Application of variogram to detect buried objects using a laser Doppler vibrometer

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Outline of the Presentation

- Introduction
- LDV and Lab experiment
- Data Characteristics
- Synthetic data generation
- Experimental variograms
- Comparison of simulated variograms
- Preliminary conclusions

Methods

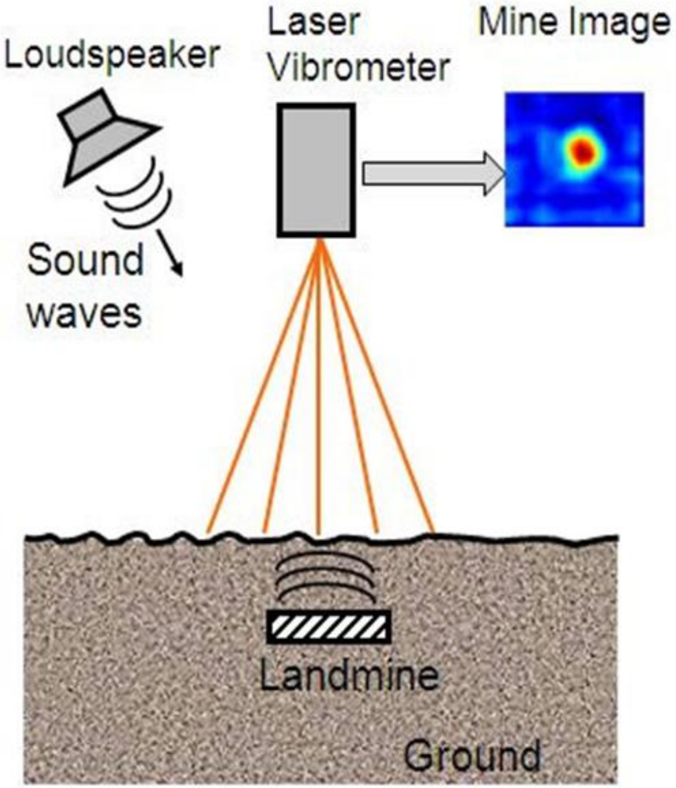
Results

Introduction

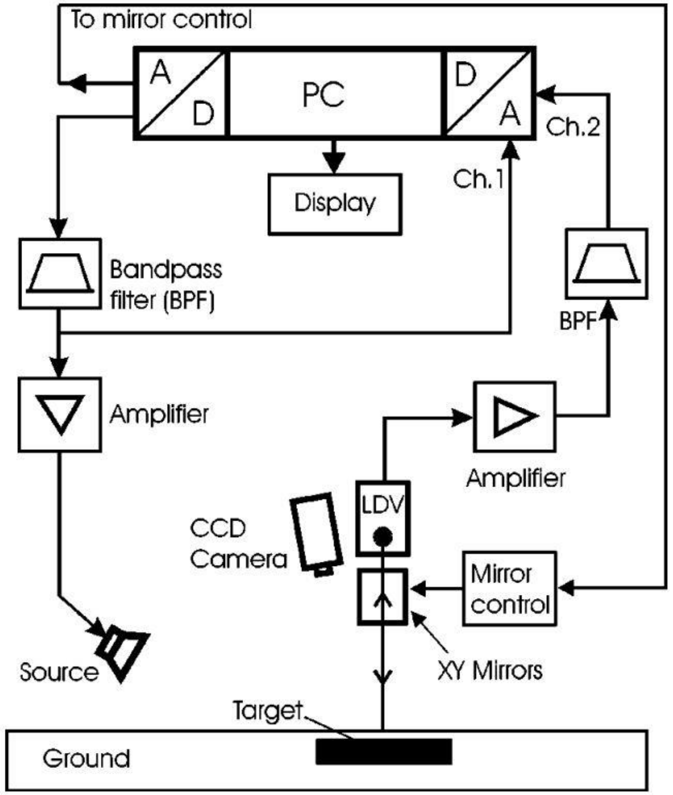
- Acoustic-seismic (A/S) coupling detection of shallow buried objects has a good application prospect in military, architecture, archaeology and other fields because of its non-contact characteristics.
- A/S coupling system exploits airborne acoustic waves penetrating the ground surface that excite seismic motion.
- We use single-point **Laser Doppler Vibrometer (LDV)** for sensing mechanical vibration of the ground surface produced by sound waves created by a loudspeaker.
- The objective is to model the spatial variability in ground vibrations (**variograms**) that can influence the outcome of buried object detection.

How LDV works?

- The airborne sound couples into the soil and excites the vibration energy of the soil matrix.
- When **a buried object is present, it distinctly changes the A/S coupled motion.**
- Due to mechanical resonance and higher mechanical compliance of the object, the ***vibrational amplitude of the surface above the object is higher than the surrounding soils.***
- This vibrational anomaly at multiple points produced by buried object is detected by LDV.
- LDV emits a laser beam onto the vibrating surface that cause a Doppler frequency shift of the reflected light which gives information about vibration magnitude.

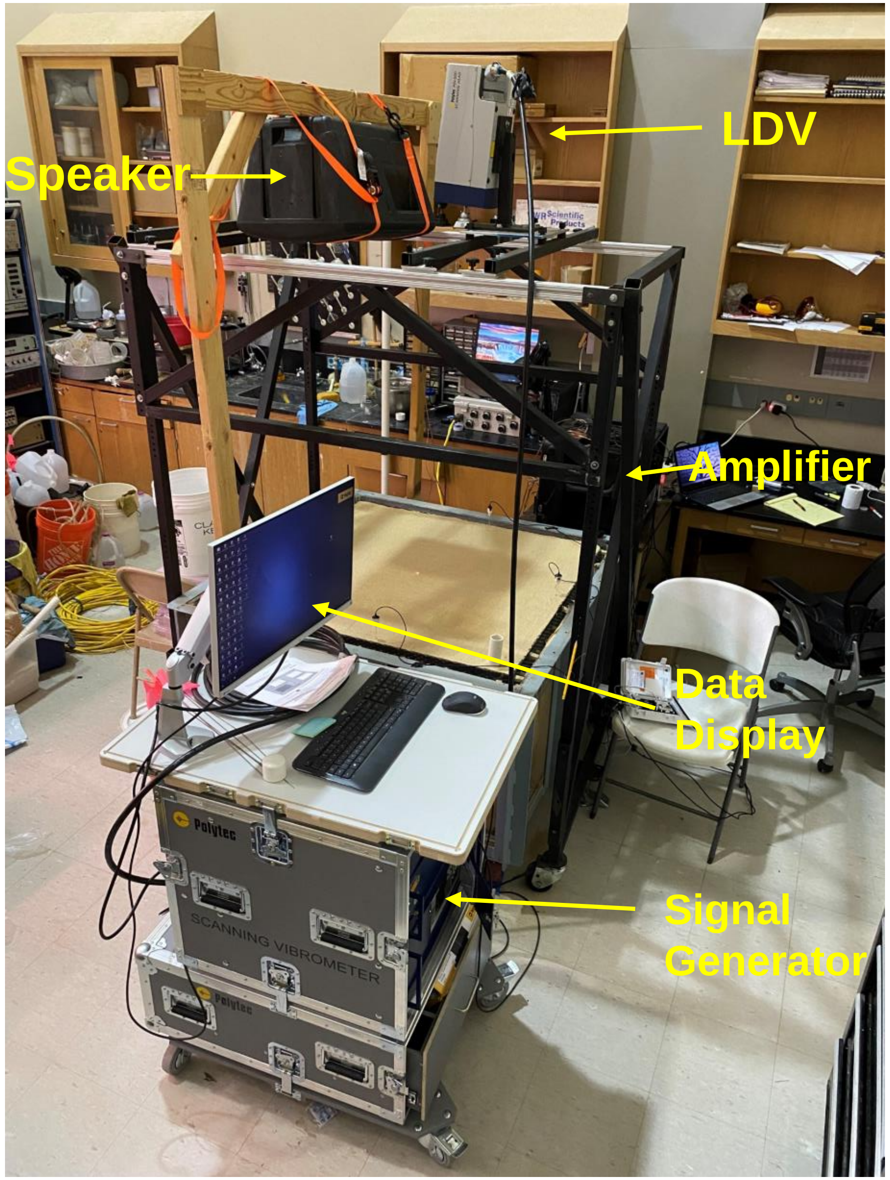


Source: Aranchuk, NCPA

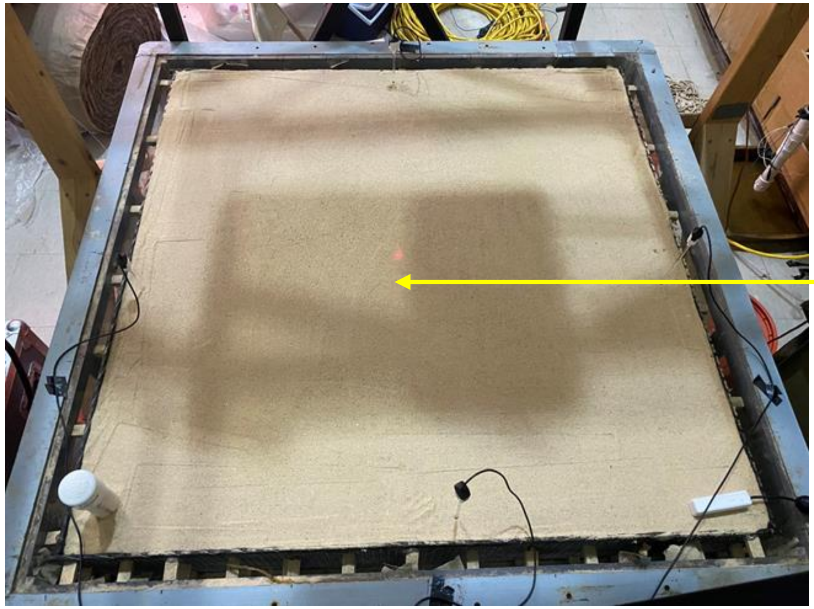


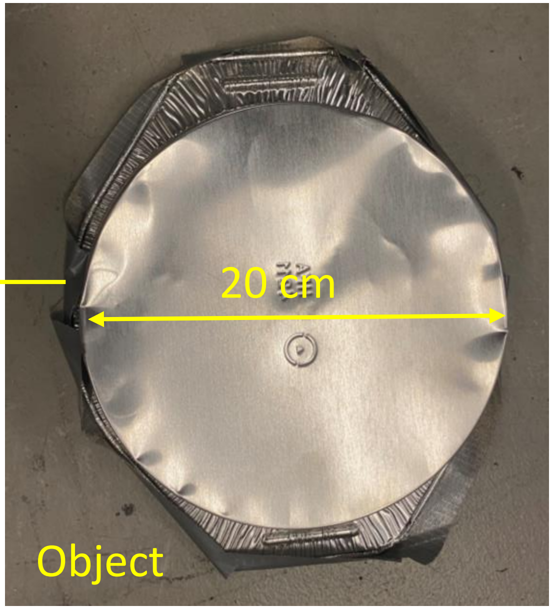
Schematic diagram of the measurement system using LDV (Sabatier, 2001)

Experimental design



Lab set-up at NCPA





- Object was buried a few inches under the **dry medium-grained sand** at the middle of the sandbox
- Pseudorandom Noise (PRN); Sound Pressure Level (SPL): 81 dB; speaker is ~ 2m away from the top of the sandbox
- Sandbox is divided into 459 (27×17) gridded points on the sand box covering 2016 (56×36) cm^2 area with ***cell size 4.4 cm^2.***

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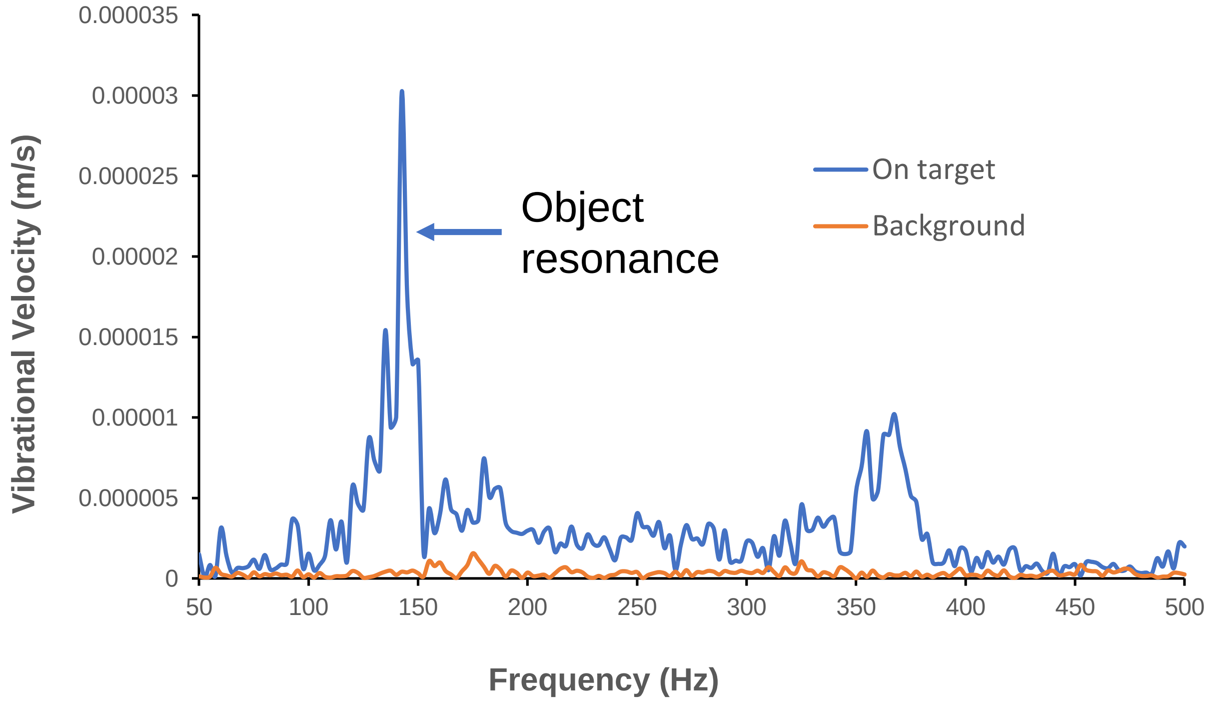
Data characteristics

- LDV provides complex FFT data that includes complex **velocity vectors at each point as a function of the corresponding frequency vectors, *Ṽ(f)*.**
- Two measurements: **with and without an object.**
- We considered frequency range from 50 to 500 Hz at 2.5 Hz interval.
- The object is resonating at **125 Hz to 150Hz frequency band.**
- The highest resonating frequency is 142.5 Hz, **but we chose the image at 137.5 Hz having the best visualization of object.**
- The ***Object*** and ***Background*** data at this frequency is used for variogram generation.



Spectrogram of vibrational velocity for points on and off target

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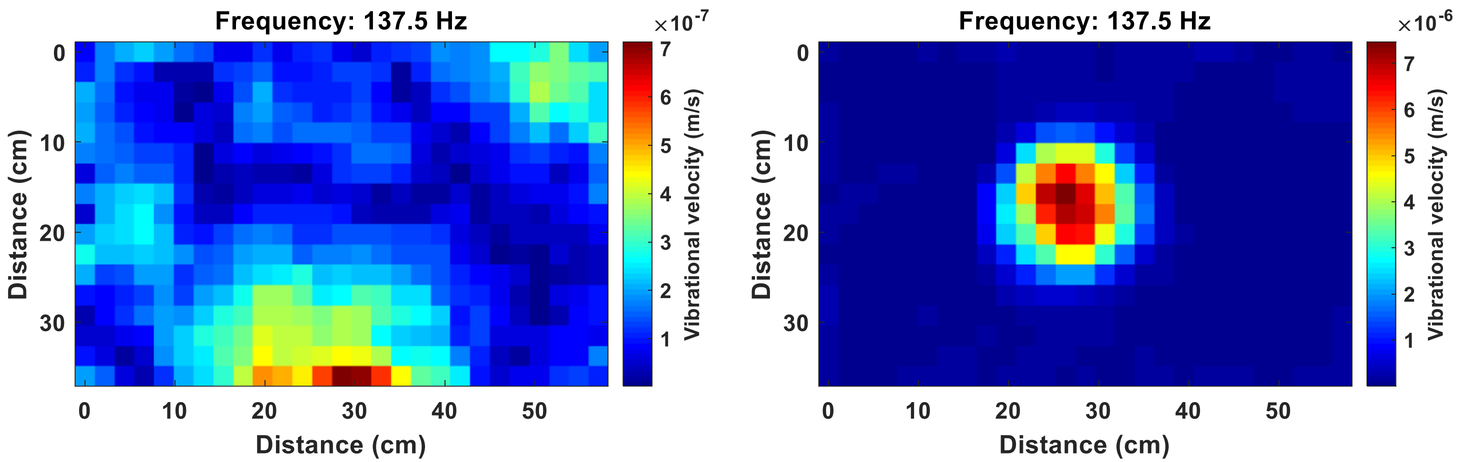
Data characteristics

- The ***buried object shows higher vibration magnitude (red circular blob in the right image) than the background.***
- This background image is chosen because of the noises to see how they affect the object signature
- Significantly higher ***variance*** of the object-data leads to the ***application of variogram*** in burred object detection



Background data

Object data

Case	Mean (m/s)	Variance (m/s)	Min (m/s)	Max (m/s)
Background	1.545e-07	1.275e-14	2.563e-09	7.133e-07
Object	5.327e-07	1.696e-12	6.304e-09	7.462e-06

Variogram/semi-variogram

- The variogram, $\gamma(h)$, is half the average squared difference between the **paired data values.**

- Variogram measures dissimilarities over lag distances.

- The vibrational ***velocity at gridded locations is considered as a random function*** to calculate the variogram.

- We assume that ***Ṽ(f) is isotropic, depends only on separation (h)***, and not a function of *x* or *y*.

$$\boldsymbol{Variogram,} \qquad \boldsymbol{\gamma(h) = \frac{1}{2N(h)} \sum_{x=1}^{N(h)} \big(z(x) - z(x+h)\big)^2}$$

h is lag distance

$z(x)$ *is value of variable at location* x

$z(x+h)$ *is value of variable at location* $x+h$

N is number of pair at h lag distances

Near things are more related than distant things

Synthetic data using 2D Gaussian Function

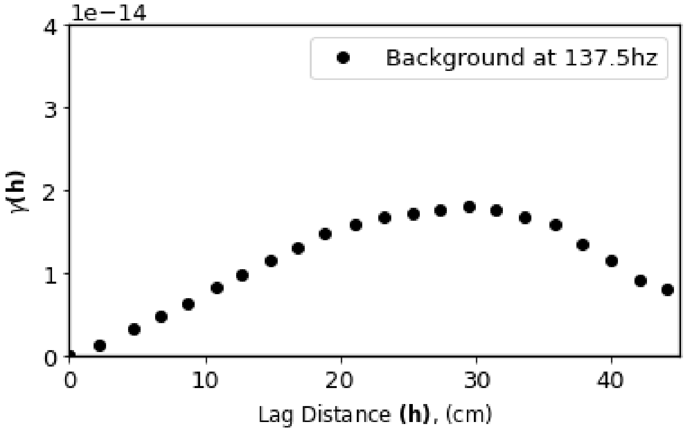
- We used 2D Gaussian function to simulate the signature of a buried object.
- This allows generation of a series synthetic data to verify to what extent a variogram can successfully detect a buried object.
- We ***changed the A value keeping σ constant to simulate object, background and some intermediate cases*** showing successive disappearances of the buried object.
- Variograms for all the cases were calculated and compared.

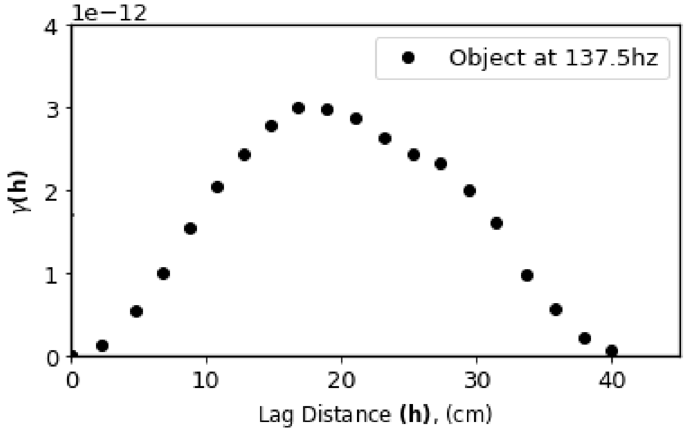
$$\boldsymbol{f(x,y) = Ae^{\left(-\left(\frac{(x-x_0)}{2\sigma_X^2}\right)+\left(\frac{(y-y_0)}{2\sigma_Y^2}\right)\right)}}$$

Where A is amplitude, x_0, y_0 is the center point, σ_X, σ_Y are the x and y spreads of the blob

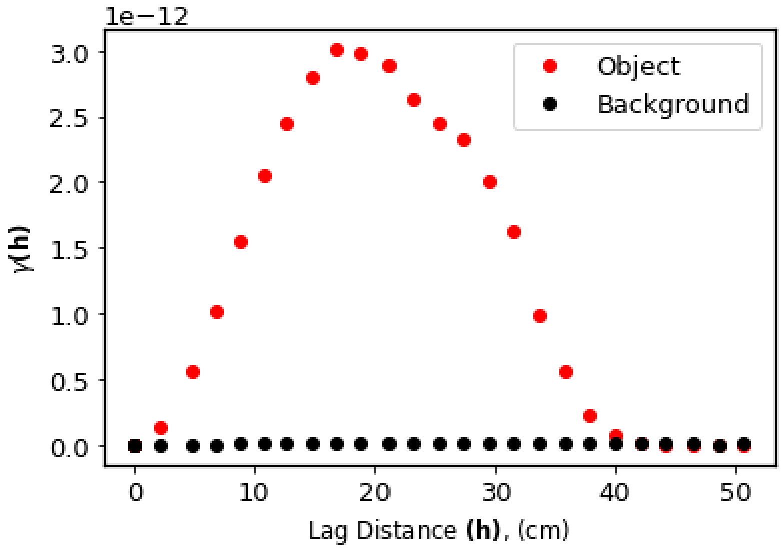
Experimental variograms

- Variogram properties: **Lag distance 2.10 cm**, lag tolerance 1.05 cm, no of lag 20, Azimuth 0^0, Azimuth tolerance 90^0c **(Isotropic)** .
- The ***initial slope of the variogram*** of the object data shows significantly high spatial dependence than the background data.
- ***The difference is prominent when in the same scale.***
- This ***bell-shaped variogram*** indicates the presence of a buried object.
- The lag distance in which variogram reaches its ***peak is comparable with the size of the object***





Background vs object at different scale



Background vs object in the same scale

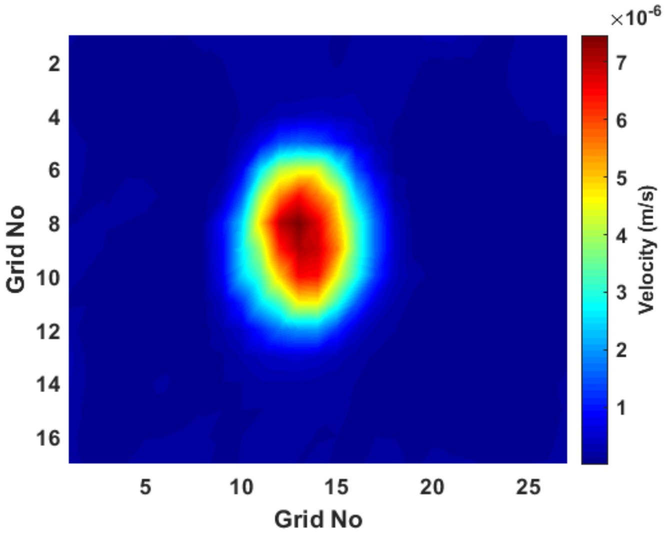
Parameters of all Gaussian simulated cases

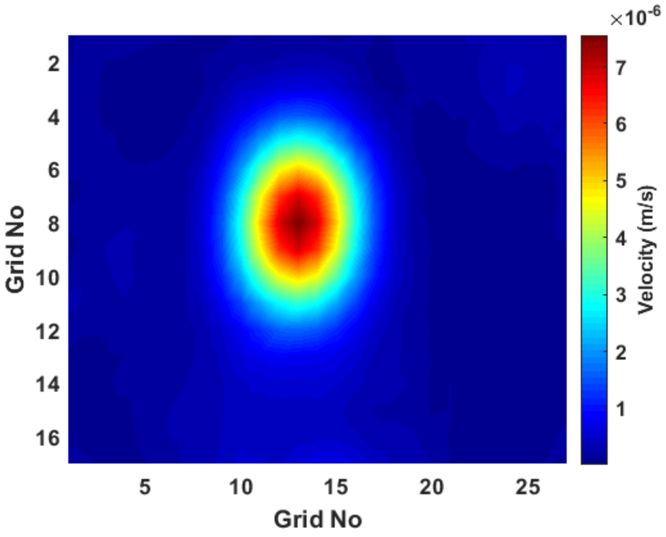
Case	A_{fit}	Mean	Variance	Min	max
Object	-	5.327e-07	1.696e-12	6.304e-09	7.462e-06
A1	7.50E-06	6.512e-07	1.589e-12	6.784e-09	7.554e-06
A2	2.50E-06	3.201e-07	1.780e-13	6.782e-09	2.554e-06
A3	8.330E-07	2.096e-07	2.781e-14	4.090e-09	8.866e-07
A4	5.00E-07	1.876e-07	1.699e-14	3.480e-09	7.134e-07
A5	3.50E-07	1.777e-07	1.421e-14	3.205e-09	7.133e-07
A6	1.50E-07	1.555e-07	1.251e-14	2.838e-09	7.133e-07
Background	-	1.545e-07	1.275e-14	2.563e-09	7.133e-07

- All simulated Gaussian cases ***with decreasing object signature*** from A1 to A6.
- ***A1 is similar to Object.***
- ***A6 is analogous to Background.***

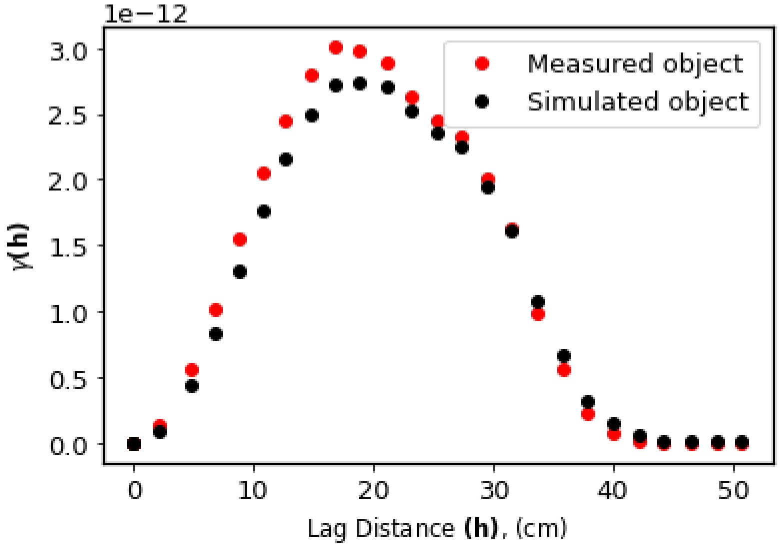
Measured vs. simulated object signature

- Background data is added in every simulated cases
- The resultant image is analogous to the original measured object image.
- ***The variograms of them also shows good agreement.***

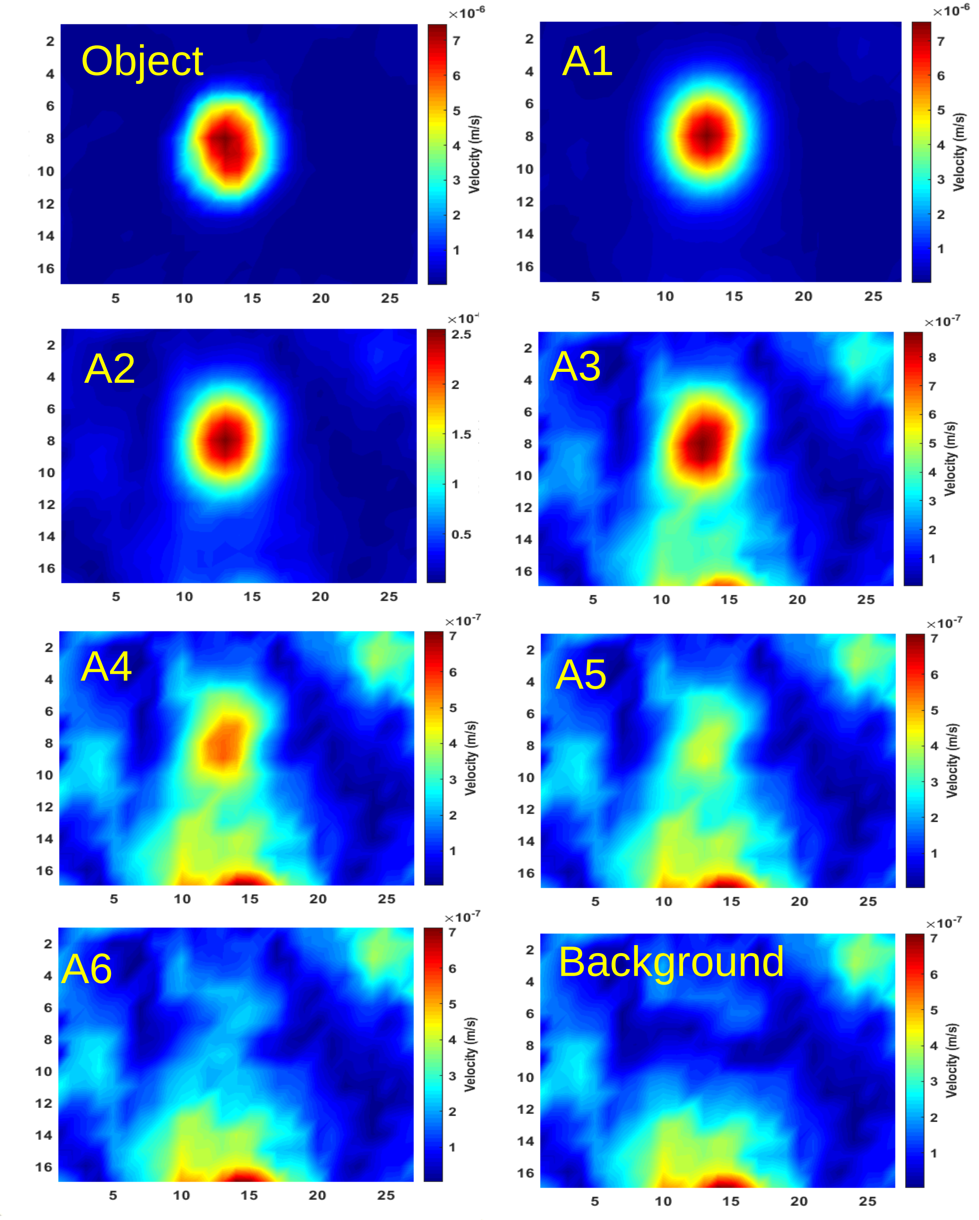


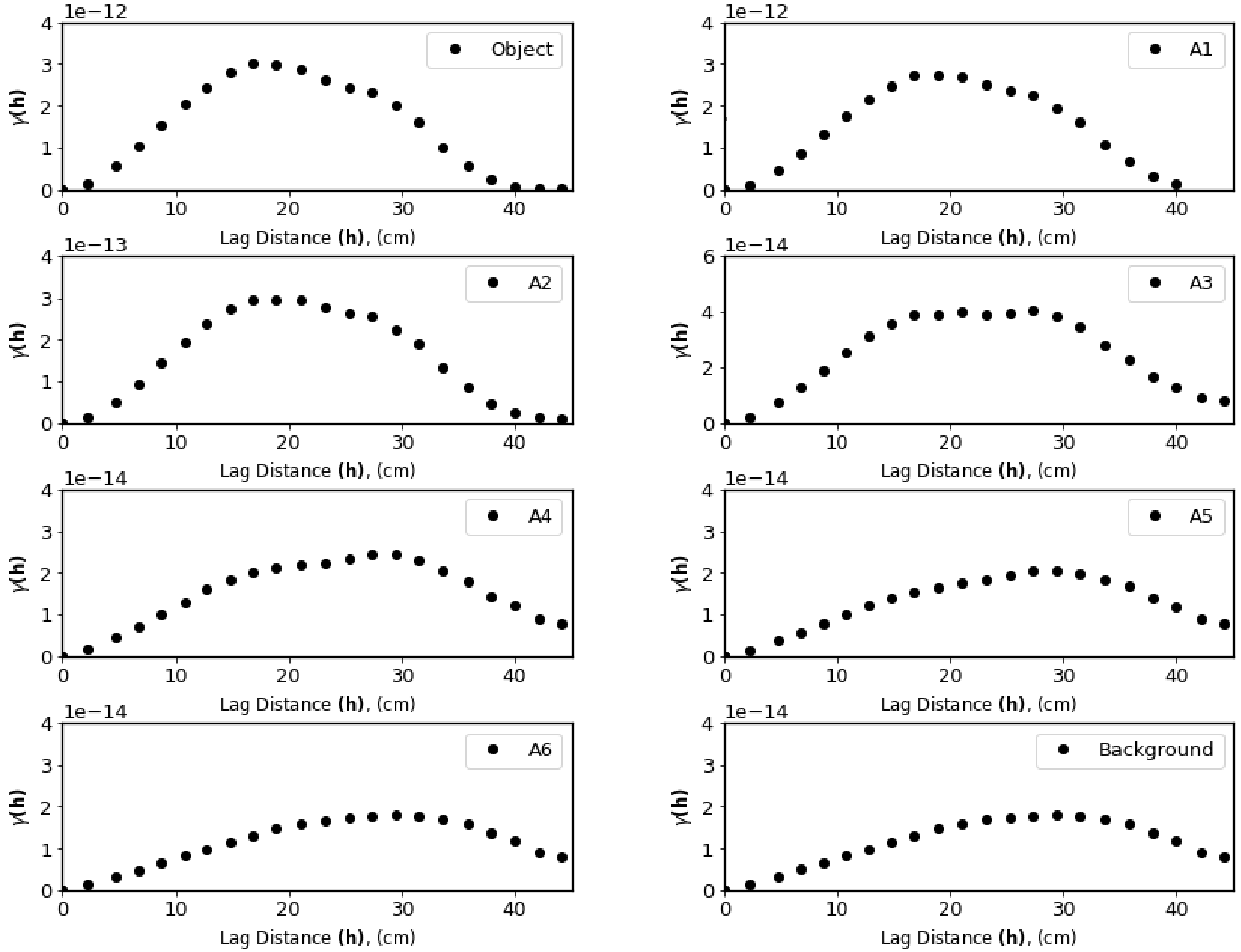


Measured vs. simulated (A1) object signature



Variograms of all simulated cases

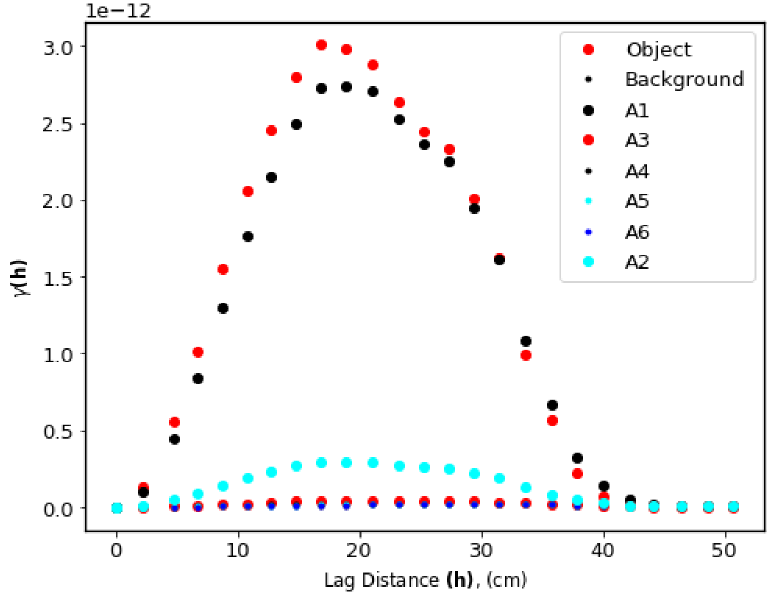


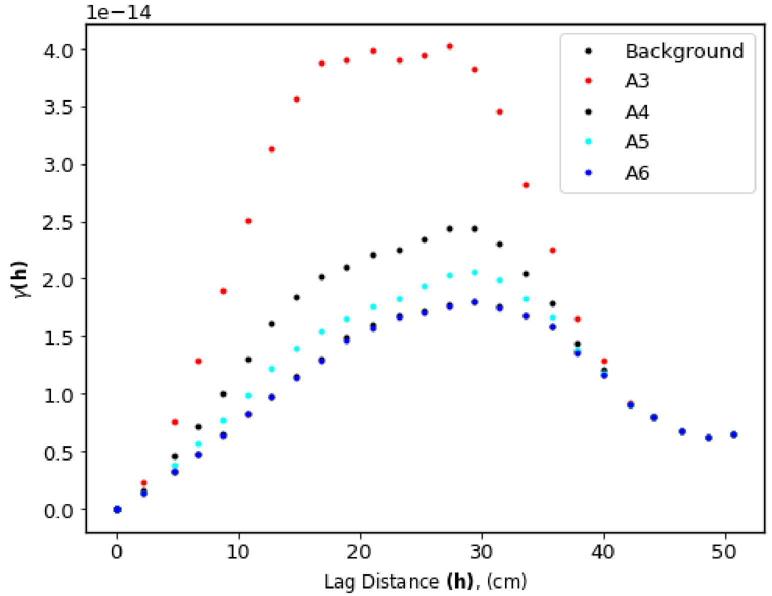


Simulated cases with Object and Background signatures, and their corresponding variograms

Variograms of all simulated cases

- Variogram can detect buried object with significantly reduced signature.
- Here up to case 4, the buried object is separable using variogram (provided that the background variability is added into the A4 simulated object data).
- However, variogram cannot detect object if not visible in the raw data.
- Variogram also demonstrates that the **variance of the data** could be the determining statistical property.





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Preliminary conclusions

- Variograms can be used to develop ***a mathematical model of buried object*** signature, which implies that the variance of the data could be the determining statistical property.

- 2D Gaussian model can be used to generate synthetic buried object signatures, and which help studying usability limit of variogram in detecting buried object.

- Object is detectable using variogram if it resonates and the ***background variability is not significant.***

- Further research is needed to develop a quantitative relationship to distinguish Object from Background using variogram.

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Any questions?

Feedback?