REMI and SPAC: A Comparison

Don Zhao

Geogiga Technology Corp.

Outline

- Overview
- Comparison by Synthetic Data
- Linear Array for Omni-Directional Sources
- Field Setup of Triangular Array for SPAC
- Conclusion

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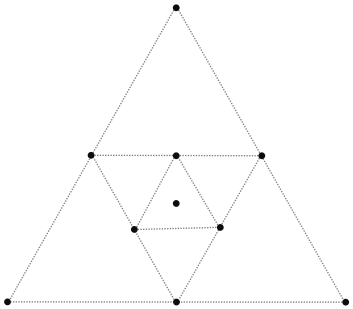
Overview: Passive Surface Wave Methods

Passive surface wave techniques can determine shear wave velocity profiles at greater depth. There are two methods commonly used to extract dispersion curves from passive surface waves.

1. REMI – Refraction Microtremor (Louie, 2001)
2. SPAC (or Extended SPAC) – Spatial Autocorrelation (Aki, 1957)



REMI uses a linear array similar to the seismic refraction method.

SPAC uses a 2D array, usually embedded equilateral triangles.

Essentially, the math behind these two methods is different.

REMI: Fundamental

$f(x,t)$ is the passive surface wave record

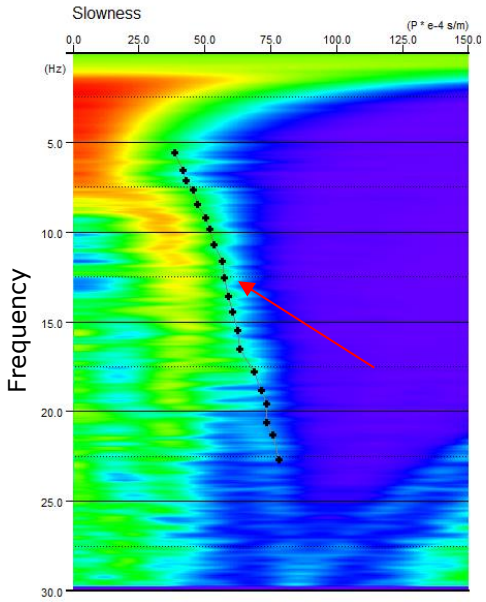
The $\tau - p$ transform in the frequency domain is conducted for forward and reverse directions along the linear array

$$f(x,t) \Longrightarrow F(\tau,p)=\int_{-\infty}^{\infty} f(x,\tau+xp)dx \Longrightarrow F(\omega,p)=\int_{-\infty}^{\infty} F(\tau,p)e^{-j\omega\tau}d\tau$$

τ: the intercept time; $p=\frac{1}{v}$: the slowness, ray parameter; $\omega = 2\pi f$: the angular frequency

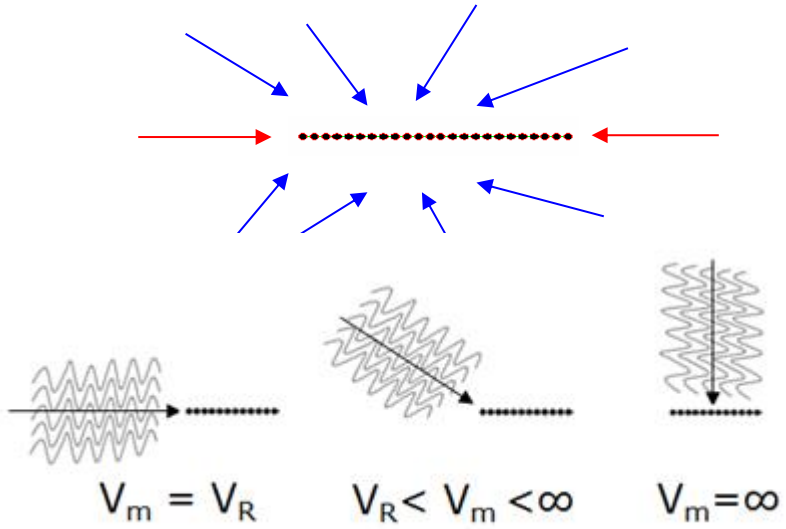
In practice, x and t are discretized. The final result is the p-f image showing the distribution of surface wave energy.

REMI: Dispersion Curve Picking



The $\tau - p$ transform is conducted for forward and reverse directions along the linear array; however the passive surface waves may originate from any unknown directions, so the dispersion curve should be picked along the envelope of the surface wave energy in p-f space with the slowest velocity.

Obviously, picking the dispersion curve along the envelope instead of peak of surface wave energy is **subjective** and causes errors, especially at low frequencies.



V_m: the measured phase velocity; V_R: the true phase velocity

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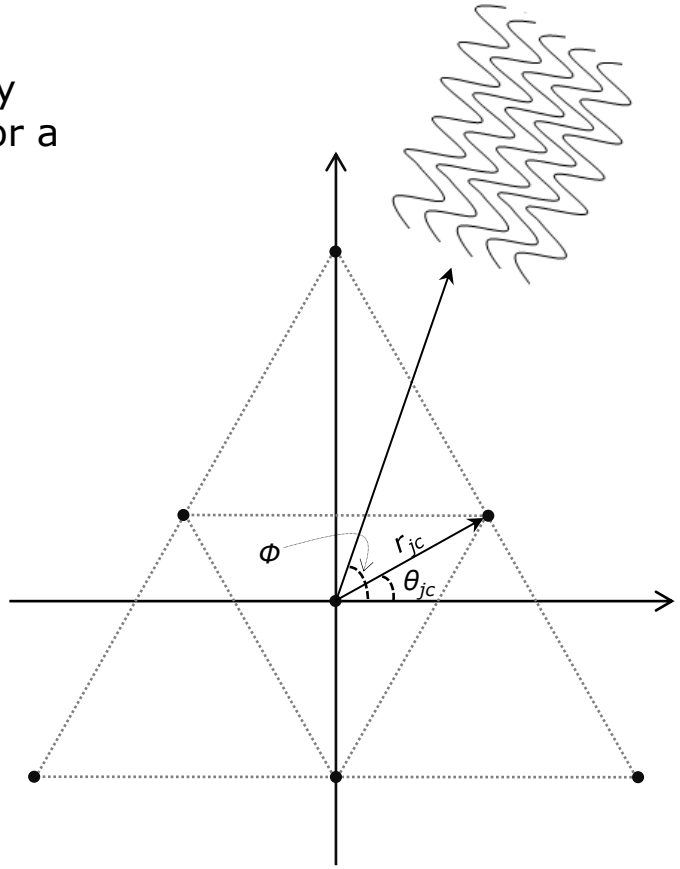
SPAC: Fundamental

Providing a set of geophones are azimuthally deployed around the circle, the coherency for a pair of geophones is defined as:

$$C_{jc}(f) = \exp[ir_{jc}k\cos(\theta_{jc} - \phi)]$$

Where r_{jc} is the distance between the j th geophone to the center at azimuthal angle θ_{jc}, k is the spatial wavenumber at frequency f, and Φ is the azimuth of propagation of a single plane wave across the array.



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SPAC: Fundamental (cont'd)

If the number of pairs of geophones approaches infinity, the spatial autocorrelation coefficient (azimuthal average of the coherency) can be expressed as:

$$c(f) = \frac{1}{2\pi}\int_0^{2\pi} \exp[irk\cos(\theta-\phi)]d\theta = J_0(rk) = J_0\left(\frac{2\pi fr}{v(f)}\right)$$

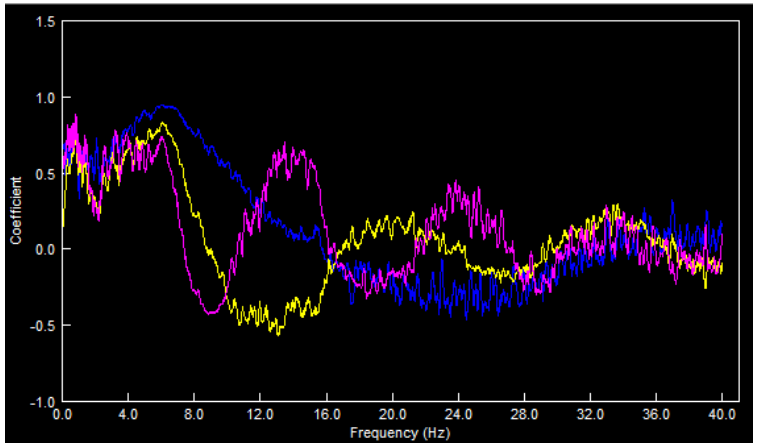
where J_0 is the Bessel function of the first kind of zero order.

1. The phase velocity v(f) can be derived by fitting the spatial autocorrelation coefficient c(f), calculated from the recorded signals, to the Bessel functions.
2. This equation implies that the linear array is allowed if the passive sources are omnidirectional, i.e. integrated around the circle over Φ with θ fixed.

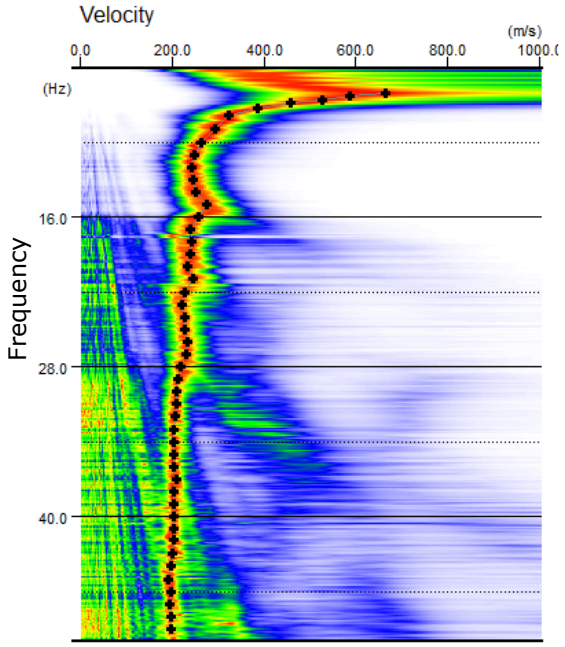
SPAC: Dispersion Curve Picking

The SPAC functions can also be expressed by the dispersion image (f-v space).

The dispersion curve is picked along the peak instead of the envelope of dispersion image, which reduces the uncertainties.



SPAC Functions



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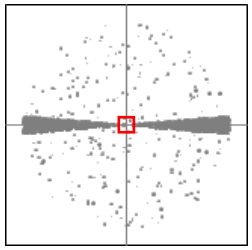
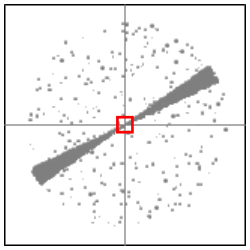
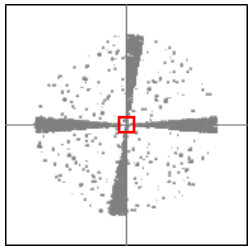
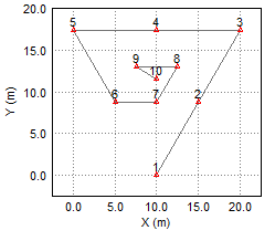
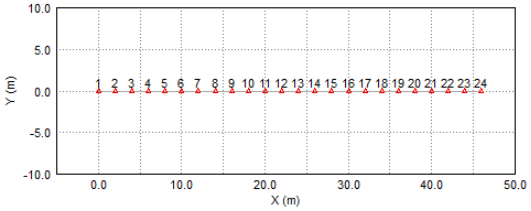
Simulation of Synthetic Data: Sources and Arrays





3000 sources with different strengths are distributed over the range of 5000mx5000m and are randomly triggered.

Four types of source distributions are simulated:

1. Omni-directional sources
2. Most sources approach along the X-axis
3. Most sources approach the X-axis at an angle of 30^0
4. Most sources approach the X-axis and Y-axis

Two types of arrays are deployed at the center:

1. Embedded triangle array

   10 geophones; outer side = 20 m

2. Linear array

   24 geophones; spacing = 2 m

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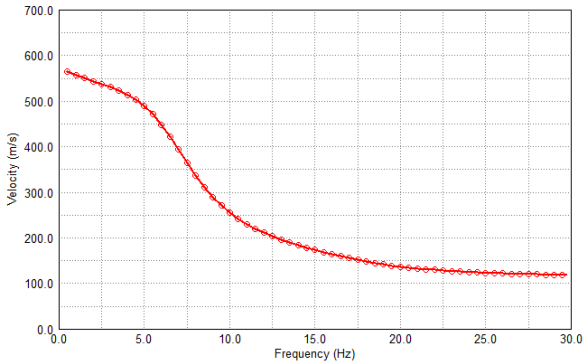
Simulation of Synthetic Data: Model and Seismic

Velocity Model

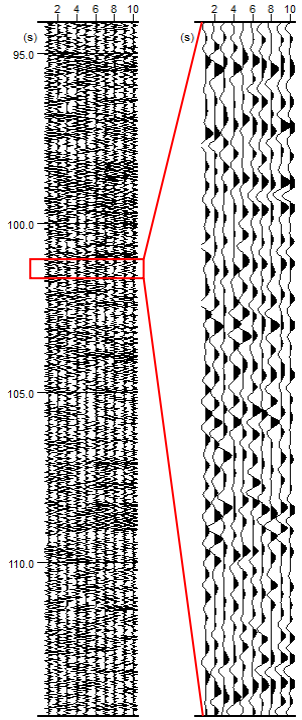
	Depth (m)	Vs (m/s)
1	3	120
2	10	230
3	25	300
4	45	350
5	75	500
6	125	550
7	621	650

Synthetic Dispersion Curve

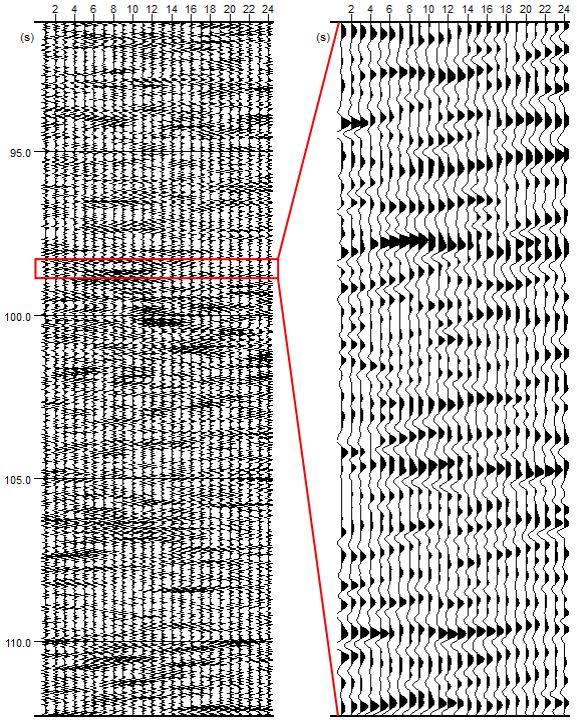


Simulated Passive Surface Wave Records

Triangular Array



Linear Array



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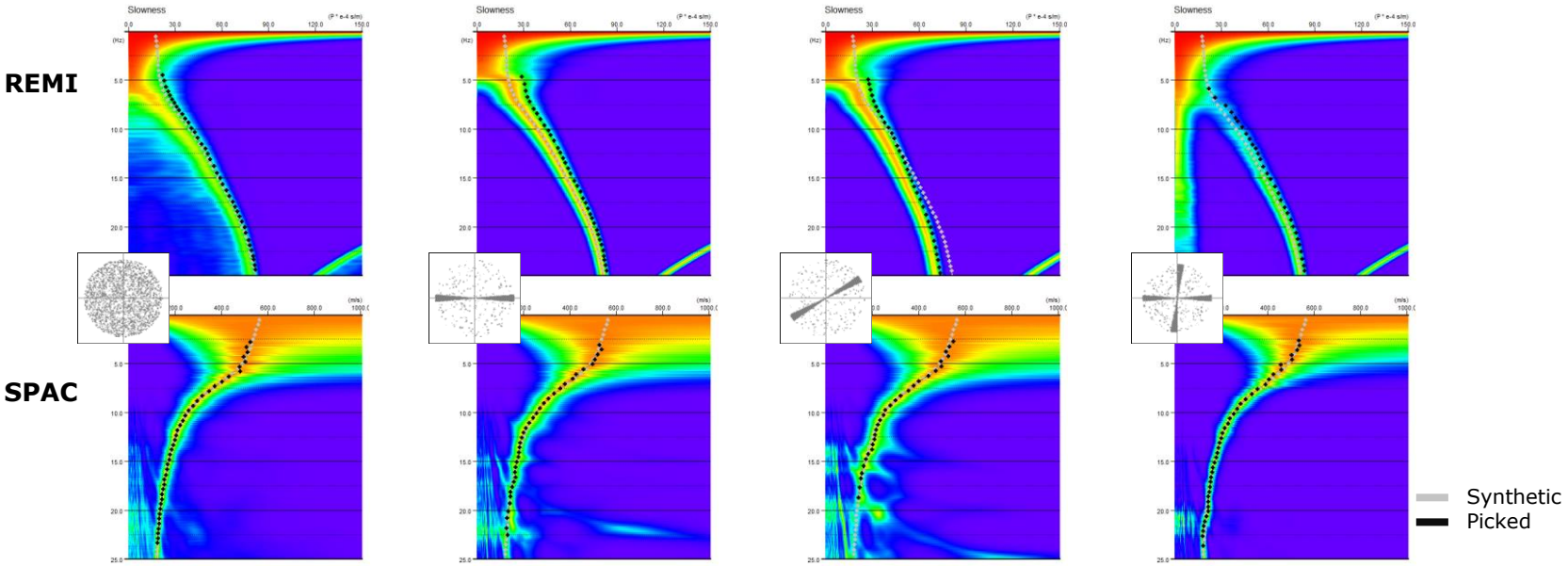
REMI vs. SPAC: Dispersion Images



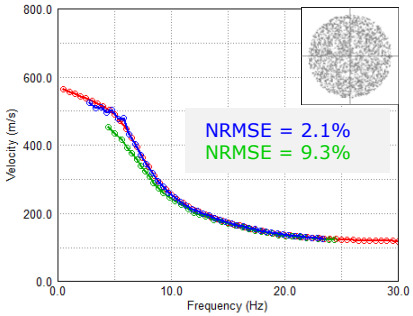
REMI

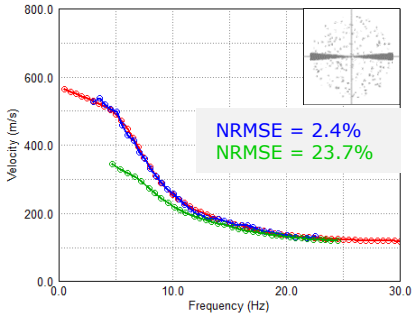
- ❑ The surface wave energy of dispersion images **vary** with the azimuths of sources.
- ❑ The envelope of surface wave energy matches the synthetic dispersion curve for omni-directional sources, but this is not true for sources within a narrow azimuth.
- ❑ When the energy propagates along the array, the curve should be picked along the peak instead of the envelope (similar to active surface waves).

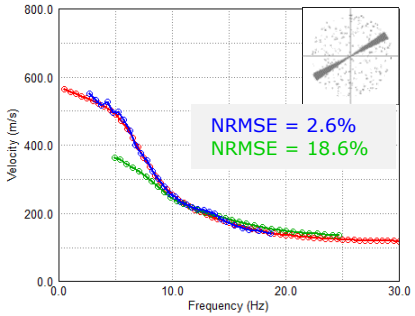
SPAC

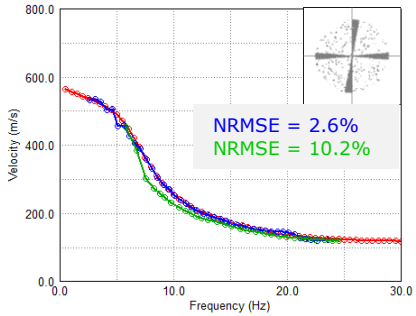
- ❑ Overall, the dispersion images are **consistent** no matter where the sources originate from.
- ❑ The peak of images matches the synthetic dispersion curve.
- ❑ The resolution decreases at lower frequencies, and some artifacts are present due to the spatial aliasing (caused by relatively fewer geophones and larger spacing).

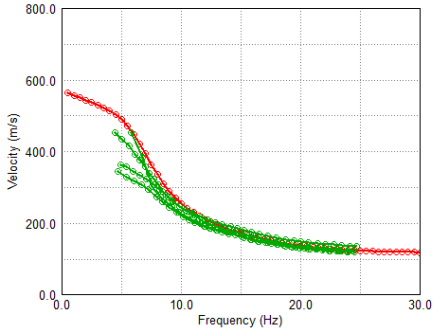
REMI vs. SPAC: Dispersion Curves

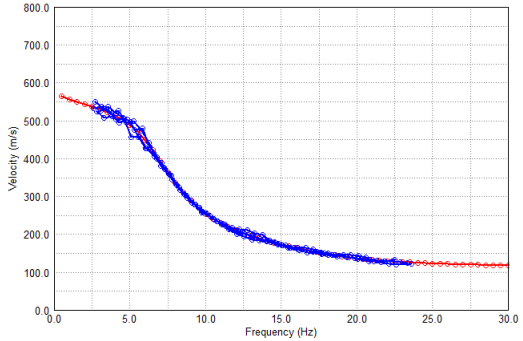












Synthetic
SPAC
REMI

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(V_{mi} - V_{pi})^2}{n}}}{\frac{\sum_{i=1}^{n} V_{mi}}{n}}$$

REMI

- ❑ The dispersion curves extracted from different azimuthal distributions of sources exhibit large variations.
- ❑ The normalized RMS error can be over 20%, especially at low frequencies for narrow azimuths of sources.
- ❑ The velocities picked along the envelope of surface wave energy tends to be smaller at low frequencies.

SPAC

- ❑ All dispersion curves extracted from different azimuthal distributions of sources are in good agreement.
- ❑ The normalized RMS error is less than 3%.

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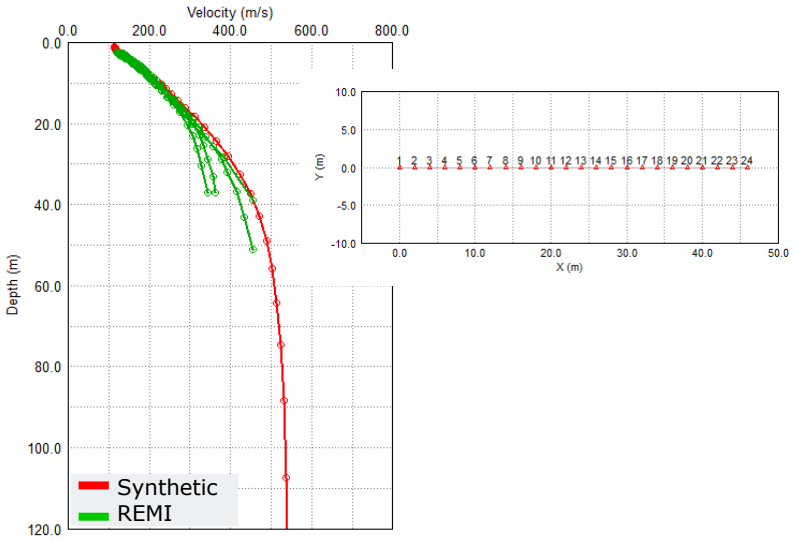
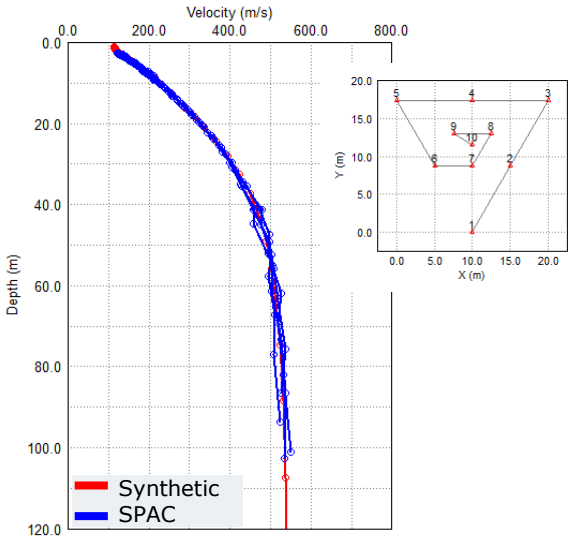
REMI vs. SPAC: Depth of Investigation

The Phase Velocity~Depth curves are converted from the Frequency~Velocity curves according to the half wavelength criteria.





REMI

- ❑ The approximate depth of investigation is around 40m (the array size = 46m).
- ❑ In practice, the length of array should not be less than 2 times of the target depth.

SPAC

- ❑ The approximate depth of investigation is around 90m (the outer side length = 20m).
- ❑ In practice, the depth of investigation can usually be greater than 2 times of the length of the outer side.

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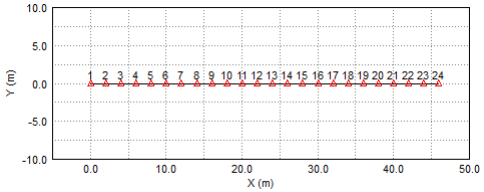
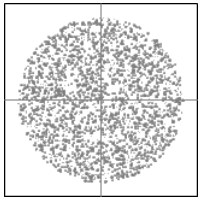
Linear Array for Omni-Directional Sources: Synthetic Data

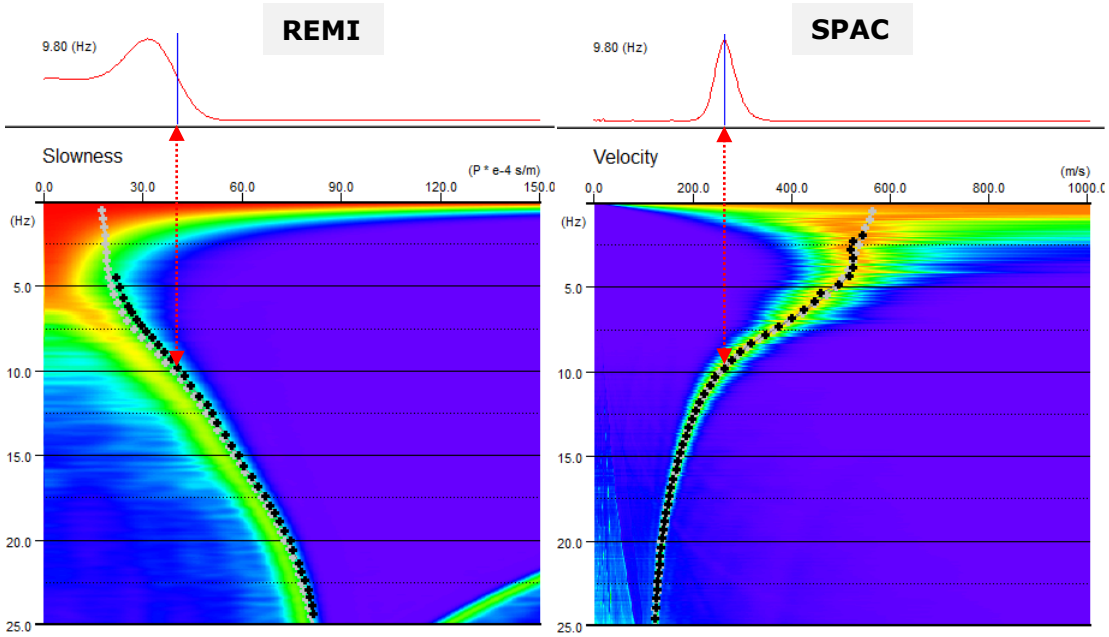
As compared, REMI works well with omni-directional sources.

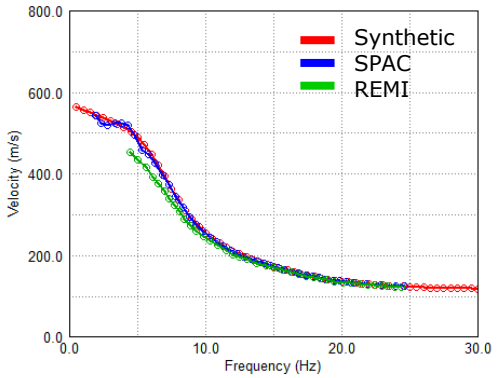
However, under the same circumstances, SPAC (ESPAC) can do even better than REMI.

Following are the results of the same synthetic data of a linear array.









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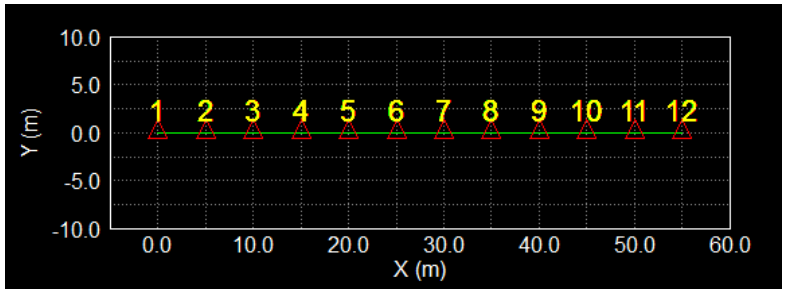
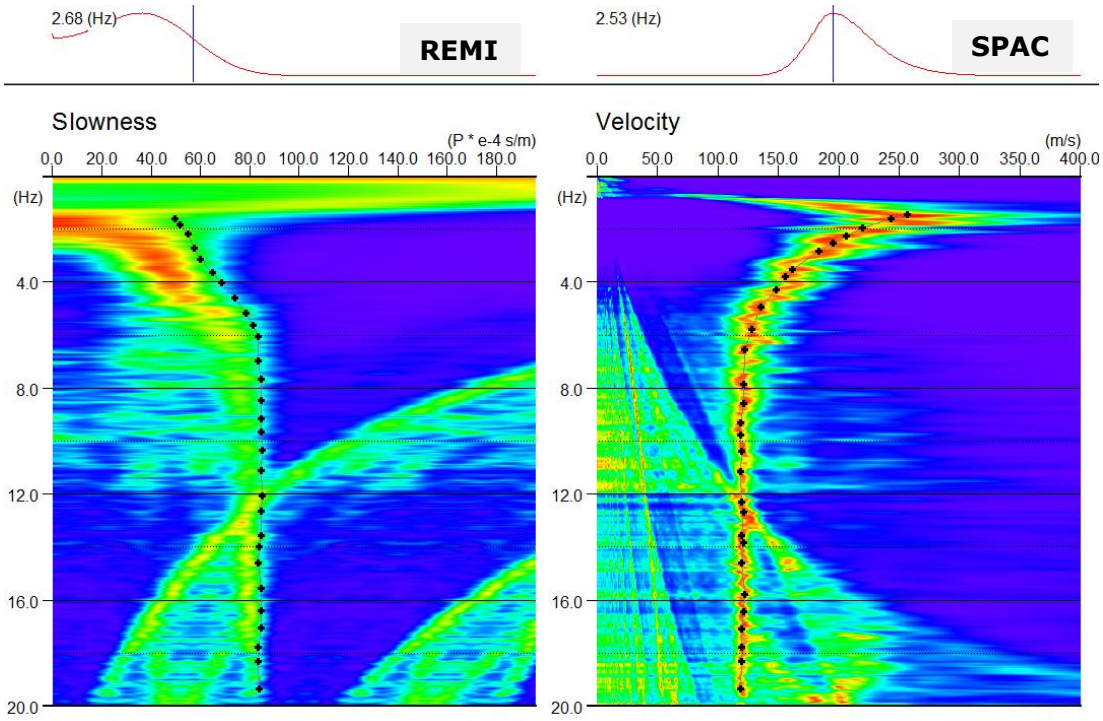
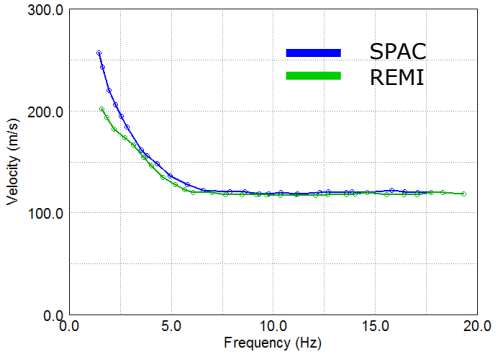
Linear Array for Omni-Directional Sources: Field Data

- 5m spacing
- 12 2Hz geophones
- 10 records, each 30 seconds
- Sampling interval: 4 ms







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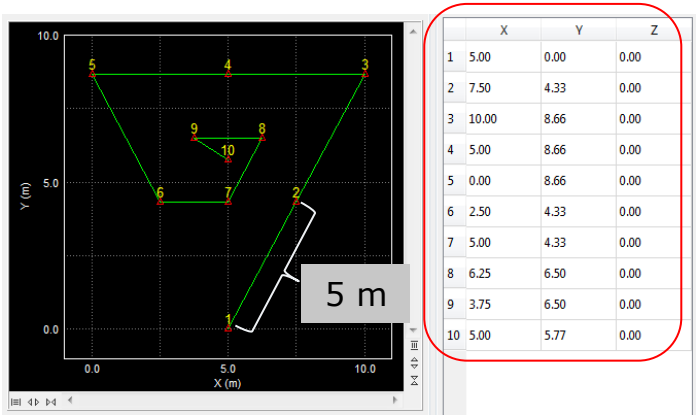
Field Setup of Triangular Array for SPAC

Because the source distributions are usually unknown, a 2-D array is highly recommended.

The 2D-array, such as cross and 'L' shape can be easily setup in the field. For best results, the triangular array should be used. The coordinate templates can be used in the field setup for convenience.



	X	Y	Z
1	5.00	0.00	0.00
2	7.50	4.33	0.00
3	10.00	8.66	0.00
4	5.00	8.66	0.00
5	0.00	8.66	0.00
6	2.50	4.33	0.00
7	5.00	4.33	0.00
8	6.25	6.50	0.00
9	3.75	6.50	0.00
10	5.00	5.77	0.00

Here is a template for a 5-meter spacing cable to set up the outer side length of 10 m.

The geometry of the triangular array looks complicated, but in fact this type of array can be set up as quickly as a linear array.

I will show you how to do at booth #17.

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Conclusion

REMI

- REMI works well with omni-directional sources, but the error significantly increases when the sources are distributed within a narrow azimuth.
- Picking along the envelope rather than the peak of surface wave energy is rather subjective and introduces more errors.
- More geophones and larger array size are required for the desired depth of investigation.
- Caution should be taken in setting up the array and picking dispersion curves.

SPAC

- The dispersion image is insensitive to the azimuths of the sources.
- For a linear array, provided there are omni-directional sources, SPAC can produce better results than REMI.
- Picking along the peak ensures high certainties, even though the resolution becomes lower at low frequencies.
- A relatively small number of geophones and small size of array can determine velocity profiles at greater depth.
- An embedded equilateral triangle array can be set up as quickly as a linear array.