MASW APPROACH TO HMA QUALITY MANAGEMENT

Proposal
To
MnDOT RFP-1034287 ("Seismic Approach to Quality Management of HMA")

1. Contact Information

Principal Investigator (PI): Choon Park, PhD
Title and Company: Founder/Principal Geophysicist, Park Seismic LLC
Address: 2 Balsam Circle, Shelton, Connecticut 06484, USA
Tel/Email: (Tel) 347-860-1223, (E-mail) choon@parkseismic.com
Co Investigator (CI): Nils Ryden, PhD
Title and Company: Research Director Norrfee Tech AB
Address: Hoby 371, 22591 Lund, Sweden
Tel/Email: (Tel) +46 733 374936, (Email) nils.ryden@norrfee.com
Co Investigator (CI): Josefin Starkhammar, PhD
Title and Company: Founder Norrfee Tech AB
Address: Hoby 371, 22591 Lund, Sweden
Tel/Email: (Tel) +46 706 171215, (Email) josefin.starkhammar@norrfee.com
Administration Staff: Jin Park
Title and Company: Operations Manager/Financial Coordinator, Park Seismic LLC
Address: 2 Balsam Circle, Shelton, Connecticut 06484, USA
Tel/Email: (Tel) 347-860-0859, (E-mail) jin@parkseismic.com

2. Project Understanding

SEISMIC APPROACH FOR ROAD MATERIAL EVALUATION – BACKGROUND

The main purpose of the compaction process applied at various stages of road construction is to achieve the level of stiffness and thickness necessary to sustain expected load stress over the entire construction area. In this sense, the quality management of HMA pavement can be regarded as being analogous to in-situ stiffness and thickness measurement. Previous research has established the 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), which was developed in the late 90s by a research group led by the PI of this proposal at the Kansas Geological Survey (KGS), has been widely used to measure stiffness (Vs) and thickness of near-surface geotechnical materials (e.g., < 30 m). A key benefit of this method has been the non-destructive characterization of seismic velocity, in contrast to destructive 1D methods such as coring. 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., 5-100 Hz).

Recognizing the potential utility of the MASW technique in compaction evaluation during road construction, MnDOT launched in 2013 a feasibility field study to further explore its effectiveness and move toward making it a routine production method. Results from the ensuing pilot study (Park and Richter, 2017) indicated that conventional MASW surveys using geophones can be highly useful in delineating stiffness and thickness distributions of pavement structures for the top few meters of depth (Figure 1). However, due to relatively low frequencies measured by using geophones (e.g., ≤ 300 Hz), the accuracy for top HMA layers was not high enough to warrant the routine use of the MASW technique. In theory, an accurate evaluation of the pavement layer would require seismic waves in the range of tens of kilohertz (e.g., 10-30 Khz). The slow speed in field measurement was regarded as another obstacle to overcome in future work.

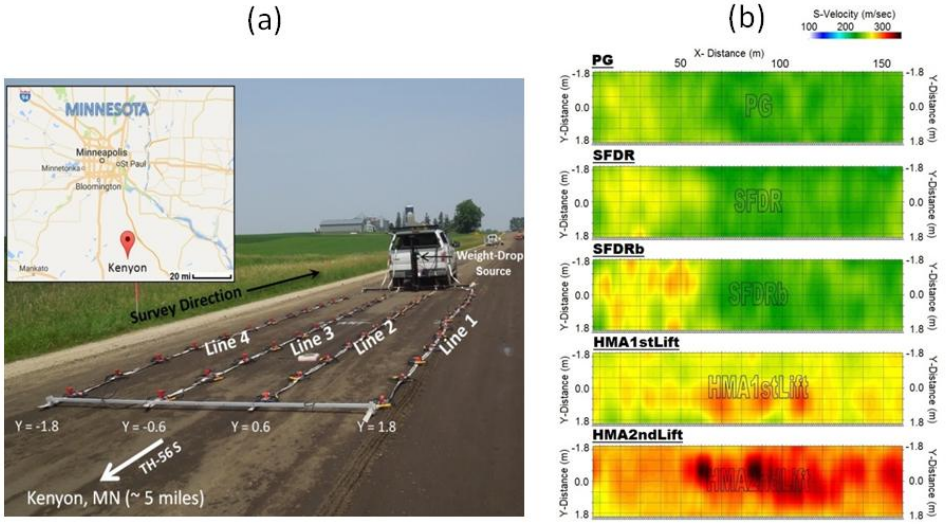

Figure 1. (a) Site location and MASW field survey configuration used during the pilot study at MnDOT, and (b) survey results of shear-wave velocity (Vs) distribution for top 1-m depth along the entire testing segment (153-m long) of FDR construction at five different stages. (From Park and Richter, 2017)

A parallel research effort undertaken in collaboration with researchers in Sweden provides potentially applicable insights. During the early 2000's, Dr. Park at KGS at the time, in collaboration with Dr. Ryden at Lund University in Sweden, applied the MASW approach to evaluate thickness (H) and stiffness (Vs) of pavement by measuring much higher-frequency surface waves (e.g., 1-30 Khz). This approach involved the delicate preparation of an accelerometer (as opposed to a geophone, which was used in previous iterations) as the high-frequency receiver (Figure 2). The results from this analysis, which were published in peer-reviewed scientific journals (for example, Ryden et al., 2004), indicated that both parameters (H and Vs) can be evaluated with a small margin of error (e.g., ≤ ±2%). However, because of the cumbersome field procedure required to array the accelerometer, and an intensive post-acquisition data analysis process, the approach was deemed at the time as requiring further modifications before practical application.

A few years later, the same Lund University team managed to eliminate the cumbersome accelerometer and instead use non-contact microphone arrays (Ryden et al., 2006). This approach had the benefit of allowing researchers to successfully measure and analyze those surface waves that were leaked into the air right above the pavement surface (often referred to as "leaky waves")(Figure 3). This opened up the possibility of non-contact measurement applied to pavement evaluation, which could enable field procedures to become much simpler and faster than the conventional ones using accelerometers, which require a lengthy and careful emplacement process.

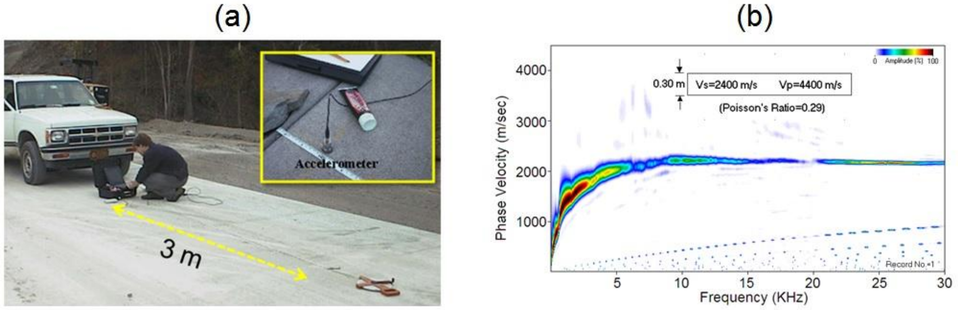

Figure 2. (a) MASW data acquisition using an accelerometer on a concrete pavement surface, and (b) data-analysis result from the Lamb-wave inversion. (From Ryden et al., 2004)

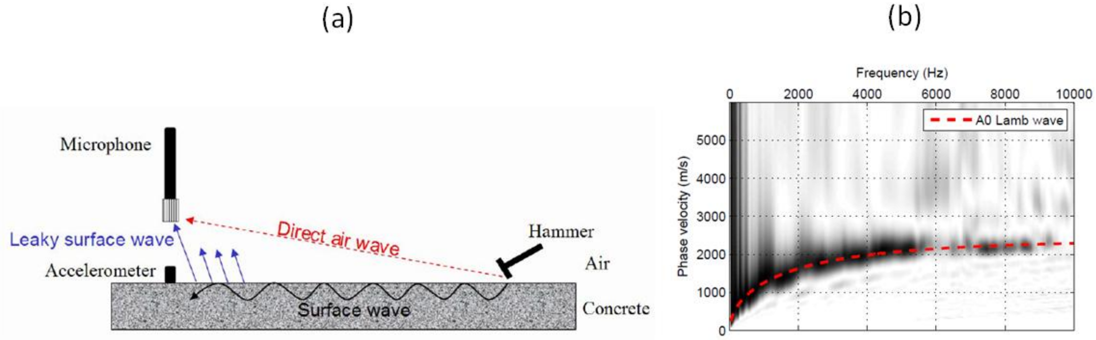

Figure 3. (a) Schematic illustrating how a non-contact (microphone) receiver can record leaky-mode surface waves above pavement surface, and (b) data-analysis result showing an asymmetric mode (A0) Lamb-wave dispersion. (From Ryden et al., 2006)

Most recently, the same group developed a non-stop approach that can keep rolling while measuring leaky surface waves at a walking speed (e.g., ~ 3 MPH). They used a single array of 47 micro-electro-mechanical sensor (MEMS) and a small solenoid impact source mounted on a trailer (Figure 4, from Bjurström and Ryden, 2017). This proved that it is possible to make the MASW measurements on pavement while in motion, potentially allowing for substantial time- and cost-savings without sacrificing accuracy. Throughout the development process, Drs. Park and Ryden have been intimately engaged in both the initial development of the MASW process as well as the specific application to non-contact, rolling impact applications to shallow pavement settings.

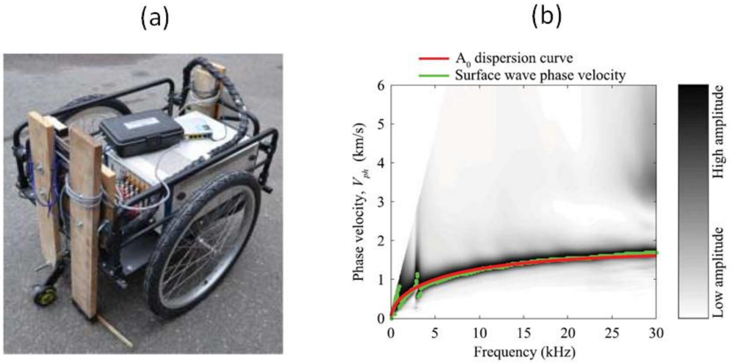

Figure 4. (a) A trailer carrying an array of microphones and a small impact source for rolling measurement, and (b) data-analysis result. (From Bjurström and Ryden, 2017)

OBJECTIVES

By applying and fine-tuning existing techniques previously outlined, we will build a seismic data acquisition system and associated data processing and visualization software package that allows for:

- non-contact (acoustic), air-coupled measurement of leaky-mode surface waves by using unconventional receiver arrays consisting of MEMS microphones (not geophones),
- non-stop rolling measurement at 3-10 MPH speed with simultaneous lane-wide coverage by using 5 or more parallel source-receiver arrays with a 2-ft separation, and
- pseudo real-time analysis and three-dimensional display of shear-wave velocity (Vs) and thickness (H) distribution of HMA pavement with 2-ft transverse and 3-ft to 10-ft (depending on rolling speed) longitudinal resolution, respectively.

We will execute a proof-of-concept demonstration at the conclusion of the project by using the prototype of such system (Figure 5).

TASKS

Tasks exist in both hardware and software components that need to be optimized before the final system construction is attempted. Conceptual illustrations of tasks are presented in Figures 5a and 5b for hardware and software components, respectively.

HARDWARE

H-1. <u>Multichannel Acquisition Device (MAD)</u>
H-2. <u>Receivers</u>
H-3. <u>Source</u>
H-4. <u>2D Array of Rolling Impact Source and MEMS Microphone Receiver (2D-RIS-MMR)</u>

SOFTWARE

S-1. <u>Acquisition Control Module (Pseudo AUTO)</u>
S-2. <u>QA/QC Module (Full AUTO)</u>
S-3. <u>Pseudo-Real-Time Analysis Module (Full AUTO)</u>
S-4. <u>Post-Acquisition Extended Analysis Module (Manual-AUTO)</u>

REFERENCES

Bjurström, H., and Ryden, N., 2017, Non-contact rolling surface wave measurements on asphalt concrete; Road Materials and Pavement Design, 20:2, 334-346, DOI: 10.1080/14680629.2017.1390491

Bjurström, H., Gudmarsson, A., Ryden, N., Starkhammar, J., 2016, Field and laboratory stress-wave measurements of asphalt concrete, Construction and Building Materials, Vol. 126, pp. 508-516. DOI: 10.1016/j.conbuildmat.2016.09.067

Park, C. B., and Richter, J., 2017, Compaction evaluation by MASW surveys (CEMS): SEG Exp. Abs., Society of Exploration Geophysicists (SEG) Ann. Mtn., Sept. 24-29, Houston, TX.

Park, C. B., Miller, R.D., and Xia, J., 1999, Multichannel analysis of surface waves: Geophysics, v. 64, n. 3, pp. 800-808.

Ryden, N., Lowe, M. J. S., Cawley, P., and Park, C. B., 2006, Non-contact surface wave measurements using a microphone; Proceedings in Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), April 2-6, Seattle, WA.

Ryden, N., Park, C. B., Ulriksen, P., and Miller, R. D., 2004, Multimodal approach to seismic pavement testing, Jouirnal of Geotechnical and Geoenvironmental Engineering, ASCE, 130(6), pp. 636-645.

Sheriff, R. E., 2002, Encyclopedic dictionary of applied geophysics: SEG Geophysical Reference Series No. 13, 4th Ed., Society of Exploration Geophysicists (SEG), Tulsa, Oklahoma, 429 pp.

Starkhammar, J., Amundin, M., Nilsson, J., Jansson, T., 2009, 47-channel burst-mode recording hydrophone system enabling measurements of the dynamic echolocation behavior of free-swimming dolphins. Journal of the Acoustical Society of America, 126, (3), pp. 959 – 962 DOI:10.1121/1.3184536

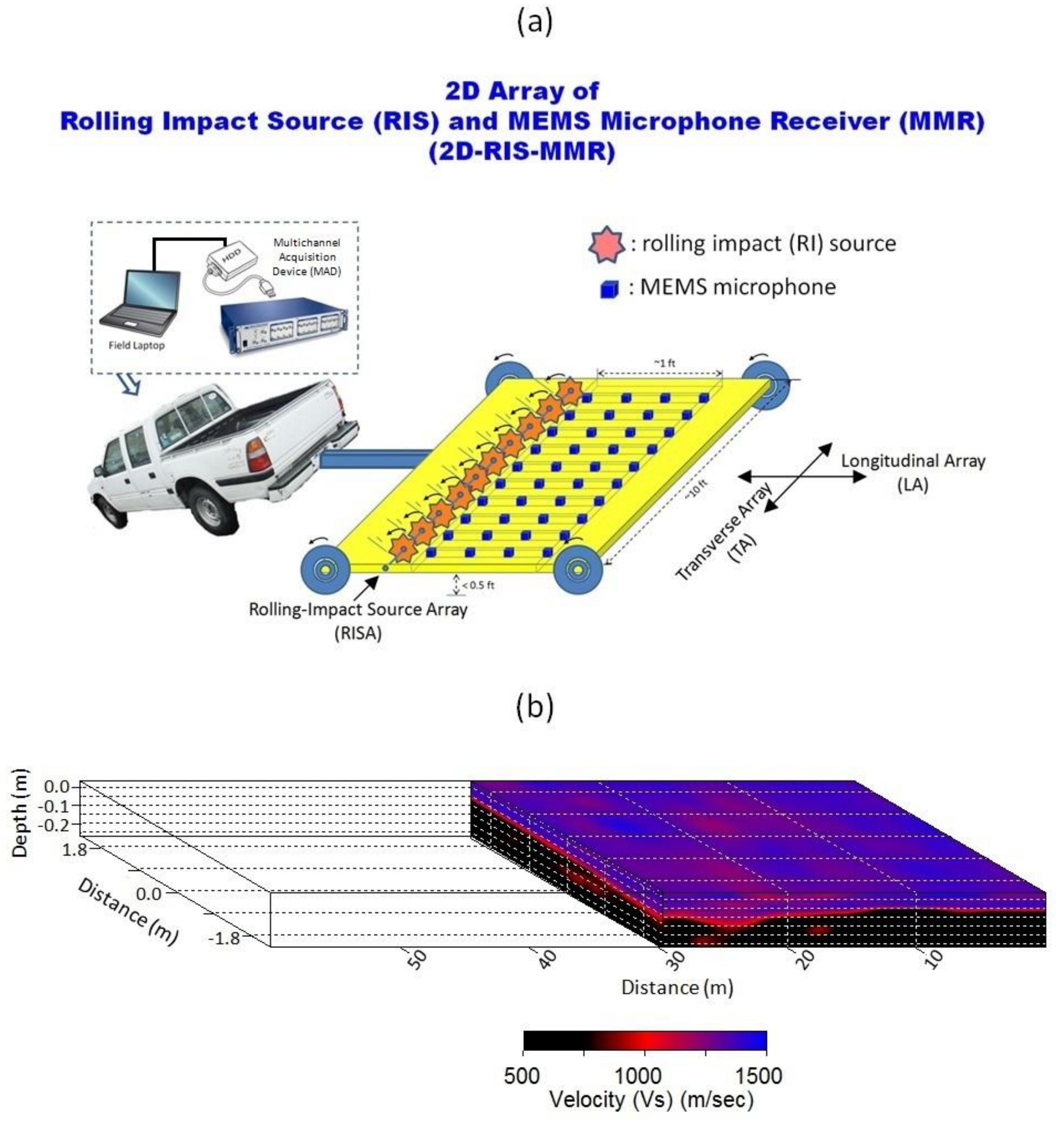

Figure 5. (a) A conceptual diagram illustrating a possible configuration of the proposed hardware system of rolling impact source and non-contact MEMS microphone arrays, and (b) an illustration to show one of the possible 3D pseudo-real-time display of output data by the proposed software.

3. Responder Experience & Qualifications

The Principal Investigator (PI), Dr. Choon Park, worked as the lead scientist during the development of MASW method at the Kansas Geological Survey (KGS) (Park et al., 1999) where he worked as a research scientist specializing in near-surface (e.g., ≤ 30 m) seismic investigation (1988-2006). Dr. Park published more than one hundred MASW-related papers. He authored the first MASW analysis software package (SurfSeis) released in 2001, and co-authored a reflection seismic analysis package (WinSeis) released in early 90s. In 2007, Dr. Park founded Park Seismic LLC, and through it has been providing technical services in MASW investigation both in the US and internationally. He has since conducted over sixty (60) applied and research MASW projects. In 2014, the company released an advanced MASW software package (ParkSEIS), which has been critically acclaimed as providing reliable and user-friendly rendering and model characterization across a range of MASW applications. Most directly relevant to this particular RFP, Dr. Park participated in the compaction evaluation by MASW surveys (CEMS) project executed at MnDOT in 2013, the resulting analyses of which were published in Park and Richter (2017). His career has been devoted to the development and application of near-surface seismic methods, and positions him as an ideal candidate to lead a team in building a seismic data acquisition system and associated data processing and visualization software package for HMA quality management.

The Co-Investigator (CI), Dr. Nils Ryden, has been the lead investigator in pavement evaluation by MASW approach since early 2000s. Dr. Ryden, in collaboration with Dr. Park, fist demonstrated that the dominant nature of pavement surface waves is Lamb waves by using the accelerometer-based MASW approach (Ryden et al., 2004). He and his co-workers published the results from the first successful non-contact measurements of pavement surface waves by using microphones (Ryden et al., 2006). Recently, Dr. Ryden also reported the successful results from the rolling measurements (Bjurström and Ryden, 2017). During the last 20 years he has shared his time between Lund University and the largest construction company in Sweden (Peab) where he has worked with pavement design, construction and maintenance in many projects. Dr. Ryden recently joined a consulting company as the research director that was founded by Dr. Starkhammar.

The Co-Investigator (CI), Dr. Josefin Starkhammar is a researcher focused on the development of state-of-the-art data acquisition systems for multichannel acoustic measurements. Dr. Starkhammar has built the fastest and largest multichannel data acquisition system with real time signal processing for studying the sonar of dolphins (Starkhammar et al., 2009). She is also a measurement hardware developer and programmer in the research field of pavement MASW measurements at Lund University (Bjurström et al., 2016). She holds a PhD in electrical measurements and a Master's of Engineering Physics. Dr. Starkhammar is working as a senior lecturer at Lund University and runs a consulting company (Norrfee Tech AB) which develops and builds non-destructive testing equipment for civil engineering applications.

Jin Park has been working as an operations manager and financial coordinator at Park Seismic LLC since 2007. Considering the international nature of this project (with multiple investigators involved), it will be crucial to have dedicated project staff who can organize schedules, coordinate logistical operations, and manage financial aspects of the project. In this regard, she is highly experienced and qualified.

4. Work Plan – Project Approach

Each task is outlined in its characteristics and how to be optimized for seamless integration to the final system. Interrelationship between different tasks and order of execution are illustrated by a flowchart in Figure 6. Corresponding investigators are listed in initials from here on; e.g., *CP* for *Choon Park*, *JS* for *Josefin Starkhammar*, *NR* for *Nils Ryden*, and *JP* for *Jin Park*. Key features of the final completed hardware/software system have been illustrated in Figure 5. Task timeline and schedule, and corresponding deliverables are presented in Table 1 and Table 2 of this proposal for hardware and software parts, respectively.

PROJECT MANAGEMENT AND ADMINISTRATION (KICK-OFF MEETING) (*JP*)

Overview of the project and clarification of the blueprint and the schedule will be implemented for each task between all four (4) participants. Communication tools and schedule (e.g., monthly video conferencing) will also be discussed. Financial and operational schedules/procedures will be detailed.

HARDWARE (*JS & NR*)

The ultimate goal of the entire hardware system is to record surface waves with as much high signal-to-noise (SN) ratio as possible while moving as fast as possible through all efforts. To achieve this goal, following tasks are designated critical and briefly described to assure the most optimum performance. Graphical illustration in Figure 5a is to be referred.

H-1. Multichannel Acquisition Device (MAD) (*JS*)
- Multichannel (e.g., 60) digital recording device by using commercially available A/D circuit boards from, for example, National Instruments (NI).
- Fast sampling (up to 30 Khz Nyquist frequency).
- Compact, heavy-duty, and light.

H-2. Receivers (*JS*)
- Sensitivity test of MEMS microphones (e.g., dynamic range, bandwidth, etc.).
- Optimum number and spacing for 1D longitudinal array (LA) needed for 2D surveys.
- Optimum number and spacing for 2D transverse array (TA) needed for 3D surveys.

H-3. Source (*NR*)
- Design and build of single rolling-impact (RI) source.
- Design and build of an array with multiple RI sources.

H-4. 2D Array of Rolling Impact Source and MEMS Microphone Receiver (2D-RIS-MMR) (*JS & NR*)
- Optimum design of the housing frame (e.g., size, material, storage for MAD, etc.).
- Control through onboard control center.
- Transmission of digital data for onboard software (e.g., wire/wireless transmission).
- GPS connected to the triggering system.

SOFTWARE (*CP*)

Software is needed for both data acquisition and analysis. The data-acquisition part will have a minimized functionality as it mainly interfaces digital output from the multichannel acquisition device (MAD) to the subsequent data conditioning, analysis, and QA/QC components of the on-board software. Figure 5b illustrates one of the possible 3D display modes of the output data by the proposed software.

S-1. Acquisition Control Module (Pseudo AUTO)
- Control of recording parameters (e.g., triggering, sampling rate, recording time, etc.).
- Control of data storage (e.g., formatting, spatial and/or temporal demultiplexing, etc.).

S-2. QA/QC Module (Full AUTO)

- Real-time source monitor to detect imperfect and/or skipped impact.
- Real-time evaluation of signal-to-noise (SN) ratio for optimum rolling speed.

S-3. Pseudo-Real-Time Analysis Module (Full AUTO)

- Spectral evaluation, temporal filtering, FK filtering for signal pre-conditioning.
- Dispersion image construction and Lamb-wave dispersion (A0) analysis.
- Evaluation of thickness (H) and shear-wave velocity (Vs) of HMA for each 1D array.
- Graphical display of H and Vs for all measurement points in 3D.
- Detection of outliers (in H and Vs) for on-site QA/QC purpose.

S-4. Post-Acquisition Extended Analysis Module (Manual-AUTO)

- Post-acquisition signal enhancement.
- Lamb-wave dispersion (A0) and calibrations for Poisson's ratio and temperature.
- Advanced inversion (optional) (e.g., frequency-velocity spectrum inversion, etc.).
- Construction of 3D velocity (Vs) and Young's (E) and shear (μ) moduli grid sets.
- Display of 3D grid data sets (Vs, E, and μ).
- Management of 3D data sets (Vs, E, and μ) to interface with external software for further presentation and analysis purposes.

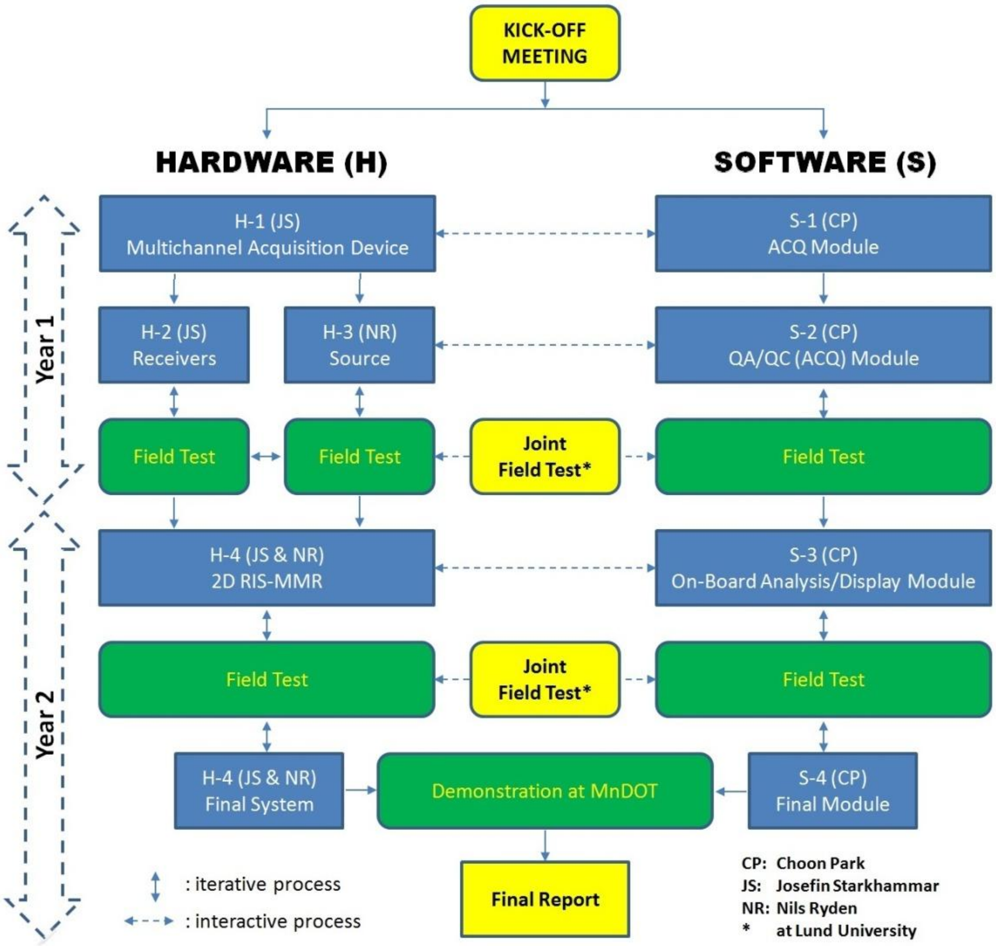

Figure 6. A flowchart illustrating the interrelationship and order of execution between different tasks.

5. Deliverables

Table 1: Timeline and Schedule of Tasks and Deliverables (Hardware)

TASKS	I[+]	Deliverables	Year 1				Year 2			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
H-1. Multichannel Acquisition Device (MAD)	JS	Quarterly Report* (Q1/Y1) ✓ photo of prototype system, initial performance evaluation, points to add/improve/modify, etc.	▨							
H-2. Receivers Field Test	JS	Quarterly Report (Q2/Y1) ✓ photo of prototype longitudinal array (LA), initial multichannel data set with LA, points to add/improve/modify, etc. ✓ video clip and photo for outdoor testing, output data sets under different conditions (e.g., none, medium, and strong wind/traffic conditions) obtained by using a small hammer, points to add/improve/modify, etc.		▨						
H-3. Source Field Test	NR	Quarterly Report (Q3/Y1) ✓ photo of prototype, brief description of operation principle, etc. ✓ video clip and photo of outside test, initial evaluation result with recorded data sets, points to add/improve/modify, etc.		▨	▨					
Joint (Hardware & Software) Field Test**	JS NR CP	Quarterly Report (Q4/Y1) ✓ video clip and photo of outdoor test of hardware (single RI and single LA) and software system, initial evaluation result with obtained data sets (different wind, traffic, and moving speed), points to add/improve/modify, etc.				▨				
H-4. 2D-RIS-MMR Field Test	JS NR	Quarterly Report (Q1/Y2) ✓ photo of prototype, brief description of structure and configuration, etc. ✓ video clip and photo of outdoor test, initial evaluation result with recorded data sets under different rolling speeds (e.g., 1 MPH, 3 MPH, 5 MPH, 10 MPH, etc.).					▨	▨		
Joint (Hardware & Software) Field Test**	JS NR CP	Quarterly Report (Q2/Y2) ✓ video clip and photo of outdoor test with combined system (2D-RIS-MMR and software), evaluation result with obtained data sets, points for finalization.							▨	
H-4. 2D-RIS-MMR (Final System)	JS NR	Quarterly Report (Q3/Y2) ✓ video clip and photo of outdoor test of the finalized system (2D-RIS-MMR), evaluation result with obtained data sets for the points designated from previous joint field test.								▨
MnDOT Demonstration	ALL	Quarterly Report (Q4/Y2) ✓ Demonstration and delivery of finalized system (MAD & 2D-RIS-MMR)								▨
Final Report	ALL	Compilation of all term reports with summary, conclusions, and recommendations.								▨

*Each investigator reports to PI (Choon Park) and PI reports to MnDOT every quarter.

[+] Investigator; CP (Choon Park), JS (Josefin Starkhammar), NR (Nils Ryden), **in Lund, Sweden (or TBD)

Table 2: Timeline and Schedule of Tasks and Deliverables (Software)

TASKS	CI[+]	Deliverables	Year 1				Year 2			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
S-1. Acquisition Control Module	CP	Quarterly Report* (Q1/Y1) ✓Flowcharts for this and final software package, and data-format prototype. ✓Screen capture of module components and user's manual. ✓Video clip – control test with multichannel acquisition device (MAD).	▨							
S-2. QA/QC Module	CP	Quarterly Report (Q2/Y1) ✓Screen capture of module components and user's manual.	▨	▨						
Field Test	CP	Quarterly Report (Q3/Y1) ✓Video clip – field test (through simulation by using actual MAD data sets). ✓Summary of AUTO performance (wind, traffic, and moving speed).	▨	▨						
Joint (Hardware & Software) Field Test**	CP JS NR	Quarterly Report (Q4/Y1) ✓Video clip – pseudo-real-time analysis performance during outdoor execution. ✓Summary of performance evaluation in accuracy, computing speed, and S/N for different data sets (wind, traffic, and moving speed). ✓Points of improvement.			▨	▨				
S-3. On-board Pseudo-Real-Time Analysis Module Field Test	CP	Quarterly Report (Q1/Y2) ✓Screen capture of module components and user's manual. ✓Summary of AUTO performance with actual field data sets (wind, traffic, and rolling speed) in accuracy, computing speed, and graphical display of results. ✓Points of improvement.	▨	▨	▨	▨	▨	▨		
Joint (Hardware & Software) Field Test**	CP JS NR	Quarterly Report (Q2/Y2) ✓Video clip – outdoor execution with 2D-RIS-MMR. ✓Summary of AUTO performance (wind, traffic, and rolling speed). ✓Points to finalize the package.						▨	▨	
S-4. Post-Acquisition Extended Analysis Module	CP	Quarterly Report (Q3/Y2) ✓Screen capture of module components and user's manual. ✓Summary of performance evaluation (comparison of results and speed).	▨	▨	▨	▨	▨	▨	▨	▨
MnDOT Demonstration	ALL	Quarterly Report (Q4/Y2) ✓Demonstration and delivery of finalized software package on USB dongle and full user's manual.								▨
Final Report	ALL	Compilation of all term reports with summary, conclusions, and recommendations.								▨

*Each investigator reports to PI (Choon Park) and PI reports to MnDOT every quarter.

[+]corresponding investigator; CP (Choon Park), JS (Josefin Starkhammar), NR (Nils Ryden), **in Lund, Sweden (or TBD)