Active and Passive Surface Wave Testing: Addressing Uncertainty using Open-Source Tools

Challenges associated with Linear Array Passive Methods

Brady R. Cox, Ph.D., P.E.
Department of Civil and Environmental Engineering
Utah State University
Logan, Utah, USA

Joseph P. Vantassel, Ph.D.
Department of Civil and Environmental Engineering
Virginia Tech
Blacksburg, Virginia, USA

Utah State University, Logan, Utah; 29 July – 1 August 2024

Passive Linear-Array Methods

- Passive linear-array methods include ReMi (Louie 2001), Roadside Passive MASW (Park & Miller, 2008), and others…
- Only ReMi will be discussed in detail herein, as it was the first developed
- All linear-array methods share common strengths and weaknesses

- Strengths:
  - It is easier to layout a 1D linear array than a 2D array of receivers

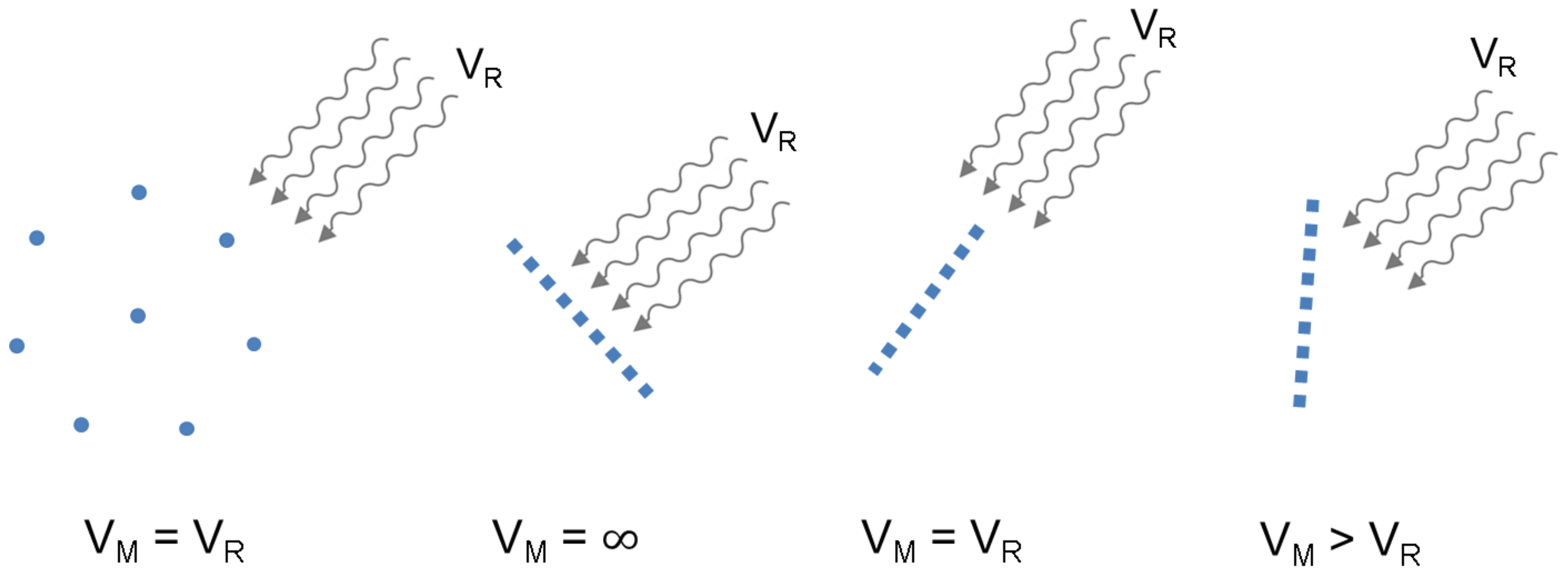
- Weaknesses:
  - It is ***impossible*** to know the direction of ambient wave propagation when using a linear array
  - Hence, one can never be assured that the measured velocity is the true velocity, no matter how you attempt to mitigate and/or account for off-line noise sources during processing

B.R. Cox,
J.P. Vantassel

Recording Ambient Noise (i.e., passive wavefields)

- Effect of noise propagation direction and array type (2D vs. linear array)
- Linear arrays can only measure the true/actual velocity if the waves are *serendipitously* propagating in-line with the array.

*Serendipitously means something that happens by chance or luck.



V_M = measured velocity
V_R = actual phase velocity

B.R. Cox,
J.P. Vantassel

How using Linear-Array Passive Methods are Justified

- Some developers of linear-array passive methods acknowledge there are significant challenges associated with recording ambient noise with linear arrays

Roadside Passive Multichannel Analysis of Surface Waves (MASW)

Choon B. Park[1] and Richard D. Miller[2]
[1]Park Seismic LLC, 2 Balsam Circle, Shelton, CT 06484
Email: choon@parkseismic.com
[2]Kansas Geological Survey, University of Kansas, 1930 Constant Avenue, Lawrence, Kansas 66047-3726
Email: rmiller@kgs.ku.edu

ABSTRACT

A 2-D receiver array, such as a cross or circular type, should be used in a passive surface wave survey to provide the most accurate results. It is often not possible to secure such a spacious area, however, especially if the survey has to take place in an urban area. A passive version of the multichannel analysis of surface waves (MASW) method is described that can be implemented with the conventional linear receiver array deployed alongside a road. Offline, instead of inline, nature of source points on the road is accounted for during dispersion analysis by scanning recorded wavefields through 180-deg azimuth range to separate wavefields from different azimuths and propagated with different phase velocities. Next, these wave fields are summed together along the azimuth axis to yield the azimuth-resolved phase velocity information for a given frequency. In addition, it is attempted to account for the cylindrical, instead of planar, nature of surface wave propagation that often occurs due to the proximity of

True, but many times it is possible. I believe, in general, people are not even trying.

How using Linear-Array Passive Methods are Justified

- Some developers of linear-array passive methods acknowledge there are significant challenges associated with recording ambient noise with linear arrays
- Thus, attempts have been made to mitigate the effects of using linear arrays through various assumptions and schemes applied during dispersion processing:
- ReMi:
  - Assume equal energy is propagating in all directions
  - Perform wavefield transformation in both directions along the linear array
  - Pick the lower-bound dispersion trend rather than peak power
- Roadside Passive MASW:
  - Scan recorded wavefields over 180-deg azimuth range and large range in potential phase velocities to find different energy peaks that could be resulting from different modes and sources. [Note: this sounds just like 2D beamforming, which requires a 2D array… I don’t understand the exact details of how this can be done with a 1D array]
  - Attempt to account for near-field effects by assuming *possible* source positions along the road

B.R. Cox,
J.P. Vantassel

Linear Arrays and Ambient Noise

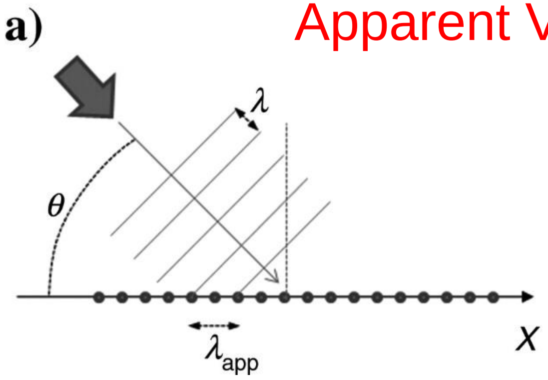
- Here are several papers that question the validity/accuracy of using a linear array to record ambient noise include:

Zywicki, D. J. (2007). "**The Impact of Seismic Wavefield and Source Properties on ReMi Estimates**". *Proc. Of Geo-Denver*, February 18-21, 2007. Denver, CO.

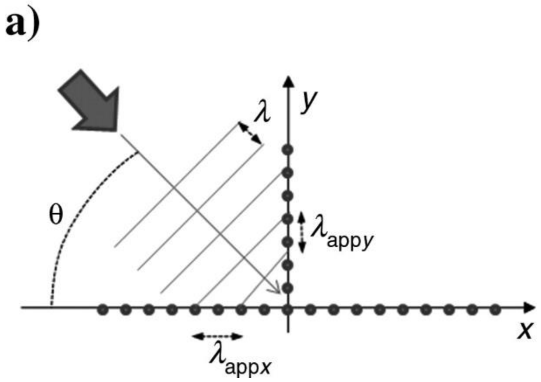
Cox, B.R., Beekman, A.N. (2011). "**Intra-Method Variability in ReMi Dispersion and Vs Estimates at Shallow Bedrock Sites**," *Journal of Geotechnical and Geoenvironmental Engineering*, 137(4), pp. 354-362.

Strobbia, C., Cassiani, G. (2011). "**Refraction microtremors: Data analysis and diagnostics of key hypotheses**," *Geophysics*, 76 (3): MA11–MA20.

Apparent Velocities



Linear Array

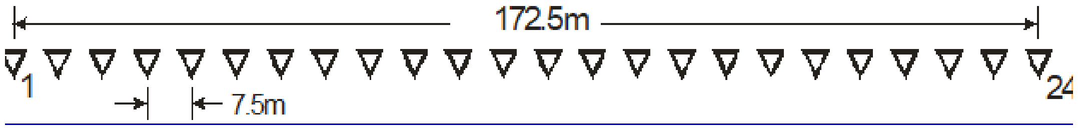


2D Array

B.R. Cox,
J.P. Vantassel

ReMI^{TM}

- Refraction (Re) Microtremor (Mi) or linear array microtremor
- 24+ 4.5Hz geophones in a linear array with 5-10m spacing is common
- Field layout similar to MASW, but typically with larger receiver spacings
- 20+ 30 second noise records collected

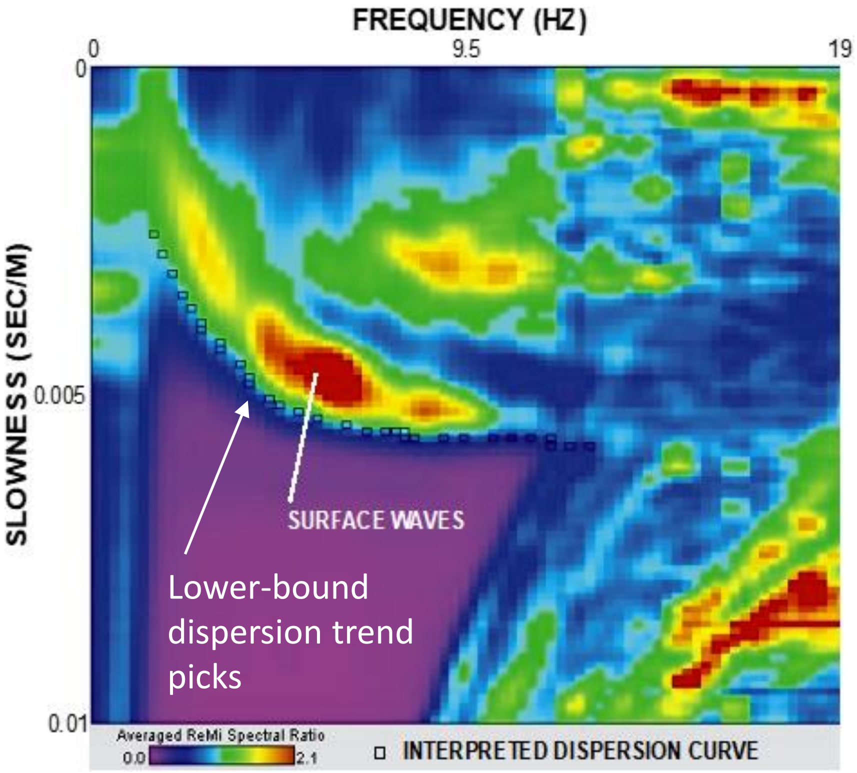


(from A.J. Martin, GeoVision)

B.R. Cox,
J.P. Vantassel

ReMI™

- Slowness-frequency (p-f) wavefield transform used to separate Rayleigh wave energy from that of other waves
- Noise can be emanating from any direction, therefore transform conducted in both directions along line
- Dispersion curve is defined as lower envelope of the Rayleigh wave energy in p-f space
  - in-line energy will have lower apparent velocity than cross-line
- Because lower envelope is picked rather than the peak, this method is more subjective than others

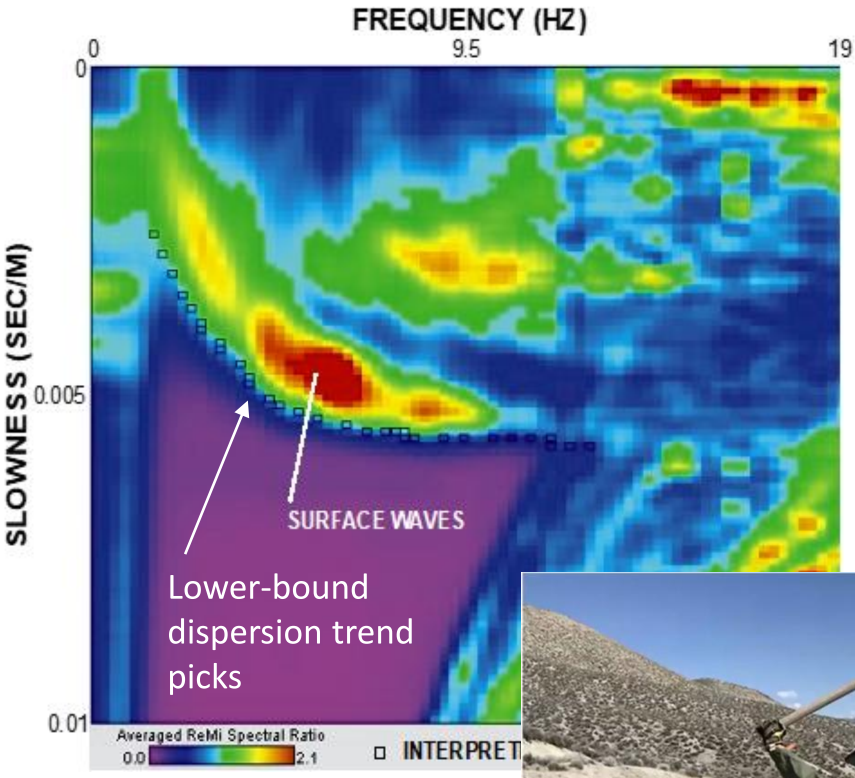


(modified from A.J. Martin, GeoVision)

B.R. Cox,
J.P. Vantassel

ReMI™

- In recent years, Louie has suggested operating an active source off the end of the array (i.e., just like MASW) during noise acquisition in order to supplement the high-frequency passive energy.
- However, Louie still recommends picking the lower-bound dispersion trend across all frequencies.
- Picking a lower-bound dispersion trend (rather than the peak) for wave energy generated in-line with a linear array is a significant departure from sound principles governing wave propagation theory.



B.R. Cox,
J.P. Vantassel

Potential Wavefield Issues

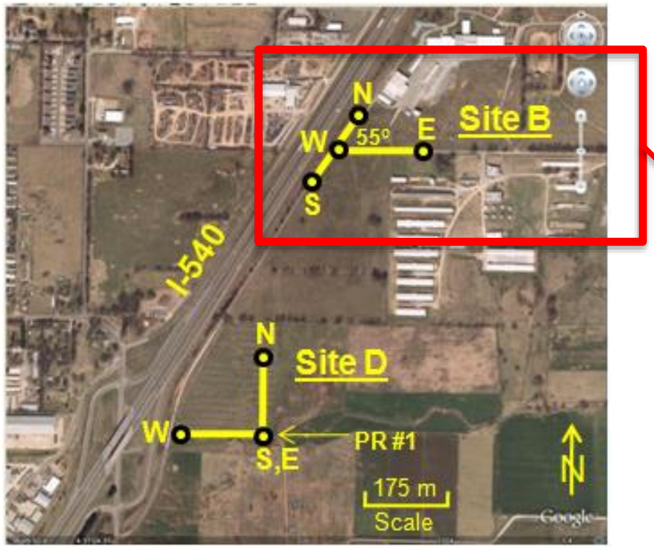
Cox and Beekman (2011)

> "ReMi calculations proceed under the key assumption that horizontally propagating energy arrives equally from all directions at a test site. If this assumption is true, Louie (2001a) states that 40.9% of the energy will appear to propagate at a velocity that is within 100-125% of the true phase velocity. Conversely, it could also be stated that even under this assumption more than 59% of the energy will appear to propagate at a velocity that is greater than 125% of the true phase velocity."

> "The assumption that equal, plane wave energy is propagating in all directions at a site is critical to ReMi theory and cannot be verified by the method. … If equal energy isn't propagating in all directions at a site, the selection of different array orientations will result in varied angles of obliquity for impinging energy, which will result in various phase velocity errors."

B.R. Cox,
J.P. Vantassel

Cox & Beekman (2011)



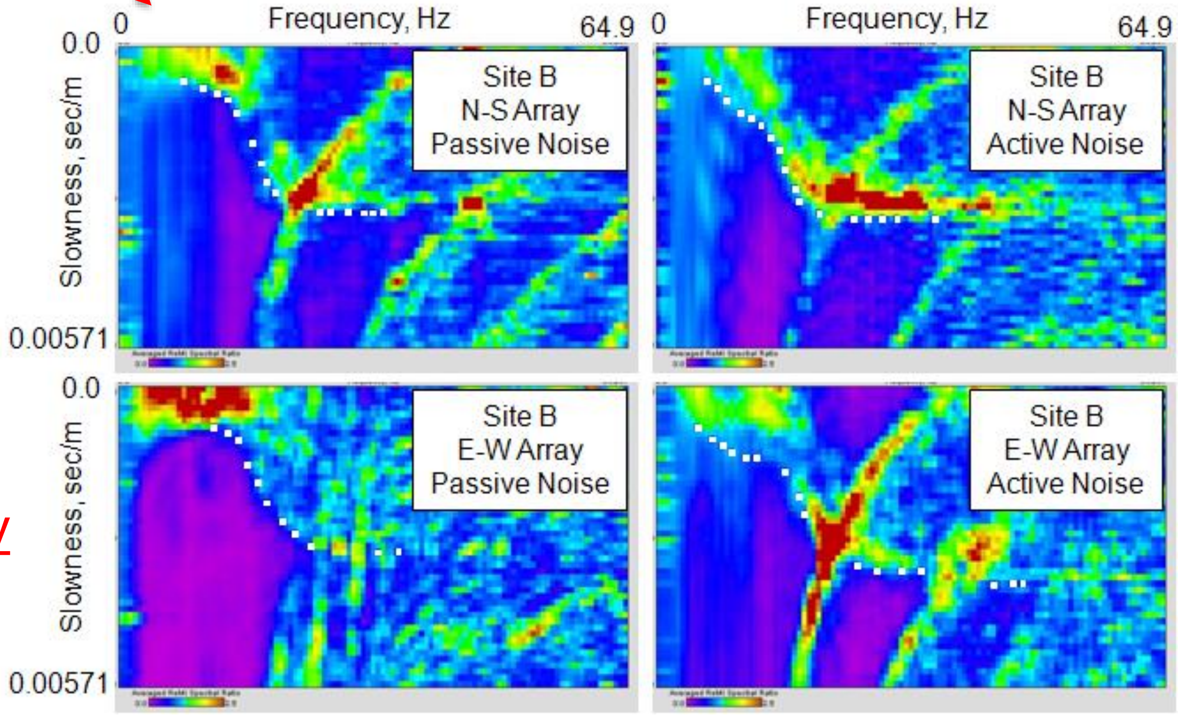
NS array

EW array

Passive Noise

Active Noise

(running or driving truck along array as suggested by Louie 2001)



B.R. Cox,
J.P. Vantassel

Cox & Beekman (2011)

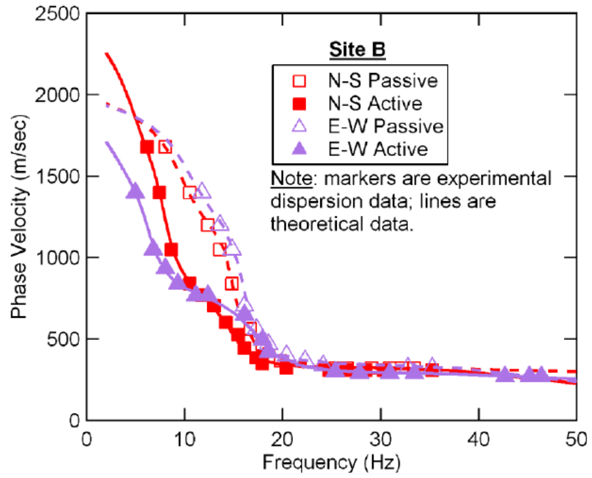


Fig. 5. Dispersion curves obtained from personnel at Optim, Inc., for the ReMi data collected at site B using two different array orientations (N-S and E-W) and two different types of noise (passive and active)

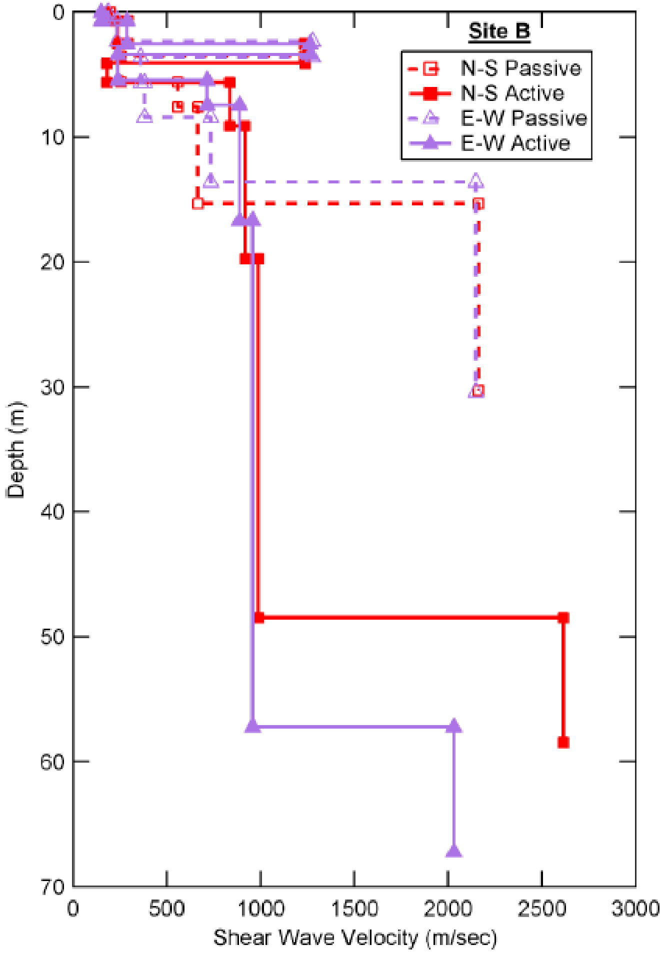


Fig. 6. Shear-wave velocity (V_s) profiles obtained from personnel at Optim, Inc., for the ReMi data collected at site B using two different array orientations (N-S and E-W) and two different types of noise (passive and active)

Same site: +30m difference in depth to bedrock

B.R. Cox,
J.P. Vantassel

Passive-Source Linear Array Methods (e.g., ReMi, Passive Roadside MASW, etc.)

Facts: Cox and Beekman (2011)

- Passive/ambient noise energy at any given site will always vary in frequency content, intensity, duration, and direction of propagation
- The direction of passive wave propagation cannot be determined with a linear array
- **Knowledge of the direction of passive energy propagation and the true velocity of its propagation are mutually dependent; one cannot be calculated without knowledge of the other** (Zywicki 2007).

Conclusions:

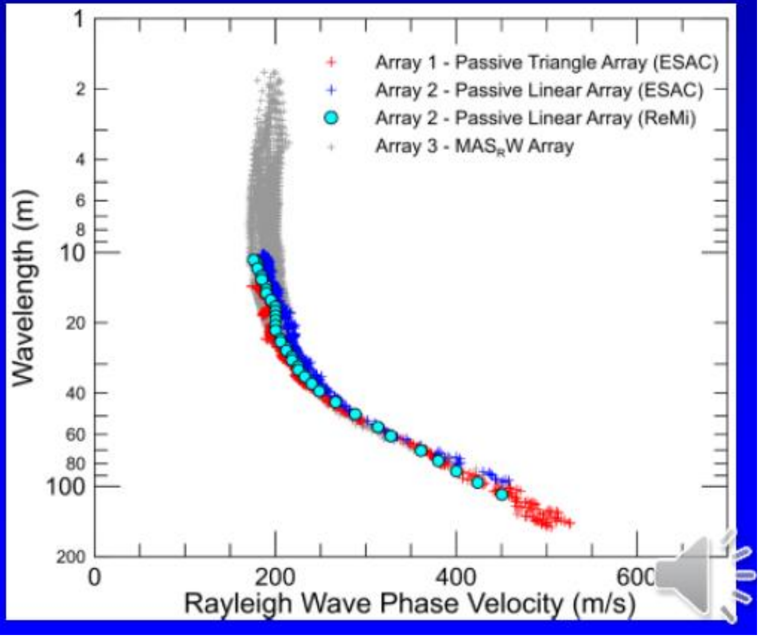
- **One cannot argue that passive-source linear array methods are theoretically robust… only a rough approximation of the dispersion data can be obtained**
- Why start with questionable dispersion data? Surface wave inversion is challenging enough when you start with robust dispersion data.

B.R. Cox,
J.P. Vantassel

From A.J. Martin (GeoVision)

Performance of linear arrays for ambient vibration measurements – sometimes they work:

- Seismic Station CE.12092.
- Rural site with infrequent traffic (~ one vehicle every 30 sec) from road to west.
- Passive surface wave data acquired along linear array orientated perpendicular to road and nested triangle array.
- Good agreement between ReMi™ and ESAC analysis of linear array.
- Good agreement between linear and nested triangle array.
- Good agreement between MASW and array microtremor data.

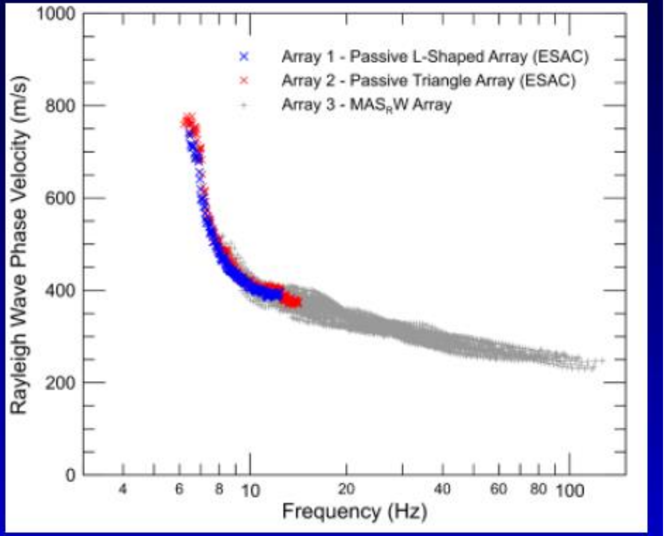


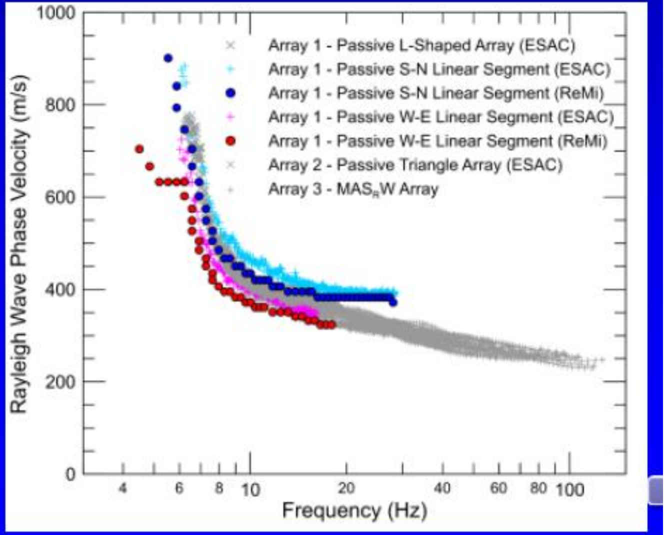
B.R. Cox,
J.P. Vantassel

From A.J. Martin (GeoVision)

but not always:

- Seismic Station CE.13921.
- Suburban site with busy road to north.
- Passive surface wave data acquired along L-shaped and nested triangle arrays.
- Good agreement between “L” and triangle arrays but poor agreement with linear arrays (both the individual segments and ESAC versus ReMi™).





B.R. Cox,
J.P. Vantassel

What do the Guidelines have to say?

- The use of passive-source linear array methods is “strongly discouraged” in the Guidelines for the Good Practice of Surface Wave Analysis (Foti et al. 2018). I am a co-author of these guidelines and I also believe we should avoid using passive-source linear array methods in engineering practice whenever it is possible to use more theoretically robust methods (i.e., 2D arrays).

- I am not the only person who feels this way. Passive-source linear array methods were also left out of the new ISO 24057 standard “Array measurement of microtremors to estimate shear wave velocity profile”.

Final Thoughts on Linear Array Passive Methods

- Depending on the nature of the noise wavefield, sometimes these methods can work quite well. You just don't know when they are going to work well and when they are not.
- You should never use linear array passive methods by themselves. Always confirm that the dispersion data is in agreement with active-source data at higher frequencies.
- Do not attempt to generate active noise by running or driving along the array. Just use standard MASW.
- If you do active testing, <u>DO NOT</u> pick the lower bound envelope. This is theoretically flawed and you will not get the correct dispersion data. You must pick the peak energy at each frequency.
- The best use of linear array passive methods it to help extend the depth of investigation of active methods slightly (i.e., to get V_{s30}) when you can't get low enough frequencies (long enough wavelengths) from your active source.
- If you want to profile deeper with greater confidence, use 2D arrays.

B.R. Cox,
J.P. Vantassel

Questions?

B.R. Cox,
J.P. Vantassel