Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Report – 1st Quarter, 2020

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April 22, 2020

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SUMMARY

This document summarizes progress during the first quarter (Q1) of the development of hardware, software, management and administration of the HMA project in year 1 of the two-year project period (2020-2021) for the tasks specified in the Scope of Work. It is prepared also for an internal archiving purpose and thus can be deemed overly thorough for a quarterly report. In the future, authors plan to use a simplified template, which can be proposed by the reviewer(s) of this report.

The project seeks to build a complete hardware and software system that measures important characteristics of HMA. Specifically, the system will consist of multiple MEMS Microphone Arrays (MMA's) configured side-by-side to measure the shear-wave velocity (Vs) and thickness (H) of one-lane width HMA layer (6-ft or 1.8-m wide). It will include an on-board software package which controls the acquisition hardware and performs pseudo-real-time data analysis to display output results (Vs and H) on the onboard computer in 3D mode (Figure 1). The total length of one array (MMA), which is the key factor determining maximum measurable thickness (Hmax) of the pavement layer, must be in 30 cm – 40 cm to measure an HMA layer as thick as 20 cm, which is currently set as the maximum thickness (Hmax = 20 cm). The minimum thickness (Hmin) is currently set to 4 cm (Hmin = 4 cm) and the highest frequency of surface (Lamb) waves needed to resolve this thickness is about 50 kHz (Figure 2). The channel spacing (dCH) in the array has to be smaller than Hmin (i.e., dCH < Hmin).

The parent hardware system adopted by modification for the project is the one built at Lund University (LTH), Lund, Sweden for other related project executed in 2019 (Ryden et al., 2019), which is referred here as SYS-RYD-2019 (Figure 3). It consists of one array of 48-channel MEMS microphones spaced in a 0.75-cm interval, which can be considered a spatially-oversampling interval. A small metal ball attached at the end of the array is used for a seismic source that generated high-frequency surface (Lamb) waves as it freely bounces off the pavement surface when in motion (Figure 3a). A 48-channel field data set of extraordinary quality obtained by using this system is displayed in Figure 3b.

The parent software to be adopted by customization for this project is the ParkSEIS (PS) package (Figure 4a) developed and released to process MASW data sets acquired for the normal soil-site investigation. It deals with seismic data sets acquired by using a geophone-receiver array that is usually a few tens or hundreds of meters long (e.g., 30 m - 300 m) to record surface waves commonly lower than 100 Hz in frequency. It is developed mainly as an in-office software package. The software package to be developed for this project, ParkSEIS-HMA, will have both in-field and in-office modules that can be operated through either touch-screen or mouse response (Figure 4b).

Before the completion of the entire system consisting of multiple MMA's, it is critically important to fully test an intermediate system consisting of only one MMA to ensure its most optimum performance. The first quarter of project execution (January-March, 2020) has focused on the optimization of these parameters in both hardware and software components that can directly influence the overall resolution of the results (Vs and H) and therefore have to be determined at the very beginning stage. In the hardware, they comprise the optimum values in number of channels per array (NCH-opt), channel spacing (dCH-opt), and number of such arrays configured transversely (NA-opt). In the software, they are the highest frequency (fmax) that it can be handle and the overall flowchart that can allow the design of some key user interfaces at the gate of the software structure.

From a practical standpoint, the number of total channels for the entire system was set to sixty four (64) channels (expandable up to 96 channels) that will be equally allocated to a multiple number of MMA's (e.g., 2-6) arranged side-by-side to cover a nominal one-lane width (6 ft or 1.8 m) on the same pass. This was, based on a consideration of the realistic amount of seismic data that can be handled in a real (or pseudo-real)-time analysis mode in the field, in addition to the budgetary constraint.

Based on the extensive spatial resampling tests executed by using a set of spatially over-sampled field data acquired by using the SYS-RYD-2019, one MMA will consist of 16 channels (i.e., NCH-opt = 16) with a 2.25-cm spacing between channels (i.e., dCH-opt = 2.25 cm). In addition, each channel will use three (3) MEMS microphones spaced with a 0.75 cm interval and connected in parallel (Figure 5). This approach of "receiver array" for one channel is adopted as an in-field attempt to increase the signal-to-noise ratio (S/N) between the Lamb (signal) and the impact-sound (noise) waves. The sound waves are the strongest noise that needs to be controlled by all means not only during the field acquisition but also during the post-acquisition data process stages. This spatial configuration for one MMA will enable a thickness (H) measurement approximately in 4 cm (Hmin) ≤ H ≤ 20 cm (Hmax) on condition that Lamb waves in a proper frequency (f) range are generated and recorded (e.g., 1 kHz ≤ f ≤ 50 kHz) (Figure 2). When the complete system is available, there will be four (4) such MMA's arranged transversely with a 0.5-m separation (Figure 1). As of March 28, 2020, all parts to build the 64-channel acquisition system have been procured at the subcontractor (Norrfee Tech, AB).

It seems necessary, however, at this stage of the project development to collect a few field data sets from different asphalt pavement conditions by using the SYS-RYD-2019 for the purpose of further examination of aforementioned parameters for one MMA. Such field test will be conducted in the near future.

Work completed for hardware development ("Task #2" in the Scope of Work) is 2.2 % by the end of March, 2020. Although it is lower than the quarterly average rate (12.5 % for a 8-quarter period), the rate is expected to accelerate significantly for the next 2 quarters, for reasons we outline below.

The first objective in the software development ("Task #3") was to upgrade the upper frequency limit (fmax) of the analyzable seismic waves in the parent software, ParkSEIS (PS), which has fmax = 5.0 kHz. Considering the maximum 50 kHz needed to resolve H = 4 cm, the upper frequency limit of the modified software package (PS-HMA) has been set to 100 kHz to account for future upgrade possibility at the earliest stage of the development. The hardware development will also account for this upper limit in measurable frequency (i.e., fmax = 100 kHz). The upgrade of ParkSEIS in fmax required a core-level modification in the existing data import, analysis, and display modules of ParkSEIS. Then, a series of data analyses were executed to properly evaluate the aforementioned optimum parameters (NCH-opt, dCH-opt, and NA-opt) to construct one MMA hardware system. A spatially over-sampled field data set, which was collected by using the SYS-RYD-2019 for a related study at LTH, was used for this purpose. Values of the optimum parameters previously stated were obtained based upon the results from these tests. Procedural details about the tests are explained in this report and related graphical contents are presented in Appendices I-III.

The influence of the pavement temperature on the accuracy of the final analysis results was briefly discussed among the investigators (Figure 6). A separate sensor will be attached to each MMA to measure the pavement surface temperature at the time of seismic measurement, which will be encoded in the seismic data header. How to calibrate the analysis step(s) and/or results for the temperature effect has been also discussed. All agreed, however, this is a topic for a separate research and the temperature data will only be used, at least until otherwise found, as a supporting data that can help the interpretation of the final analysis results of Vs and H.

The topic of data format was discussed between the hardware (Norrfee Tech) and the software (Park Seismic) developers. The former uses the LabVIEW as a developing platform and therefore uses its default format (TDMS), while the latter follows the ParkSEIS (PS) format. To account for the special characteristics of this seismic approach, a new data format ("HMA" format) has been proposed for a seamless communication between the two parts (Figure 7).

Work completed for software development ("Task #3") is 9.1 % by the end of March, 2020.

A significant amount of time has been spent for project management and administration ("Task #1") by all (3) investigators as well as the administrative staff, especially during the first two months (January-February). During the month of January, the project-launching-related operations, such as the Kickoff and Technical Advisory Panel (TAP) meeting (held on January 23), required all (4) participants to frequently communicate with each other not only to prepare for the meeting but also to refresh and refine the contents and schedules outlined in the original proposal as well as in the contract. A separate website dedicated to this project was created (Figure 8) and has been updated a few times each month to reflect the project progress as well as to improve the overall format of the site. A Google blog site was also created as a platform for all project participants to exchange files and to communicate with each other effectively. During the month of February, all had to work on how to prepare materials for monthly invoicing process (e.g., invoices, progress reports, and supporting documents). This process has become more familiar and getting less time for all.

All participants have been meeting once a month (2:15 pm EST on the last Tuesday) online via Skype for about an hour to discuss concurrent topics and issues. The administration staff has been keeping the meeting minutes to post on the website and on the blog. The staff is organizing, maintaining, and facilitating all administrative aspects of the project.

Work completed for Task #1 is 6.2 % for the prime contractor (Park Seismic) and 1.8 % for the subcontractor (Norrfee Tech) by the end of March, 2020.

Overall work (Tasks #1-#5) completed are 15.2 % and 4.0 % for the prime and the sub contractors by the end of March, 2020 (Figure 9).

PROJECT OVERVIEW

The goal of this project is to develop a seismic system that acquires seismic surface (Lamb) waves propagating through the asphalt (HMA) pavement layer for the purpose of measuring shear-wave velocity (Vs) and thickness (H) of the HMA layer. The system will include an onboard software package that analyzes the acquired seismic data in pseudo-real-time mode and display the results of Vs and H in a 3D fashion (Figure 1). It will consist of multiple receiver arrays so that a 6-ft wide pavement surface can be surveyed simultaneously with a 1-2 ft transverse resolution while the surveying vehicle continuously rolls at a speed of 30 MPH or faster.

Figure 10a illustrates the conceptual schematic of the system as presented in the original project proposal. Multiple longitudinal arrays of independent impact sources were originally proposed. The most recent study results (Ryden et al., 2019) obtained by using a similar system (SYS-RYD-2019), however, showed a different approach can be more effective that used a small steel ball freely bouncing off the pavement surface when the constraining vehicle is in motion (Figure 1). By adopting this, the system for this project will use only one impact source common to all MEMS Microphone Arrays (MMA's) as illustrated in Figure 10b. The MMA, however, may require its own independent impact source (or one to be shared by two MMA's, not all four) if the "one common source" turns out, from field test, ineffective because of the attenuation issue for those farther arrays from the source.

The prime contractor, Park Seismic LLC, oversees the entire project and develops the software package, while the subcontractor, Norrfee Tech AB, develops the hardware part of the proposed system. The entire work executed to accomplish the project goal is categorized into five (5) tasks as described in the "Scope of Work" of the project contract and summarized below:

- 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

In this report, progress and accomplishment by the two contractors are described in the corresponding tasks listed above.

HARDWARE DEVELOPMENT ("TASK #2")

The progress in the hardware development is summarized in this section.

Parent Hardware System ("SYS-RYD-2019")

The parent hardware system (Figure 3) to be adopted by modification for this project was developed by Norrfee Tech for a related study (Ryden et al., 2019) at Lund University (LTH), Lund, Sweden. We will denote this as "SYS-RYD-2019" throughout this report. It consisted of a 48-channel MEMS Microphone Array (MMA) with a 0.75-cm interval between microphone receivers, a 12-bit A/D converter, and associated control modules in LabVIEW. The small receiver interval is considered a spatially oversampling configuration that was initially designed purely for research purpose. In theory, this would allow a thickness (H) measurement as small as one receiver interval (i.e., 0.75 cm) if "high enough frequencies" of surface waves are properly measured and analyzed. Total length of the array (L) (36 cm) is long enough to handle the thickness as large as 20 cm (or even larger), again on condition that "proper low frequencies" are analyzed. The A/D converter applies a band-pass filter with a practical passband in 0.5 kHz - 50 kHz. This analog filter is essential to attenuate harmful ambient noise that may saturate the limited dynamic range of the converter (12-bit), especially at low-frequency side (e.g., < 1 kHz). The frequency of 0.5 kHz would be low enough to allow the analysis of H as large as 20 cm (i.e., Hmax = 20 cm) (Figure 2). The frequency of 50 kHz will be high enough to allow Hmin = 4 cm (Figure 2). This high end of analog filter, however, will be extended for this project to allow additional capacity for even a smaller thickness analysis (i.e., H ≤ 4 cm). Previous studies (e.g., Bjurström and Ryden, 2017), however, indicated Lamb waves on asphalt surface higher than 50 kHz attenuate so rapidly that they are usually not clearly observed at far offsets (e.g., ≥ 30 cm). This high-frequency limit will be further tested with different impact-energy sources once the system of one MMA is available.

Project Hardware System Under Development ("SYS-HMA")

Although the SYS-RYD-2019 would be more than optimal for the requirements of one array, it would encounter some practical limits, if multiple of such arrays are used simultaneously as needed for this project, in the amount seismic data to be handled for in-field process and also in the budgetary constraint. For example, it would be a 192-channel system if four (4) MMA's are to be built with the current SYS-RYD-2019. Instead, a series of analyses are executed with a 48-channel ("oversampled") data set collected by using the SYS-RYD-2019 for the purpose of examining the optimum channel spacing (dCH-opt) and number of channels per array (NCH-opt). It was also examined how many MMA's can be used transversely to achieve a spatial resolution in 1-2 ft range for a total number of channels practically allowed (e.g., 50-100 channels). Details about this experiment are presented in the next section of software development.

Based on the results from the aforementioned experiments, the channel spacing will be 2.25 cm (i.e., dCH = 2.25 cm), which is three (3) times longer than the one in SYS-RYD-2019 and one MMA will have a total of 16 channels (i.e., NCh-opt = 16). In addition, three (3) consecutive MEMS microphones spaced with a 0.75-cm interval will be electronically connected in parallel to increase the signal (Lamb wave)-to-noise (impact sound wave) ratio as more details are explained in the next section. This configuration allows the same MMA circuit boards used in SYS-RYD-2019 to be used with a minimal modification (Figure 5). There will be four (4) of such MMA's arranged at an 0.5-m transverse interval in the finalized receiver array (Figure 10b), totaling 64 channels.

To further ensure the optimal qualification, however, more field data sets will be collected before these parameters are finalized by using the SYS-RYD-2019. The purpose will be to further examine the SN ratio of seismic waves from asphalt layers of different qualities.

As of March 28, 2020, hardware components to build the 64-channel acquisition system (except for the MMA components) have been procured at Norrfee Tech. The system construction process is scheduled to begin soon. Specifications and prices (in SEK, Swedish krona) for all procured items are presented in Appendix IV.

SOFTWARE DEVELOPMENT ("TASK #3")

The progress in the software development is summarized in this section.

Parent Software Package – ParkSEIS (PS)

The parent software package to be adopted by customization for this project is the ParkSEIS (PS) package, which was developed for the normal soil-site MASW (Park et al., 1999) investigation. It deals with surface wave data sets collected by using a geophone array usually a few tens to hundreds meters long (e.g., 30 m - 300 m). This software usually handles surface waves in low frequencies (e.g., 5 Hz - 100 Hz) and can handle surface waves up to 5 kHz without any issues in analysis and display modules.

Test For Optimum Hardware Configuration

The first task in the software development was to upgrade the upper frequency limit (fmax) of the analyzable seismic waves in ParkSEIS (PS). Considering the maximum 50 kHz needed to resolve H = 4 cm (Figure 2), the upper frequency limit of the software package customized for this project, "ParkSEIS (PS)-HMA", has been set to 100 kHz at the earliest stage to account for a room for future upgrade. The upgrade in fmax required a core-level modification in the existing data import, analysis, and display modules of ParkSEIS. Then, a series of data analyses were executed to properly evaluate the aforementioned optimum parameters (NCH-opt, dCH-opt, and NA-opt) to construct one MEMS Microphone Array (MMA) hardware system. A spatially over-sampled field data set collected by using the SYS-RYD-2019 (Figure 3) was used for this purpose. Values of the optimum parameters previously stated were obtained based upon the results from these tests. Procedural details about the tests are explained below. More related graphical contents are presented in Appendices I-III.

A 48-channel field record with a channel spacing (dx) of 0.75 cm is tested to evaluate the optimum channel spacing (dCH-opt) and, therefore, the optimum of number of channels per (longitudinal) array (NCH-opt), while keeping the overall length of the array fairly the same (i.e., 36 cm). This evaluation will also determine the optimum number of transverse arrays (NA-opt) within the maximum number of channels available (64). Considering this 48-channel record as an ultimate reference for the highest quality one can obtain, the spatial re-sampling has been attempted to increase (decrease) the channel spacing (the number of total channels) by using two different approaches (Figure 11). The spatial resampling test included receiver spacing (number of total channels used) of 2dx (24-CH), 3dx (16-CH), 4dx (12-CH), 5dx (10-CH), 6dx (8-CH), 7dx (7-CH), 8dx (6-CH), and 12dx (4-CH). For each tested channel spacing, displays of re-sampled seismic record, corresponding dispersion image, and the evaluation of SN ratios are presented in Appendices I-III.

The original relatively small spacing (0.75 cm) was tested on how to minimize any adverse effect from strong air (sound) waves generated by the impact source that have significantly lower velocity (e.g., 330 m/sec) than that of the pavement surface waves (e.g., 2000 m/sec). The low air-wave velocity results in very short wavelengths (e.g., 1-3 cm) at high frequencies (e.g., ≥ 10 KHz) that can adversely interfere, through the spatial aliasing phenomenon, with the useful Lamb-wave energy trend in the dispersion image, the ultimate data space that is used to evaluate velocity (Vs) and thickness (H) of the HMA layer. Therefore, it is critical to control this effect as much as possible during data acquisition (as well as during the post-acquisition data processing steps). In this sense, the Lamb waves are considered as signal, while the air waves are considered as noise during the test. The comparison mainly focused on the overall amplitudes of signal (Lamb) and noise (air) waves observed in the dispersion image constructed from the original and the re-sampled field records. This is accomplished through the frequency-summation (FRQ-Sum) method (Park, 2016) that sums all energy in the dispersion image along the frequency axis for a given frequency range (i.e., 0.5-50 KHz) (Figure 12). Peak amplitudes in the summed curve is directly related to the signal-to-noise (SN) ratio of non-dispersive surface waves (e.g., flat portion of the fundamental-mode of asymmetric Lamb waves, A0, and air waves). On the other hand, the velocities where the peaks occur represent the phase velocities of the corresponding wave events.

The most desirable configuration parameters of the array (i.e., dCH-opt and NCH-opt) are the ones that result in the highest Lamb-wave (signal) amplitude and the lowest air (noise) wave amplitude.

Two types of spatial re-sampling approaches are considered; i.e., simple re-sampling (decimation) and stack-re-sampling. Both approaches are graphically explained Figure 11. The former is identical to simply increasing the receiver (channel) spacing by using only those traces falling into the new receiver locations from the original record. On the other hand, the latter approach connects (in parallel) those receivers falling in-between the new extended receiver spacing. This approach has been used for long in the seismic exploration surveys as a field attempt to attenuate the strong, but propagating at much lower velocity, the ground-roll surface waves (Telford et al., 1976). Detailed testing results of the two approaches are presented seperately in Appendices I and II. The side-by-side comparisons of the two approaches are presented in Appendix III.

In the simple re-sampling case (Table 1 and Charts 1 and 2 in Figure 13), the peak amplitudes of signal (Lamb) waves slightly decreases as the receiver spacing (number of total channels used) increases (decreases) from 53.8% at 1dx to 45.5% at 12dx (Chart 1). The peak amplitudes of noise (air) waves also decreases from 48.5% at 1dx to 35.9% at 12dx (Chart 1). As a result, the signal (Lamb)-to-noise (air) ratio did not change significantly (e.g., 1.17 – 1.41) (Chart 2). This indicates the SN ratio is not significantly affected by the receiver spacing (or number of total channels used) within the tested range; i.e., 1dx (48-CH) – 12dx (4-CH). More details are presented in Appendix I.

Phase velocities of signal (Lamb) and noise (air) waves evaluated from the peak amplitudes remained the same, within one velocity interval (40 m/sec) used during the dispersion image generation, at 2400 m/sec and 360 m/sec, respectively (Table 1 in Figure 13). The relatively high velocity of Lamb waves resulted from the special type of pavement at the survey site, a relatively fresh concrete pavement. The higher air-wave velocity (than the normal 340 m/sec) resulted from the vertical offline offset effect of the receiver array hanging above (instead of being in direct contact with) the pavement surface by about 15 cm. According to the SN ratio and the accuracy in the velocity estimation outlined above, a 4-channel array with a 12dx channel spacing (9.0 cm) would be used without compromising the SN ratio between the Lam and the air waves as far as this particular data set is concerned. However, this number of channels (4) would be too small to handle other challenges in data quality (e.g., other types of noise). In this sense, the optimum number (NCH-opt) should be greater than ten (10) at the least.

In the stack-re-sampling case (Table 2 and Charts 3 and 4 in Figure 14), however, the peak amplitudes of signal (Lamb) waves slightly increases (instead of decreases) until the spacing extended to 5dx (10 total channels) from 53.8% (1dx) to 56.6% (5dx), and then slightly decreases from 56.6% (5dx) to 47.1% (12dx) (Chart 3). On the other hand, the peak amplitudes of noise (air) waves rather rapidly decreases from 48.5% (1dx) to 22.2% (5dx), and then slightly increases from 22.2% (5dx) to 32.2% (12dx) (Chart 3). As a result, the signal (Lamb)-to-noise (air) ratio increases rapidly from 1.11 (1dx) to 2.55 (5dx) and then decreases from 2.55 (5dx) to 1.46 (12dx) (Chart 4). However, the SN ratio is always higher for a given re-sampled spacing (e.g., 2dx, 3dx, etc.) than that of the simple re-sampling case previously outlined (Table 2). This indicates the approach of stacking wavefields from adjacent MEMS microphone receivers enhances the relative energy of the signal (Lamb) waves while suppressing the noise (air) wave energy at the same time. This effect appears to continuously increase until the stacking takes place up to 5 consecutive receivers and then the effectiveness decreases (Chart 4). Phase velocities of signal (Lamb) and noise (air) waves evaluated from the peak amplitudes remained the same, within one velocity interval (40 m/sec) used during the dispersion image generation, at 2400 m/sec and 360 m/sec, respectively (Table 2). According to the SN ratio and the accuracy in the velocity estimation outlined in

Table 2, a 4-channel array with a 12dx channel spacing (9.024 cm) would be used without compromising the SN ratio between the Lamb and the air waves as far as this particular data set is concerned.

From the experimental results outlined above, it is obvious that the stack-re-sampling is superior to the other simple re-sampling approach because it increases not only the S/N (Lamb/air) but also the absolute amplitude of the Lamb waves until the spacing extends to 5dx (Table 2, Charts 3 and 4 in Figure 14). This means that by using a fraction of the original number of channels (i.e., 10 instead of 48), one can achieve the higher SN ratio. As shown in Chart 4, the SN ratio rapidly increases as the stacking takes place for the first 3-5 intervals. Although the stacking at 5 intervals (5dx) resulted in the highest SN ratio, the 3dx would have a few practical advantages for the three following reasons. First, it still provides a significant increase in SN ratio (the second highest among all nine tested values) that will be effective enough. Second, the 5dx would result in a too-coarse spatial sampling (3.75 cm) that can be challenging in measurement of the target minimum thickness (i.e., Hmin = 4 cm). Third, the 3dx configuration would make it possible to use the current receiver circuit board designed for the previous project (SYS-RYD-2019) with a minimal modification as illustrated in Figure 5.

In conclusion of this section, it is recommended connecting (in parallel) three (3) consecutive MEMS microphones, which are spaced with a current interval of 0.75 cm, to become one channel. This will make the new channel spacing (dCH-opt) become 3 x 0.75 = 2.25 cm. This configuration will allow the current circuit boards for MMA (SYS-RYD-2019) can be used by grouping three successive microphones electronically in parallel. Then, the new MMA will have a total of 16 channels consisting of all (48) microphones previously used for the old MMA in SYS-RYD-2019. The final 2D array configuration will consist of four (4) of such arrays arranged transversely with a 0.5-m separation (Figure 10b).

Data Format ("HMA Format")

The topic of data format was discussed between the hardware (Norrfee Tech) and the software (Park Seismic) developers. The former uses the LabVIEW as a developing platform and therefore uses its default format (TDMS), while the latter follows the ParkSEIS (PS) format, which is a modified version of the SEG-Y format invented in early 1980s. Although the PS format developed as an optimum solution for the near-surface seismic investigation at the time, it is regarded a redundant and also incomplete format for this HMA project because of unconventional characteristics of the project in the surveying apparatus (e.g., a tiny MEMS-receiver array with a fraction of centimeter spacing vs. a 100-m geophone array with a 4-m spacing) and associated frequencies being handled (e.g., 50 kHz to resolve 5-cm thickness vs. 50 Hz to resolve 5-m depth of a soil site). On the other hand, the TDMS format also contains a significant number of redundant elements as far as this project is concerned, which must have originated from the need to be a format most general for all engineering purposes. By accounting for the core characteristics of this special seismic approach, a new data format ("HMA" format) has been proposed for a seamless communication between the two parts. Figure 7 illustrates the main structure of the HMA format and Figure 15 shows the corresponding convention for record and trace headers.

ParkSEIS (PS)-HMA | Flowchart and Key Gating User Interface

Overall structure of the ParkSEIS (PS)-HMA package is illustrated in the flowchart (Figure 16). Two key modules will be bundled together; i.e., the one for in-field operation ("In-Field Module") and the other one for in-office operation ("In-Office Module"). The former will include sub modules related to the field data collection in addition to the data-process and -display sub modules, which are the standard components in the in-field module. There will be three types of process modes; i.e., one performs the entire sequence of data process on its own according to the default (automatic) parameterization approach (Full-AUTO), the other performs in a similar way to the previous Full-AUTO mode but allows the operator's intervention at a few key processing stages for interpretation and adjustment (if necessary) of parameters (Pseudo-AUTO), and the last type allows the operator to fully examine and control all steps of process (Extended-Manual). The display part of the software will enable the visualization of all sorts of data (input, output, and intermediate QA/QC data sets) in 1D, 2D, and 3D modes.

With the "In-Field" module, one can change (if chosen) all default parameters in Acquisition (ACQ) Control (e.g., fmax, recording time, analog filter setting, etc.), Data File Control (e.g., storage paths for raw and processed data sets, raw-data format, etc.), and intermediate process for QA/QC. Pressing the "ARM" button will set the system in active mode and the survey operation will start by an appropriate signal coming from an external device (e.g., the 1st impact sound from the source). Once an incoming data file is detected, the subsequent Full-AUTO process will analyze it immediately to save the results at a designated place, which will activate the display module to progressively visualize the output in 3D.

The" In-Office" module will provide a full freedom in both process and display. One will be able to process an entire set (or part) of the obtained field data through any of the three process options to examine the results at different stages in the sequence with a full freedom to manually adjust parameters. One can also visualize results at different stages. Figure 17 shows the design of several key user interfaces at the gate of the software under development (PS-HMA). User will be able to respond to all main menus via the touch-screen or the mouse option.

Figure 18 shows typical 3D display modes incorporated in the ParkSEIS-3D (Park, 2019), which will be the parent module to be customized for the display part of ParkSEIS-HMA. All display dimensions will be appropriately adjusted, and all output results of velocity (Vs) and modulus (e.g., Young's and/or shear) will be displayed progressively in real- to pseudo-real-time mode along with the surface coordinate information facilitated by the onboard GPS unit.

Temperature Calibration

The influence of the pavement temperature on the accuracy of the final results (Vs and H) was briefly discussed among the investigators.

The asphalt mastercurve (Figure 6a) dictates that the stiffness (Vs) of HMA layer changes with temperature. Moreover, the amount of change varies with frequency for a given temperature (Figure 6b), making the task of accurate calibration highly challenging. Although the exact mechanism through which the temperature influences the evaluation of asphalt velocity (Vs) and thickness (H) during the Lamb-wave-dispersion analysis is not clearly documented yet, it is clear it has a systematic influence on the evaluation of velocity (Vs) as illustrated in Figure 6b; i.e., higher temperature results in reduced velocity (Vs).

How to calibrate the analysis step(s) and/or results for the temperature effect has been also discussed. All agreed, however, this is a topic for a separate research and the temperature data will only be used, at least until otherwise found, as supporting data that can help the interpretation of the final analysis results of Vs and H. A separate sensor will be attached to each longitudinal array (MMA) to measure the pavement surface temperature at the time of seismic measurement, which will then be encoded in the seismic data header. The display software module will include an option to display the temperature data for a designated (or entire) section in the surveyed area.

Because of the potential complications raised by the temperature effect on the thickness (H) evaluation, a frequency-spectral analysis approach, for example, the Impact-Echo method (Sansalone and Carino, 1986), may also be considered to improve the overall accuracy in addition to the Lamb-wave dispersion analysis.

PROJECT MANAGEMENT AND ADMINISTRATION ("TASK #1")

It is essential to periodically remind the ultimate project goal and update the overall status of the project progress among all project participants. Equally important are the financial management and communication of overall project status to MnDOT and posting updates online. These operations executed for the 1st quarter are outlined here. Most related contents are also posted online at the following dedicated website.

Website

A separate website (Figure 8) dedicated to this project was created in January, 2020, for the purpose of publicizing the project nature. The site has been updated a few times each month to reflect the project progress as well as to improve the overall format of the site especially during the first month. A Google blog site, not publically open, was also created as a platform for all project participants to exchange files and to communicate with each other effectively. However, other tools such as Slack and Team are also being examined by the staff as an alternative tool of enhanced performance.

Meetings

A significant amount of time has been spent for project management and administration by all investigators and the administrative staff, especially during the first two months (January-February). The project-launching-related operations, such as the Kickoff and Technical Advisory Panel (TAP) meeting (held on January 23), required all (4) participants to frequently communicate with each other not only to prepare for the meeting but also to refresh and refine the contents and schedules outlined in the original proposal as well as in the contract. All participants have been meeting, for about an hour, once a month online at 2:15 pm EST on the last Tuesday via Skype to discuss concurrent topics and issues. The administration staff has been keeping the meeting minutes to post on the website and on the blog. The staff is organizing, maintaining, and facilitating all administrative aspects of the project including the monthly invoicing and progress reporting as outlined below.

Monthly Invoicing and Progress Reporting

During the month of February, all had to work on how to prepare materials for monthly invoicing process (e.g., invoices, progress reports, and supporting documents). By the end of March, this process has become more familiar and getting less time for all. Work completed for Task #1 is 6.2 % for the prime contractor (Park Seismic) and 1.8 % for the subcontractor (Norrfee Tech) by the end of March, 2020 (Figure 9). Overall works (Tasks #1-#5) completed are 15.2 % and 4.0 % for the prime and the sub contractors for the same period (Figure 9).

Summary of each month's progress is listed below.

January, 2020:

Task-by-task summary tables of the progress report are presented in Appendix V.

The project officially started as of January 6, 2020. As each participant was revisiting the original project proposal, scope of work, description of tasks, and the project schedule, technical contents and the overall work flowchart were discussed for clarification of assigned tasks and interaction with other participants' tasks. General frameworks of the hardware and software were drafted. Blueprints for hardware system building and software package development were prepared. Early clarification of potential issues in the hardware, software, administrative, and budgetary aspects has been attempted. Communication methods among all participants were discussed. A dedicated web site (this HMA site) was planned to open soon for public access. A blog was also to be prepared soon as a means to post each participant's outcomes for mutual communication and calibration purposes. This blog will be open only among the project participants.

Technical and administrative contents of the project were prepared to present during the Kickoff and the 1st TAP (Technical Advisory Panel) meeting scheduled on January 23, 2020. Temperature calibration, which may be necessary during the dispersion analysis of Lamb waves, was briefly discussed as the topic was raised during the TAP meeting as a potential issue.

Project administration and management aspects (e.g., communication method, scheduling, monthly invoicing, reporting, and payment, etc.) have been heavily discussed and executed throughout the entire month.

Kickoff and Technical Advisory Panel (TAP) Meeting (January 23, 2020) are summarized online and the minutes are also available online.

February, 2020:

Task-by-task summary tables of the progress report are presented in Appendix V.

A new data format convention was proposed by the software developer (Dr. Choon Park) to maximize the downloading speed and compatibility between the current hardware design base (that uses the LabVIEW TDMS format) and the software development base (that uses the ParkSEIS format). Considering the vast amount of data that, when completed, will be coming from the acquisition system for the pseudo-real-time onboard analysis, there should be a compact data format without unnecessary overhead information that will allow the software package focus directly on the analysis algorithm rather than spending extra time for data importing. Click for a brief demonstration of the new format on YouTube. A temporary data format, however, will be used as a communication tool to deliver data sets already collected by using a similar hardware system developed for other related projects at the Lund University until the hardware system for this project is fairly ready to be tested with the software package. The KGS format (a modified SEG-Y format) will be used until then. A field data set collected by using the 48-channel MEMS microphones at the Lund University has been delivered to Park Seismic for the evaluation, by using the ParkSEIS MASW software package, of the optimum number of channels per longitudinal array (NCh-opt) and the optimum channel (receiver) spacing (dx-opt).

Modification of the ParkSEIS software, the base software package to be developed into the software packaged for this HMA project, has started. The first task is to upgrade its capacity to handle the highest frequency from 5 KHz to 100 KHz. This process is currently being applied to all related components in data import, display, FFT, and the 2D-wavefield transformation module to generate the dispersion image data sets.

Main hardware components have been specified and the first pricing quote has been received at the Norrfee Tech, AB. It seems the overall hardware budget (now re-estimated approximately as $35K) is higher than the one originally proposed (~$30K). It has been discussed to submit an amended budget proposal by shortening the overall project period so that the part of the labor cost can be reallocated into the hardware budget. This topic will be continuously discussed as the project advances.

March, 2020:

Task-by-task summary tables of the progress report are presented in Appendix V.

Hardware Parts Ordered: Parts to build multichannel acquisition system (MAS) have been ordered at National Instruments (NI). They are the main components needed to build a 64-channel acquisition system (expandable up to 96 channels). Other accessory parts (e.g., MEMS microphones) will be ordered soon.

Specifications of parts ordered (as listed on the quotation in English/Swedish) are posted online.

Optimum Number of Channels Per Array (March, 2020): The final system will consist of multiple linear (1D) MEMS microphone arrays arranged along the transverse direction side by side (see Figure 5 in the original proposal). It is critically important to figure out the optimum configuration of the one (longitudinal) array in the channel spacing (dx-opt) and the number of channels allocated per array (NCh-opt). By using a field data set acquired with a 48-channel MEMS microphones with a very small channel spacing (i.e., dx=0.75 cm) (i.e., spatially over-sampled) over a special type of asphalt pavement in Sweden, a series of test have been executed through two types of spatial re-sampling approaches; i.e., the simple re-sampling of decimation and the stack-re-sampling approaches. The former simply reselects existing traces (channels) from the original full (48-channel) field record with a greater spacing (e.g., 2dx, 3dx, 4dx, etc.) by discarding in-between traces. On the other hand, the latter stacks (instead of discarding) them to make a new trace obtained with a greater spacing. This stack approach, called "receiver array", has been used for a long time in the seismic exploration for the purpose of attenuating the strong, but propagating at very low velocity, ground roll surface waves. These two re-sampling approaches are compared in the performance of enhancing the signal (Lamb) waves while attenuating the noise (air) waves at the same time.

According to the test results, it seems a 16-channel array with a 5dx (=3.75 cm), or a 4dx (=3.0 cm), channel spacing that connects (in parallel) all in-between MEMS microphones arranged with the current spacing of 0.75 cm. This means the stack-re-sampling approach turned out more effective than the other simple re-sampling (decimation) approach. With this configuration, the system will be able to handle HMA layers in a thickness (H) range of 4 cm (Hmin) - 20 cm (Hmax).

PROJECT PROJECTION

It is projected that the hardware acquisition system for one 16-channel MEMS Microphone Array (MMA) will be built during the next two quarters (2nd and 3rd), while the associated software package for the in-field module will be ready during this period for the Full-AUTO process for one MMA. However, a brief field test will be conducted by using the parent system, SYS-RYD-2019, over a few HMA pavements of different qualities for the purpose of evaluating the overall range of SN ratios that may further influence on the decision of optimum parameters for one MMA. This data set will also be used to examine the practical accuracy in the thickness (H) evaluation, which may be tested in combination with the Impact-Echo (IE) method (Sansalone and Carino, 1986).

Improvement of the impact source ("Bouncing Ball") will also be accomplished during this period so that impact time and impact strength can be controlled. The first joint-field test (hardware and software) will be performed during mid-late Fall of this year (October-November, 2020). Construction of the 2D-array system and associated software modules including the 3D process/visualization will be accomplished during the first 1-2 quarter(s) of the next year (2021). Intensive and extensive field tests will follow afterward [e.g., 3rd – 4th Qtr(s)].

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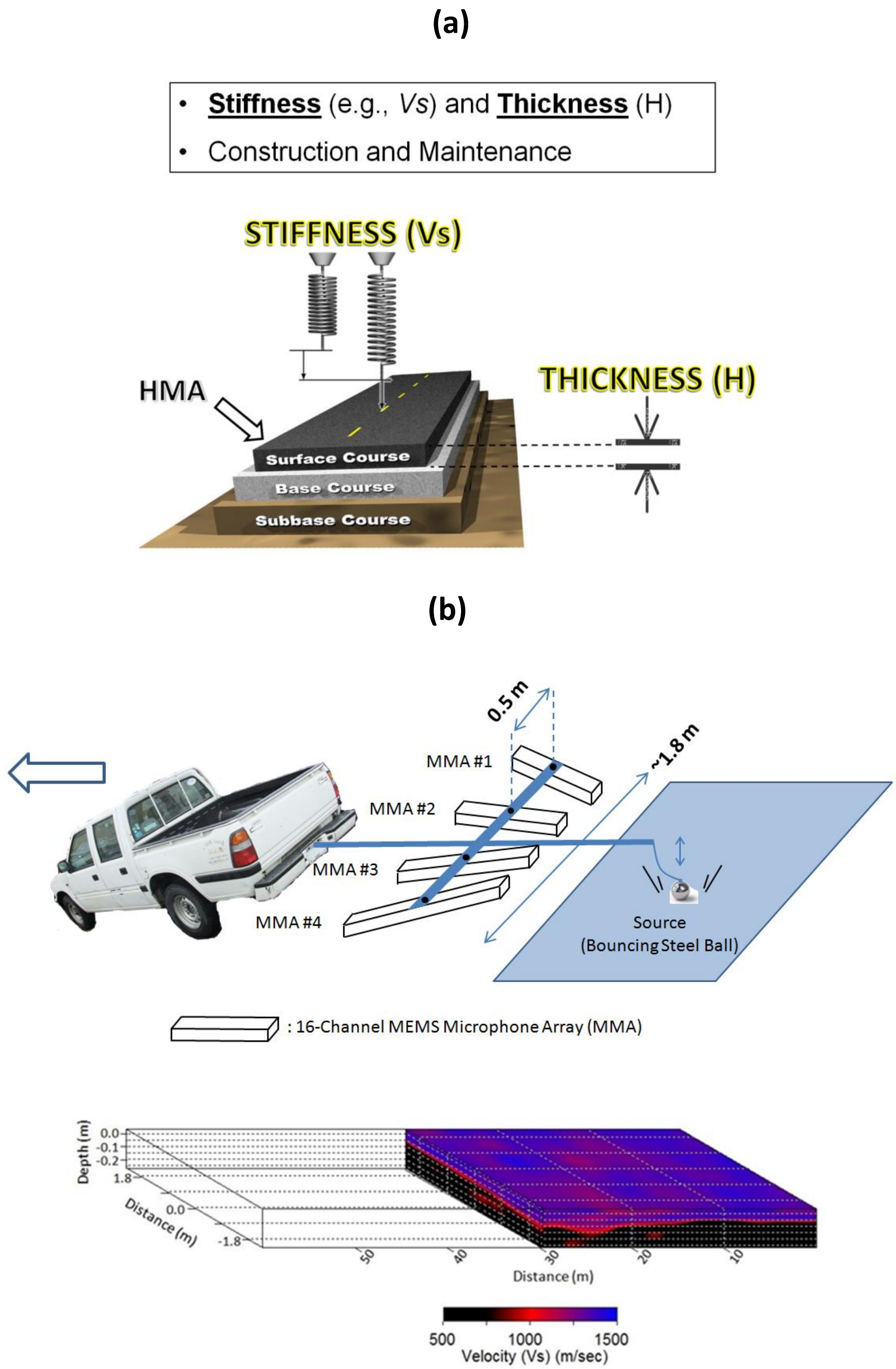


Figure 1. (a) The goal of this (HMA) project is to evaluate the shear-wave velocity (Vs) and thickness (H) of HMA layer. The Vs is the a direct indicator of a solid material's stiffness. (b) Updated schematic of the project deliverables consisting of multiple MEMS Microphone Arrays (MMA's) with possibly one common impact-source ("bouncing ball") and associated software package.

Frequency and Thickness (H)

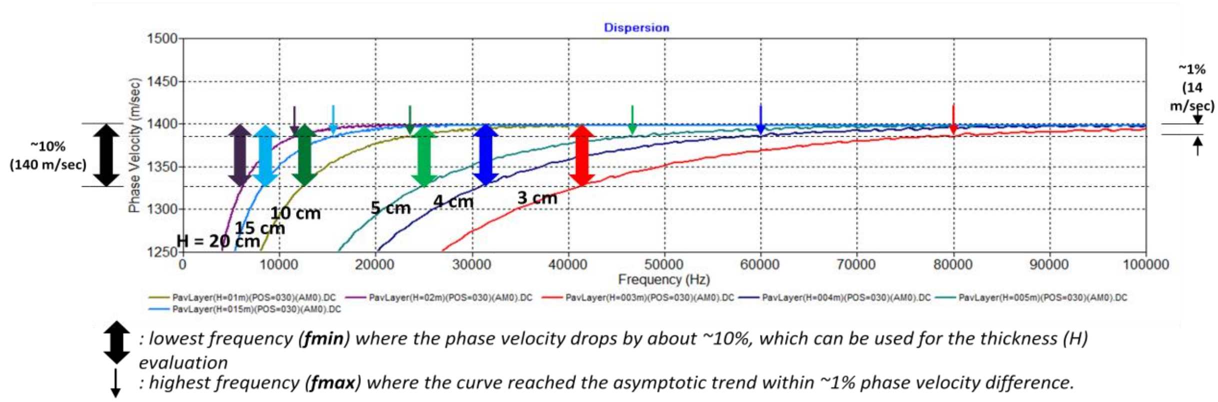
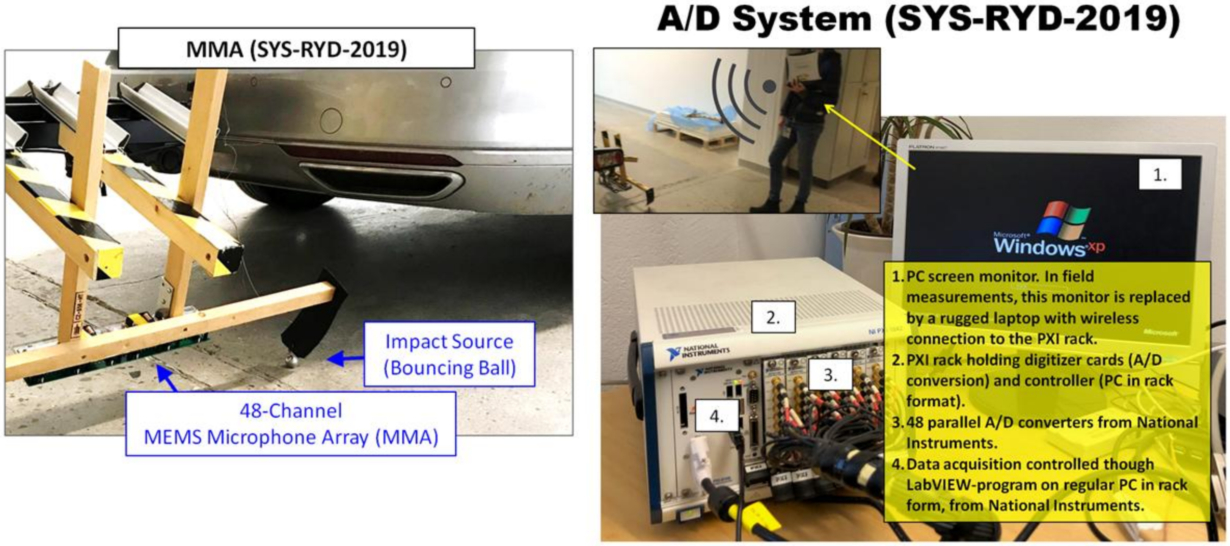


Table 1:
Key Frequency Range (*fmin* and *fmax*) for Thickness (H) Evaluation

Thickness (H) (cm)	20	15	10	5	4	3
fmin (KHz)	6.0	9.0	13.0	25.0	32.0	42.0
fmax (KHz)	12.0	16.0	24.0	47.0	60.0	80.0

Figure 2. The Lamb wave dispersion curves (A0's) for different thicknesses (H's) of HMA layer focused into a narrow zone of phase velocity (1250 m/s - 1500 m/s) for frequency sensitivity analysis. Based on the examination of these curves, approximate frequency ranges needed for thickness analysis are summarized in the table.

(a)



(b)

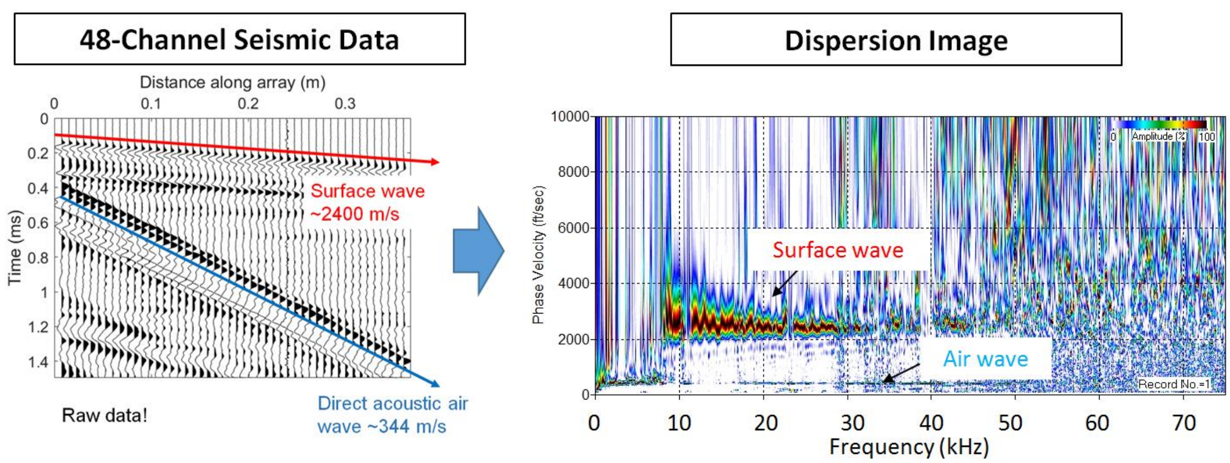
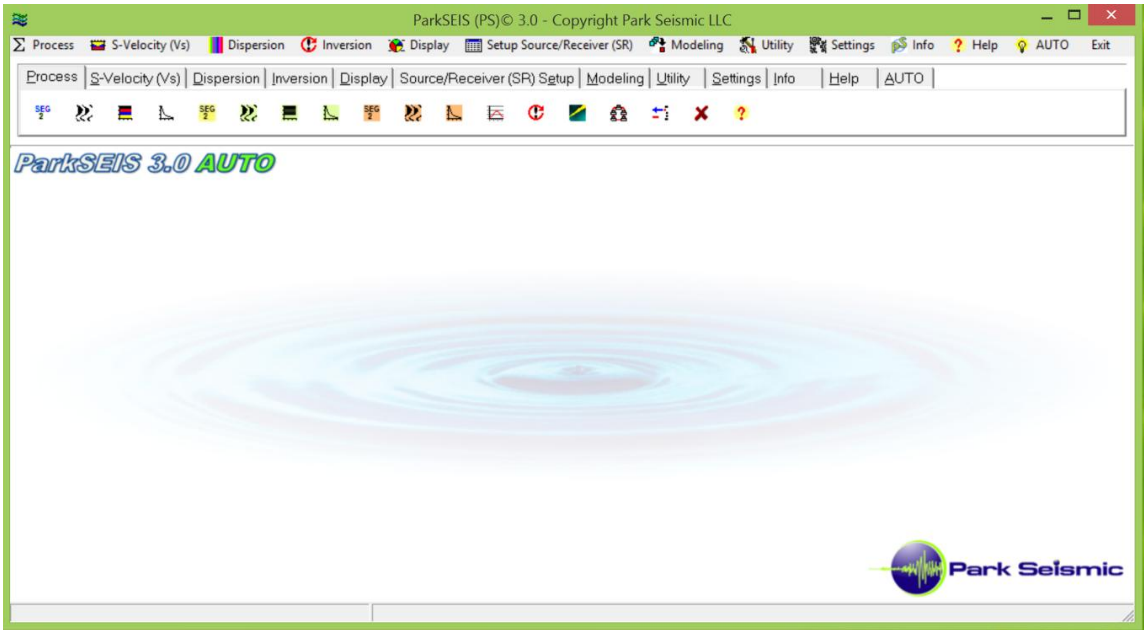


Figure 3. (a) The parent hardware system (referred as "SYS-RYD-2019") that is adopted by modification for this project. The 48-channel MEMS Microphone Array (MMA) (left) and the remaining components including the A/D converter (right) are shown. (b) A field seismic data of extraordinary quality collected by using this system (left) and corresponding dispersion image (right) showing the Lamb-wave dispersion (A0) trend clearly (From Ryden et al., 2019).

(a)



(b)

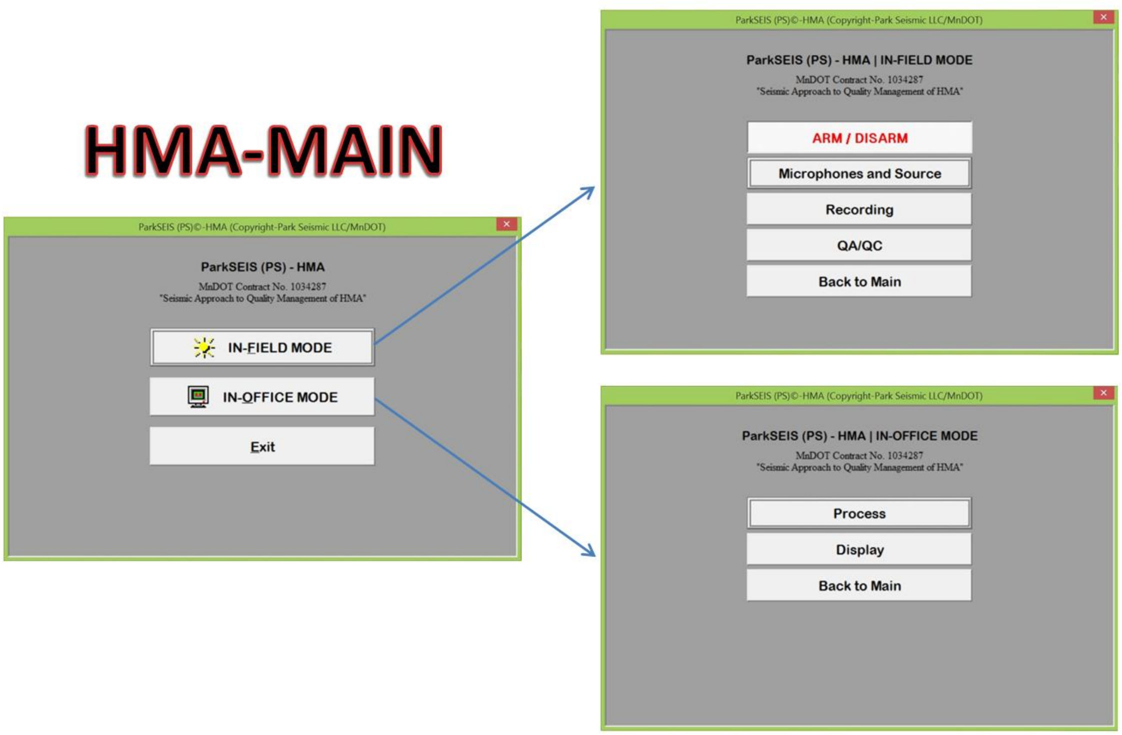


Figure 4. (a) A screen capture of the parent software package of ParkSEIS (PS), which was developed mainly as an in-office software package, and (b) screen captures of the gating user interfaces of the software under development for this project, ParkSEIS-HMA, that will consist of the two main modules ("In-Field" and "In-Office" modules).

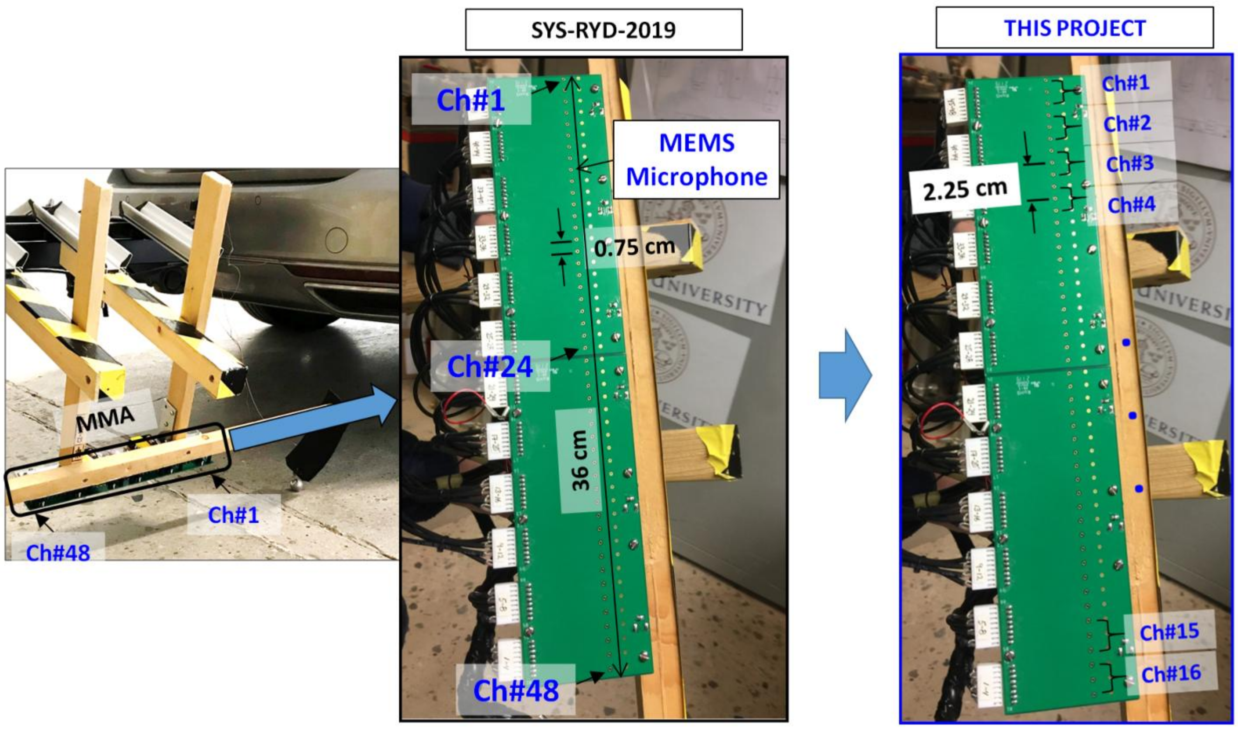
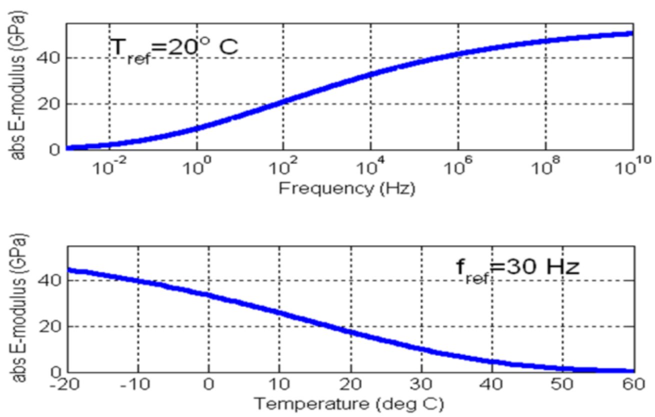


Figure 5. The configuration of the MEMS Microphone Array (MMA) circuit board used for the parent hardware system (SYS-RYD-2019) (left) and the configuration that will be used for the project system (SYS-HMA) (right).

(a)

Background – Asphalt Mastercurve

- A mastercurve is used to describe the dynamic E-modulus (E^*) as a function of frequency (f) and temperature (T).



Sigmoidal function

$$\log \left|E^*\right| = a_1 + \frac{a_2}{1 + e^{(a_3 - a_4 \log f_{red})}}$$

Reduced frequency

$$f_{red} = a_T f$$

Shift factor

$$\log a_T = -\frac{C_1 (T - T_{ref})}{C_2 + T - T_{ref}}$$

(b)

Non-Contact-Rolling Pavement MASW

(Bjurström and Ryden, 2017)

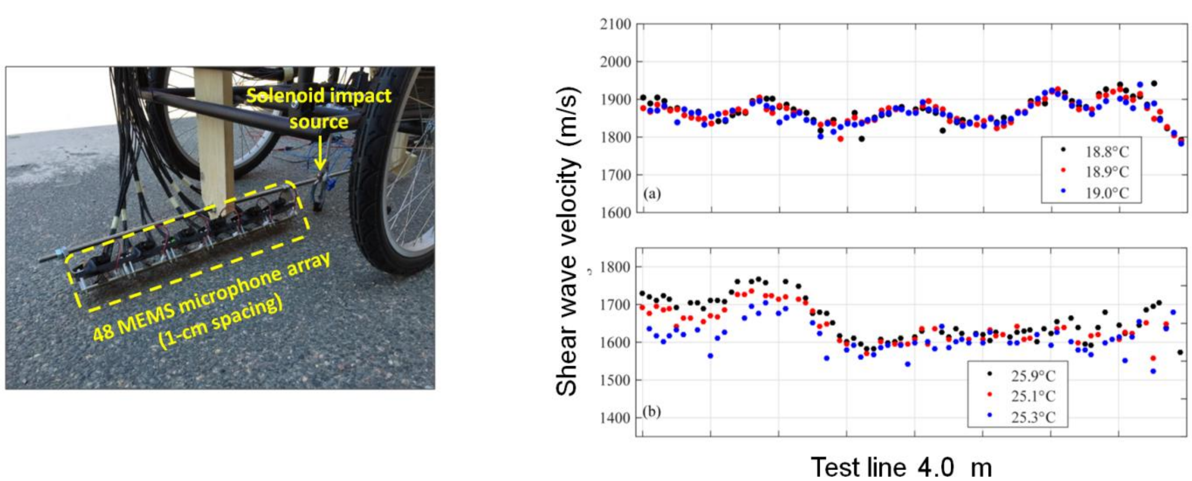


Figure 6. (a) The asphalt master curve indicating the temperature dependency of asphalt stiffness, which also varies with frequency of seismic waves. (b) Field acquisition apparatus (left) and measurement results (right) that show the variation of velocity (Vs) with temperature.

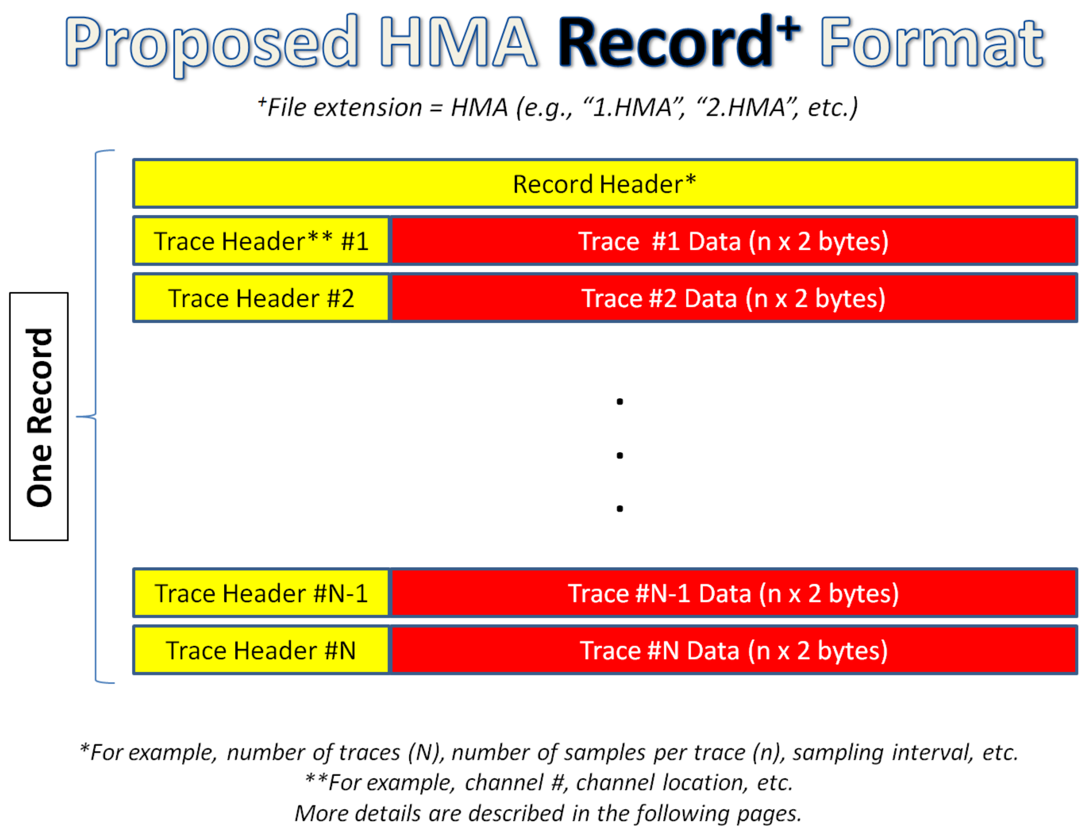


Figure 7. A new data format ("HMA Format") invented for this project for the purpose of communicating between the hardware acquisition system (SYS-HMA) and the acquisition control part of the project software package (ParkSEIS-HMA).

Figure 8. A screen capture of the main page of the web site created for this HMA project.

Scope of Work ("Seismic Approach to Quality Management of HMA")	
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**

Progress Summary (March, 2020) - Park Seismic LLC

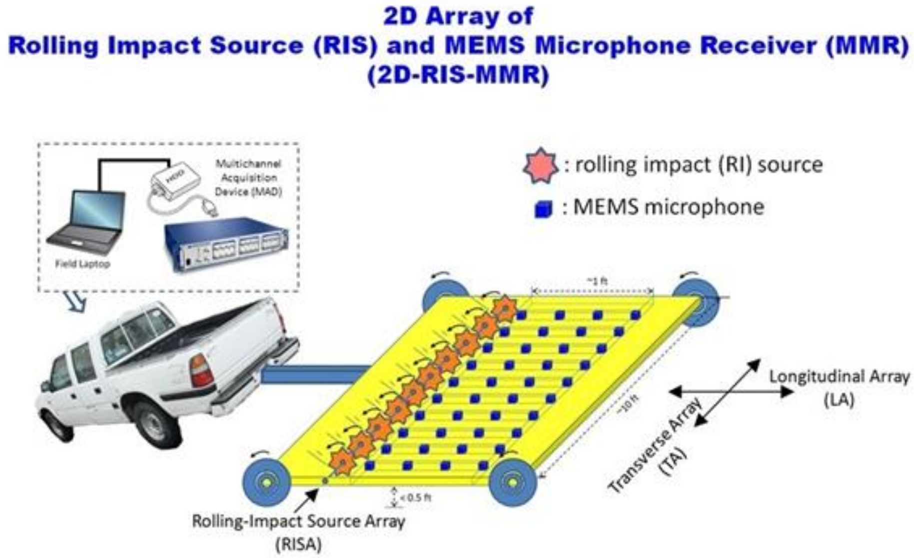
Task	% of Total Contract	ENGINEERING ESTIMATE				Hours Budget	Hours Accrued This Period	Total Hours Accrued To Date	*% of Budget Hours Used
		% Work Completed This Period	% Work Completed To Date	Weight % Completed This Period	Weight % Work Completed to Date				
1	2	3	4	5	6	7	8	9	10
Task 1	25%	**5.4%**	**24.2%**	**1.4%**	**6.2%**	260	**14**	**63**	**24.2%**
Task 2	2%					20			
Task 3	63%	**7.5%**	**14.5%**	**4.7%**	**9.1%**	640	**48**	**93**	**14.5%**
Task 4	2%					20			
Task 5	8%					84			
TOTALS:	100%			**6.1%**	**15.2%**	1024	**62**	**156**	**15.2%**

Progress Summary (March, 2020) - Norrfee Tech, AB

Task	% of Total Contract	ENGINEERING ESTIMATE				Hours Budget	Hours Accrued This Period	Total Hours Accrued To Date	*% of Budget Hours Used
		% Work Completed This Period	% Work Completed To Date	Weight % Completed This Period	Weight % Work Completed to Date				
1	2	3	4	5	6	7	8	9	10
Task 1	5%	**5.0%**	**40%**	**0.2%**	**1.8%**	40	**2**	**16**	**40%**
Task 2	82%	**0.8%**	**2.7%**	**0.7%**	**2.2%**	742	**6**	**20**	**2.7%**
Task 3	3%					30			
Task 4	7%					64			
Task 5	3%					30			
TOTALS:	100%			**0.9%**	**4.0%**	906	**8**	**36**	**4.0%**

Figure 9. Progress summary tables up to the most recent month (March, 2020) for the prime (Park Seismic) and the sub (Norrfee Tech) contractors in all (5) tasks specified in the Scope of Work on top.

(a)



(b)

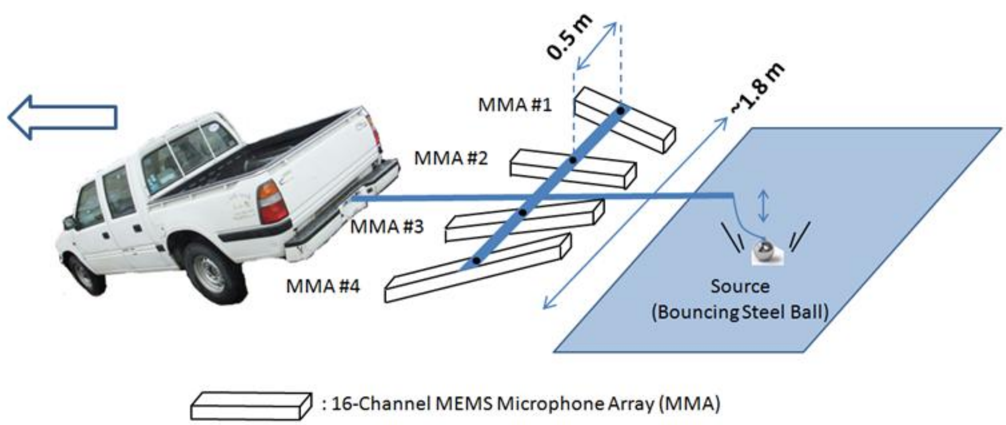


Figure 10. Comparison of the schematics for overall configuration of the project product presented (a) in the original proposal and (b) in the most updated development plan.

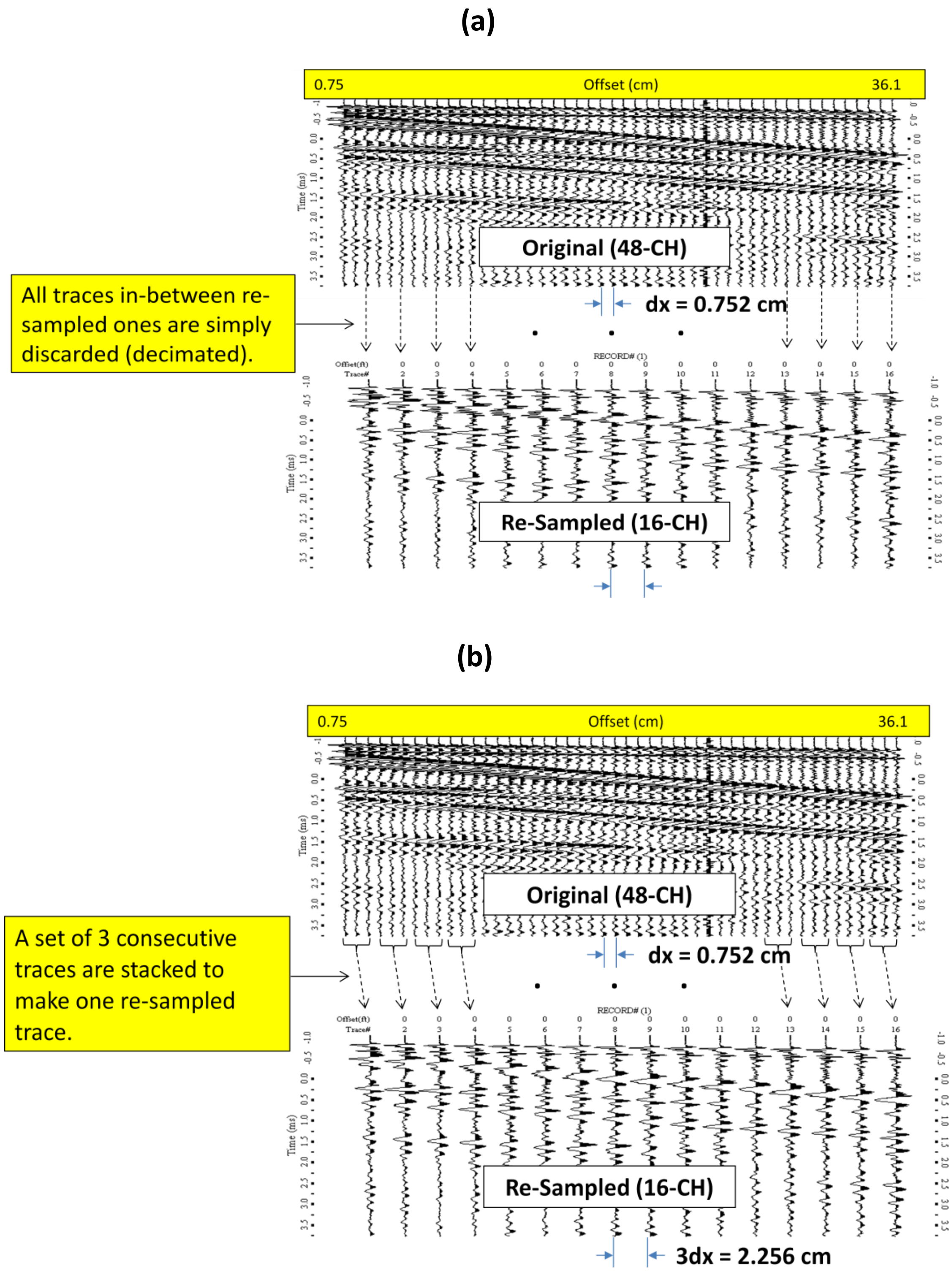


Figure 11. (a) An example of the simple re-sampling that selects every 3rd trace (receiver) from the original field record of 48-channel acquisition with a channel spacing (dx) of 0.75 cm. (b) An example of the stack-re-sampling approach, in which three (3) consecutive traces (channels) are stacked first and then the stacked trace becomes the re-sampled trace.

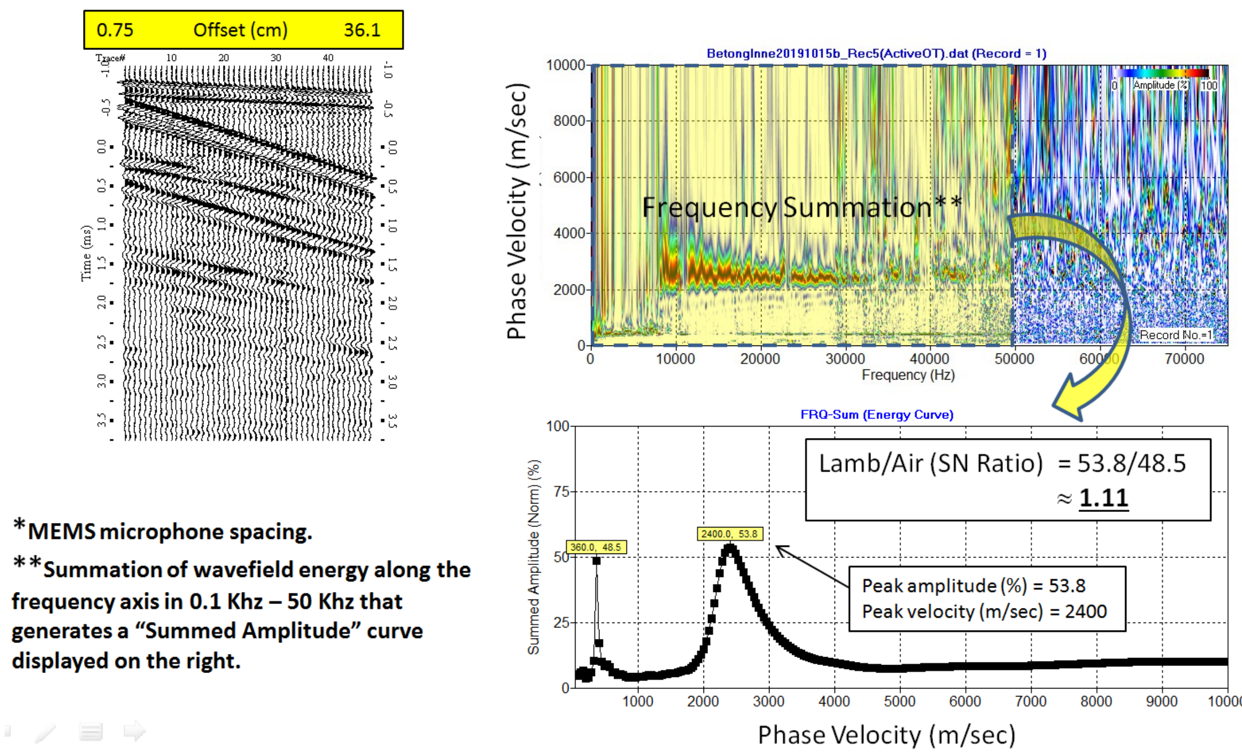


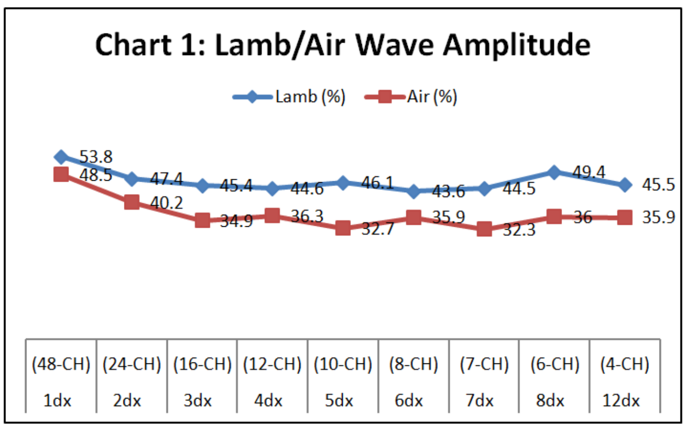
Figure 12. The way to evaluate the signal (Lamb)-to-noise (impact sound) (SN) ratio in the measured seismic data as evaluated by using the Frequency-Summation (FRQ-Sum) method in Park (2016).

SUMMARY [Simple Re-sampling (Decimation)]

Table 1: Summary of testing parameters for the "simple re-sampling" case.

	1dx (48-CH)	2dx (24-CH)	3dx (16-CH)	4dx (12-CH)	5dx (10-CH)	6dx (8-CH)	7dx (7-CH)	8dx (6-CH)	12dx (4-CH)
Lamb Amp* (%)	53.8	47.4	45.4	44.6	46.1	43.6	44.5	49.4	45.5
Air Amp* (%)	48.5	40.2	34.9	36.3	32.7	35.9	32.3	36.0	35.9
Lamb/Air	1.11	1.17	1.30	1.23	1.41	1.21	1.38	1.37	1.27
V-Lamb (m/sec)**	2400	2400	2400	2360	2400	2400	2400	2440	2440
V-Air (m/sec)**	360	360	360	360	360	360	360	360	360

**Normalized amplitude (%) of Lamb and Air waves observed in the FRQ-Sum curve. Testing details are presented in Appendix I.*
***Phase velocity of the peaks in the FRQ-Sum curve corresponding to Lamb and air waves. Testing details are presented in Appendix I.*



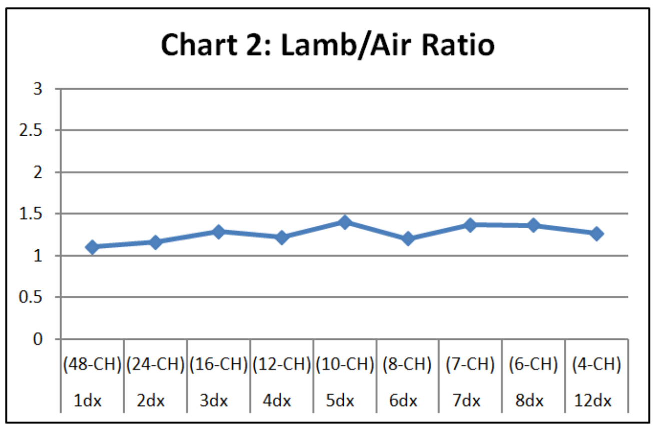


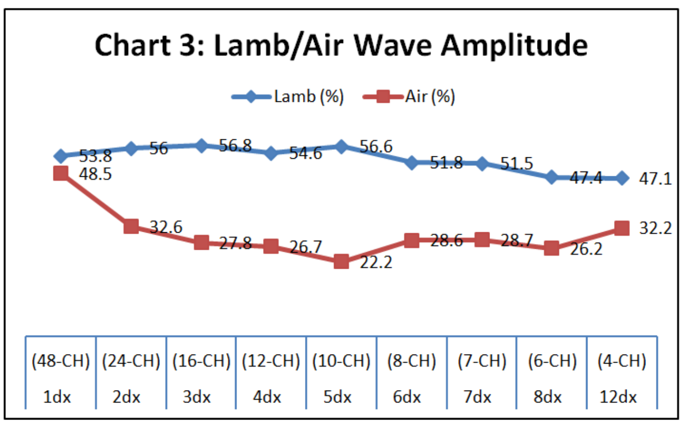
Figure 13. Summary of the test results from the simple re-sampling (decimation) approach.

SUMMARY (Stack-Re-sampling)

Table 2: Summary of testing results for the "stack-re-sampling" case.

	1dx (48-CH)	2dx (24-CH)	3dx (16-CH)	4dx (12-CH)	5dx (10-CH)	6dx (8-CH)	7dx (7-CH)	8dx (6-CH)	12dx (4-CH)
Lamb Amp* (%)	53.8	56.0	56.8	54.6	56.6	51.8	51.5	47.4	47.1
Air Amp* (%)	48.5	32.6	27.8	26.7	22.2	28.6	28.7	26.2	32.2
Lamb/Air	1.11	1.72	2.04	2.04	2.55	1.81	1.79	1.81	1.46
V-Lamb (m/sec)**	2400	2360	2360	2360	2400	2360	2400	2360	2400
V-Air (m/sec)**	360	360	360	360	360	360	360	400	360

**Normalized amplitude (%) of Lamb and Air waves observed in the FRQ-Sum curve. Testing details are presented in Appendix II.*
***Phase velocity of the peaks in the FRQ-Sum curve corresponding to Lamb and air waves. Testing details are presented in Appendix II.*



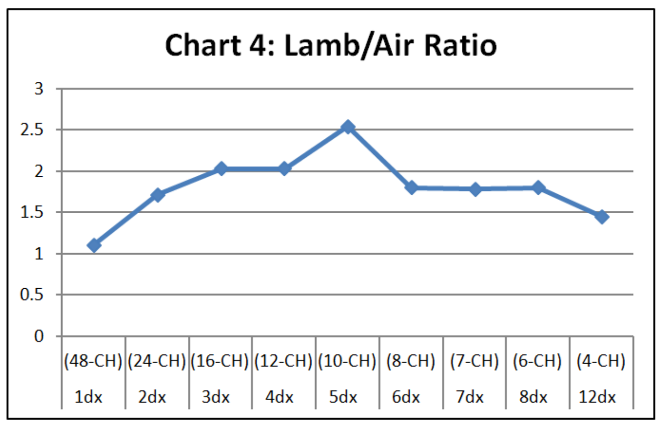


Figure 14. Summary of the test results from the stack-re-sampling approach.

Proposed HMA Format (Record Header⁺)

⁺20 elements of 4-byte floating-point data (20 x 4 bytes)

Header #	Usage	Default Value
1	**HMA format indicator (e.g., 1234.567)**	**1234.567**
2	**Record number (e.g., '1' for file "1.HMA")**	**0.0**
3	**Number of channels (traces) (e.g., 24, 48, etc.)**	**N/A***
4	**Sampling interval in microseconds (e.g., 10.0)**	**N/A***
5	**Number of samples per trace (e.g., 15000)*(Note: should be ≤ 32000)***	**N/A***
6	**X (longitudinal coordinate) (e.g., GPS-Longitude for source or any ref. point)**	**0.0**
7	**Y (transverse coordinate) (e.g., GPS-Latitude for source or any ref. point)**	**0.0**
8	**Z (elevation) (e.g., GPS-elevation for source or any ref. point)**	**0.0**
9	Future use	0.0
10	Future use	0.0
11	Future use	0.0
12	Future use	0.0
13	Future use	0.0
14	Future use	0.0
15	Future use	0.0
16	Future use	0.0
17	Future use	0.0
18	Future use	0.0
19	Future use	0.0
20	Future use	0.0

**No default value available (i.e., always specifically assigned)*

Proposed HMA Format (Trace Header⁺)

⁺10 elements of 4-byte floating-point data (10 x 4 bytes)

Header #	Usage	Default Value
1	**Channel # (e.g., 1, 2, etc.)**	**N/A***
2	**X (longitudinal coordinate) (e.g., GPS-Longitude for this channel or any point)**	**0.0**
3	**Y (transverse coordinate) (e.g., GPS-Latitude for this channel or any point)**	**0.0**
4	**Z (elevation) (e.g., GPS-elevation for this channel or any point)**	**0.0**
5	Future use	0.0
6	Future use	0.0
7	Future use	0.0
8	Future use	0.0
9	Future use	0.0
10	Future use	0.0

**No default value available (i.e., always specifically assigned)*

Figure 15. HMA format convention for record (top) and trace (bottom) headers. The main structure of the format is presented in Figure 7.

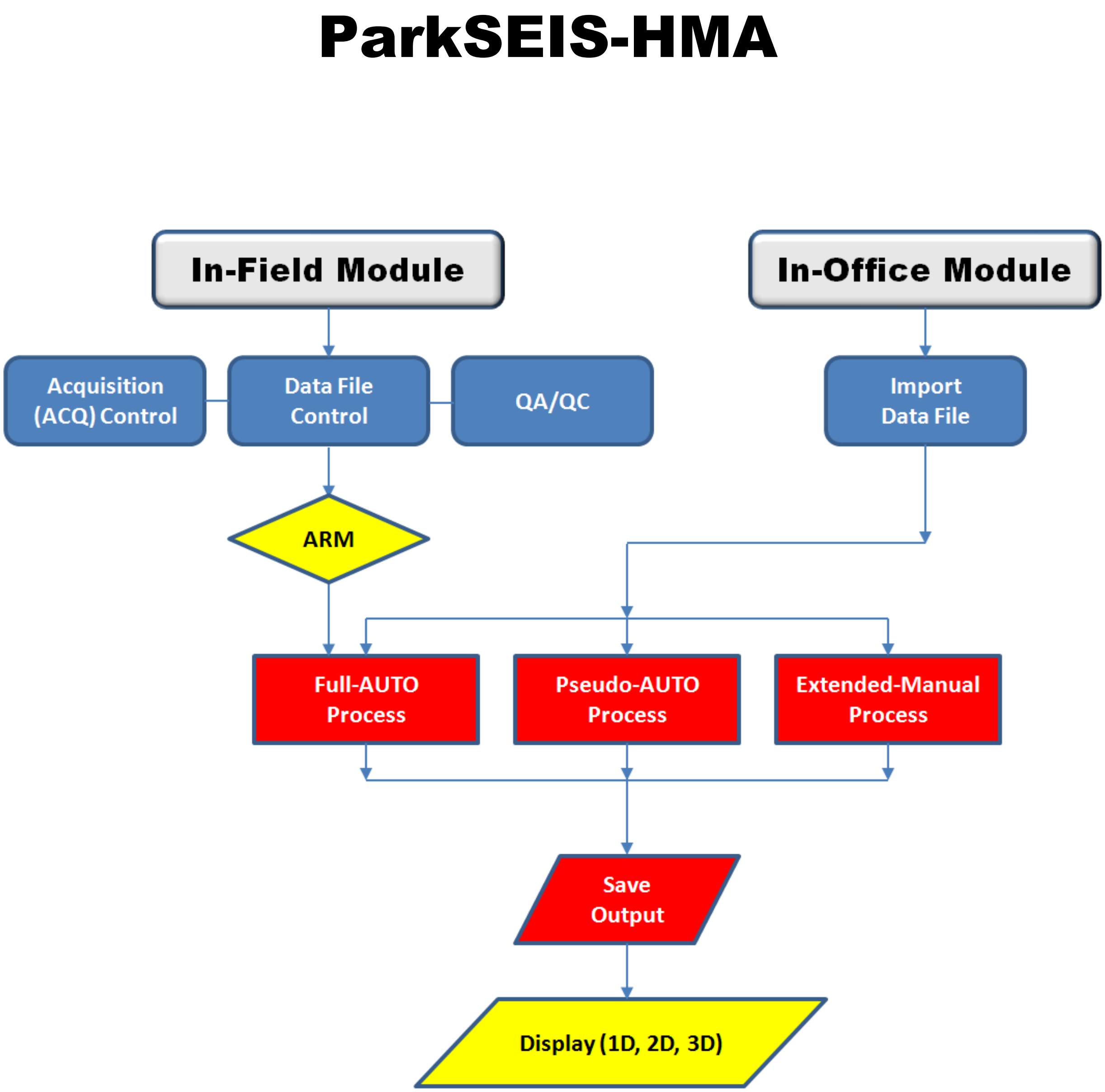
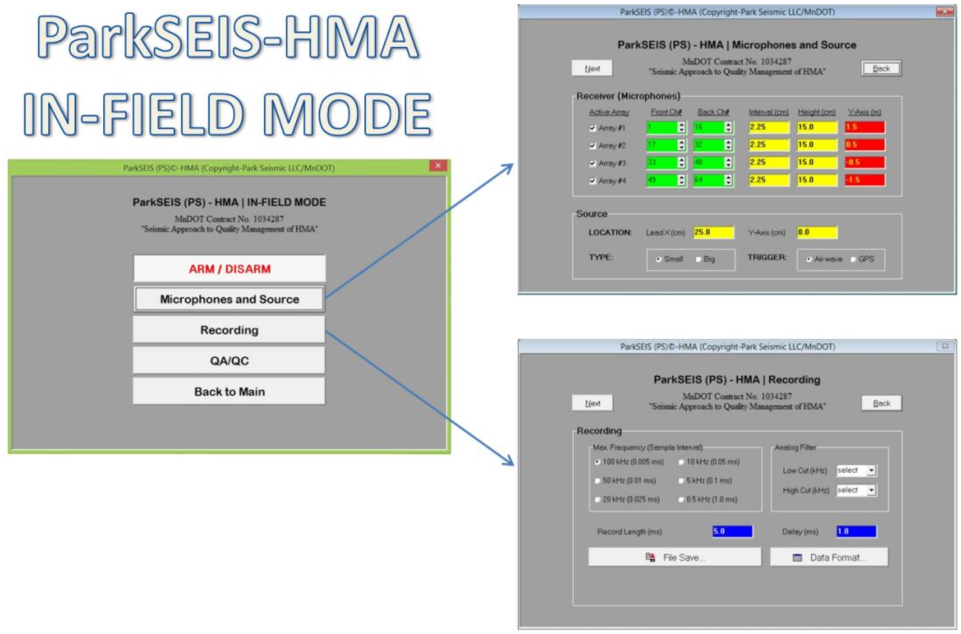


Figure 16. Flowchart of the ParkSEIS-HMA, the software package under development for HMA project.

(a)



(b)

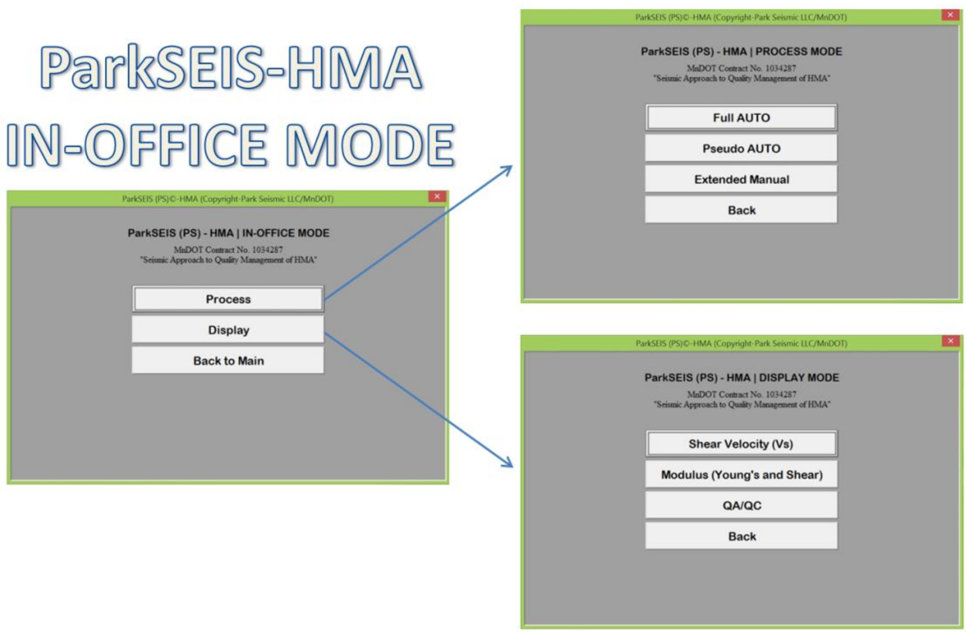


Figure 17. User interfaces designed at the gating part of the ParkSEIS-HMA for (a) "In-Field" and (b) "In-Office" modules.

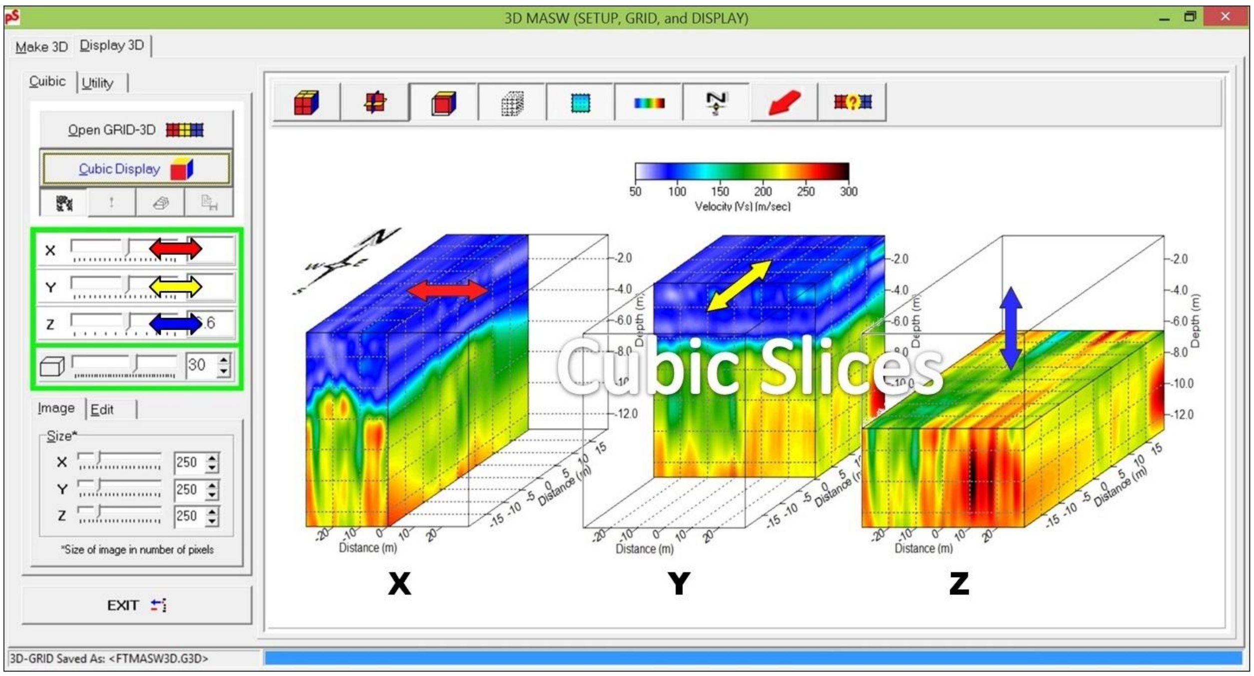


Figure 18. A 3D visualization mode by ParkSEIS-3D (Park, 2019) of the shear-wave velocity (Vs) data set obtained from a dedicated 3D MASW survey at a normal soil site by using the conventional geophone-array approach.