receiver array of MEMS microphones spaced at a 0.75-cm interval. A small solenoid device delivered an impact when the operator pushed a button during the rolling survey. Because of the impact source that had to be almost stationary to make a proper impact, the rolling speed was extremely slow (e.g., < 0.5 MPH). Ryden et al. (2019) soon replaced it with a small steel ball (e.g., 1 cm) hanging down from the receiver array that bounced up and down spontaneously making impacts when the system is in forward motion (Figure 3). This approach presented a practical rolling survey that can continuously move at a moderate speed (e.g., 10 MPH – 30 MPH).

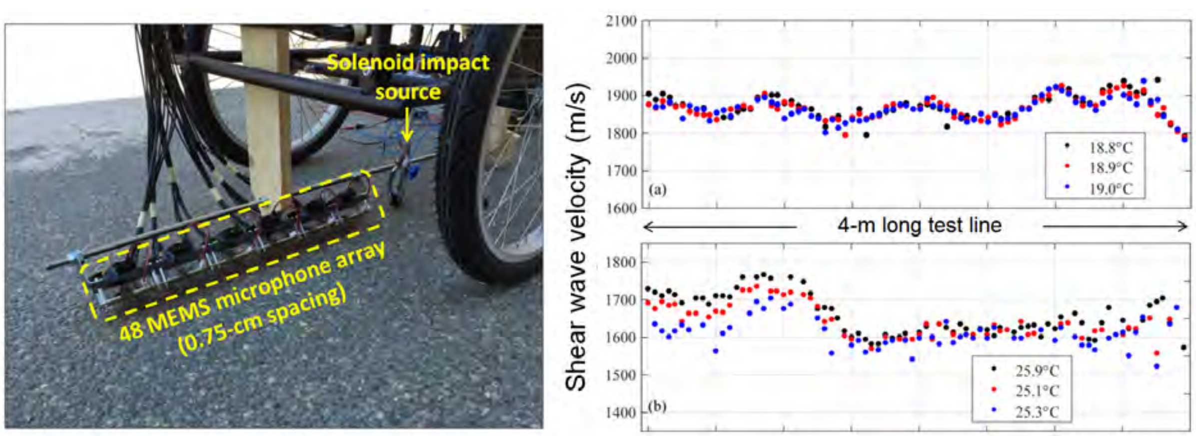


Figure 7. The first rolling measurement of the leaky-mode Lamb waves by using a 48-channel MEMS-microphone array (left) and analyzed shear-wave velocities at different temperatures (right) (Bjurström and Ryden, 2017).

SEISMIC APPROACH TO QUALITY MANAGEMENT OF HMA – AN MNDOT PROJECT

In January 2020, the Minnesota Department of Transportation (MnDOT) launched a project funded by National Road Research Alliance (NRRA) that builds such a system that one can routinely use in the field for the quality management of Hot Mix Asphalt (HMA) pavement by using a seismic method. When fully completed, the project will produce a 2D receiver-array system consisting of four (4) 1D MEMS microphone arrays arranged transversely so that a certain width of pavement (e.g., 4 ft) can be measured simultaneously. The system can be easily harnessed on a simple apparatus on the back of a car–for example, a bicycle rack. The survey vehicle can travel at a 10-30 MPH speed making a high-density rolling measurement, for example, one measurement every 2 ft. The on-board GPS and IR sensors record the location and temperature data, respectively, for geo-referencing and temperature-referencing of the final results of the velocity (Vs) and thickness (H). The dedicated software package installed on the on-board laptop computer analyzes incoming data in a fully automated mode to display the results on the computer screen almost in real time.

It is a 2-year project in which Park Seismic LLC (PSL) participates as the prime contractor and Norrfee Tech AB (NTA) participates as the subcontractor. PSL builds the software package while over sighting the entire project. NTA builds all the hardware components while providing technical consultations. NTA previously built the 48-channel system used in Bjurström and Ryden (2017) and Ryden et al. (2019) (Starkhammar et al., 2007). A dedicated web site in PSL home page provides details about all aspects of this project (parkseismic.com/HMA-Project.html). For example, the original project proposal, awarded contract, scope of the work, and the technical advisory panel (TAP) members are posted. The project progress has been updated every month at the site.

Hardware – Data Acquisition System. By referencing to the 48-channel system used in Ryden et al. (2019), another similar yet more appropriate system for this project had been designed. Considering the 2D nature of the receiver array consisting of multiple 1D arrays, it was discussed to reduce the number of channels per array so that the size of one field record does not become a challenge for the analysis software. After a series of field test followed by the numerical down-sampling simulations in number of channels, the optimum number was determined as 16 channels. The velocity (Vs) and thickness (H) results obtained from the down-sampled 16-channel field records were identical to those obtained from the full 48-channel records within an acceptable margin of difference (e.g., < 1%). A 64-channel National Instrument (NI) PXI system was procured that has a 16-bit dynamic range and a maximum 200 kHz sampling rate. The system saves output data in the NI format of Technical Data Management System (TDMS). It has a higher dynamic range than the predecessor (12-bit), which can make the measurement robust enough even under a high level of seismic wave attenuation especially during the warm-temperature surveys (e.g., > 20 °C). The system refresh time is faster, which is a great advantage for a quick in-field initiation of the new survey. The same overall length of the array previously used (i.e., ~35 cm) is kept. In consequence, the new receiver spacing became 3 times longer (2.25 cm) than the previously used (0.75 cm). Through numerical modeling , this receiver configuration was tested to be optimum for the thickness (H) in 5 cm $\leq$ H $\leq$ 30 cm and the velocity (Vs) in 500 m/s $\leq$ Vs $\leq$ 3000 m/s. Although double steel balls were used in Ryden et al. (2019) on both ends of the array to compensate for possible tilting effect of the array, only one source at front side is used for the new system. Using only one impact source is critically important for the final 2D array to avoid the wave interference from multiple sources. The array orientation will be maintained through different approaches. More details about the hardware development can be found at the project web site.

Software – ParkSEIS HMA (PS-HMA). The ParkSEIS (PS) software package developed for the ordinary MASW applications is used as the parent module to develop the new package for the project. The PS package mostly deals with surface waves in 1-300 Hz range to investigate depths in 0-30 m. The data-analysis module is based on the Rayleigh-wave dispersion equation (Schwab and Knopoff, 1972). In consequence, the core part of the PS algorithm had to be shifted toward the Lamb-wave dispersion properties, while the time/frequency and distance scales had to be significantly downsized in both analysis and display modules. The new software package under development is named ParkSEIS-HMA (PS-HMA). The package also has a limited acquisition-control module that can set a few recording parameters that can critically influence the quality of field data such as triggering level of impact sound, pre-trigger time, number of samples, etc. The key points during the PS-HMA development have always been on the accuracy of the results (Vs and H), fast analysis speed, and the full automation of the process. The fast speed is essential for the on-site quality control purposes. The full automation is also essential to handle thousands of field records obtained from a single survey.

PS-HMA (Sound Wave Mute). The first pre-conditioning applied to the raw field record is the mute process to eliminate the impact sound wave that is always recorded as the most energetic wave event. If not properly suppressed, its energy dominates the entire frequency-phase velocity spectrum during the subsequent wavefield transformation (Park et al., 1998), resulting in a dispersion image where the signal Lamb-wave energy is completely missing (Figure 8). The mute process must remove the sound wave with a proper tapering window to avoid the harmful effect of the reverberation that can reduce the accuracy during the evaluation of Vs and H. At the same time, the process should leave the signal Lamb waves intact. When the offset of the impact source (X1) is long enough compared to the receiver array length (L) (e.g., X1 $\geq$ 1L), both arrivals of Lamb and sound waves are well separated in the time-offset space. An automatic mute approach based on the pre-trigger time can then be enough effective. The Lamb waves, however, can rapidly dissipate due to the attenuation when X1 becomes long. X1 therefore usually has to remain within a fraction of the array length (e.g., X1 $\leq$ L/2). This tight distance of X1 and occasional inconsistency in the sound waveform make the pre-trigger-time-based mute approach less consistent and less reliable. A time-offset method that employs the

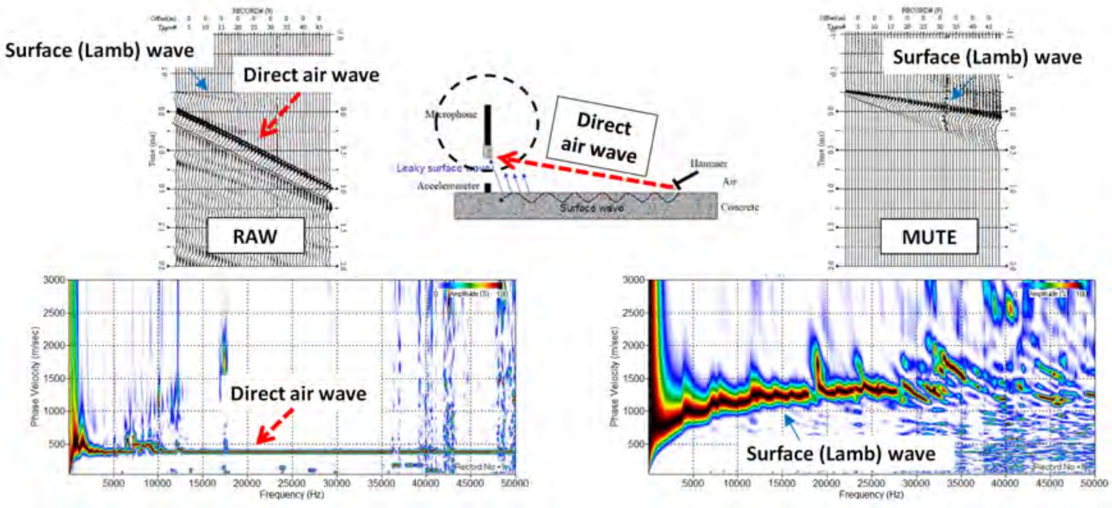


Figure 8. A raw field record and its dispersion image (left column) and the same record after air-wave mute and its dispersion image (right column).

linear-move-out (LMO) stacking (Yilmaz, 1987) has been developed that automatically detects the onset time and apparent velocities of Lamb and sound waves. It then applies the mute process with the most optimum parameters. More details can be found at the project web site.

PS-HMA (Evaluation of Vs and H). A new approach, rather than conventional ones, has been developed to evaluate the velocity (Vs) and thickness (H) in a sequential mode. It is based on the fundamental-mode asymmetric Lamb dispersion curve (A0) at the high frequency side (e.g., 20-30 kHz) for the velocity (Vs) evaluation. It then calculates the thickness (H) by comparing theoretical A0 curves, of the same value of evaluated Vs, for different thicknesses (H's) at relatively low frequencies (e.g., 1-20 kHz). This approach can be fully automated through the frequency-summation approach by Park (2016). More details can be found at the project web site.

PS-HMA (In-Field and In-Office Modules). The startup graphical-user-interface (GUI) of PS-HMA is displayed in Figure 9 showing that the package consists of basically two major modules; in-field and in-office. The in-field option pursues the fastest analysis so that the field-data monitoring and visualization of the results can be available during and right after the survey. It accomplishes the goal through the spatial down-sampling of field records; for example, 4 ft x 2 ft resolution from actual 2 ft x 1 ft resolution. The reduced sampling density, however, is still high enough for on-site quality management. The in-office option will use the full data density so that the results of the highest spatial resolution can be available within hours after return to the office. In addition, a more advanced inversion approach can be chosen to run overnight so that a new set of results can be available next morning. There are multiple display modules in PS-HMA that can depict the quality of the raw field records during the survey. For example, a module can display the signal-to-noise ratio (S/N) of each record just obtained, while another module displays its spatial location based on the GPS data. In PS-HMA, all incoming records are processed almost in real time and the new results are continuously added on the existing charts of Vs and H displayed on different tabs.

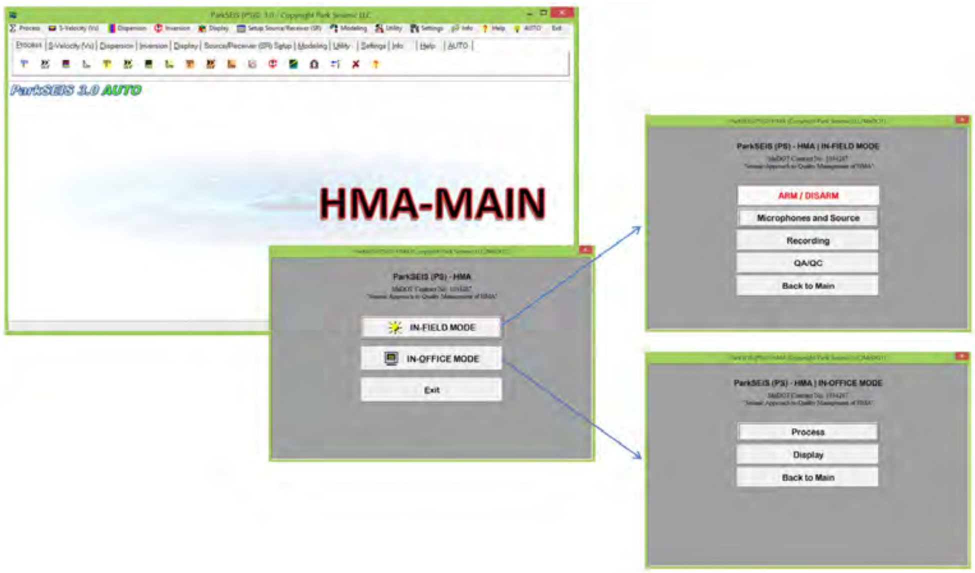


Figure 9. The main graphical user interface (GUI) of the ParkSEIS-HMA (PS-HMA) software package that shows two modes of operation; "In-Field Mode" and "In-Office Mode." GUI's for each mode are shown on the right.

FIELD TEST WITH 1D (16-CHANNEL) ARRAY

A new 16-channel data-acquisition system was built at Norrfee Tech as of February 2021 that used a 1D receiver array of MEMS microphones spaced with a 2.5-cm interval. Figure 10 shows a photo of the array harnessed on a bicycle rack of a passenger car. The array was covered by cloths to protect it from the moisture and gravels on the road. A small rolling impact source is attached to a separate rigid frame attached to the rack, not to the array itself, to minimize the transmission of impact vibration to the receiver array. The array is attached to the rack by using two holding plates to strictly maintain the parallel orientation with the ground surface. The photo taken from the back side shows that the array is slightly tilted along the transverse direction. This is to reduce the amount of sound waves trapped between the array and the ground that will reduce the S/N.

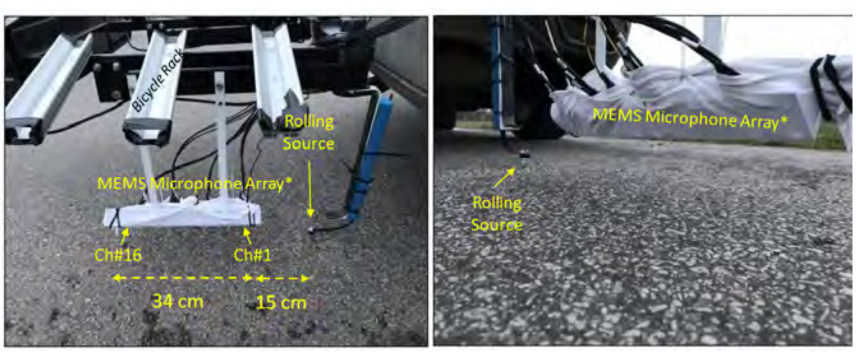


Figure 10. Side (left) and back (right) views of the 16-channel MEMS microphone array.

Joint Field Test (JFT) of Hardware and Software (Lund, Sweden). Norrfee Tech performed the first field test of both hardware and software components on February 23, 2021, on a road near Lund, Sweden. The purpose was to jointly test the hardware system of the newly developed 1D 16-channel MEMS microphone array and the ParkSEIS-HMA software package (PS-HMA) for the 1D system under a real survey condition. The survey vehicle moved at about 16 knot/hour (~20 MPH) speed for about 3 minutes to travel approximately 1.2-km distance. The survey collected forty (40) production TDMS files of fifty (50) records per TDMS file. As a result, a total of 2000 records of 16-channel acquisition were collected. Number of records and the survey distance indicate that, on average, one record was collected every 2-ft distance. The PS-HMA was performing file transfer, conversion, and subsequent data analysis in pseudo-real-time mode inside the survey vehicle (Figure 11). Figure 11 also shows all data points marked on a Google map. This map was created separately after survey by using the GPS data, that was recorded every one second during the survey, and the time stamp encoded in each 16-channel record. It will be, however, similar to the display mode incorporated in the final version of the PS-HMA. Figure 12 shows one of the PS-HMA QA/QC modules that displays the signal-to-noise ratio (S/N) of the acquired records almost in real time (with a few seconds lag). It also identifies false-trigger (FT) records that are discarded from the subsequent analysis. There were eight (8) FT records out of 2000 total records collected, resulting in an extremely low FT ratio (0.4 %).

Figure 11. The on-board PS-HMA software processing data almost in real time during the joint field test (JFT) (left) and sampled data points plotted on a Google map (right).

Joint Field Test (JFT) – Results. The data-analysis results were being displayed on the on-board computer screen almost in real time during the survey (with a few minutes lag on average). They showed acquired Lamb waves have extremely high signal-to-noise (SN) ratio of about 93% (Figure 13); e.g., a SN of 100% means all Lamb waves and no noise, while 0% means all noise and no Lamb waves. This unusual quality seems to be the result of the high fidelity of the new acquisition system. It seems the low-temperature of the asphalt also contributed to the high quality because of the low attenuation of the seismic waves. Figure 13 shows the results of velocity (Vs) and thickness (H) being displayed on separate tabs in PS-HMA during the survey. The temperature data (T) were also being displayed on its own tab. The results of shear-wave velocity (Vs) showed an average of about 1800 m/s, while those of the thickness (H) showed an

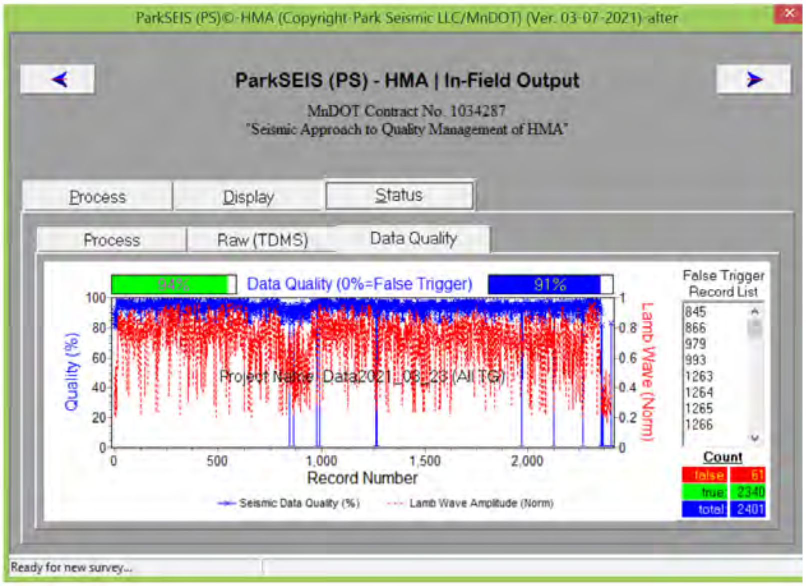


Figure 12. A PS-HMA display showing data quality.

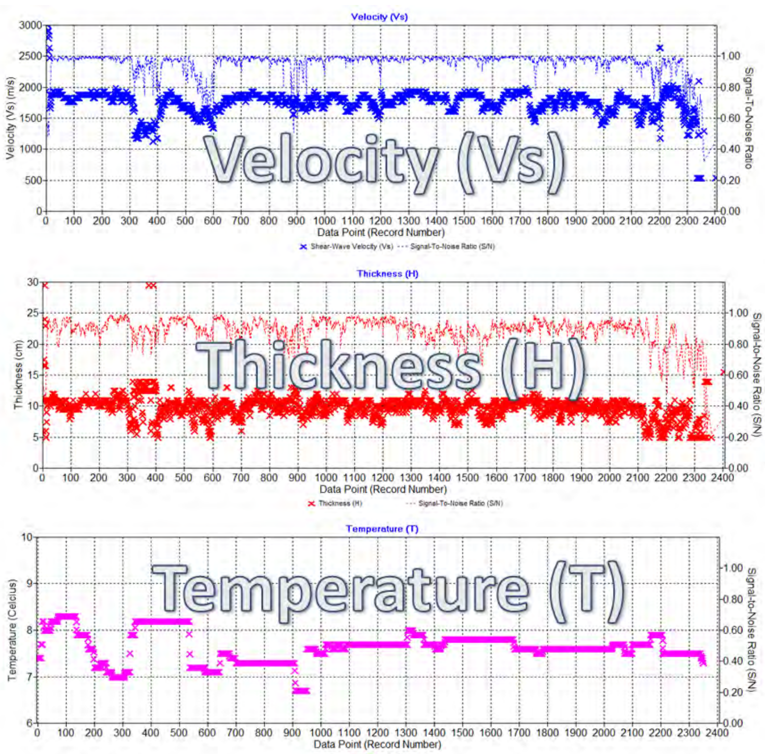


Figure 13. Results of velocity (Vs) and thickness (H) of HMA pavement being displayed during the survey in the PS-HMA software in reference to the measured temperature. They are displayed in three (3) different tabs in the software.

average of about 10 cm. Both values seem highly reasonable and realistic. The temperature data showed an average of 6.5 degrees in Celsius with ±0.5 °C variation along the entire road surveyed. One example of 16-channel field record is presented in Figure 14. It shows an extremely high-quality Lamb waves that are visible even in the raw-data display. After muting the sound waves, the Lamb waves look as if they were numerical data without any noise at all.

DISCUSSION

Figure 15 shows the design of the 2D receiver array currently being discussed among the investigators. The main purpose of the 2D array is to survey a certain width of road simultaneously in one survey trip. The configuration in the figure is the most optimum arrangement of multiple 1D arrays that uses one common impact source. The possibility of using multiple sources dedicated to each 1D array was discarded at the early stage of the project development. This was due to possible complications arising from the interference of both Lamb and sound waves generated by other sources. The configuration also allows maximum transverse coverage for a given source offset (X1). A longer X1 can result in a 2D array that can cover a wider width of the road (i.e., dY $\propto$ X1). Because of the attenuation property of the asphalt, it seems X1 can only be extended to a fraction of the array length (L); e.g., X1 $\leq$ L/2. As the degree of attenuation changes with temperature, X1 should be adjustable in the final array frame. The optimum X1 at different temperature ranges (e.g., 0-10 °C, 10-20 °C, 20-30 °C, etc.) will be established in the near future through field test by using the current 1D array.

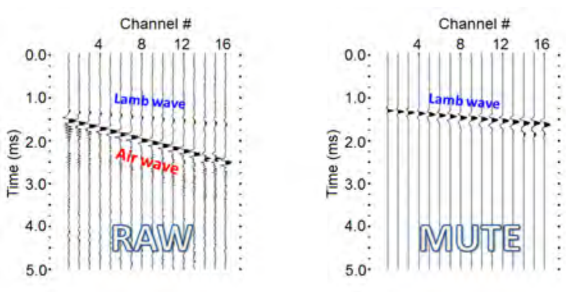


Figure 14. A typical 16-channel raw field record collected during the joint field test (JFT) survey (left) and the same record after air-wave mute (right).

The current concept of rolling impact source with a small metal ball (or object) is currently being scrutinized to find the ways to control the impact strength, spatial interval, and possibly spectral bandwidth of the generated Lamb waves. It seems, however, a separate research topic just begun.

The software package (PS-HMA) will soon include an X-Y map to display the measured points, possibly with a pre-inserted Google map. It will then enable the surveyor to examine whether a sufficient spatial sampling has been achieved or not. Then, the survey may continue at certain areas to fill more data points.

CONCLUSTIONS

A system of 16-channel MEMS-microphone array flying about 10-cm over the HMA pavement at a speed of 20 MPH successfully recorded the leaky-mode Lamb waves of extraordinary quality. During the field survey, the small metal impact source attached to the system frame and hanging down in front of the array spontaneously generated the high-quality seismic waves at a 2-ft interval on average along the 1.2-km HMA road. The on-board dedicated software package analyzed the acquired 2000 records almost in real time and displayed the results of velocity (Vs)

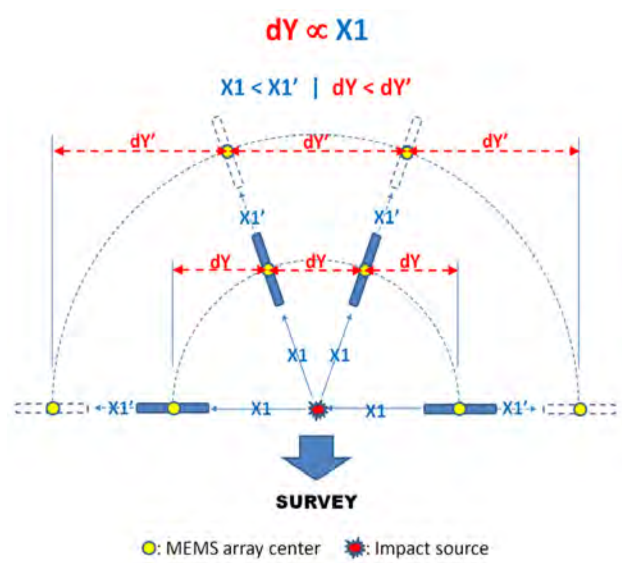


Figure 15. Schematic of the future 2D receiver array consisting of four (4) 1D arrays to survey a certain width of the road simultaneously with an equal transverse interval (dY).

and thickness (H) of HMA pavement with reference to measured temperature at each sampled point along the surveyed road. Although the strict accuracy of the results still remains to be further examined, the analyzed values appear highly reasonable and realistic considering all circumstances. In this sense, the preliminary conclusion is that the approach is a practical HMA quality management tool that can be routinely and conveniently used in the field. When fully completed, the final 2D system will consist of multiple number of current 1D components to cover a wider area of the road simultaneously, presenting an even more practical approach.

ACKNOWLEDGMENTS

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Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Final Report – APPENDIX IV

TAPPER 64 – User's Manual

Park Seismic LLC
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Shelton, Connecticut

July 29, 2022

Seismic System for HMA Evaluation (TAPPER 64)

Seismic System Developed Under

MnDOT Contract No. 1034287
"Seismic Approach to Quality Management of HMA"
January 2020 - June 2022

User's Manual

Prepared By

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Principal Geophysicist
Park Seismic LLC

June 2022

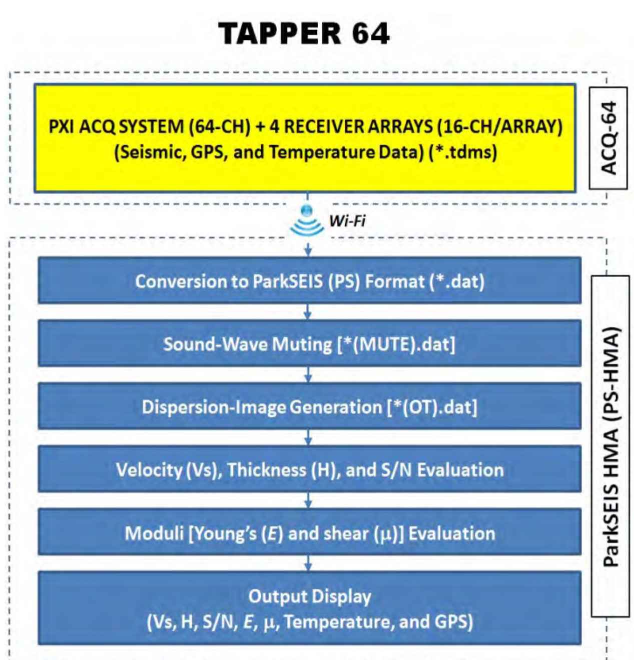
Table of Contents

1. Overview

TAPPER 64 is a 64-channel seismic system that collects seismic data in a rolling mode along the hot-mix-asphalt (HMA) road by using four (4) MEMS microphone arrays (16-channel each). The four (4) arrays are transversely arranged to cover a certain width of HMA pavement simultaneously (adjustable within 0.5 m - 1.0 m). The onboard laptop computer analyzes incoming seismic data automatically and displays output results of shear-wave velocity (Vs), thickness (H), Young's (E), and shear (μ) moduli, and temperature of HMA pavement with respect to distance (m) and GPS coordinates in plan view maps. The system records the leaky-mode seismic (Lamb) surface waves generated from an impact source located at equidistance from each array. The Lamb waves initially travelling horizontally along the pavement surface are transmitted into the air above the pavement surface ("leaked") in the form of sound waves, which are then detected by the MEMS microphones. Historical development of underlying theories is well described in the original proposal to the project (MnDOT Contract No. 1034287 | "Seismic Approach to Quality Management of HMA") that funded the development of this system. TAPPER 64 represents a technical realization of the two-decade-long studies.

The most sensitive part of the acquisition system is the impact source that can directly influence on the quality of acquired data. It is a small bolt with cap nut tightened in a zip tie, which is attached to a vertical rod installed in front of the arrays. It is hanging down on the pavement surface in a slant angle. The receiver-array panel is harnessed on the back of a survey vehicle into a 2-in hitch receiver. When the vehicle starts moving, the impact source will initially drag on the pavement surface. Then, it will soon start bouncing up and down to generate impacts once the vehicle reaches at a cruising speed between 20 and 30 MPH. Each impact-generated high-pitched sound is detected by channel #1, which will then make the PXI recording system record a 64-channel 5-ms seismic data with 1.5-ms pre- and 3.5-ms post-trigger times, respectively. Each record will also include temperature (°C) and GPS (LAT/LON) data measured near the impact point. When 20 of such records are stored in the memory, they are saved as one TDMS file in a folder of PXI, which is also a stand-alone Windows computer.

Whenever a new TDMS file is saved, the ParkSEIS-HMA (PS-HMA) software package installed on an onboard laptop computer will start processing it immediately. The laptop computer communicates with the PXI via Wi-Fi connection and therefore can "view" the PXI computer whenever necessary through the remote desktop connection from the onboard laptop computer.

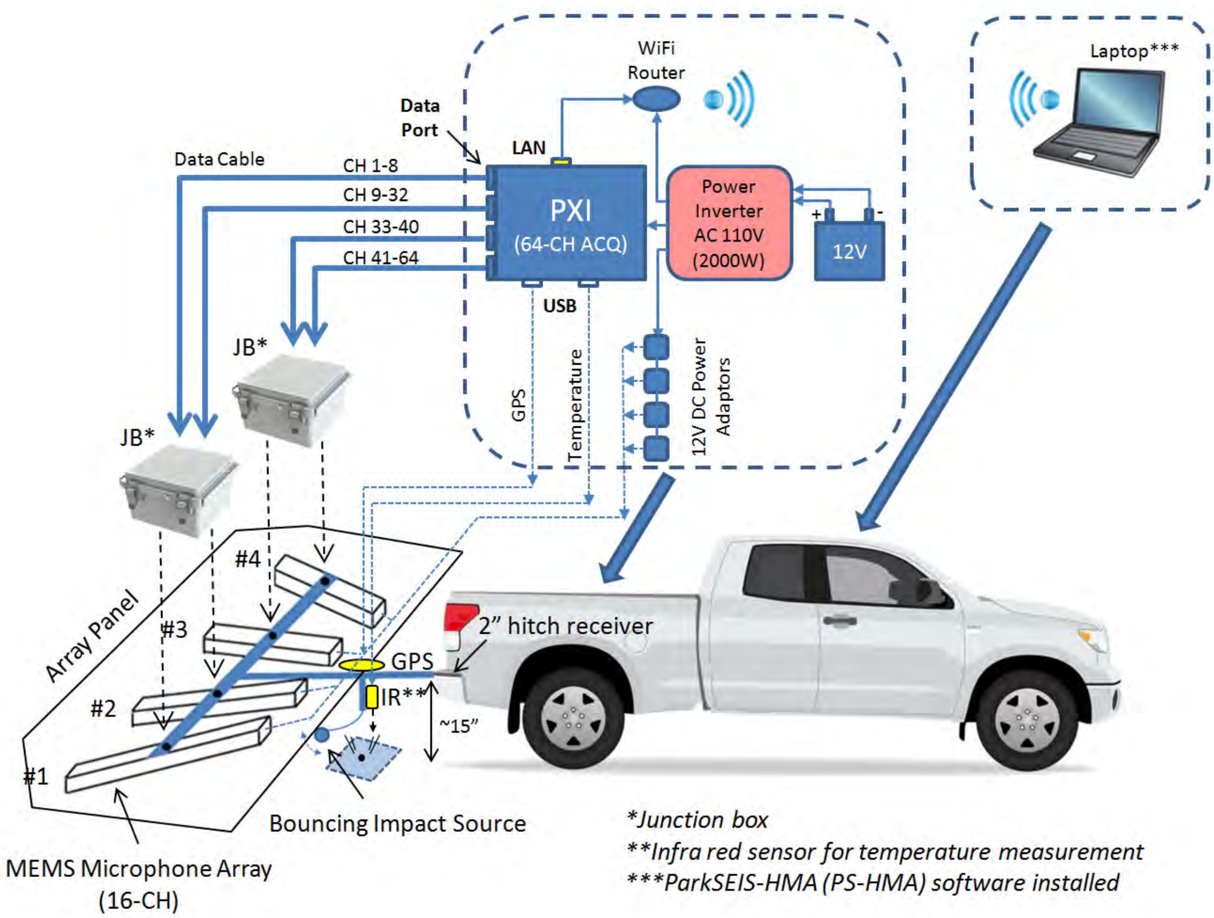


The 64-channel acquisition system (ACQ-64) is designed and built at Norrfee Tech AB in Lund, Sweden, by expanding the 1D system previously developed for a study in 2019. The ParkSEIS-HMA (PS-HMA) software package is developed by expanding its parent package of ParkSEIS AUTO (v. 3.0) first released in September 2017. The overall architecture of TAPPER 64 is presented in a schematic displayed in this page.

2. Overall System Schematic and Photos

2.1 System Schematic

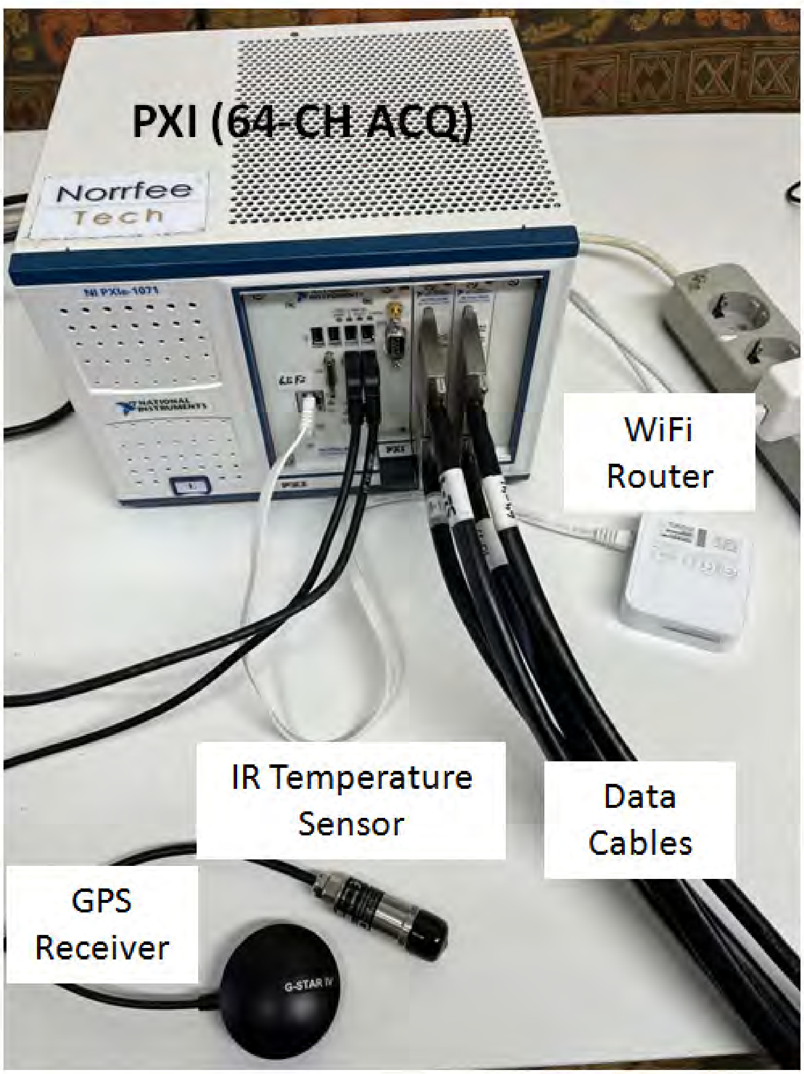
All hardware components for data acquisition (ACQ-64) consist of four (4) MEMS microphone arrays (16-channel per array) and a 64-channel National Instrument PXI recording system. Pushing the switch once will turn on the PXI system, which is a stand-alone Windows computer that automatically runs the acquisition control software as a startup program. A separate laptop computer has the ParkSEIS-HMA (PS-HMA) software package installed, which controls several key features of PXI system (e.g., recording parameters, initiation and termination of recording) and performs all steps of data analysis and display of the results. PXI and laptop communicate via Wi-Fi connection. PXI does not have its own dedicated display monitor, while the laptop can access it through the remote desktop connection whenever necessary. To start a new survey, turn on the PXI first and then laptop. When first booted, it usually takes about two minutes until both computers fully establish the wireless connection. Launch the PS-HMA program on the laptop. See the "Quick Guide for New Survey" for more details.

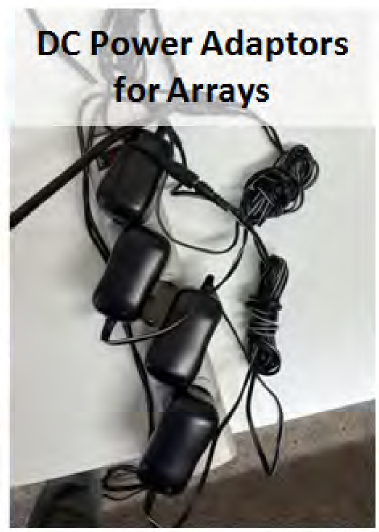


2.2 Item Photos

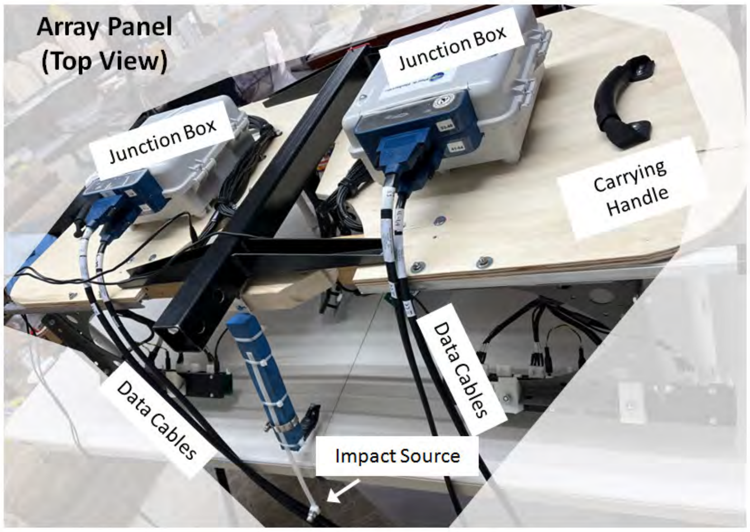
Array Panel Connected to Survey Vehicle (2" Hitch Receiver)

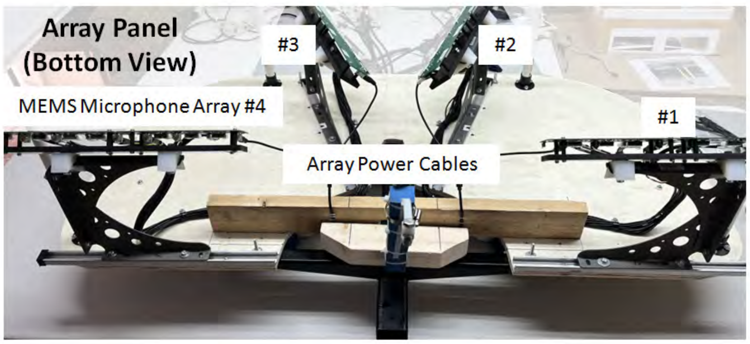
PXI Recording System and Peripherals



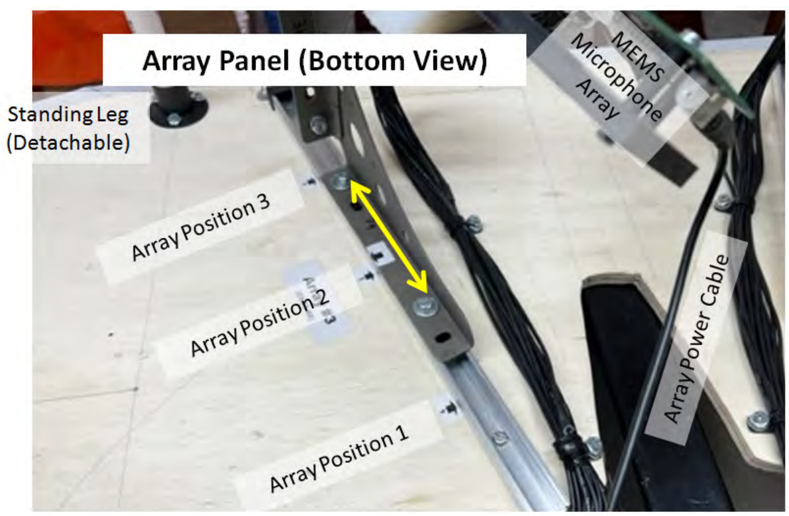


MEMS Microphone Arrays (4 x 16-channel arrays) and Array Panel (Top and Bottom Views)



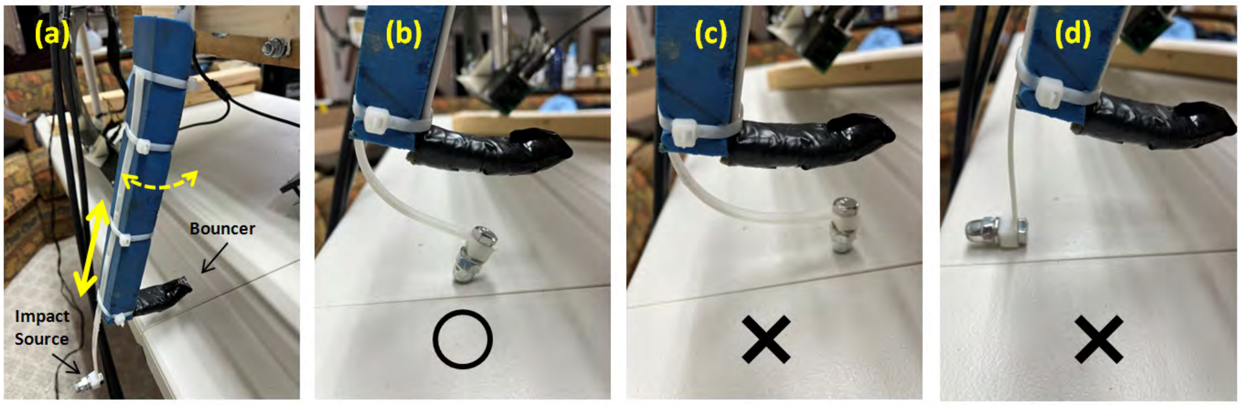


Sliding Array Holder



3. Impact Source

The impact source (a 5/16-in bolt with cap nut) is screwed into the head of a zip tie, which is attached to the hanging foam road by using thin zip ties (a). The foam road can be slightly bent, if necessary, to adjust its height above the ground surface (a). The bouncer will prevent the source from over swinging. The length of the source zip tie below tip of the holding rod is important. It should be just enough length to make the zip tie properly angled with respect to the ground surface (b). If it is too long (c), it will simply drag on the surface without making impacts. It will not make impacts, either, if it is too short (d).



4. Quick Guide for New Survey

CAUTION: ***The MEMS microphone arrays are only 4-5 inches (about 10 cm) above the pavement surface. To protect the arrays from damage, it is critically important to use the system on a flat road surface without any surface objects. It is recommended driving slowly around the survey site beforehand to examine the surface condition.***

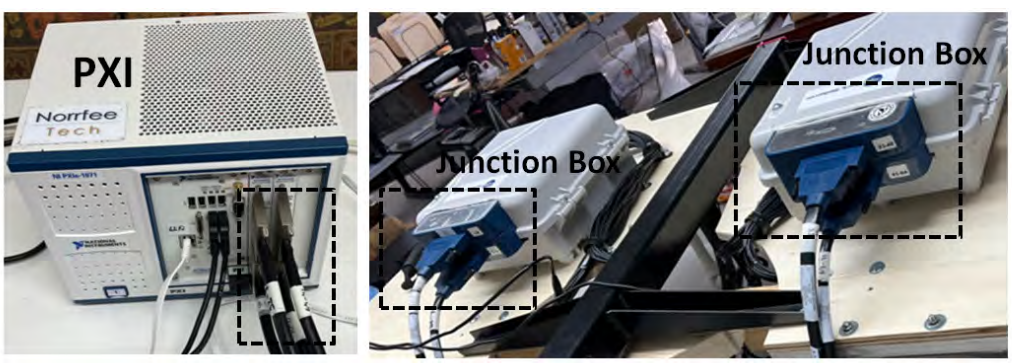
To start a new survey, please follow the steps outlined below. How to properly prepare hardware components is outlined first, and then the procedure to set the software settings is described.

4.1 Hardware Setup

1. This step is optional. Before heading to the survey site, prepare an orthophoto file of the site map by following the procedure described in the "How to Prepare an Orthophto" in the "Using GPS Display" section. Copy the file (*.gcf) on a USB drive that can be plugged in the laptop computer whenever the ParkSEIS-HMA (PS-HMA) software needs it to display the Google map on the background of GPS points. The PS-HMA will display GPS points without background satellite map if the file is not available.

2. Insert the array panel to the 2-inch hitch receiver on the back of the survey vehicle.

3. Connect 4 data cables between PXI and junction boxes by carefully checking the channel numbers labeled on the cables and junction boxes.

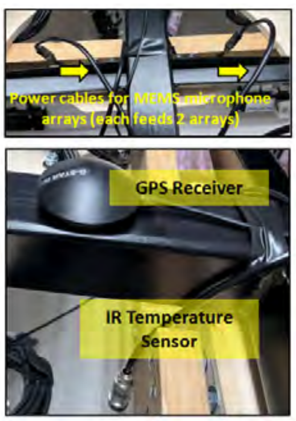


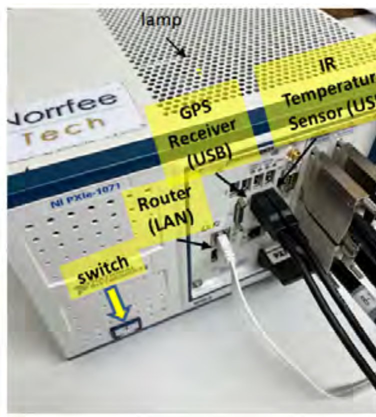
4. Connect DC (12V) power cables (2 of them) to MEMS microphone arrays. See the photo below. Each female power cable attached on the array panel is connected to 2 arrays. Connect WiFi router to the LAN port of the PXI. Connect GPS receiver and IR (temperature) sensor cables to the USB ports of PXI. Place the GPS receiver, which has a mounting magnet at the bottom, on

top of the metal beam of the array panel. Place IR (temperature) sensor on the front side of the bar holding the impact source by using a black tape. Its sensing tip should be pointing down toward the pavement surface.

5. Connect the power inverter to a12V car battery. See the photo below. Turn the inverter on. Connect all power cables to the inverter (or to the power strip connected to the inverter); i.e., power cables for PXI, MEMS microphone arrays, and WiFi router. Make sure all power lights are on in the router and power adaptors for arrays. The lamp inside PXI will be on once its power cable is connected to the power source even if it is not turned on yet. It is recommended not to connect PXI to the power source when it is not used.

6. Turn on the PXI by pushing its power switch once. See the photo below. PXI is a stand-alone Windows computer. It should be turned off through a proper way as explained later in the software setup. Never use the physical switch to turn it off. Wait for 2 minutes so that the windows operating system in PXI is fully loaded and the startup ACQ software is properly initiated. At this time, turn on the laptop computer that has the ParkSEIS-HMA (PS-HMA) software package installed. Follow the steps described in the "Software Setup."

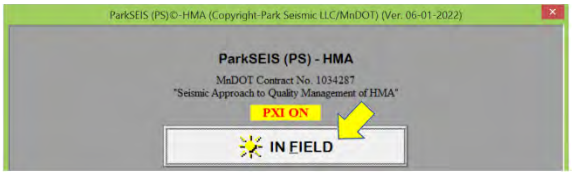




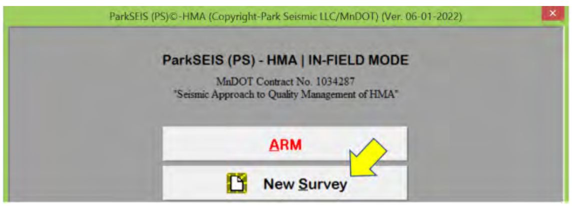
4.2 Software Setup

1. In 2 minutes after the PXI is turned on, run the ParkSEIS-HMA (PS-HMA) software in the laptop computer. If the PS-HMA main dialog shows "PXI ON" in a yellow label, then it means both computers (i.e., PXI and laptop) are communicating via Wi-Fi connection. The acquisition system is ready. Proceed to setup the software properly. Otherwise, close the PS-HMA program and wait for another 1 minute to run it again when PXI is ready.

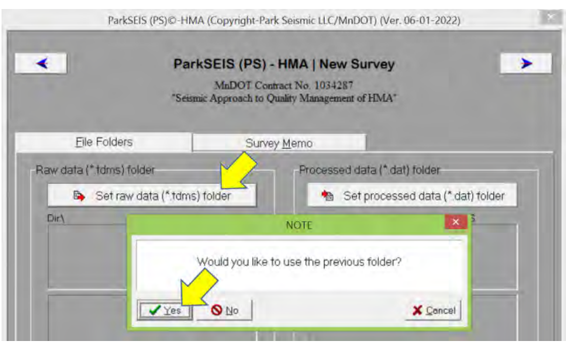
2. Click the "IN FIELD" button.



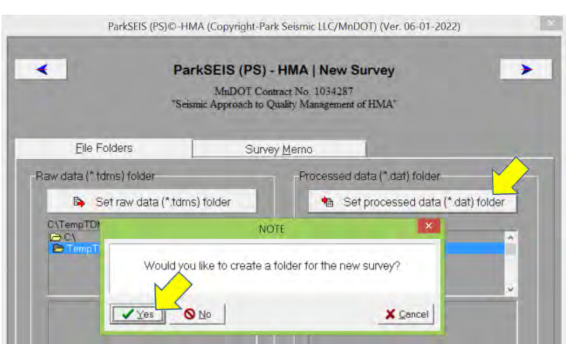
3. Click the "New Survey" button.



4. Click the "Set raw data (*.tdms) folder" button. This is the folder in PXI computer where the raw data files are saved, which is mapped via Wi-Fi as a network folder in the laptop. Click "Yes" to use the folder already set previously. Otherwise, find and assign the network folder (e.g., "M:\MeasurementFiles").

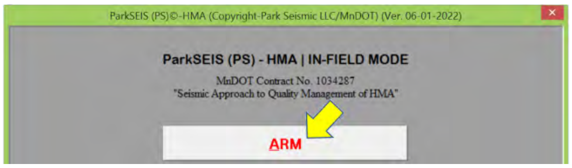


5. Click the "Set processed data (*.dat) folder" button. This is a new folder being created in the laptop where all processed files are saved. Click "Yes" to create a folder for the new survey. It will create a project folder within a designated directory ("c:\Seismic Data"). For example, a folder "c:\Seismic Data\Data2022_06_01" will be created for the first survey on June 1, 2022. If another survey is executed on the same day, then a new hyphenated folder will be created (e.g., "c:\Seismic Data\Data2022_06_01-1").



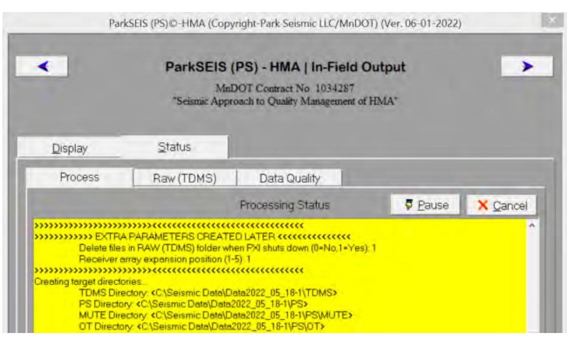
6. Click the back arrow to go back to the previous menu.

7. Click the "ARM" button.

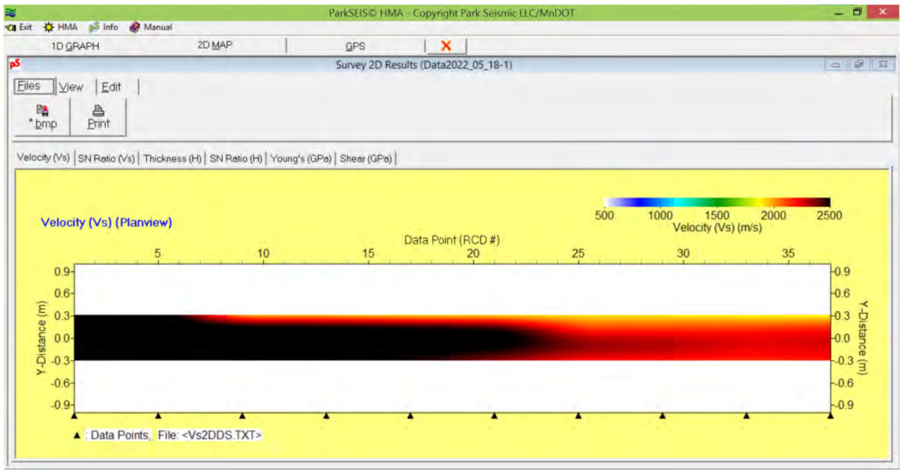


8. The system is now armed and will record data whenever an impact is detected from the high-pitched sound in channel #1. The survey can now proceed by driving the vehicle at a cruising speed (20 - 30 MPH). It is important to move within the cruising speed. An excessively slow speed (e.g., < 10 MPH) will not generate impacts, while a fast speed (e.g., > 30 MPH) can make the impact source string torn apart if the pavement surface is rough. Once a raw seismic file is saved in the PXI folder and this is detected by the PS-HMA software, then the program will start processing data files. Each data file (*.tdms) contains twenty (20) records created from twenty (20) consecutive impacts. Each record has 5-ms data samples from all 4 arrays of 16 channels each (a total of 64 channels). Not all impacts will create the records. Only those impacts that generate solid high-pitched sound will trigger the system to record the data. Some records may contain sound waves only if ambient noise triggered the recording or may not have the leaky seismic (Lamb) waves if the impact was not strong enough. These records are, however, usually properly handled by the subsequent data analysis by PS-HMA program.

   Once the proceeding survey properly generates impact and the PS-HMA program starts processing, then it will show the progress in the status tab in yellow color. The status tab will turn into green color when the analysis of all collected raw files (*.tdms) is finished.

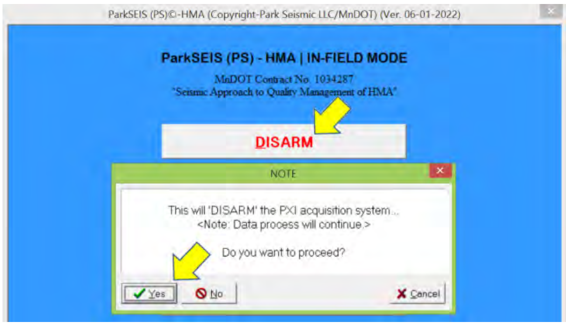


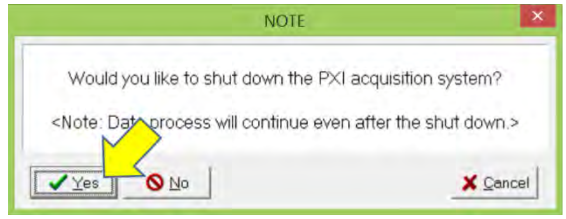
   Process results of each file (20 records) will be displayed as illustrated below. Displays will be continuously updated as more files are processed.



The survey vehicle may continue to proceed for about 1 minute. This will collect about 50 files (1000 records) and have traveled several hundred meters of distance (about 1000 ft). Then, the vehicle can stop until the entire procedure of data anlaysis finishes. It will take about 20 minutes to finish the process. During this period, the PS-HMA main dialog will disappear and only the display of results will be visible. Clicking the "HMA" menu, as illustrated below, will always invoke the dialog again if the process status needs to be checked again.

If the survey is finished at the current site, it is recommended, while waiting for the process to finish, to "DISARM" the PXI system and then shut it down completely to minimize unexpected system risks (e.g., sudden power loss). To do so, go back to IN FIELD main menu in the PS-HMA dialog. Then, click the "DISARM" button as illustrated blow. The message will inform that the current data process will continue even after disarm. The program will then ask if you wish to shut the PXI down. Click "Yes" and then wait for the process to finish. It will take about 1 minute for PXI to shut down.





Never shut down PXI by using the physical switch because it is a stand-alone computer with Windows operating system. It should always be shut down through PS-HMA software. If this approach fails for any reason, then it should be shut down via remote desktop access by clicking the icon in the system tray as illustrated below.

To survey a long distance (e.g., > 1000 ft), stop and wait for current data-analysis process to finish without disarming the system. Then, continue the survey for about 1 minute again. Repeat this procedure multiple times to finish the planned survey distance (e.g., 5000 ft). This is the safest way to avoid the potential memory loss in both computers that may cause unexpected program crash. Once the system is disarmed, next new survey will have to take place after PXI is completely shut down and then turned on again.

5. Software – ParkSEIS HMA (PS-HMA) Package

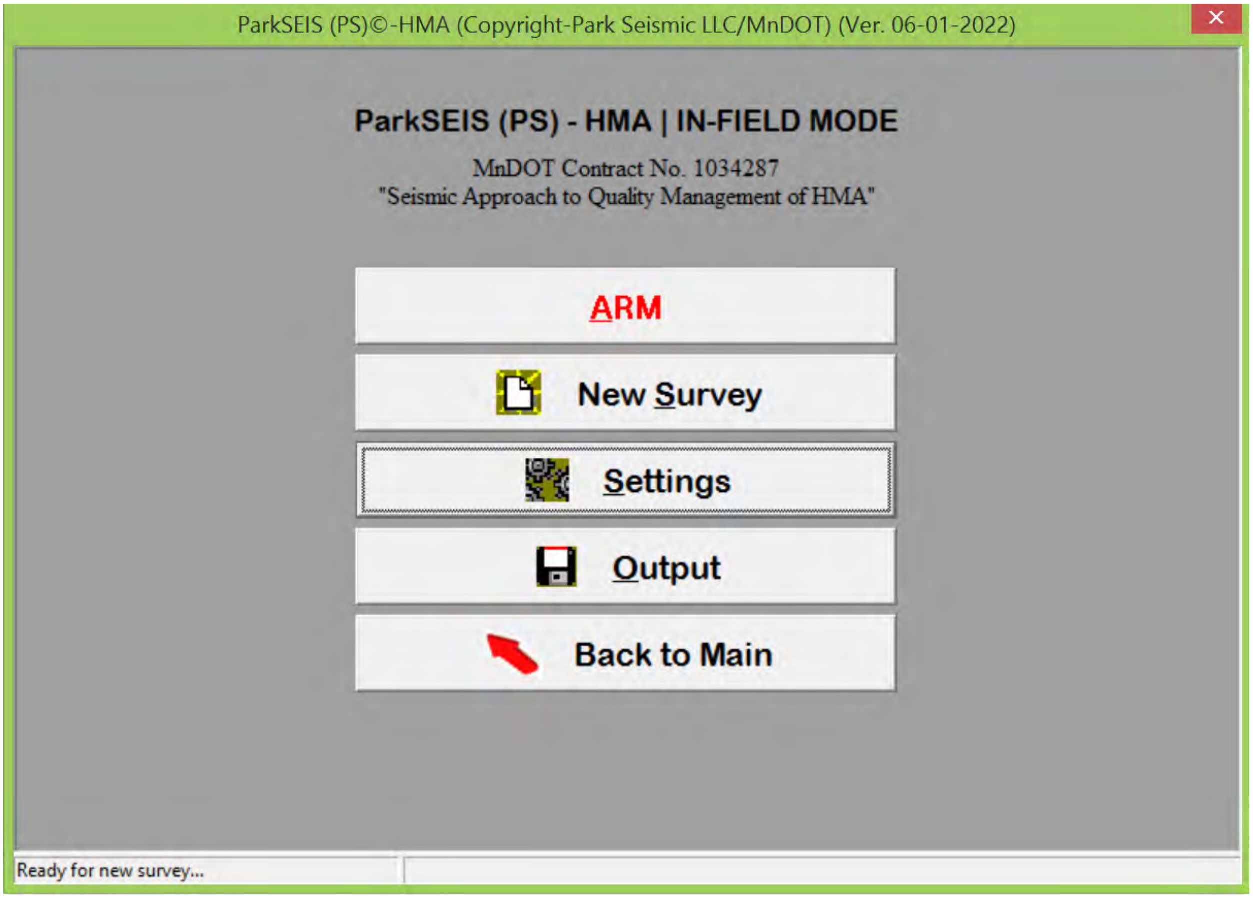
The main component of the software package ("PS-HMA Main Dialog") is explained here. The other subsidiary components (e.g., "Info" and "Tools") are self-explanatory.

5.1 HMA Main Dialog

IN FIELD To begin a new survey in the field. This will control the recording system (PXI) and will process seismic files as they are collected in pseudo-real time mode. It will display process results of shear-wave velocity (Vs) and thickness (H) of the HMA pavement in plan view maps. Young's and shear moduli maps are also displayed. Surveyed points (impact points) are displayed from GPS data in UTM coordinates. A site Google map file (*.gcf) prepared in an orthophoto format can be imported in the background. Other QA/QC related parameters are also displayed (e.g., signal-to-noise ratios).

IN OFFICE After the survey, the collected data sets can be re-processed with different parameters (e.g., using a more-advanced algorithm), which will take a longer time than the usual process time taken by the "IN FIELD" mode. All survey results (Vs, H, moduli, QA/QC, etc.) and log files (e.g., survey memo) can be displayed in plan view maps (Vs, H, and moduli), charts (QA/QC), and ASCII files (log files). The key output results (Vs, H, moduli, and GPS) can be displayed in ASCII files, which can be imported into Excel. Seismic data files acquired during the survey can be displayed.

5.2 IN FIELD MODE



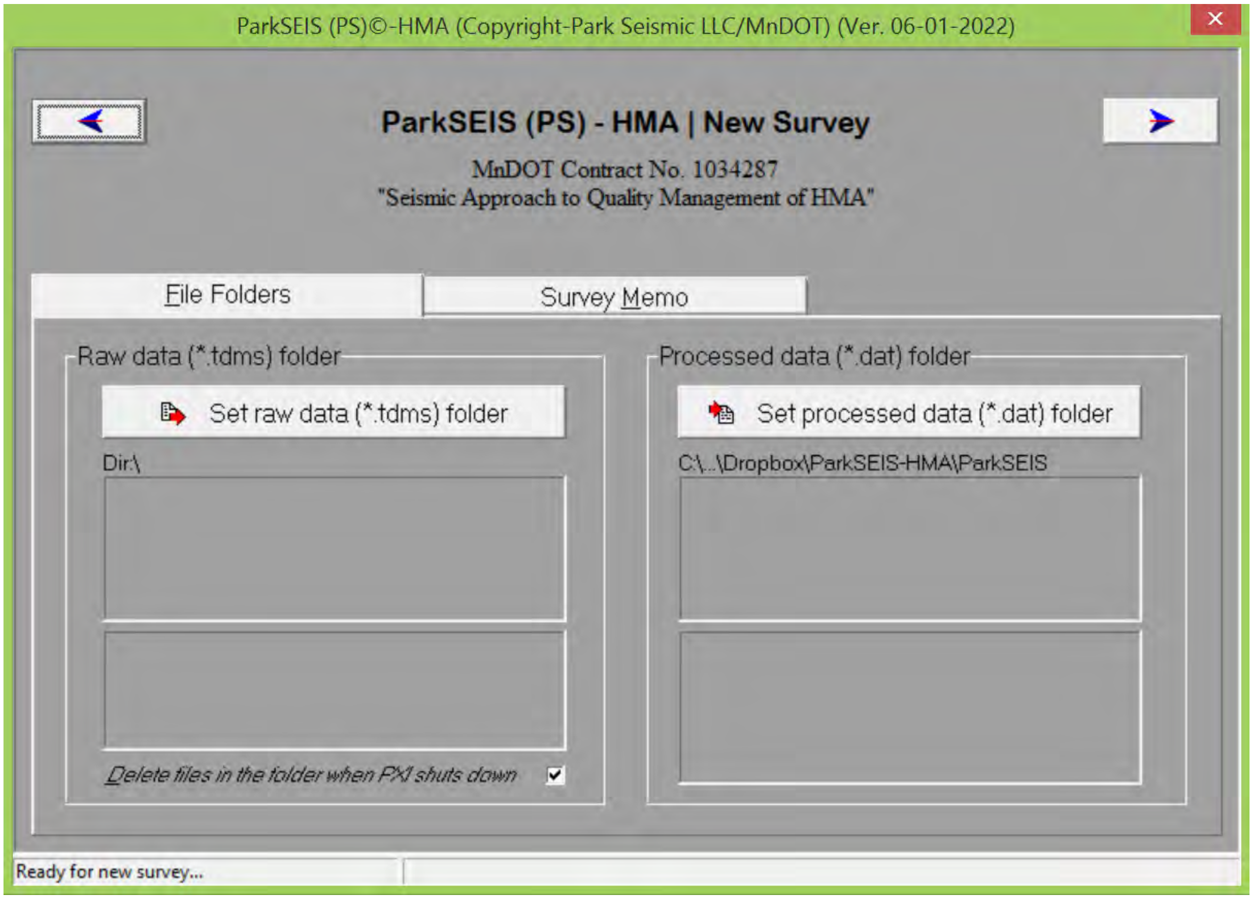
ARM Arms PXI system (that must be turned on at least two minutes before the PS-HMA program runs). Any external impact sound will trigger the system to record data from all (4) MEMS microphone arrays. Pressing this button again will "disarm" the system so that it will not respond to the external impact sound. The system must be armed only after file folders are set by pressing the "New Survey" button.

New Survey To begin a new survey, the button has to be pressed first to specify the folders for input (raw) seismic files and analyzed output results.

Settings All parameters related to data acquisition of PXI system and data analysis by PS-HMA program can be changed here. The key parameters are data averaging (binning) size, spatial sampling size, evaluation method, Poisson's ratio, and density values. Default values, however, will be optimal unless there are special reasons to change them.

Output Status of raw field file conversion, data quality variation, and corresponding analysis progress is displayed. All results of a previously executed survey can also be displayed. This can also be accomplished through the "IN OFFICE" mode.

5.2.1 IN FIELD | New Survey

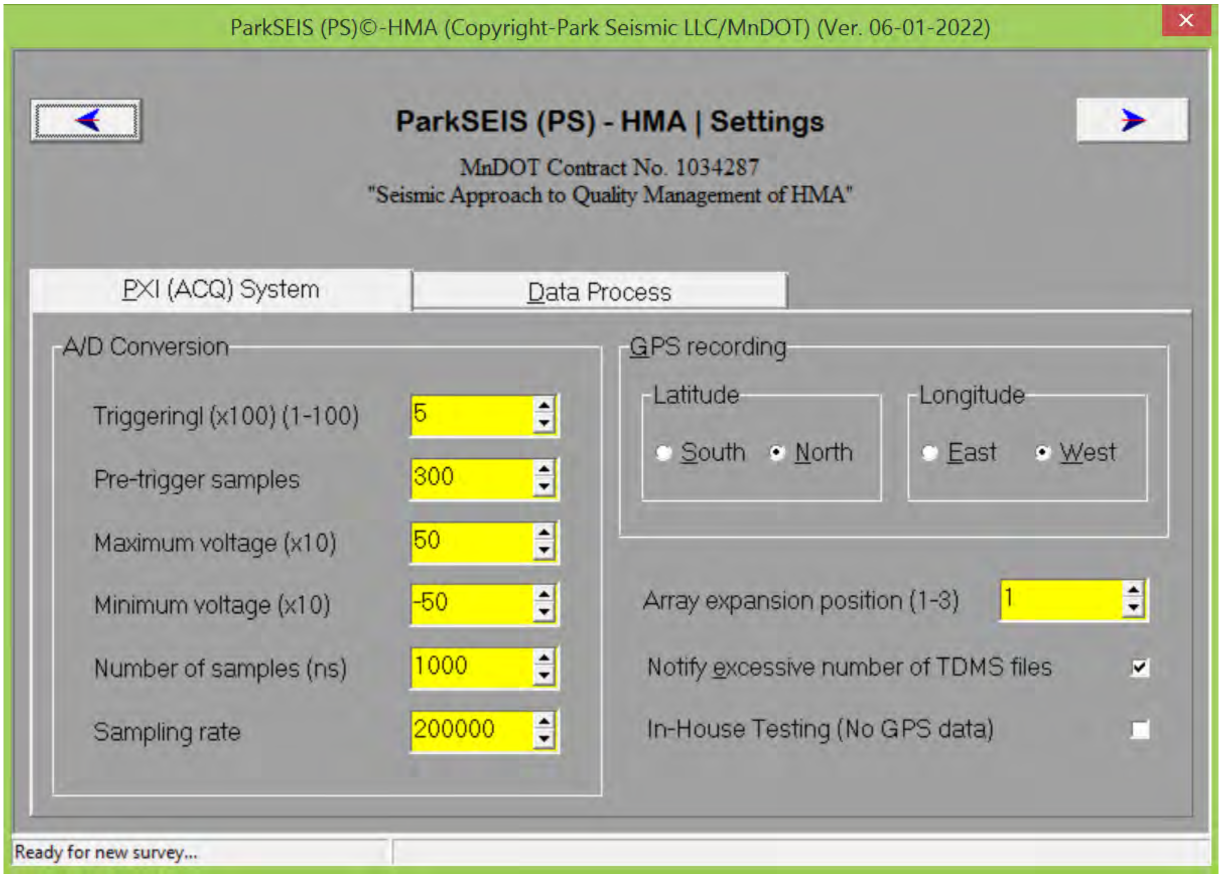


Files Folders Input (raw data) and output (processed data) folders are specified here. Raw seismic data files are saved in a folder in the PXI computer, which is mapped as a network drive (M:) via WiFi connection. Click the "Set raw data (*.tdms) folder" to set this folder. If the folder was previously assigned, then the same folder can be chosen to be used. Click the "Set processed data (*.dat) folder" to set a folder for all output results. It will create a dated folder (e.g., "...\Data2022_06_01") within the designated folder in C drive ("C:\Seismic Data"). Another survey on the same day will use a hyphenated folder name (e.g., "...\Data2022_06_01-1").

Survey Memo Any survey-relaed information worthy to note can be written here. It will be saved as a separate file ("Survey Memo.txt") and can be retrived afterward whenever the survey results are displayed. Survey purpose(s), site conditions, survey logistics, etc., can be specified.

5.2.2 IN FIELD | Settings

PXI (ACQ) System



Triggering* The voltage of impact sound (multiplied by 100) that triggers the PXI system to record and save the data in the buffer. A value of '5' means 0.05 volt (50 mv).

Pre-trigger samples* Number of samples before the triggering point that is taken from the buffer as part of the data samples to be saved. Then, more number of samples that equals number of samples (ns) minus this number will be added to make one complete set of samples to be saved for each channel.

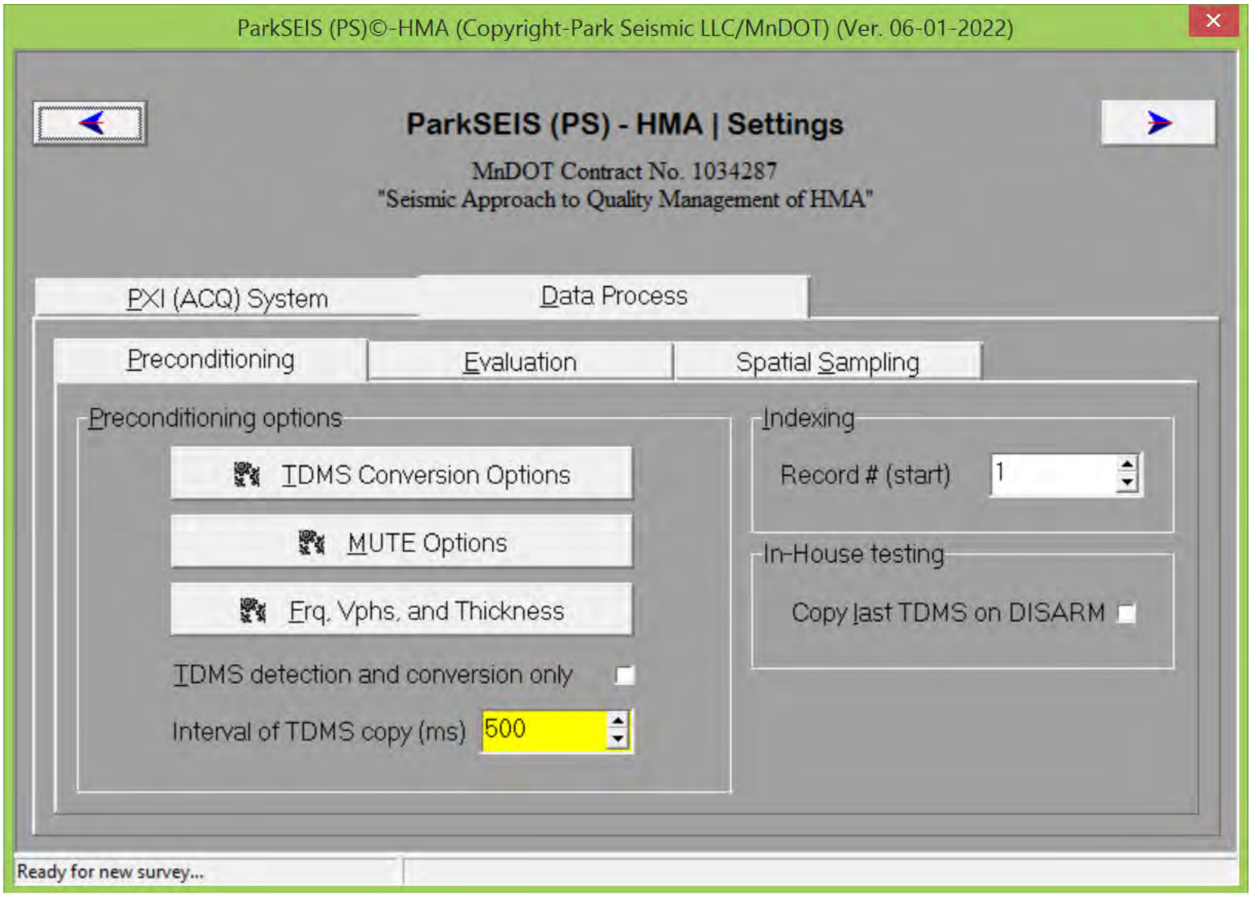
Maximum (Minimum) voltage* Max (Min) voltages (multiplied by 10) used to amplify the sound signal from each channel. A value of '50' means 5 volts.

Number of samples* Total number of samples saved in each channel.

Sampling rate* How fast sampling proceeds. A sample rate of "200000" is a 20 kHz sampling frequency, which will result in a maximum (Nyquist) frequency of 10 kHz for the output data.

**Not recommended to use different values than the default ones.*

Data Process - Preconditioning



TDMS Conversion Options* Parameters related to the conversion of TDMS (raw) data into ParkSEIS (PS) format can be changed here. Most parameters are only related to the software development purposes and ordinary users will not need to consider changing values.

MUTE Options* Parameters related to the optimum muting of impact-generated sound waves. Current default values are set after extensive testing with both real field and modeled numerical data sets. Arbitrary changes may result in significant reduction in the accuracy of the final results of velocity (Vs) and thickness (H) of HMA pavement.

Frq, Vphs, and Thickness* Parameters related to the shear-wave velocity (Vs) evaluation (e.g., range of frequency and phase velocity) and the thickness (H) evaluation (e.g., range of thickness and its resolution) can be changed here. Current default values are set after extensive testing with both real field and modeled numerical data sets.

TDMS detection and conversion only* Used only when testing saved raw data (TDMS) files in association with file detection algorithm of PS-HMA software. Not for ordinary use.

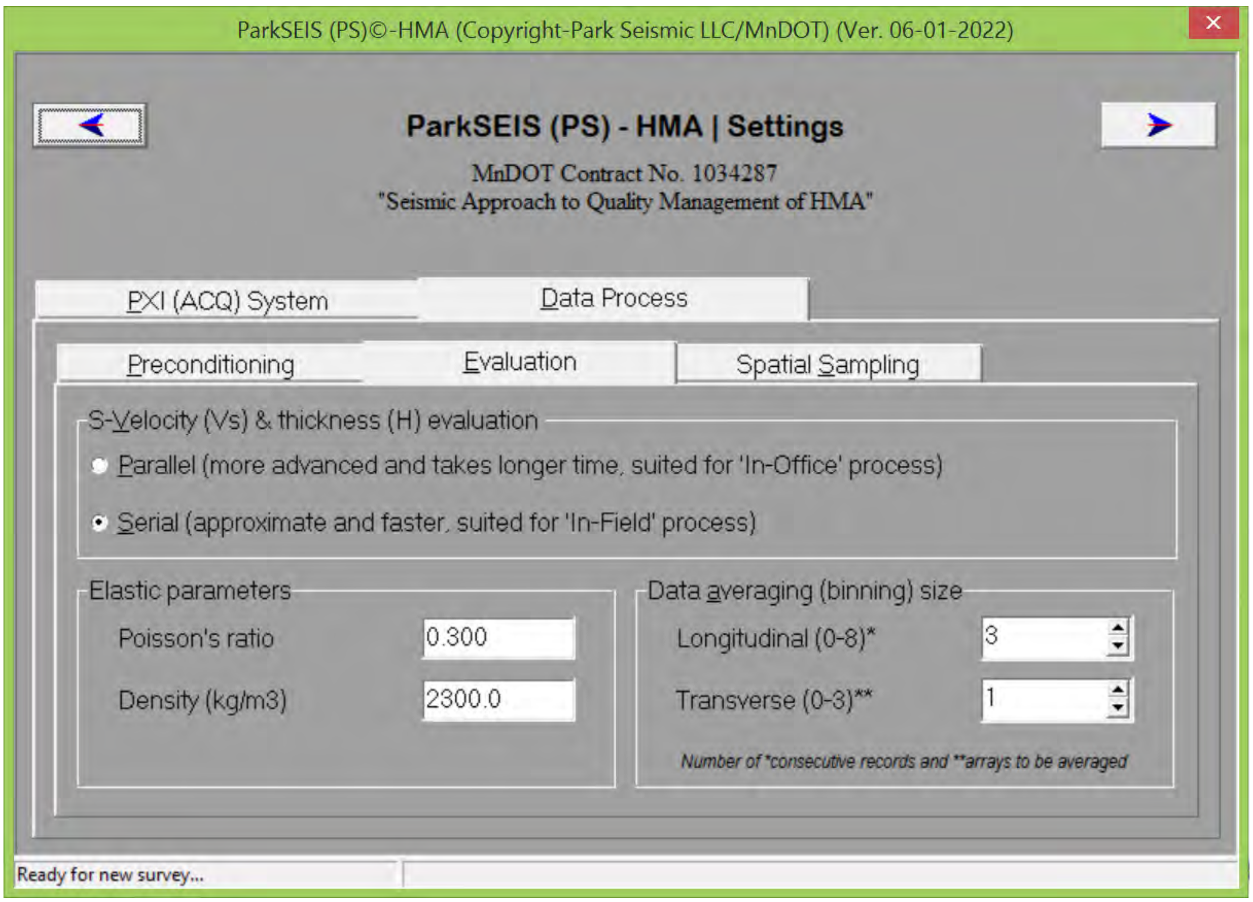
Interval of TDMS copy (ms)* The interval between successive copying of raw data (TDMS) files can be changed here. This is related to the file copying speed of PS-HMA software related to the Windows file explorer.

Indexing* The first number that will start as the record number for a given survey.

In-House testing* This option is used only for testing purposes of PS-HMA software under special circumstances. Not for ordinary use.

**Not recommended to use different values than the default ones.*

Data Process - Evaluation

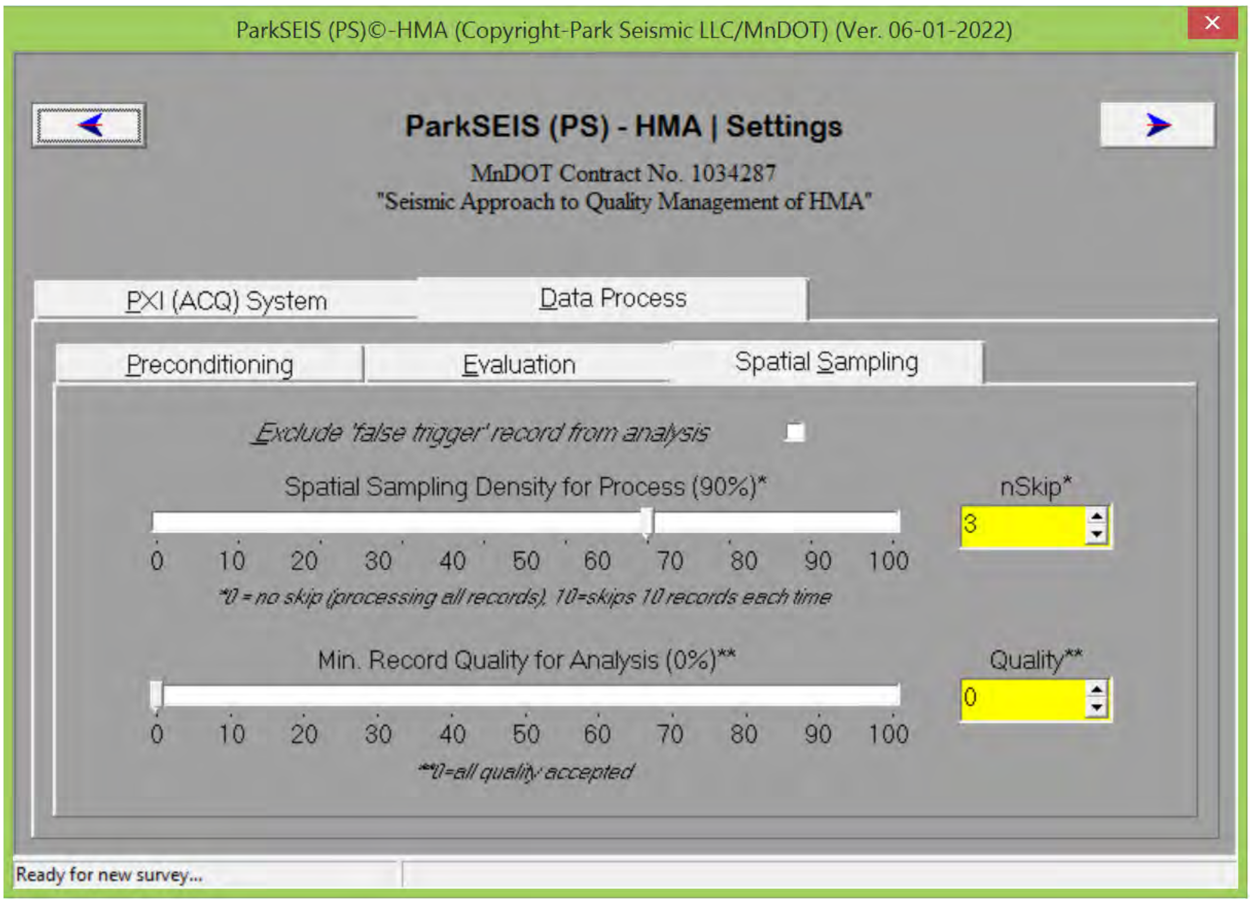


S-Velocity (Vs) & thickness (H) evaluation Two methods are available; an approximate (fast) method and an advanced (slower) method. The fast method is the optimum method to be used during the field survey, while the slower method can be used in the office for more accurate results and a higher spatial resolution.

Elastic parameters Poisson's ratio and density values can be changed here. Both are used during the evaluation of the velocity (Vs) and thickness (H). Both are also used for the calculation of Young's modulus, while density is used for shear modulus. Current default values are most optimal for typical HMA pavement.

Data averaging (binning) size Longitudinal and transverse spatial sampling densities for data analysis can be changed here. For example, values of 3 and 1 for longitudinal and transverse sizes, respectively, will average 3 consecutive records from previous and next records for a given array (e.g., #1 array) and 1 record from each array on both sides (e.g., records from #1 and #3 arrays for array #2). The resultant effects are the increased signal-to-noise ratios (S/N) along both longitudinal and transverse directions at the expense of decreased spatial resolution. The smaller numbers (e.g., 0 and 0) will result in a meaningful increase in the spatial resolution only if the collected records maintain high S/N values. It is therefore a tradeoff between the two (i.e., spatial resolution and S/N).

Data Process - Spatial Sampling

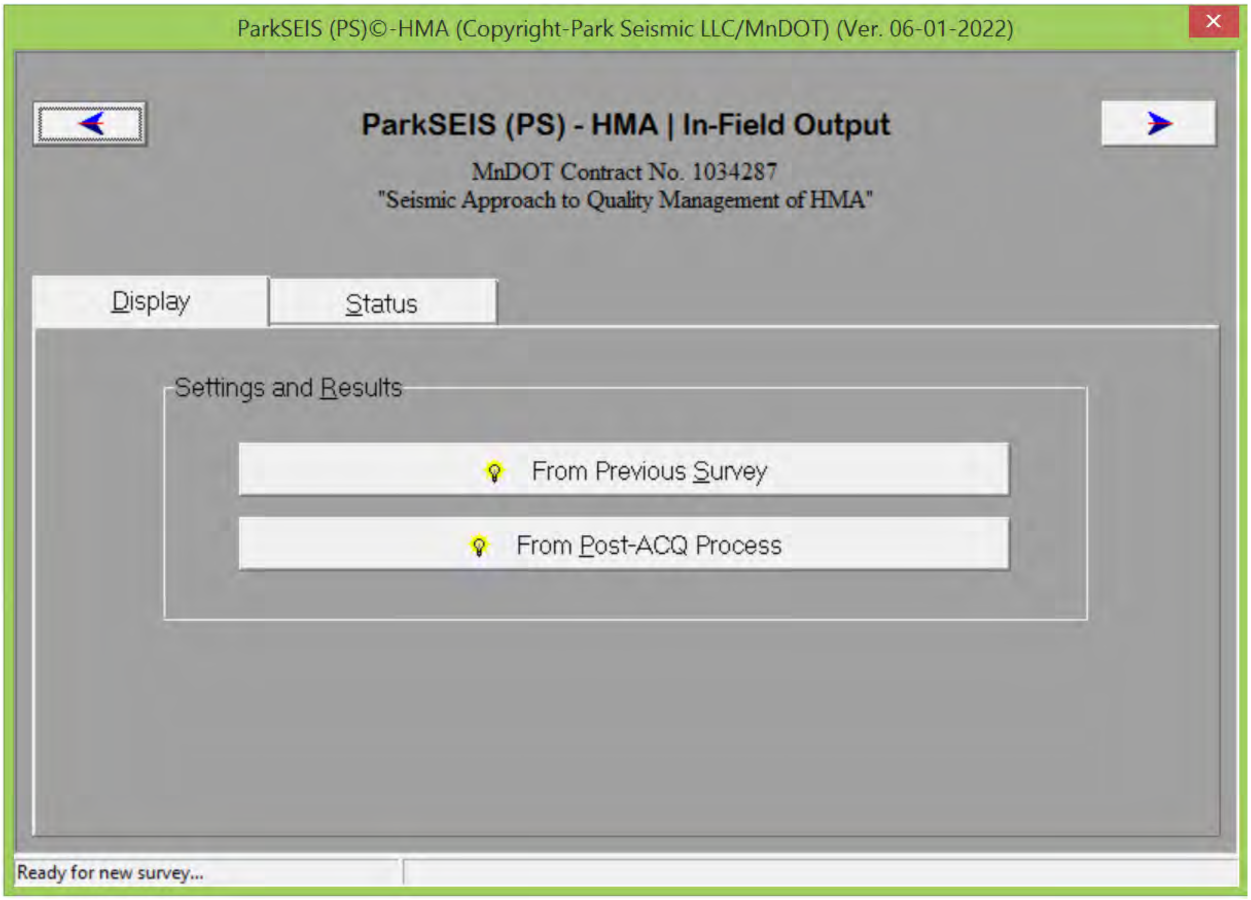


Spatial Sampling Density for Process Longitudinal spatial sampling density can be changed here. This will directly impact the longitudinal spatial resolution of the final results in velocity (Vs) and thickness. For example, a value of 3 will skip next 3 records after processing current record. Considering an average impact rate of 2 impacts/m at a cruising speed (e.g., 20 MPH), this will result in a longitudinal spatial density of 1 impact per two meters (i.e., 0.5/m). This will also directly affect the overall processing time during the survey. This option will not change the actual spatial sampling of raw data, which will always occur whenever a valid impact is made.

Min. Record Quality for Analysis The minimum S/N can be set here that will determine if a record is used for subsequent analysis or not. If S/N is lower than the specified value, then it will not be used for the analysis. A zero (0) value means all records, regardless of S/N values, will be used for the analysis. This (0) is the default value because other signal enhancing approaches (e.g., longitudinal and transverse averaging) usually compensate for the low S/N records.

5.2.3 Output

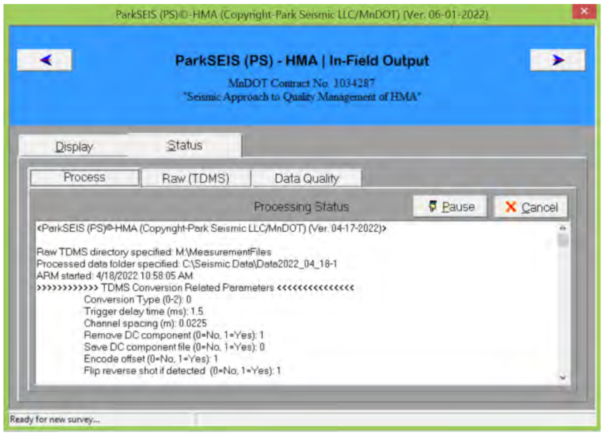
Display



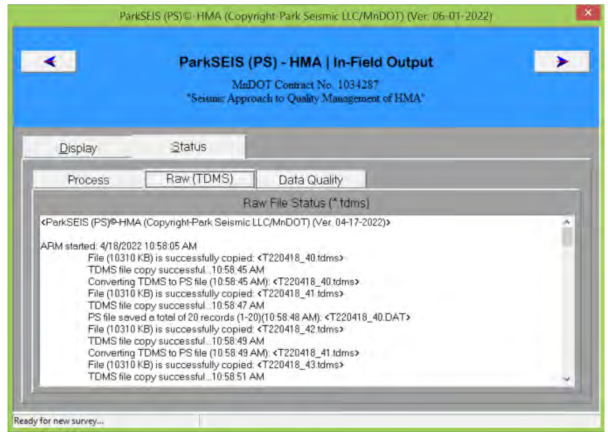
Display All results (Vs, H, and moduli) of a previous survey can be displayed here. If the survey data was processed again via IN OFFICE mode by using different process paramters (i.e., Post-ACQ Process), then they can be displayed by clicking the "From Post-ACQ Process" button.

Status

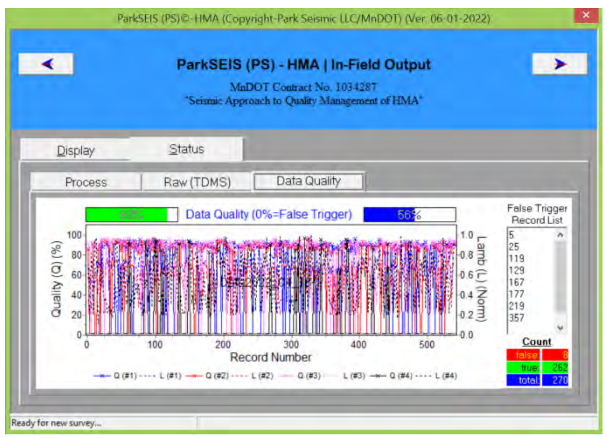
Process Tab



Raw (TDMS) Tab



Data Quality Tab

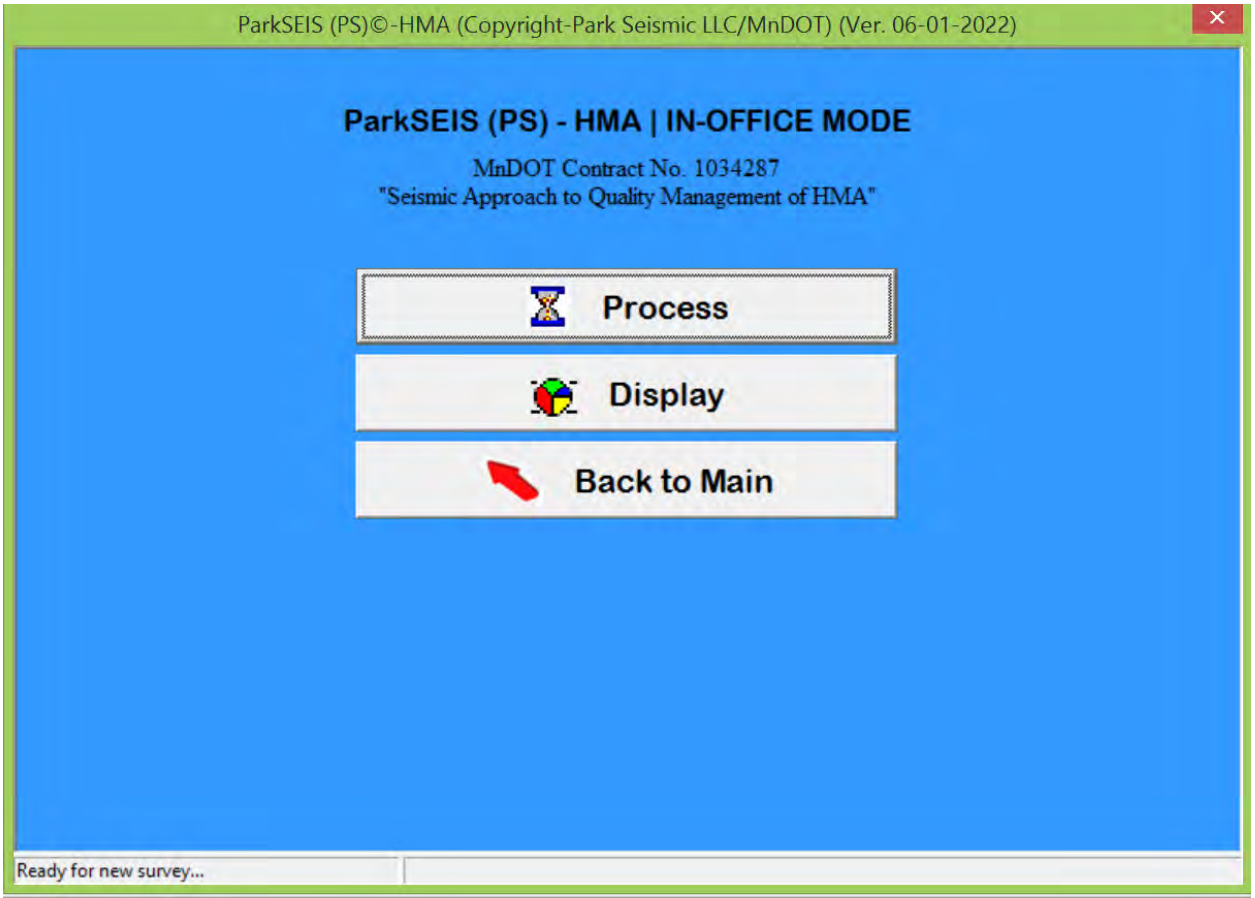


Process Processing status of all records during the survey is displayed here.

Raw (TDMS) Copying and conversion status of raw data files during the survey is displayed here.

Data Quality Overall data qualities are displayed here separately for all 4 arrays. The "Quality (Q)" represents a comprehensive S/N for each array (e.g., Q#1, Q#2, etc.) that is based on S/N and Lamb wave amplitudes. The "Lamb (L)" represents the (max) normalized amplitude of detected Lamb waves after impact sound waves are muted. It can be a more objective index of how strong Lamb waves are than the overall S/N. The "False Trigger Record List" displayed on the right-side pane shows those records of false trigger that basically contain ambient noise only without any useful signal (Lamb) waves.

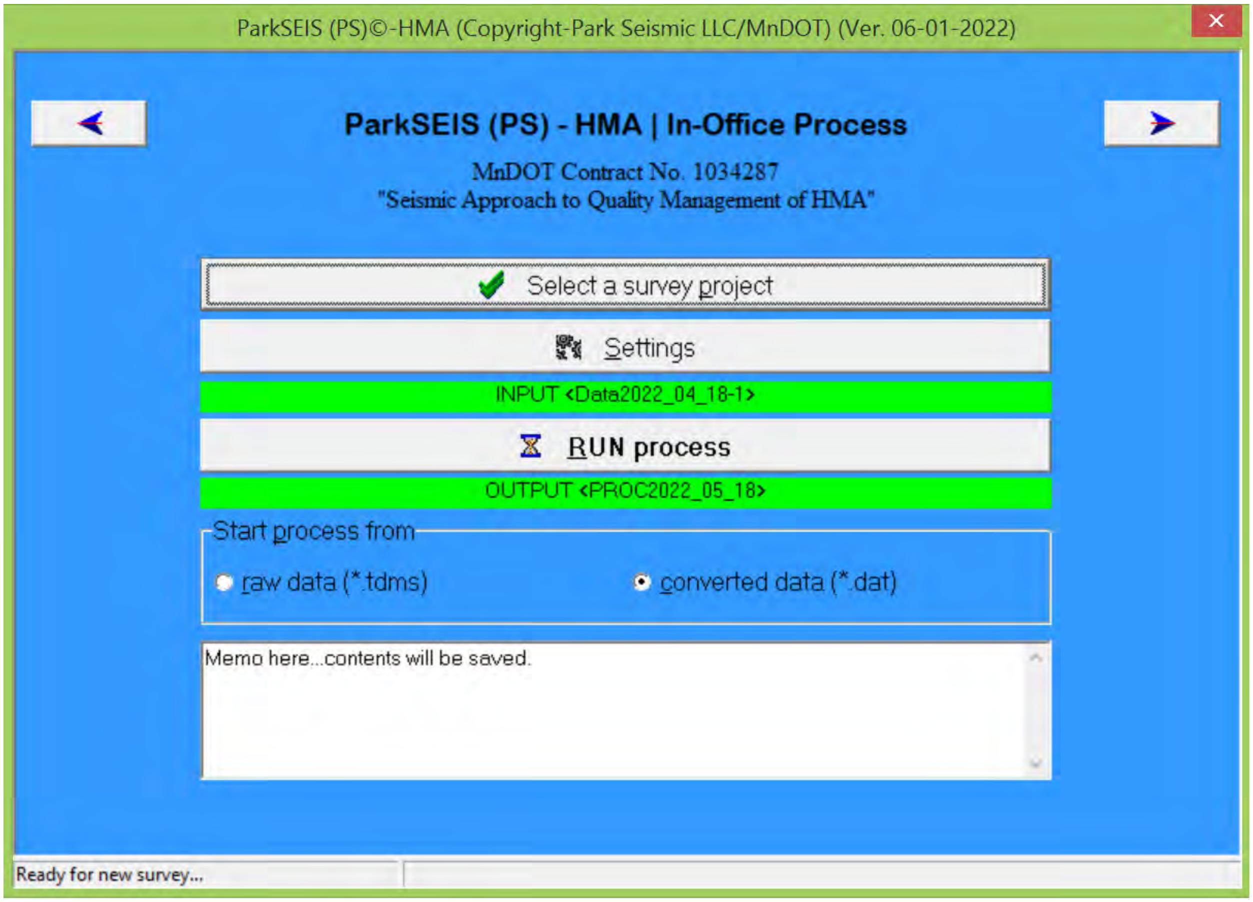
5.3 IN OFFICE MODE



Process A data set from a previous survey can be re-processed with different parameters in, for example, evaluation method, spatial analysis density, averaging (binning) sizes, etc.

Display Full results from a previous survey (or a Post-ACQ process) can be displayed.

5.3.1 IN OFFICE | Process



Select a survey project A previous survey (e.g., "...\Data2022_06_01") is selected. All data-process-related parameters used during the survey are also imported. The program will ask if all of them are to be reset to the optimal values for the advanced but longer process ("IN OFFICE"). It is recommended to accept the offer.

Settings All data-process-related parameters can be manually changed here. Refer to the "Settings" in "IN FIELD" mode.

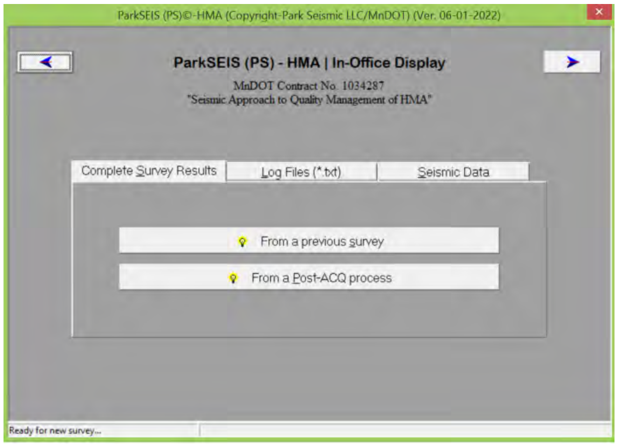
Run process Launches the new process with updated parameters. New results will be displayed at the end.

Start process from The process can start from either raw (*.tdms) or converted (*.dat) data files. As far as seismic data is concerned, the converted data will be 100% identical to the raw data. Therefore, it is recommended always to start from this (*.dat) option. However, if other type of data (e.g., GPS) needs to be updated, then the raw (*.tdms) option can be chosen.

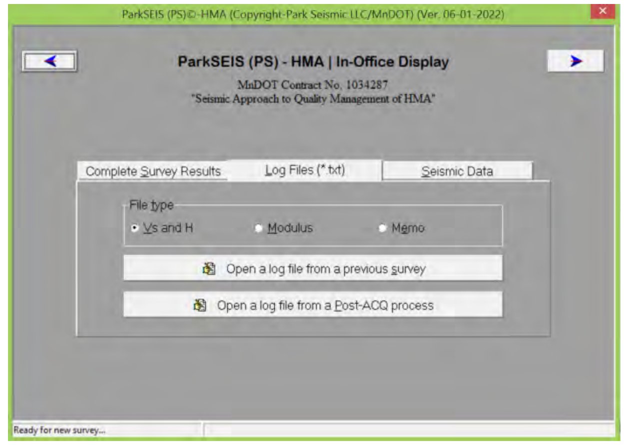
Memo Any information worthy to note can be typed in here (e.g., purpose of the reprocess, parameters changed, etc.). It will be saved as a separate file ("Process-Memo.txt").

5.3.2 IN OFFICE | Display

Complete Survey Results Tab



Long Files (*.txt) Tab



Seismic Data Tab

Complete Survey Results A complete set of results from a previous survey (e.g., Vs, H, moduli, etc.) can be displayed by clicking the "From a previous survey" button. The same from a previous "Post-ACQ Process" can also be displayed by clicking the "From a Post-ACQ process" button.

Log Files (*.txt) A log file saved during a previous survey (or during a previous "Post-ACQ Process") can be displayed here by clicking the "Open a log file from a previous survey" (or "Open a log file from a Post-ACQ process") button. Three different types of log files can be selected; velocity and thickness (Vs and H), modulus (shear and Young's), and memo (survey or post-ACQ process).

Seismic Data A seismic data file (*.dat) can be displayed here that was saved during a previous survey (or during a previous "Post-ACQ Process"). Features of the display module can be found from the user guide posted online. Dispersion image files (*OT*.dat) can also be displayed if chosen. Features of this type of display are explained in section 3 of this user guide posted online.

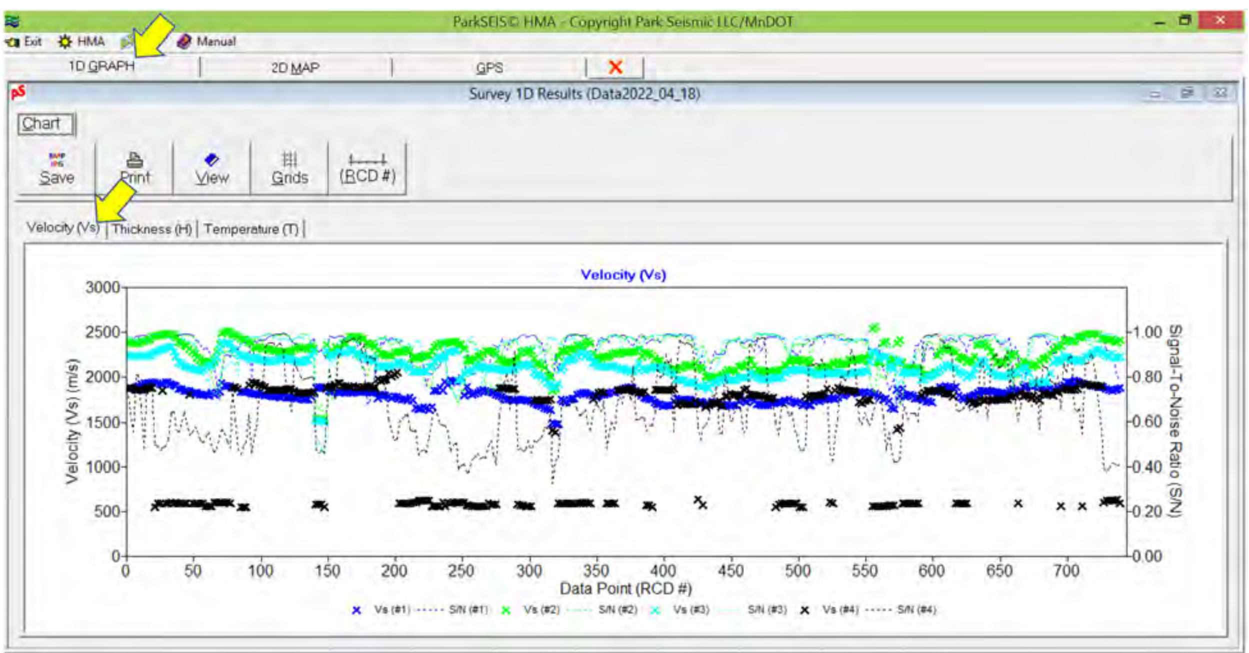
5.4 Full Output Results

Type of output results are presented in the table below with the method of availability.

Type	Availability		
	Graphical		Text (*.txt)
	1D	2D	
Shear Velocity (Vs)	√	√	√
Signal-To-Noise Ratio (S/N) (Vs)	√	√	
Thickness (H)	√	√	√
Signal-To-Noise Ratio (S/N) (H)	√	√	
Young's Modulus (GPa)		√	√
Shear Modulus (GPa)		√	√
Temperature	√		√
GPS (LAT/LON)		√	√
Log (Survey Memo, Process Memo)			√

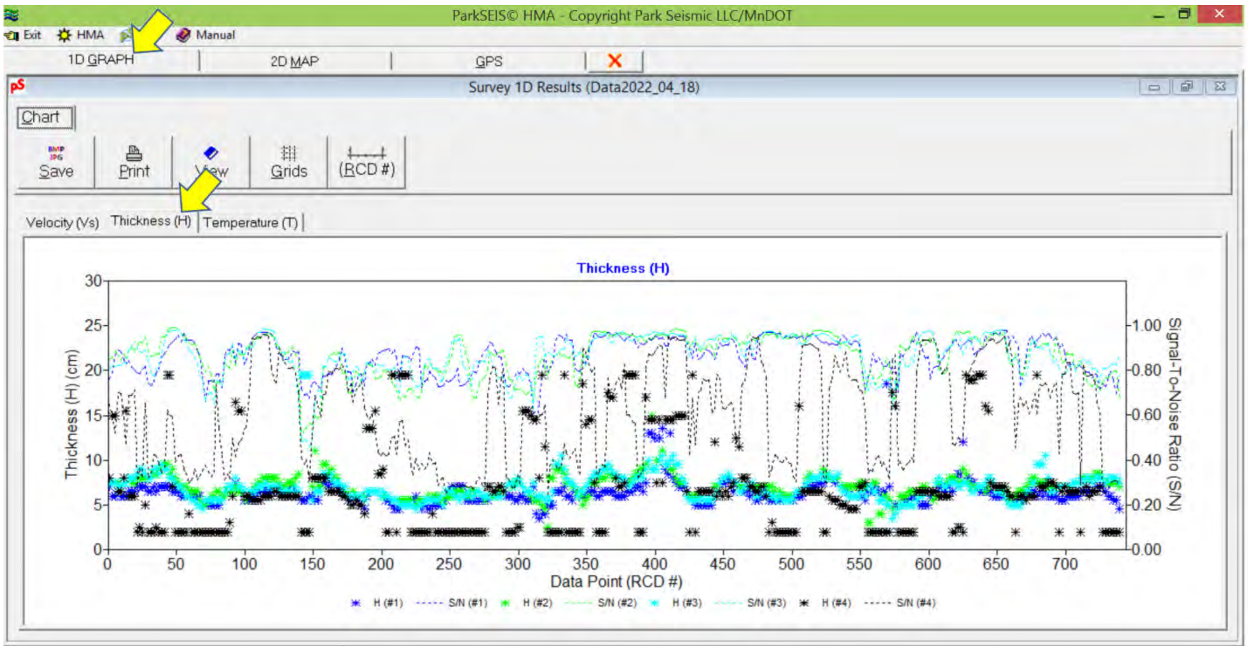
5.4.1. GRAPHICAL DISPLAY | 1D*

Shear Velocity (Vs)

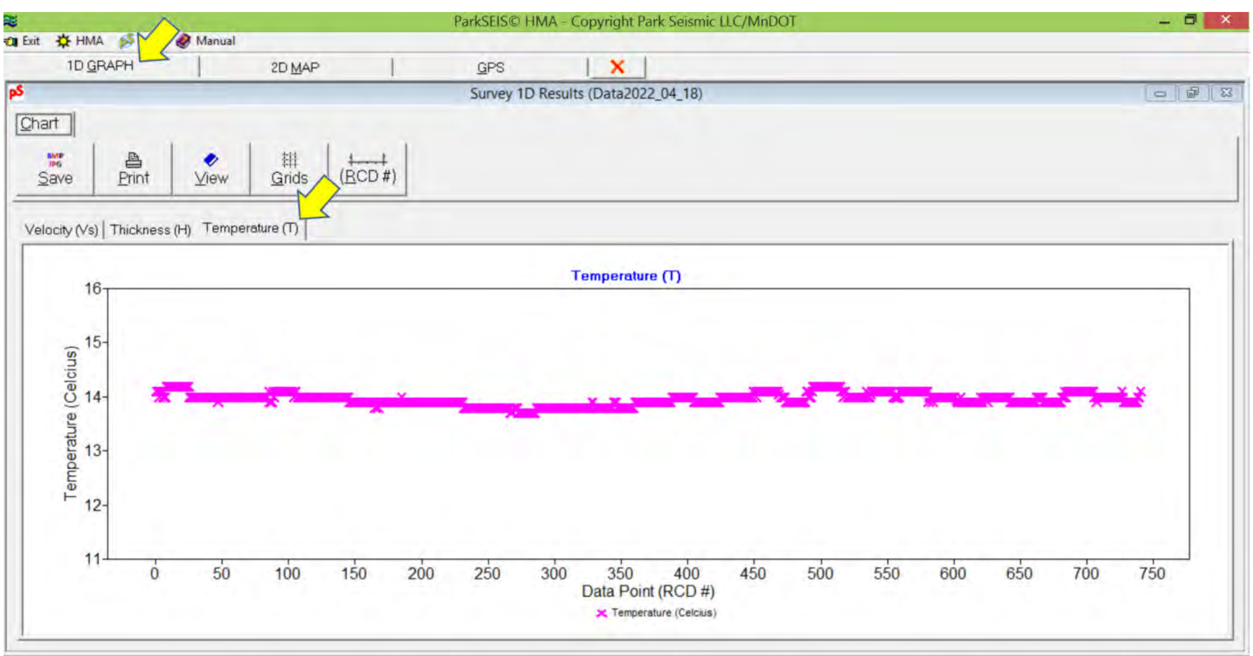


**For the controllable features of 1D display module, please see the user guide of the parent module. The "(RCD #)" button changes the horizontal axis to distance (m) from record number.*

Thickness (H)

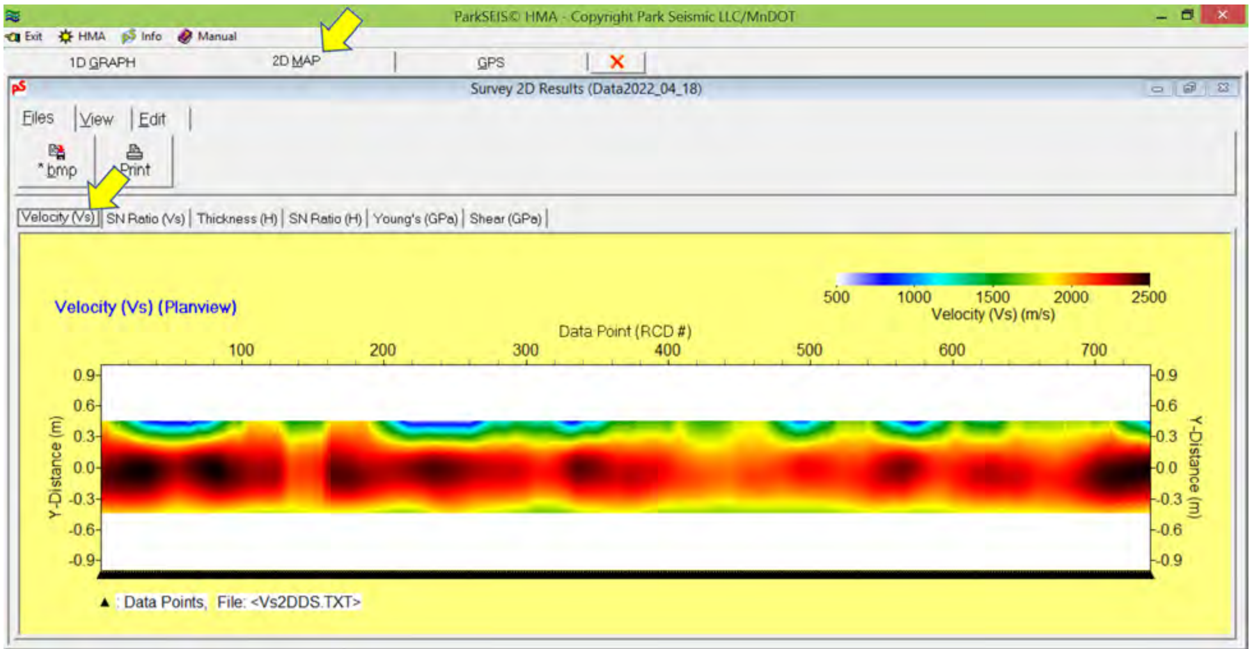


Temperature (°C)



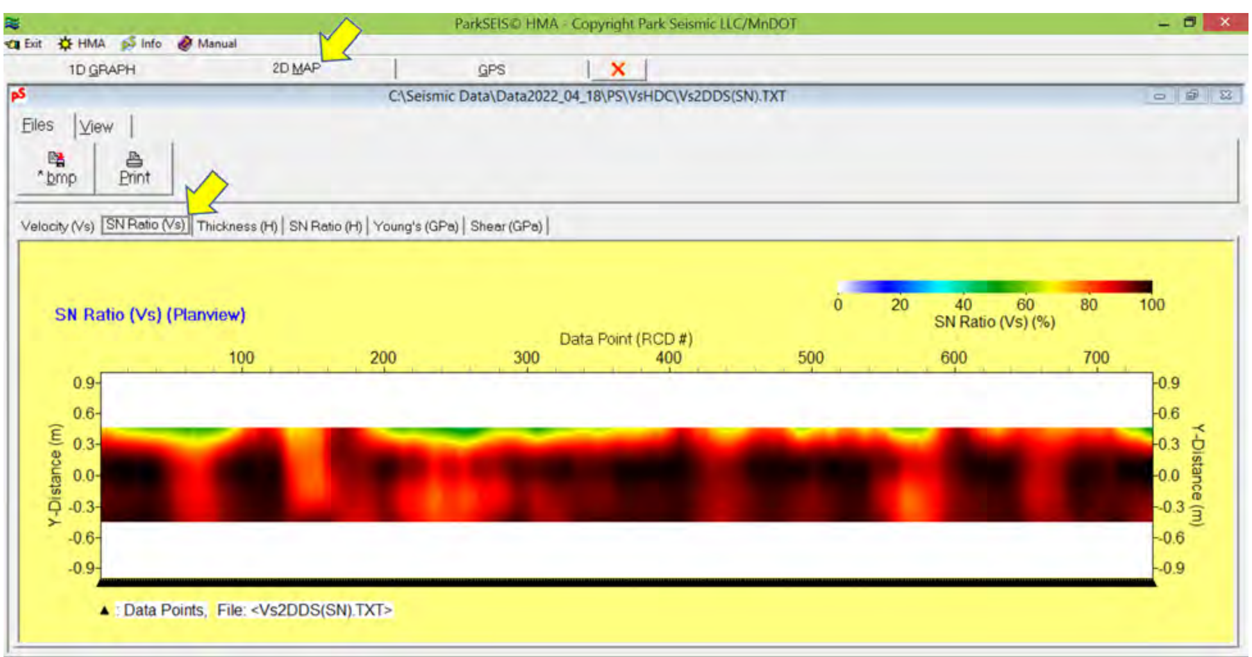
5.4.2 GRAPHICAL DISPLAY | 2D*

Shear Velocity (Vs)

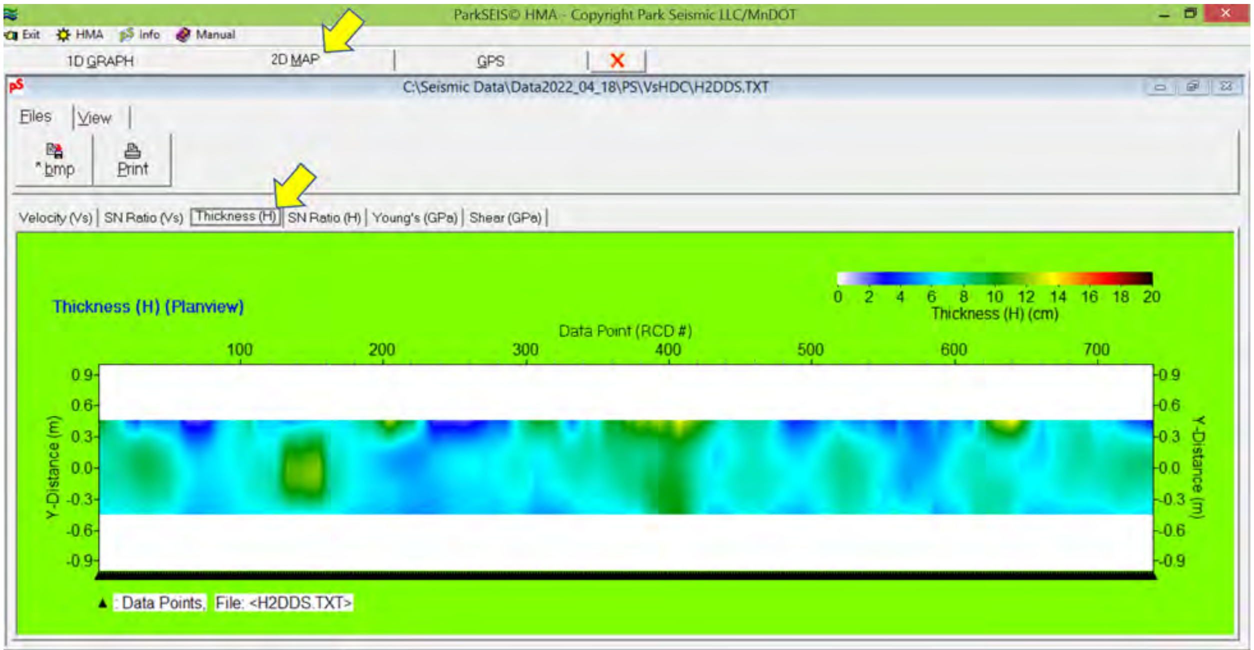


**For the controllable features of 2D display module, please see the [user guide](#) of the parent module. The "(RCD #)" button changes the horizontal axis to distance (m) from record number.*

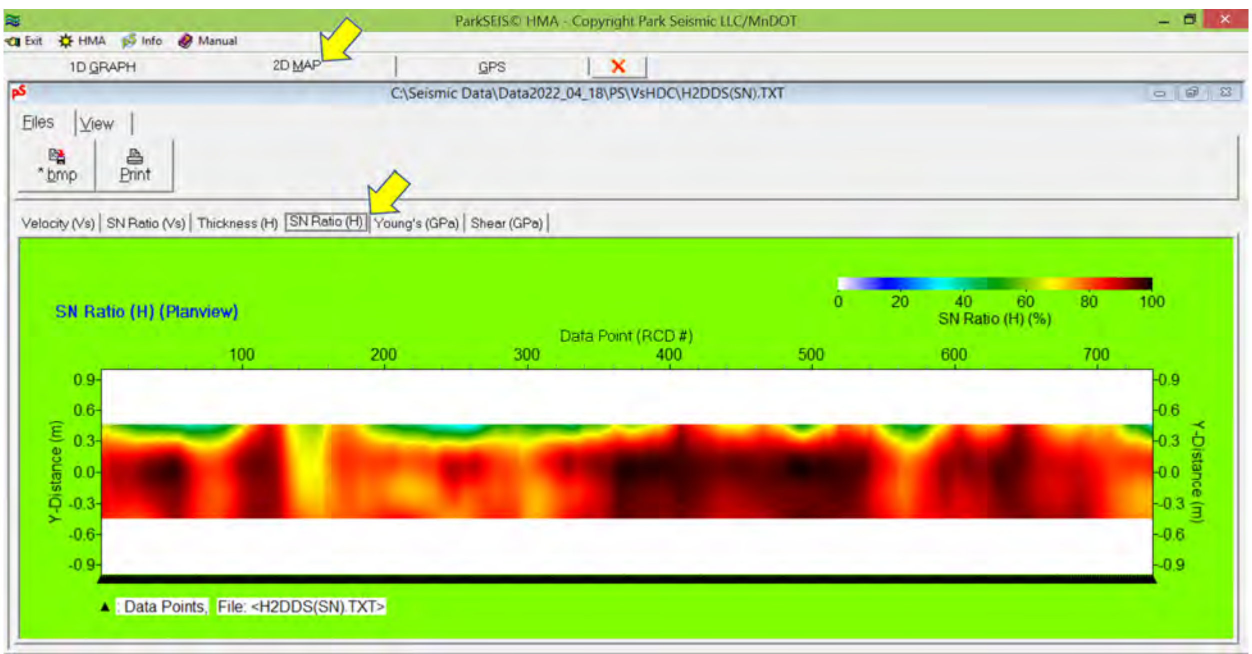
Signal-To-Noise Ratio (S/N) (Vs)



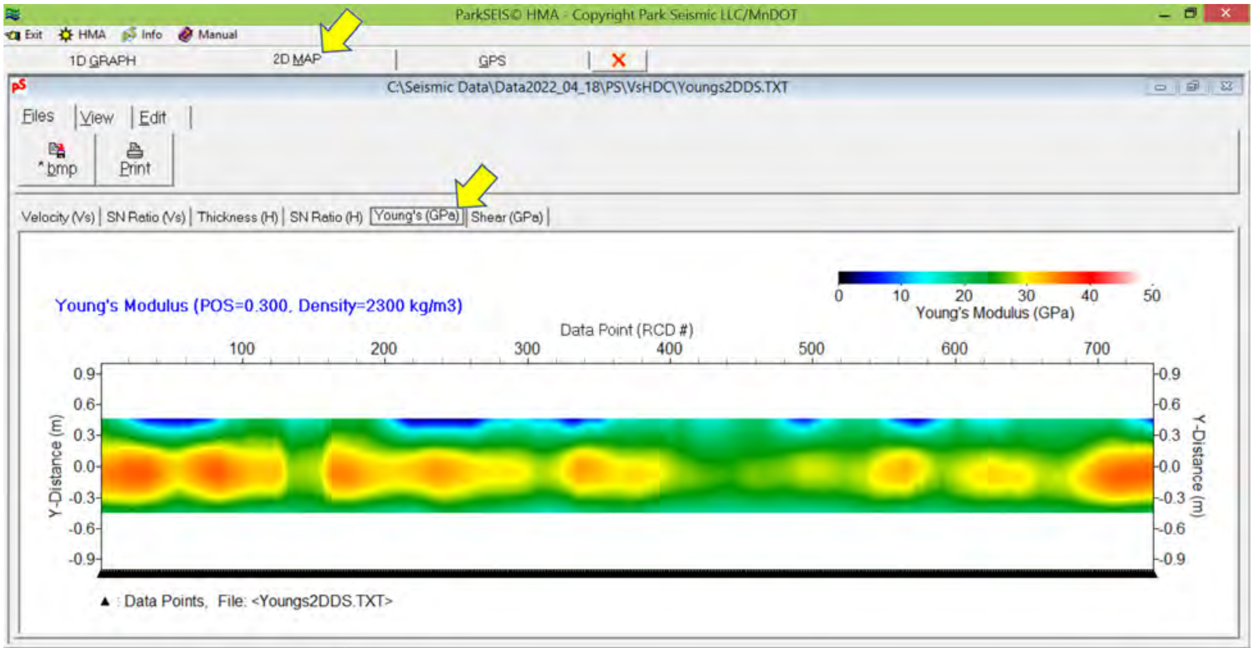
Thickness (H)



Signal-To-Noise Ratio (S/N) (H)

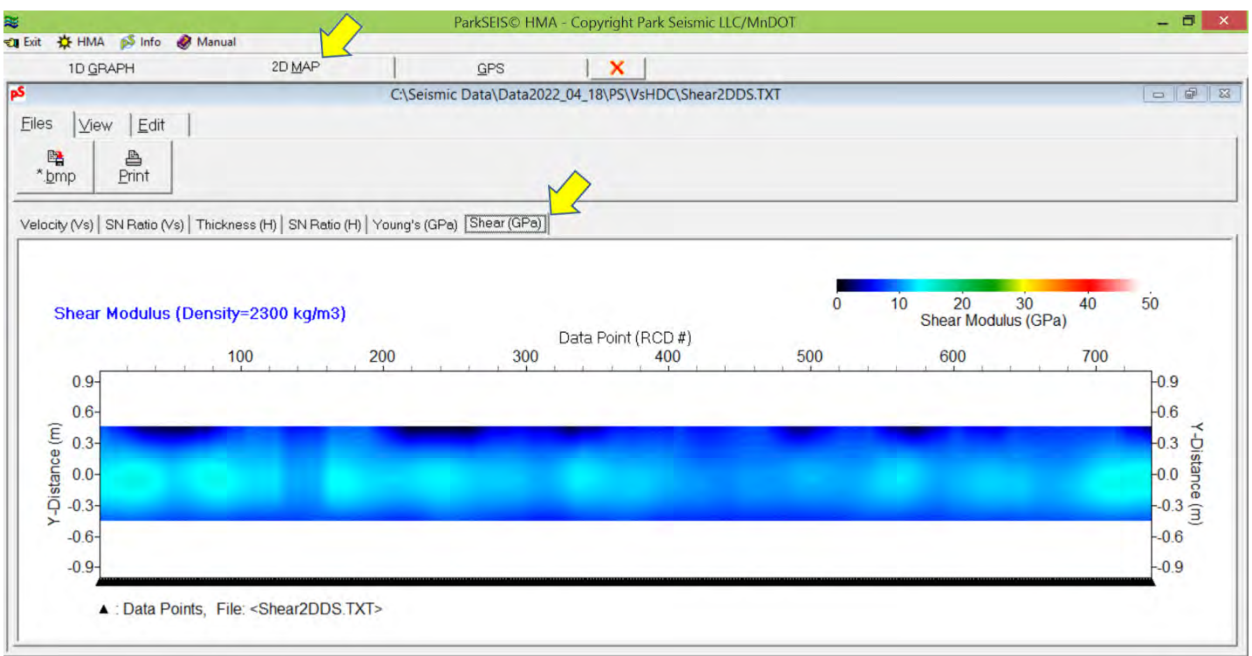


Young's Modulus (GPa)*



**Moduli maps can be updated by using different values of Poisson's ratio and density by selecting the "Edit" tab in the top tool panel.*

Shear Modulus (GPa)



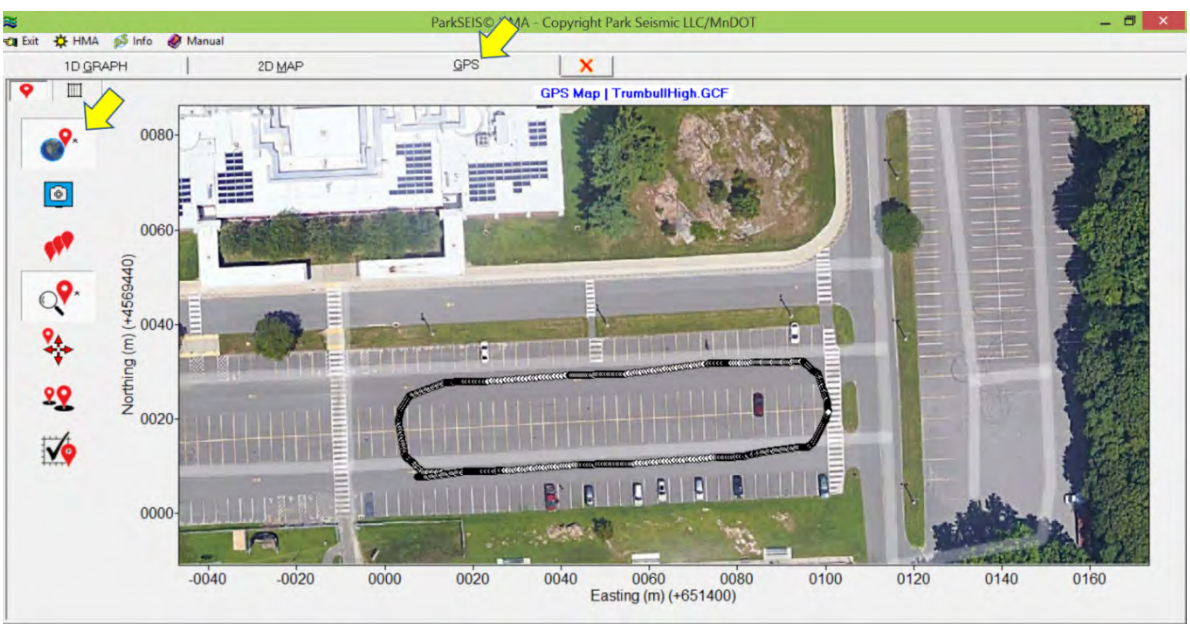
5.4.3 GPS DISPLAY

UTM Display

This is the original display mode when the "GPS" tab is first selected.

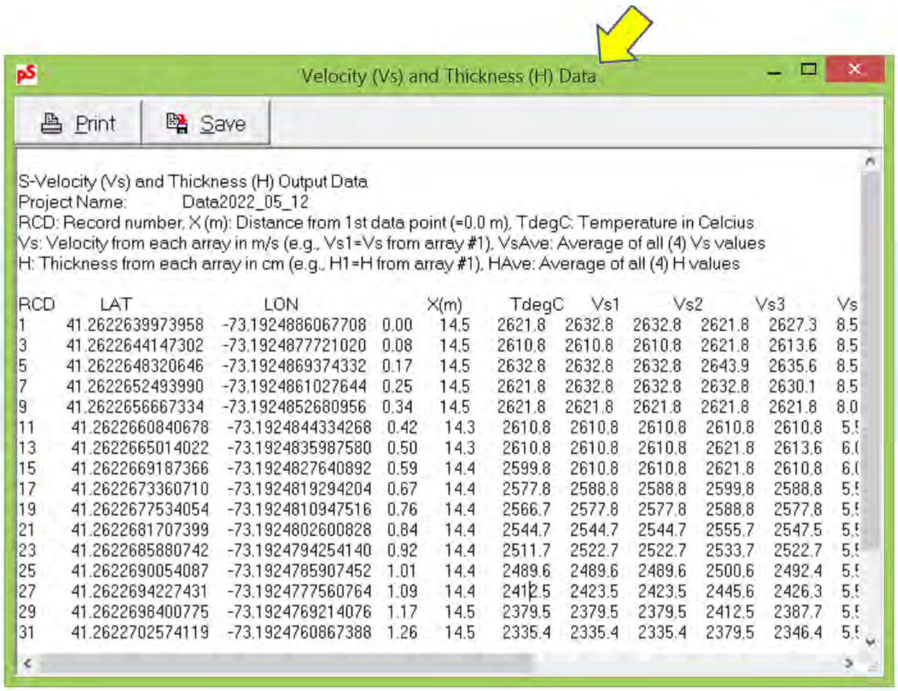
UTM with Orthophoto (*.gcf)

An orthophoto of the site combined with location information (*.gcf), prepared beforehand, can be imported by clicking the button as illustrated below. Steps to prepare such a file (*.gcf) are explained in the "GPS Display" section.



5.4.4 Text Files

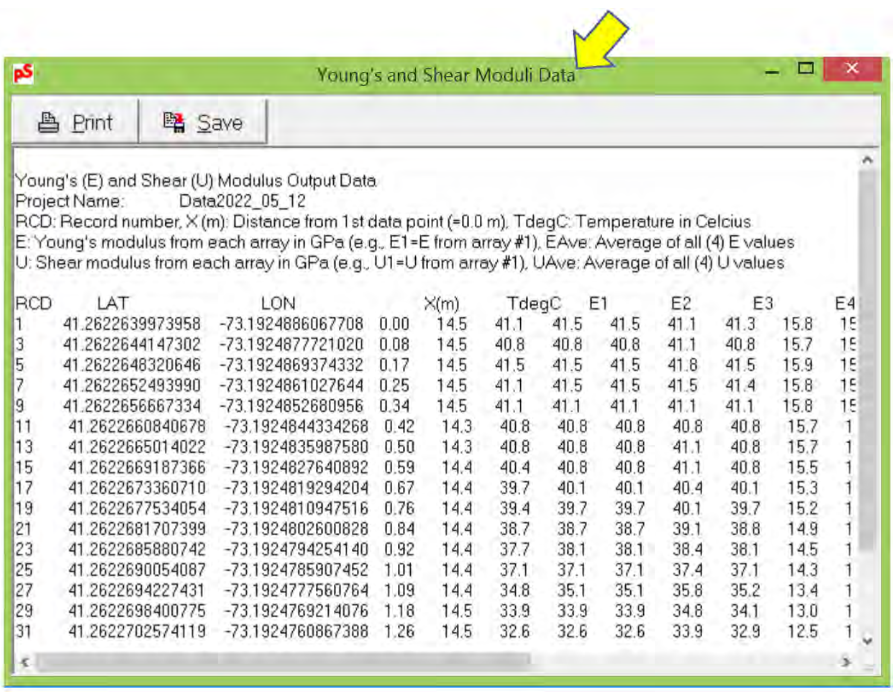
Velocity (Vs) and Thickness (H) Data
("Velocity-Thickness-Data.txt")



S-Velocity (Vs) and Thickness (H) Output Data
Project Name: Data2022_05_12
RCD: Record number, X (m): Distance from 1st data point (=0.0 m), TdegC: Temperature in Celcius
Vs: Velocity from each array in m/s (e.g., Vs1=Vs from array #1), VsAve: Average of all (4) Vs values
H: Thickness from each array in cm (e.g., H1=H from array #1), HAve: Average of all (4) H values

RCD	LAT	LON	X(m)	TdegC	Vs1	Vs2	Vs3	Vs		
1	41.2622639973958	-73.1924886067708	0.00	14.5	2621.8	2632.8	2632.8	2621.8	2627.3	8.5
3	41.2622644147302	-73.1924877721020	0.08	14.5	2610.8	2610.8	2610.8	2621.8	2613.6	8.5
5	41.2622648320646	-73.1924869374332	0.17	14.5	2632.8	2632.8	2632.8	2643.9	2635.6	8.5
7	41.2622652493990	-73.1924861027644	0.25	14.5	2621.8	2632.8	2632.8	2632.8	2630.1	8.5
9	41.2622656667334	-73.1924852680956	0.34	14.5	2621.8	2621.8	2621.8	2621.8	2621.8	8.0
11	41.2622660840678	-73.1924844334268	0.42	14.3	2610.8	2610.8	2610.8	2610.8	2610.8	5.
13	41.2622665014022	-73.1924835987580	0.50	14.3	2610.8	2610.8	2610.8	2621.8	2613.6	6.
15	41.2622669187366	-73.1924827640892	0.59	14.4	2599.8	2610.8	2610.8	2621.8	2610.8	6.
17	41.2622673360710	-73.1924819294204	0.67	14.4	2577.8	2588.8	2588.8	2599.8	2588.8	5.
19	41.2622677534054	-73.1924810947516	0.76	14.4	2566.7	2577.8	2577.8	2588.8	2577.8	5.
21	41.2622681707399	-73.1924802600828	0.84	14.4	2544.7	2544.7	2544.7	2555.7	2547.5	5.
23	41.2622685880742	-73.1924794254140	0.92	14.4	2511.7	2522.7	2522.7	2533.7	2522.7	5.
25	41.2622690054087	-73.1924785907452	1.01	14.4	2489.6	2489.6	2489.6	2500.6	2492.4	5.
27	41.2622694227431	-73.1924777560764	1.09	14.4	2412.5	2423.5	2423.5	2445.6	2426.3	5.
29	41.2622698400775	-73.1924769214076	1.17	14.5	2379.5	2379.5	2379.5	2412.5	2387.7	5.
31	41.2622702574119	-73.1924760867388	1.26	14.5	2335.4	2335.4	2335.4	2379.5	2346.4	5.

Modulus Data
("Modulus-Data.txt")

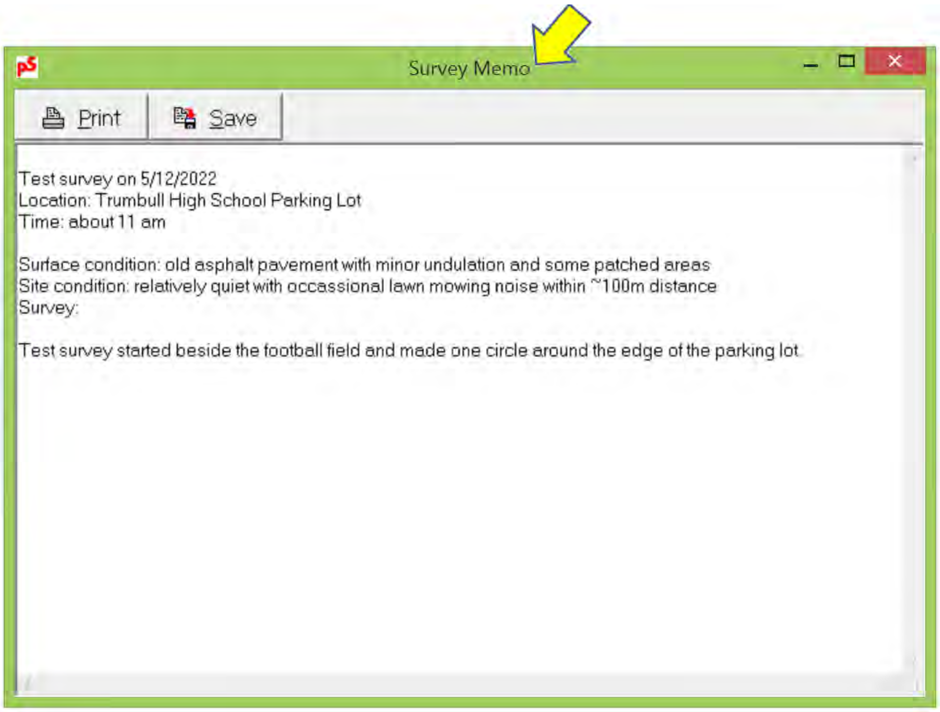


Young's (E) and Shear (U) Modulus Output Data
Project Name: Data2022_05_12
RCD: Record number, X (m): Distance from 1st data point (=0.0 m), TdegC: Temperature in Celcius
E: Young's modulus from each array in GPa (e.g., E1=E from array #1), EAve: Average of all (4) E values
U: Shear modulus from each array in GPa (e.g., U1=U from array #1), UAve: Average of all (4) U values

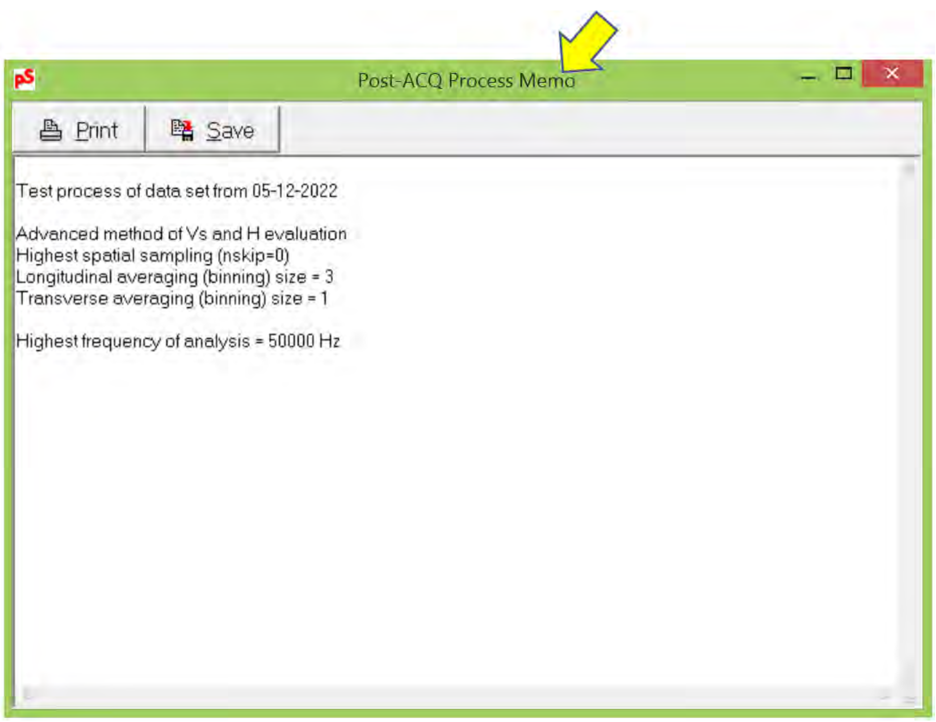
RCD	LAT	LON	X(m)	TdegC	E1	E2	E3	E4			
1	41.2622639973958	-73.1924886067708	0.00	14.5	41.1	41.5	41.5	41.1	41.3	15.8	15
3	41.2622644147302	-73.1924877721020	0.08	14.5	40.8	40.8	40.8	41.1	40.8	15.7	15
5	41.2622648320646	-73.1924869374332	0.17	14.5	41.5	41.5	41.5	41.8	41.5	15.9	15
7	41.2622652493990	-73.1924861027644	0.25	14.5	41.1	41.5	41.5	41.5	41.4	15.8	15
9	41.2622656667334	-73.1924852680956	0.34	14.5	41.1	41.1	41.1	41.1	41.1	15.8	15
11	41.2622660840678	-73.1924844334268	0.42	14.3	40.8	40.8	40.8	40.8	40.8	15.7	1
13	41.2622665014022	-73.1924835987580	0.50	14.3	40.8	40.8	40.8	41.1	40.8	15.7	1
15	41.2622669187366	-73.1924827640892	0.59	14.4	40.4	40.8	40.8	41.1	40.8	15.5	1
17	41.2622673360710	-73.1924819294204	0.67	14.4	39.7	40.1	40.1	40.4	40.1	15.3	1
19	41.2622677534054	-73.1924810947516	0.76	14.4	39.4	39.7	39.7	40.1	39.7	15.2	1
21	41.2622681707399	-73.1924802600828	0.84	14.4	38.7	38.7	38.7	39.1	38.8	14.9	1
23	41.2622685880742	-73.1924794254140	0.92	14.4	37.7	38.1	38.1	38.4	38.1	14.5	1
25	41.2622690054087	-73.1924785907452	1.01	14.4	37.1	37.1	37.1	37.4	37.1	14.3	1
27	41.2622694227431	-73.1924777560764	1.09	14.4	34.8	35.1	35.1	35.8	35.2	13.4	1
29	41.2622698400775	-73.1924769214076	1.18	14.5	33.9	33.9	33.9	34.8	34.1	13.0	1
31	41.2622702574119	-73.1924760867388	1.26	14.5	32.6	32.6	32.6	33.9	32.9	12.5	1

Log Files

"Survey Memo.txt"



"Process-Memo.txt"

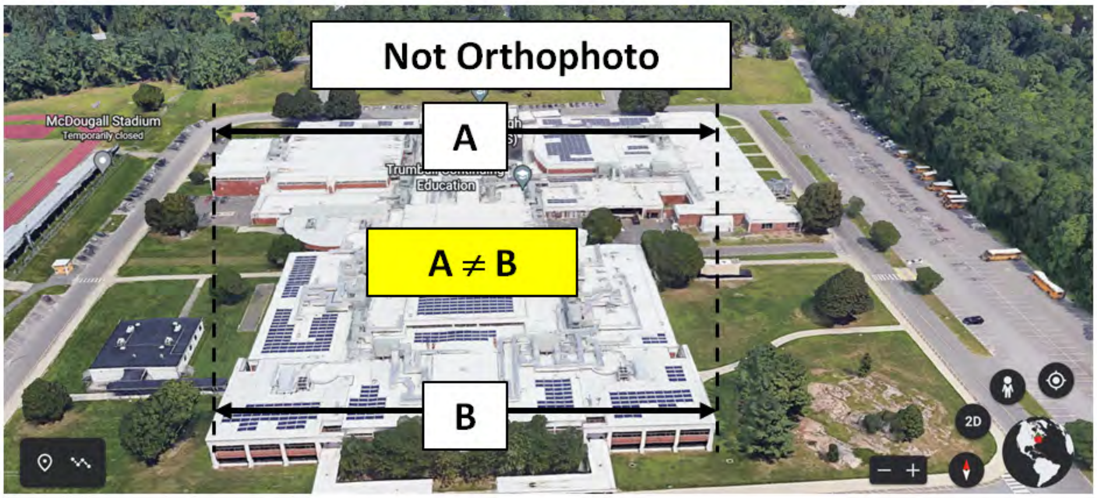


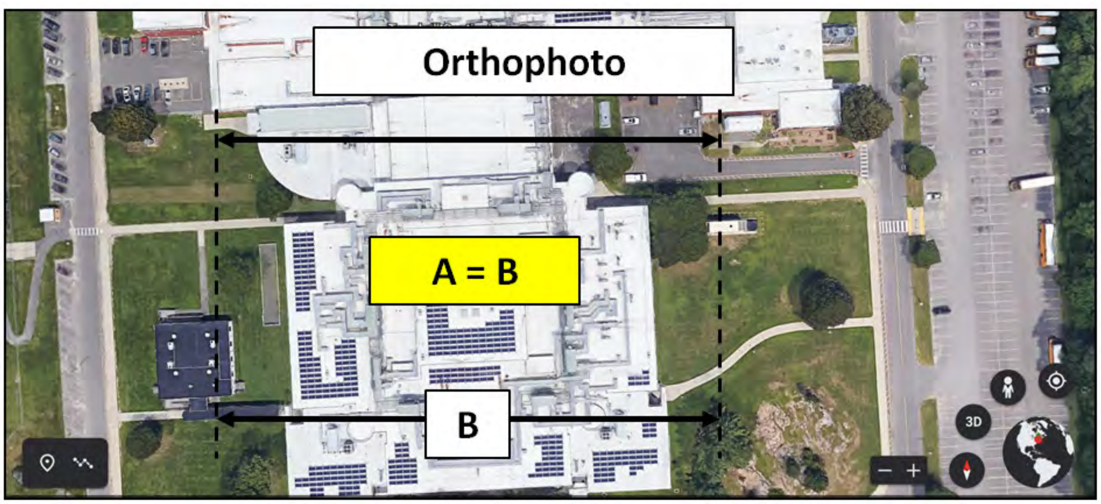
5.5 Using GPS Display

5.5.1 How to prepare an Orthophoto

What is an Orthophoto?

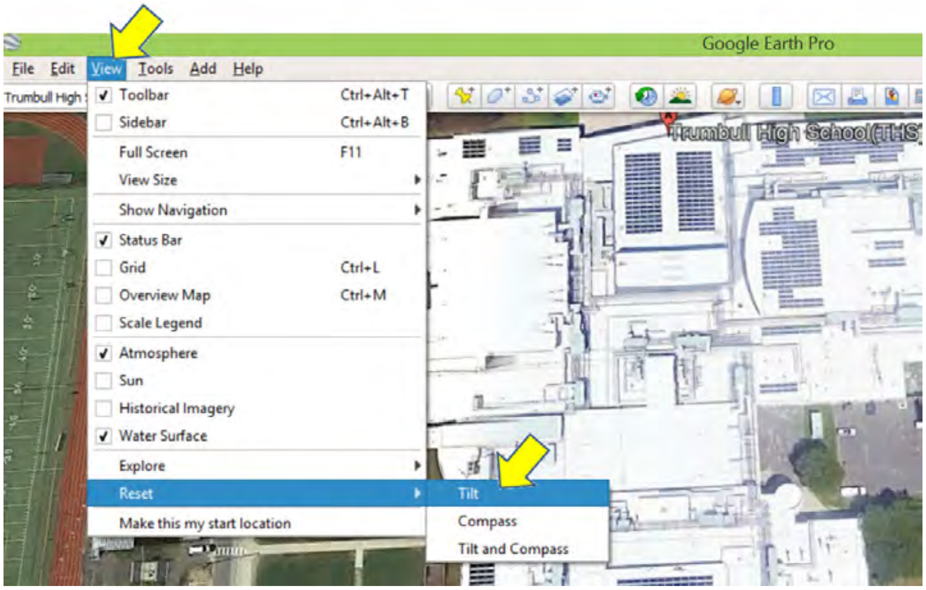
It is a map photo where distance scale is the same everywhere in the photo as illustrated below.



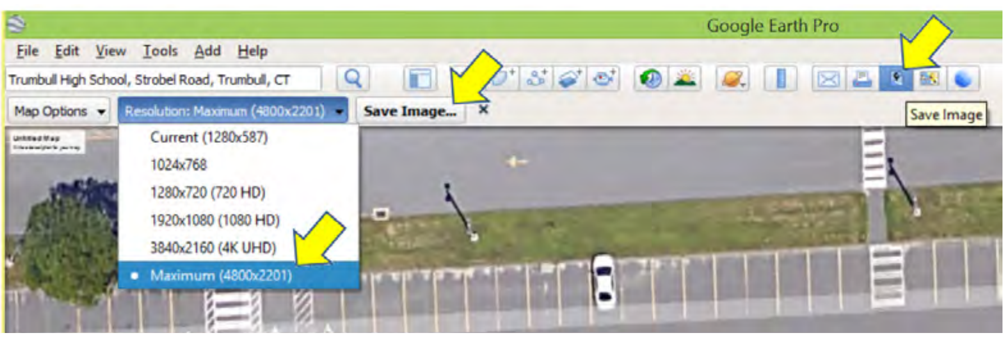


To prepare an orthophoto map, use a Google map browser that can save a map with a high resolution (e.g., 4800 x 2201). The procedure is briefly demonstrated below by referring to Google Earth Pro.

Navigate into the survey site and display the map with the site as much centered as possible. Go to the "View" option in the menu bar, select the "Reset", and then click the "Tilt" option as illustrated below. This process may have to be repeated whenever the map is changed with mouse scroll and panning actions because they may display the map with perspectives.



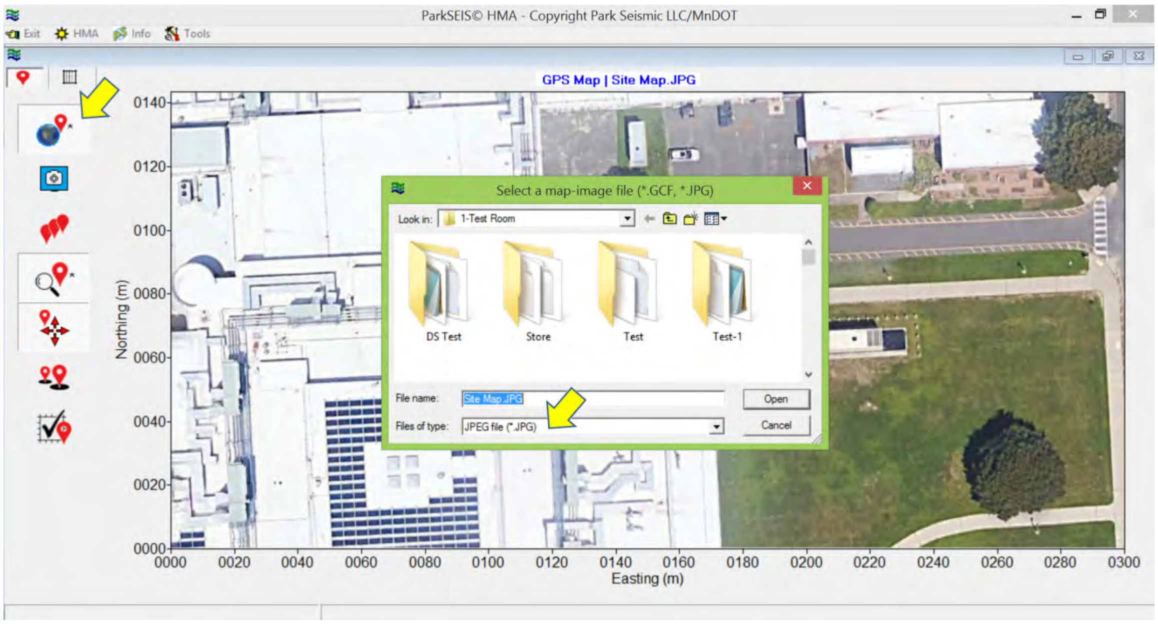
Once map image is properly centered with an optimum scale, click the "save image" icon in the top tool panel as illustrated below (top right arrow). Then, select the maximum resolution (e.g., 4800x2201) (bottom left arrow). Click the "Save Image..." button (center arrow) to save the image (e.g., "Site Map.jpg"). This saved map photo has the same distance scale along any direction. However, its location information (LAT/LON) is not assigned yet. This will be done inside the PS-HMA program, which is explained below.



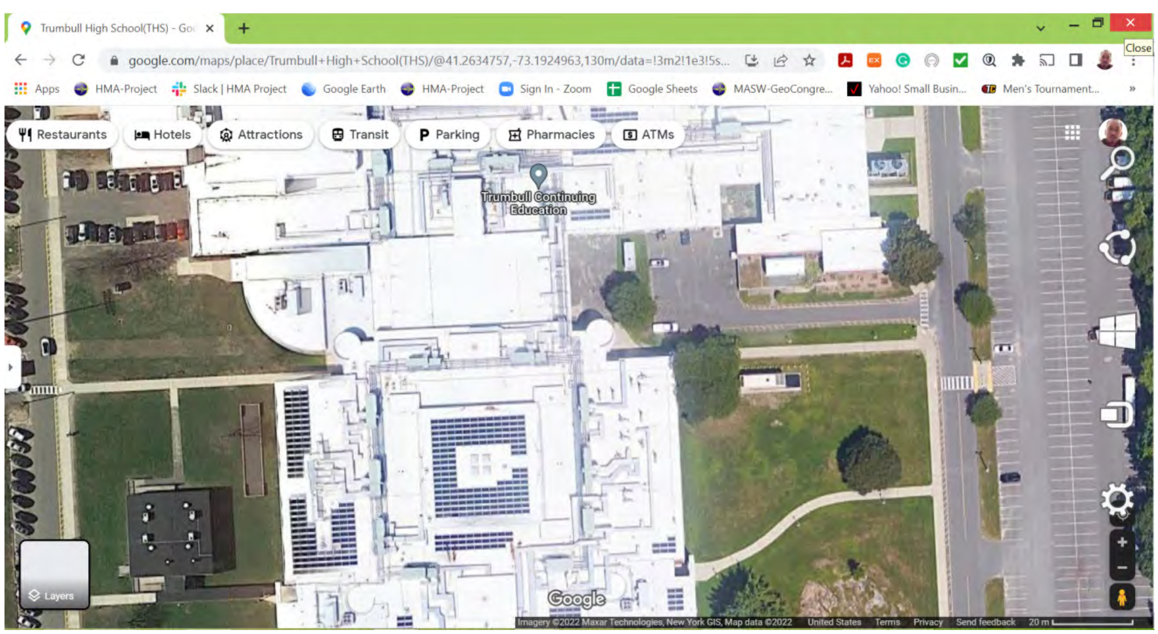
5.5.2 How to Assign Location Info (LAT/LON) to Orthophoto

Run PS-HMA program and close the main HMA dialog by clicking the "Exit" button in the main HMA dialog. Then, go to "Tools" in the top main menu bar and click the "Orthophoto for GPS display (*.gcf)" option (see below). A separate window for GPS operation will be displayed.

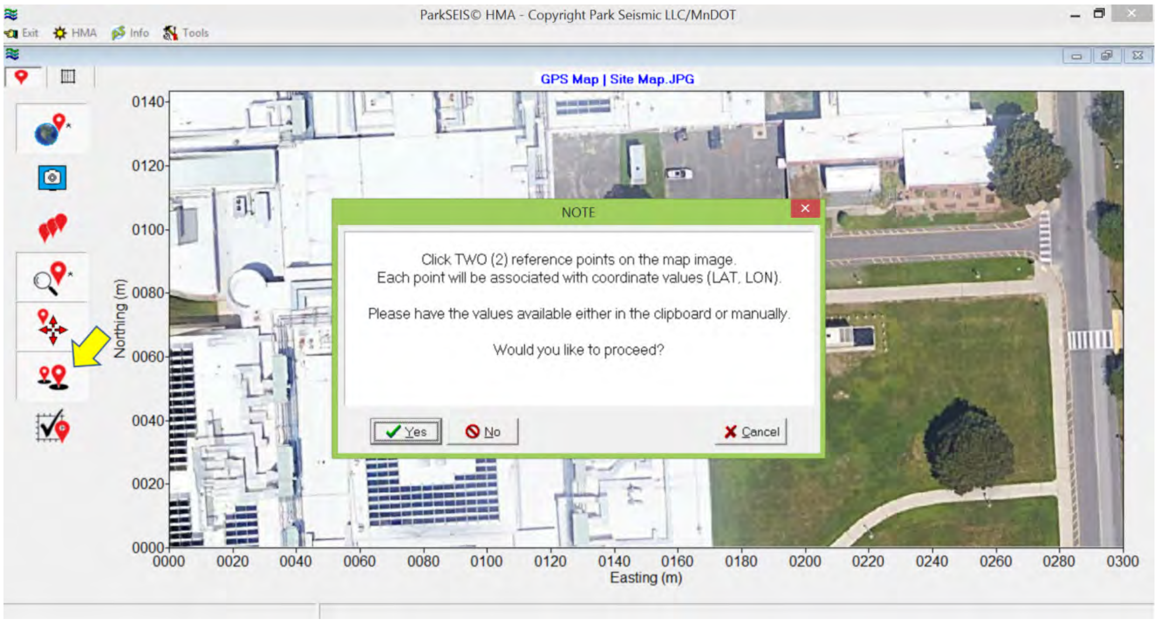
Click the import button on top in the left tool pane (see below). Then, select the "JPEG file" in the file type box and import the previously saved orthophoto (e.g., "Site Map.jpg").



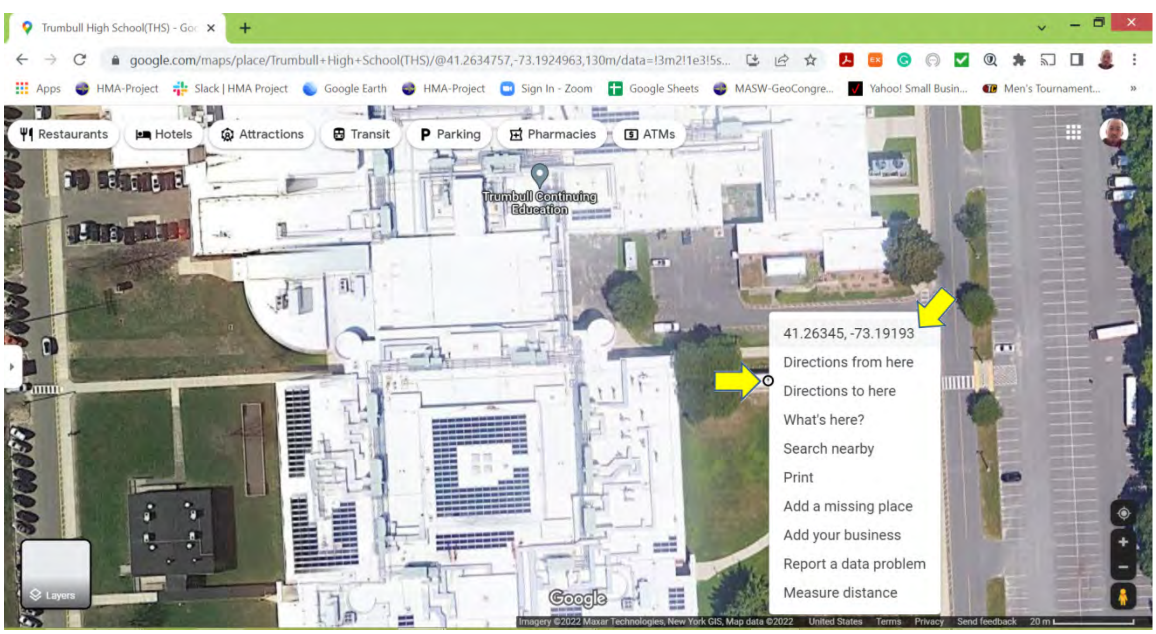
Actual map scale should not match that of the chart that holds the image in the background because the two scales are not matched yet. The next steps will accomplish this. First, launch a Google map browser that can show the location information (LAT/LON) of any clicked point. At the time of this manual preparation, there was no such option found in the Google Earth Pro. Therefore, an ordinary Google satellite map is used as illustrated here (e.g., maps.google.com). Navigate into the same area displayed in the orthophoto map displayed in the PS-HMA program. It does not have to be in the exact same display scale, but can be in a similar scale for the convenience of accomplishing the remaining procedure.



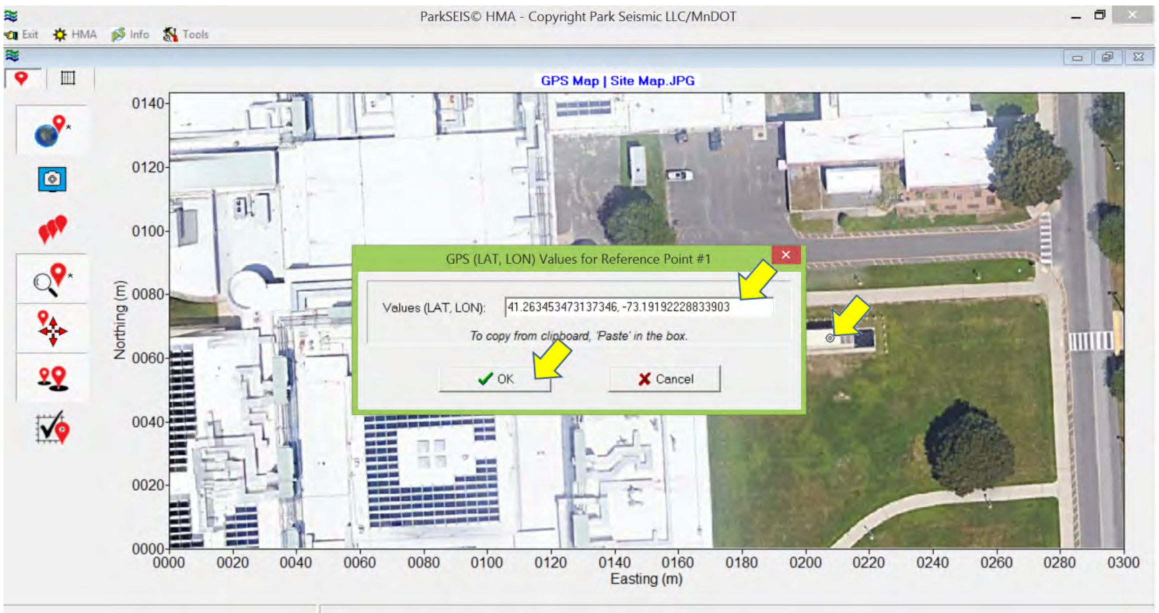
Come back to PS-HMA program and click the "Set two reference points..." button as illustrated below. This will start the process of taking location information from two different points in the Google satellite map.



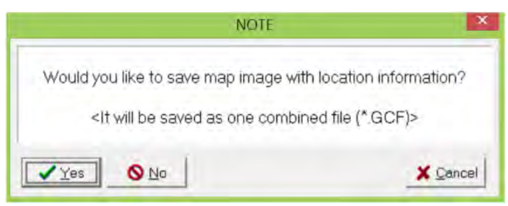
To get the location information of the 1st reference point, go to the Google satellite map and identify a point easy to remember (e.g., a small black dot on top of the small building as marked by a small circle below). Click the point to create a mark on the map and then "right-click" to display pop-up options (see below). The top row shows latitude (LAT) and longitude (LON) of the clicked point. Click any part of the top row that will copy the two numbers as they are.



Go back to the PS-HMA program and click the same point on the map. An edit box will be displayed where the previously copied values are to be pasted (see below) by right clicking the mouse (or pressing Ctrl and v keys simultaneously) in the edit box. Click the "OK" button to finish the setup for the 1st point. Repeat the same for the 2nd point by selecting another easy-to-remember point in the Google satellite map. This new point must be located a certain distance away from the 1st point for a maximized accuracy in location mapping (e.g., apart more than 20% of the map width).



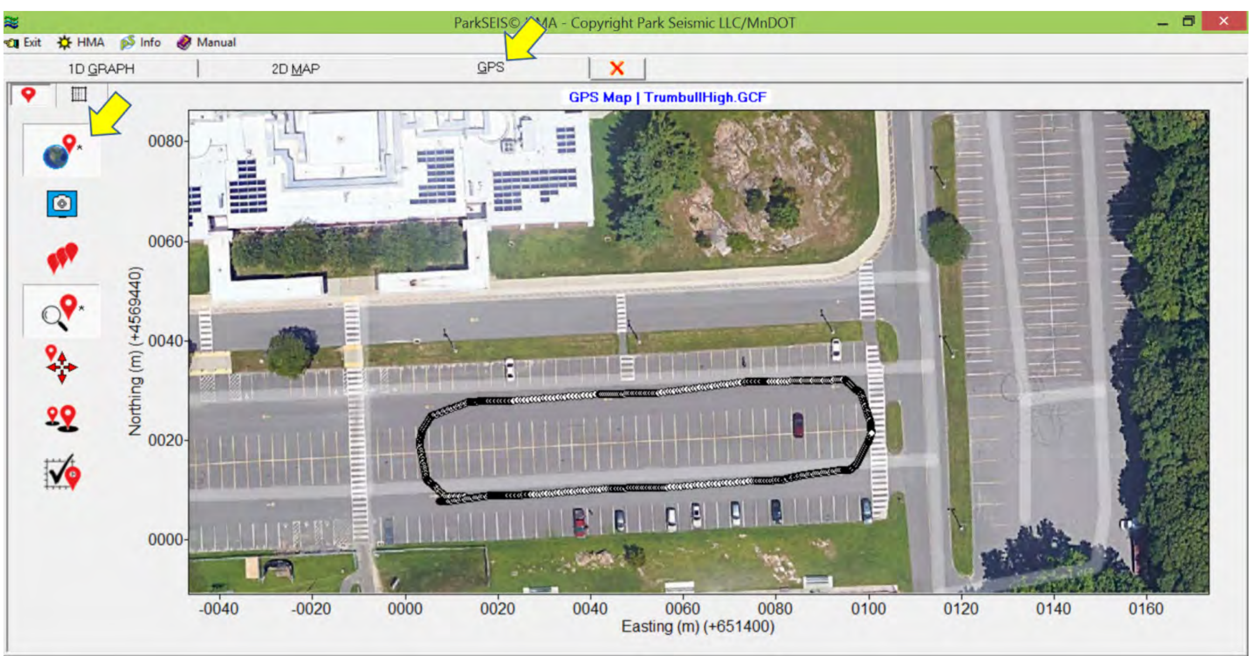
The program will ask to save the map with location information as a graphic-combined file (*.GCF) (e.g., "Site Map.gcf") so that it can be imported into the GPS data display later. If future surveys will take place at the same (or nearby) site, then the saved file can also be designated as a default GCF file, which can be conveniently imported by right-clicking the import button without need to navigate into the folder where the file (*.cgf) is saved.



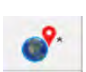
5.5.3 Importing Graphic Combined File (*.gcf) to GPS Display

Display of survey results always includes GPS tab where recorded GPS points are displayed in UTM coordinates without background satellite image. This is the original display mode when the "GPS" tab is selected.

Click the import button on top in the left tool pane (see below). Then, import the previously prepared file (*.gcf). The chart scales will be accordingly adjusted to match the scales embedded in the file. Mouse scroll and panning actions will be applied to both background image and GPS data points as one combined unit. Other options in the tool panel are explained below.



Map Tool Page 



Imports a Google map image in combined graphic file (*.gcf) or in JPEG file (*.jpg). Right click will enable to import the default file (*.gcf) previously designated.

Enables to capture screen image of Google satellite map. This is a method of preparing a graphic combined file (*.gcf) in a low resolution (e.g., 1920x1080). See the "Screen Capture for Orthophoto File (*.gcf)" section.

Show/hide GPS data points.

Scroll zoom map image. Right click to control zoom speed. Shift click for full-size display.

Pan map image.

Set two reference points for location information. Or, restores previous settings if exist.

Fix current map image and chart settings after some changes are made.

Change attributes of GPS marks.

Chart Tool Page

Pan all (map image and chart) at the same time.

Show/hide grid lines.

Scroll zoom chart. Right click to control zoom speed.

Pan chart.

Scroll zoom in (left) and out (right).

Print displayed image.

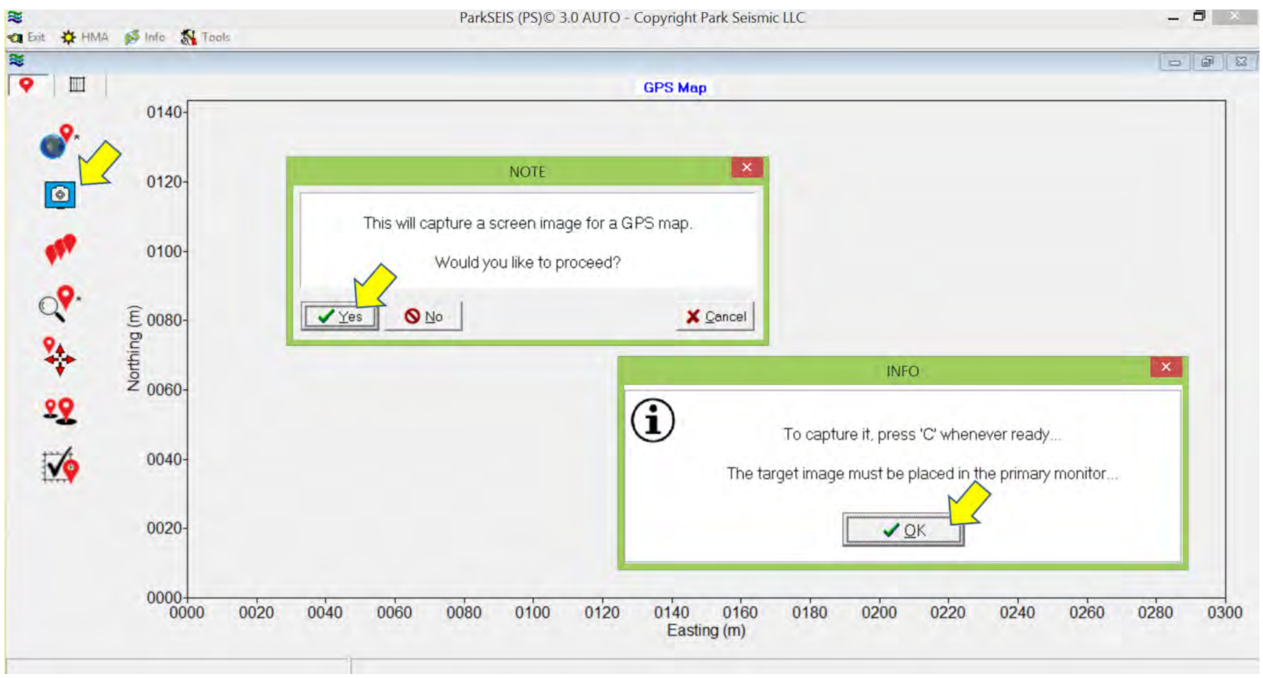
Save displayed image.

5.5.4 Screen Capture for Orthophoto File (*.gcf)

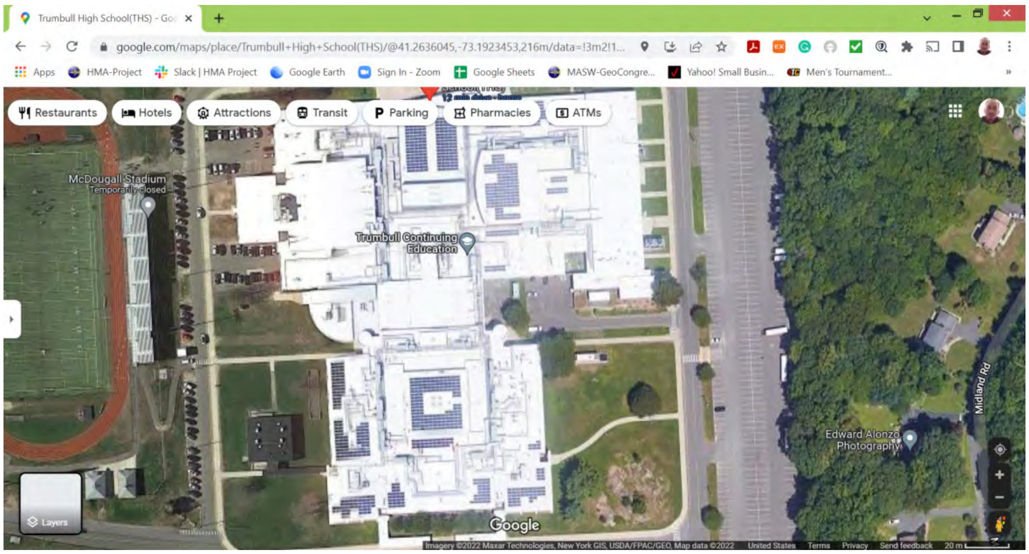
This is another way of creating an orthophoto image and then its graphic combined file (*.gcf) by using a common Google map (e.g., maps.google.com). It is a simpler method than previously introduced in the "How to prepare an Orthophoto" section. However, the image resolution is limited by the size of the monitor (e.g., 1920 x 1080).

Go to "Tools" in the main menu and then select the "GPS Display" option as illustrated below.

Once the GPS form is displayed, click the "Capture Screen Image" button in the left tool panel. After displaying a couple of message dialogs, the program window will be hidden and ready to capture the screen image whenever the key 'C' is pressed.

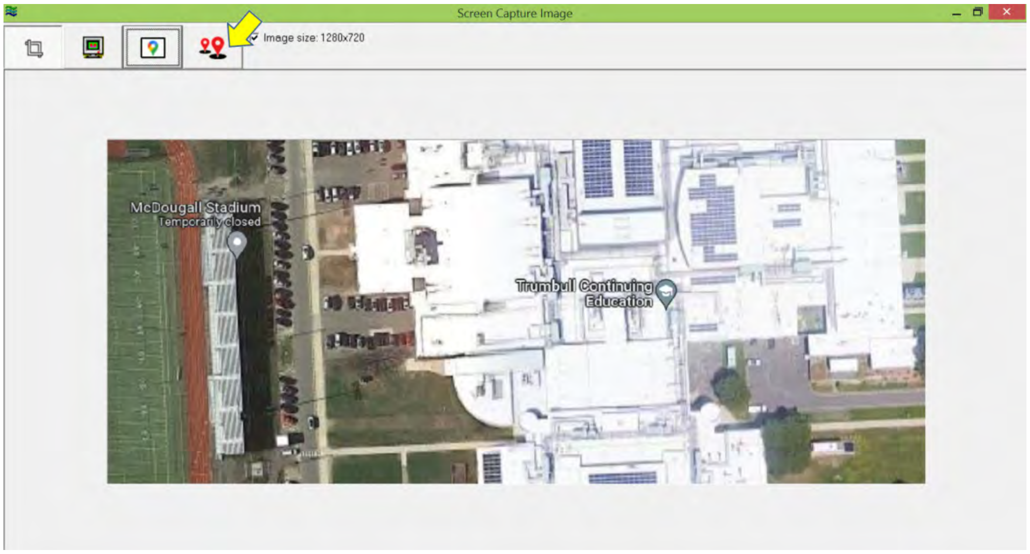


First, run the Google map browser and display the survey area as illustrated below.

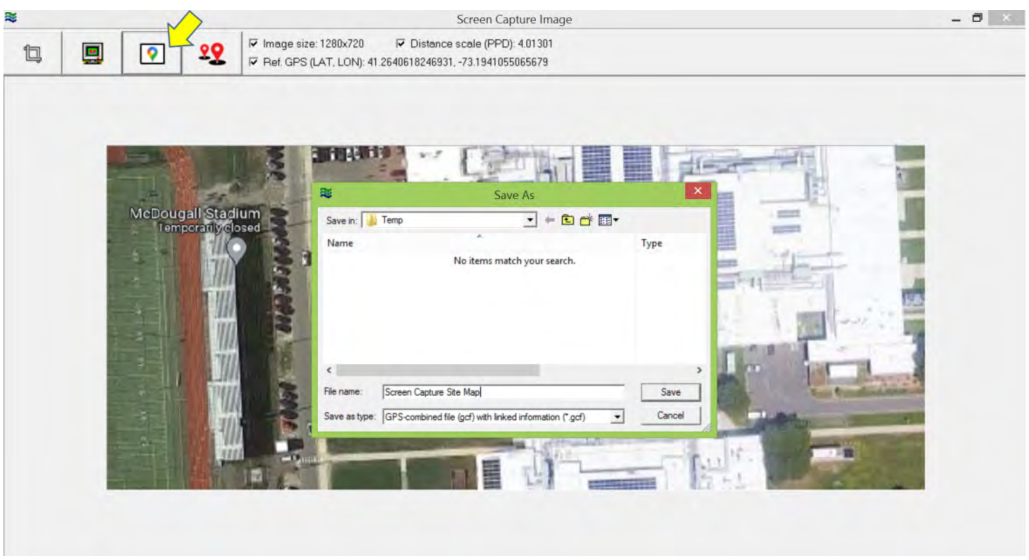


Then, hit the 'C' key. Another window will show the screen image captured in a frame inside the display form as illustrated below. Use mouse to trim the image as necessary (illustrated below). Function buttons available in the form are marked in the figure below.

Then, click the "Reference GPS" button in the top tool panel. The remaining steps are identical to the steps explained in the "How to Assign Location Info (LAT/LON) to Orthophoto" section that assign the LAT/LON information to the two reference points by going back and forth between the two images; one displayed in the current form and another displayed in the Google map browser.



Once the reference points are assigned, then save the image as a graphic combined file (*.gcf).



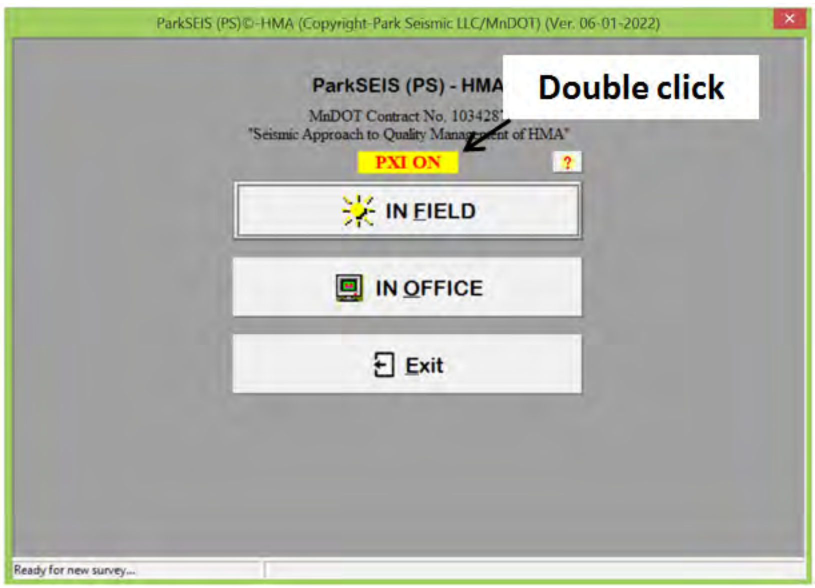
6. Troubleshooting

6.1 PXI would not shutdown

Whenever PXI would not shutdown normally from the ParkSEIS-HMA (PS-HMA) software at the end of a survey, follow the steps outlined below. This may happen when the PS-HMA is closed abnormally without going through the normal PXI shutdown steps. Never use physical switch to shut it down. PXI and the laptop computers must be connected through the Wi-Fi connection for the steps outlined below to work properly.

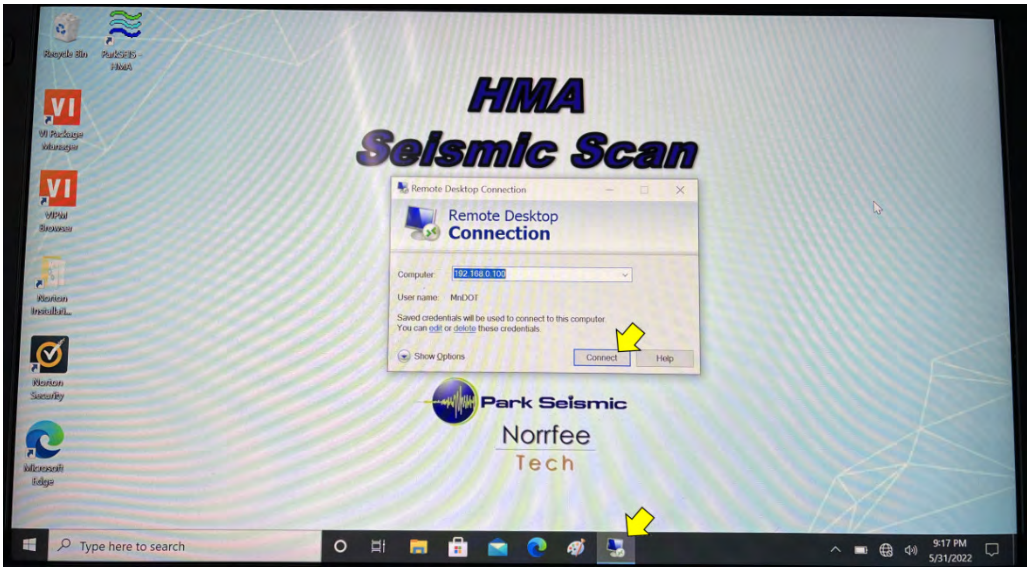
6.1.1 Shutdown from ParkSEIS-HMA (PS-HMA) software

Run the PS-HMA software and then double click the "PXI ON" label. Make sure to delete all files on the PXI measurement folder before shut down when prompted.

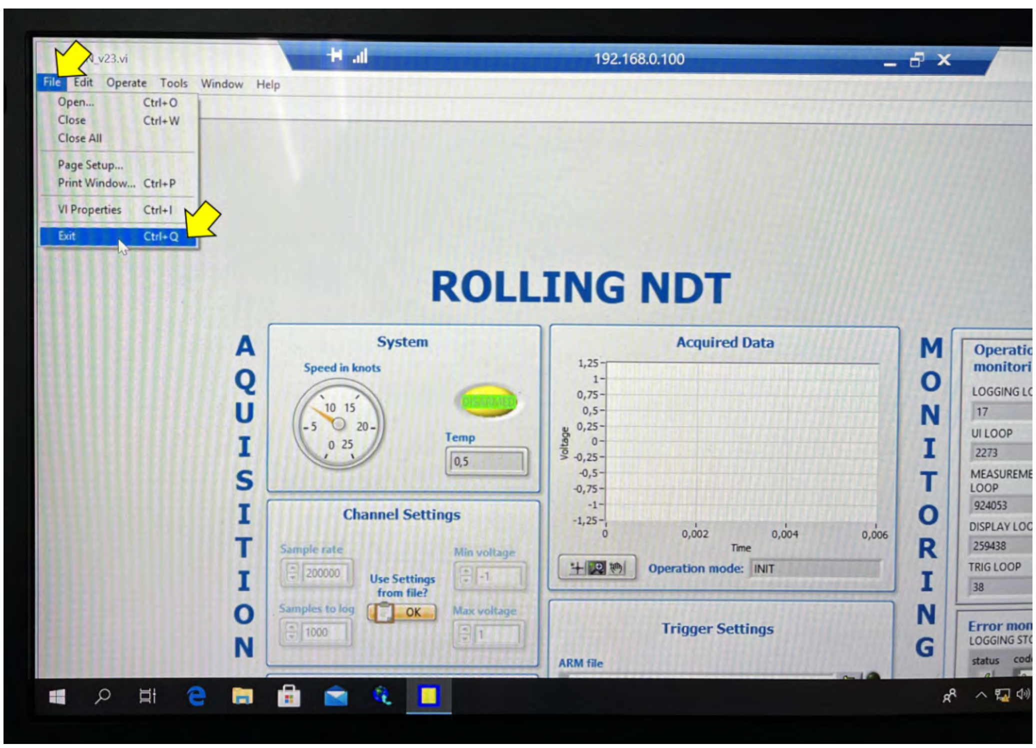


6.1.2 Manual shutdown by accessing PXI

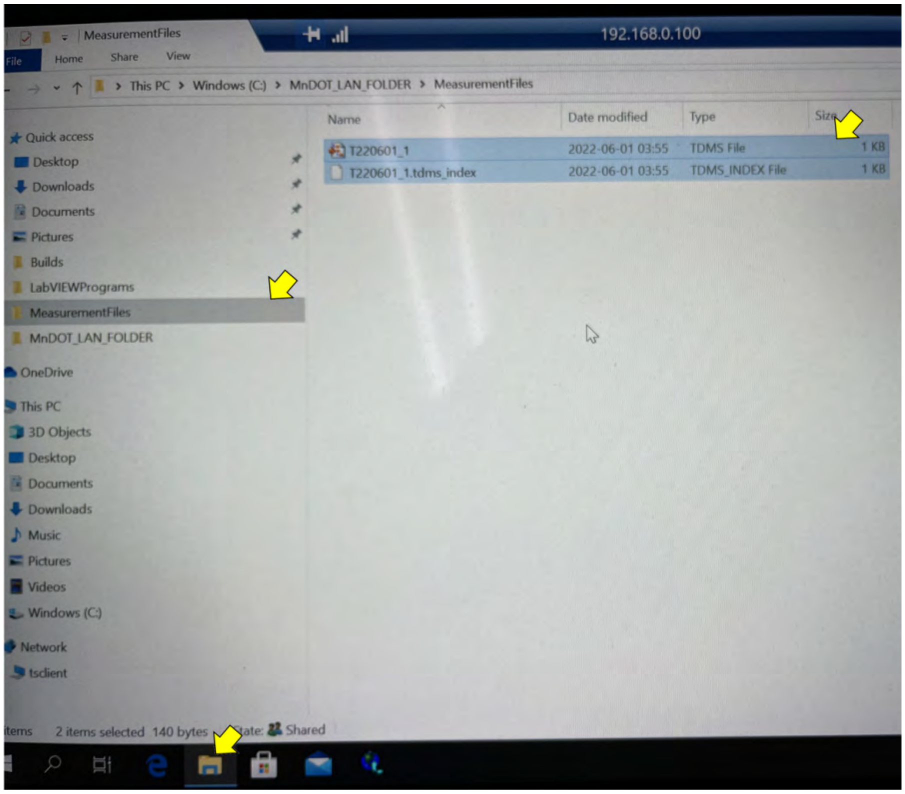
The PXI computer can be accessed through the remote desktop connection from the laptop computer. Click the "Remote Desktop Connection" icon in the system tray as illustrated below. Click the "Connection" button. After a few seconds, the laptop will show the desktop screen of the PXI computer.



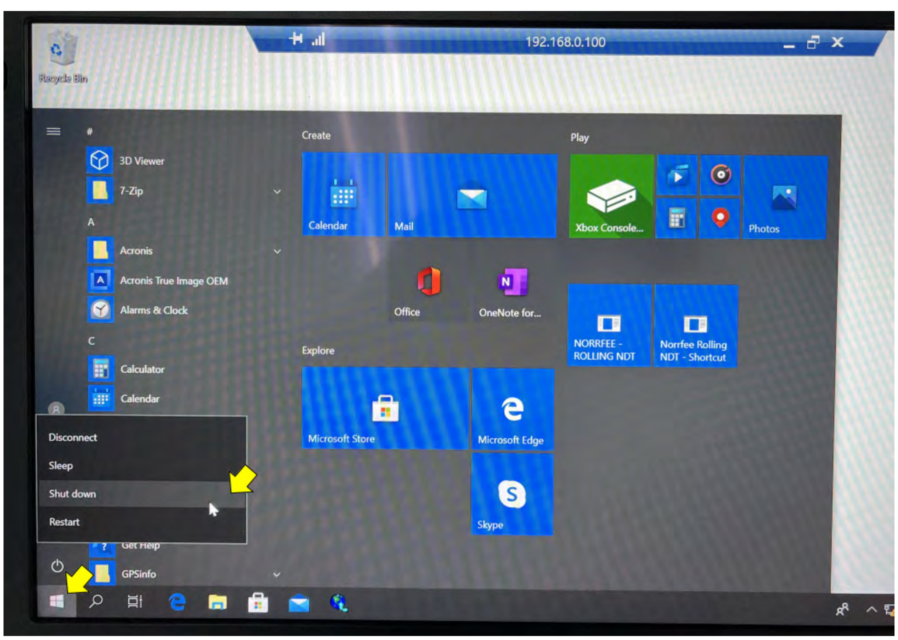
If the "ROLLING NDT" software (the PXI control software) is running in the background, then close it by accessing the "File" and then "Exit" as shown below.



Click the "MeasurementFiles" folder and then delete all existing files if there are.



Shut down through the Windows Start menu as illustrated below.



6.2 PXI shutdown accidentally

To check if PXI can be turned on normally again, turn it on by using the physical switch. Make sure Wi-Fi router is connected and powered up. Turn on the laptop computer and wait for about one minute. Click the "Remote Desktop Connection" icon in the system tray. If this connection goes through successfully and PXI computer screen is visible, then PXI started normally and there was no issue from the previous accidental shutdown. To shut it down again, run the ParkSEIS-HMA (PS-HMA) software and double click the yellow "PXI ON" label. Or, continue the new survey.

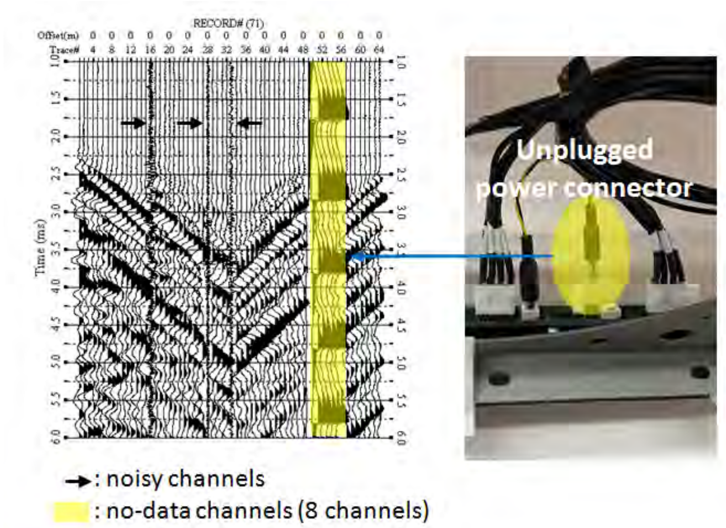
If the connection fails, then it means the PXI could not start normally again. Connect a separate external monitor and a keyboard to PXI and then follow the steps listed on the "Windows did not shut down properly" screen.

6.3 No triggering during the survey

If the ParkSEIS-HMA (PS-HMA) screen does not change when it is under "ARM" status while the survey is proceeding and making impacts, then it means the system is not "triggered" to record data. This can happen for multiple reasons. First, the power adaptors may not be plugged in the power source. Second, the power connectors may be loosely plugged in the array. Third, data cables can be loosely connected on both or either ends.

6.4 Noisy or no-data channels

A noisy channel (see below) may occur because of multiple reasons. It can be electronic reason in the circuit board. Or, it can be a mechanical reason near the MEMS microphone (e.g., micro vibration of electronic/mechanical components or tiny particle inside the microphone). It usually contains high-frequency vibrations that are outside the useful signal waves (e.g., > 30 kHz) (see below) and therefore does not make any noticeable change in the analysis results. The channel may become normal again when the noise source disappears. However, the "no-data" channels can be troublesome because they happen in a multiple of one array-board channels consecutively (8) (see below). This happens due to the power loss to the board. So, check all power connectors to the array if this happens.



6.5 ParkSEIS-HMA (PS-HMA) software closed abnormally

If the ParkSEIS-HMA (PS-HMA) software is closed abnormally (e.g., a crash due to memory loss after a long process), then PXI cannot be shut down normally. Then, run the PS-HMA software again and double click the yellow "PXI ON" label to force the PXI shutdown.