Imaging with Ambient Noise III

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Outline: Coherent Interferometry (CINT) and its applications

1. Kirchhoff migration
2. Incoherent interferometry
3. Decoherence frequency and length; Coherent interferometry
4. Adaptive estimation of $\Omega_d$ and $X_d$
5. Optimal illumination and waveform design
6. Optimal subspace selection
The array imaging configuration with the central wavelength $\lambda_0$ as unit of length.

The random fluctuations in the propagation speed (on the right) are generated by random Fourier series. The correlation length is comparable to the central wavelength (for maximum wave-medium interaction) and the standard deviation is about 3%.
Passive traces (array data)

All sources emit the same pulse at the same time instant. Locating the sources using the array data is the passive array imaging problem.
Active traces (array data)

Note that multiple scattering arrivals are invisible in the random medium.
Assume that the background velocity is known. Denote the deterministic background Green’s function by $\hat{G}_0(x, y, \omega) = \frac{e^{i \omega \tau(x, y)}}{4\pi|x-y|}$. We can use the following imaging functional for the reflectivity $\rho(y^S)$:

$$I^{KM}(y^S) = \sum_{x_s, x_r} P(x_r, x_s, \tau(x_s, y^S) + \tau(y^S, x_r))$$

Here $\tau(x, y) = |x - y|/c_0$ is the travel time from $x$ to $y$ when the speed of propagation is $c_0$. This does not work in clutter because the deterministic travel time cannot deal with the delay spread in the traces. The delay spread is due to the scattering from the random inhomogeneities.
Incoherent Interferometry

Delay spread manifests itself in the frequency domain as random phases. To avoid this random phase problems in Kirchhoff migration imaging we mimic physical time reversal by computing cross-correlations of data traces, the interferograms, and summing

\[
I^{\text{INT}}(y^S) = \sum_{x_r, x_{r'}} P(x_r, \cdot) *_t P(x_{r'}, \cdot) \big|_{\tau(x_r, y^S) - \tau(x_{r'}, y^S)}
\]

The interferograms are given by

\[
P(x_r, \cdot) *_t P(x_{r'}, \cdot) (t) = \int_{-\infty}^{\infty} P(x_r, s) P(x_{r'}, s - t) ds
\]

Here we consider for simplicity the source imaging problem. Arrival time information is lost since only travel time differences are relevant. So this imaging functional has poor range resolution. However, its cross range resolution is relatively stable in random media.
In the frequency domain we have

$$I^{\text{INT}}(y^S) = \int d\omega \left| \sum_{x_r} \hat{P}(x_r, \omega) e^{-i\omega \tau(x_r, y^S)} \right|^2$$

This is almost Matched Field Imaging

$$I^{\text{MF}}(y^S) = \int d\omega \left| \sum_{x_r} \hat{P}(x_r, \omega) \hat{G}_0(x_r, y^S, \omega) \right|^2$$

$$\hat{G}_0(x, y, \omega) = \frac{e^{i\omega \tau(x, y)}}{4\pi|x - y|}$$

that is widely used in sonar and elsewhere in more general situations (waveguides, enclosures, etc) with a suitable $\hat{G}_0$. 
The trace cross-correlation

\[ P(x_r, \cdot) \ast_t P(x_{r'}, -\cdot)(t) \]

does not have a peak if \( |x_r - x_{r'}| > X_d \).

The phases of \( \hat{P}(x_r, \omega_1) \) and \( \hat{P}(x_r, \omega_2) \) decorrelate when \( |\omega_1 - \omega_2| > \Omega_d \).

Both \( X_d \) and \( \Omega_d \) can be ESTIMATED from the array data directly.
Coherent interferometric imaging

To combine good random phase cancellation, which KM does not have but matched field methods have, with exploitation of residual coherence we use the Coherent Interferometric imaging functional:

\[
I^{\text{CINT}}(y^S; X_d, \Omega_d) = \int \int d\omega_1 d\omega_2 \sum \sum |x_r - x'_r| \leq X_d 
\hat{P}(x_r, \omega_1) \hat{P}(x'_r, \omega_2) e^{-i(\omega_1 \tau(x_r, y^S) - \omega_2 \tau(x'_r, y^S))}
\]

If we take \(X_d = a\) and \(\Omega_d = B\), which means that there is no smoothing, then the CINT functional is just the Kirchhoff migration functional squared: \(I^{\text{CINT}} = (I^{\text{KM}})^2\). The case \(\Omega_d = 0\), suitably interpreted, is incoherent interferometry.
Adaptive Selection of $X_d$ and $\Omega_d$

For CINT to be effective we need to be able to determine the decoherence length and frequency adaptively. We do this by minimizing the bounded variation norm of the (random) functional $I^{CINT}$

$$\{X^*_d, \Omega^*_d\} = \arg\min_{X_d, \Omega_d} \|I^{CINT}(\cdot; X_d, \Omega_d)\|_{BV}$$

where

$$\|f\|_{BV} = \int |f(y)|dy + \alpha \int |\nabla f(y)|dy$$

The bounded variation norm is used because it is smoothing on small scales but is respectful of large scale features (discontinuities). The smoothing is limited by the $L^1$ norm. Other sparsity-type norms can be used, such as entropy norms.

The parameter $\alpha$ is chosen so that the two terms in the BV norm balance.
What about denoising the data first and then migrating?

The array data $P$, not the image, could be denoised by minimizing

$$\alpha||P - Q||_{\text{PROX}} + ||Q||_{\text{REG}}$$

over $Q$. This is an expensive calculation for large array data sets. The denoising can also be done by harmonic analysis methods: decompose the data $P$ in some well chosen basis (ridgelets?), threshold the Fourier coefficients below some level and reconstruct to get the denoised data $Q$. After the denoising one can do Kirchhoff migration with $Q$ as array data.
Coherent interferometric imaging results

Coherent Interferometry images in random media with $s = 3\%$.

**Left Figures:** $X_d = a$, $Ω_d = B$ (Kirchhoff Migration, no smoothing)

**Middle Figures:** $X_d = X_d^*$, $Ω_d = Ω_d^*$ (Adaptively selected optimal smoothing)

**Right Figures:** $X_d < X_d^*$, $Ω_d < Ω_d^*$ (Too much smoothing)
• Without smoothing there is no statistical stability of the image: Different realizations of the random medium give different images. Smoothing, especially in frequency, gives stable but blurred images.

• Statistical stability of the image is very important because it allows further processing with deblurring methods. We have used Level Set Deblurring methods successfully, provided that we have a good estimate of the amount of blurring.

• The optimal decoherence frequency $\Omega_d^*$ is not known and it is determined adaptively, as explained above. So is the decoherence distance $X_d^*$. 
Resolution theory for specific models

A resolution theory can be developed based on several assumptions about the random medium and the propagation regime. Such assumptions are NOT used in the numerical simulations.

- With the paraxial approximation, the white noise limit, and a high frequency expansion we reduce all theoretical calculations to the use of one relatively simple formula obtained from the random Schrödinger equation: a second order moment formula.
- One other regime where analytical results can be obtained: Layered media. In no other regime do we have, or expect, analytical results.
### Summary: Resolution limits

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<th>Known Rand (TR)</th>
<th>Unknown Rand (CINT)</th>
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<tbody>
<tr>
<td><strong>Range</strong></td>
<td>$\frac{c_0}{B}$</td>
<td>$\frac{c_0}{B}$</td>
<td>$\frac{c_0}{\Omega_d}$</td>
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<tr>
<td><strong>Cross Range</strong></td>
<td>$\frac{c_0L}{\omega a}$</td>
<td>$\frac{c_0L}{\omega a_e} \sim X_d$</td>
<td>$\frac{c_0L}{\omega X_d} \sim a_e$</td>
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Resolution limits in deterministic media and in random media, when the random medium is known as in physical time reversal, and when the random medium is not known as in coherent interferometry.
Coherence is essential in array imaging. A more physical, and more conventional, way to measure coherence is through the transport mean free path $l^*$. In the regime where waves energy propagates by diffusion, the diffusion coefficient is given by

$$D = \frac{c_0 l^*}{3}.$$ 

If the transport mean free path $l^*$ is small compared to the range $L$ of the object to be imaged then migration methods, including CINT, will not work. In our numerical simulations $l^*$ is of the order of $L$, which is the regime where we expect CINT to be effective.
Optimal illumination and waveform design

Optimal illumination in array imaging is up to now aimed at DETECTION. That is, if $\hat{f}(\vec{x}_s, \omega)$ is the signal in the frequency domain that is emitted at $\vec{x}_s$ then the signal received at $\vec{x}_r$ is given by

$$\sum_{s=1}^{N_s} \hat{\Pi}(\vec{x}_r, \vec{x}_s, \omega) \hat{f}(\vec{x}_s, \omega).$$

The total power received at the array is given by

$$\mathcal{P} = \int_{|\omega - \omega_0| \leq B} d\omega \left| \sum_{r=1}^{N_r} \sum_{s=1}^{N_s} \hat{\Pi}(\vec{x}_r, \vec{x}_s, \omega) \hat{f}(\vec{x}_s, \omega) \right|^2.$$

We want to maximize this functional over all illumination signals $\hat{f}(\vec{x}_s, \omega)$ with the normalization

$$\int_{|\omega - \omega_0| \leq B} d\omega \sum_{s=1}^{N_s} \left| \hat{f}(\vec{x}_s, \omega) \right|^2 = 1.$$
In general, Optimal Illumination for Detection (SVD) produces images with bad resolution. Just like in Adaptive Coherent Interferometry we can, however, introduce an optimal illumination objective that is tied to the resolution of the image itself. We now show the results of numerical simulations using this approach to optimal illumination.
Left: Image; Center: Illumination Weights; Right: Probing Pulse.
Optimal Illumination, Deterministic Medium

Left: Image; Center: Illumination Weights; Right: Probing Pulse
The algorithm

We compute first the weighted average of the migrated traces

\[ \hat{m}(\bar{x}_r, \bar{y}^S, \omega) = \sum_{s=1}^{N_s} w_s \hat{f}_B(\omega - \omega_0) \hat{\Pi}(\bar{x}_r, \bar{x}_s, \omega)e^{-i\omega[\tau(\bar{x}_r, \bar{y}^S) + \tau(\bar{x}_s, \bar{y}^S)]}. \]

We then cross correlate these migrated traces

\[
\mathcal{J}_{\text{CINT}}(\bar{y}^S; w, \hat{f}) = \int_{|\omega - \omega_0| \leq B} d\omega \int_{|\omega' - \omega_0| \leq B} d\omega'
\int_{|\omega' - \omega| \leq \Omega_d} d\omega'
\sum_{r=1}^{N_r} \sum_{r' = 1}^{N_r} \hat{m}(\bar{x}_r, \bar{y}^S, \omega) \hat{m}(\bar{x}_{r'}, \bar{y}^S, \omega')
\]

where \( w = (w_1, \ldots, w_{N_s}) \).
We determine \( w \) and \( \hat{f} \) by minimizing an objective function \( O(w, \hat{f}) \) that quantifies the quality of the image. We take it to be the \( L^1 \) norm. We then determine the weights \( w = (w_1, \ldots, w_{N_s}) \) and the waveform \( \hat{f}(\omega) \) as minimizers of \( O(w, \hat{f}) \), subject to the following constraints. The weights should be nonnegative and sum to one:

\[
\sum_{s=1}^{N_s} w_s = 1, \quad w_s \geq 0, \quad s = 1, \ldots, N_s.
\]

The support of \( \hat{f}(\omega) = \hat{f}_B(\omega - \omega_0) \) is restricted to the fixed frequency band \( [\omega_0 - B, \omega_0 + B] \), we ask that

\[
\hat{f}_B(\omega - \omega_0) \geq 0, \quad \text{for all } \omega \in [\omega_0 - B, \omega_0 + B]
\]

and its integral is one.
Optimal subspace selection and CINT

Another way to introduce an optimization process using the SVD is by subspace selection. Let

$$D \left[ \hat{\Pi}(\omega); \omega \right] = \sum_{j=1}^{p} \sigma_j(\omega) d_j(\omega) u_j(\omega) v_j^*(\omega)$$

a subspace selector with weights \(\{d_j(\omega)\}\). Now let

$$m(\vec{x}_r, \vec{x}_s, y^S, \omega; d) = D \left[ \hat{\Pi}(\omega); \omega \right] e^{-i \omega (\tau(\vec{x}_r, y^S) + \tau(\vec{x}_s, y^S))}$$

The CINT imaging functional to be optimized is:

$$I^{CINT}(y^S; d) = \int \int_{|\omega - \omega'| \leq \Omega_d} d\omega d\omega' \sum_{|\vec{x}_r - \vec{x}_r'| \leq X_d} \sum_{|\vec{x}_s - \vec{x}_s'| \leq X_d} m(\vec{x}_r, \vec{x}_s, y^S, \omega; d) m(\vec{x}_r', \vec{x}_s', y^S, \omega; d)$$
Summary of CINT and Imaging in Random Media

- Coherent interferometry, which is the back propagation of local cross-correlations of traces, deals well with partial loss of coherence in cluttered environments.
- **Adaptive estimation** of the space-frequency decoherence addresses well the issue of learning the unknown environment.
- The key parameters $\Omega_d$ and $X_d$, which characterize the clutter, play a triple role: they are thresholding parameters for CINT, they determine its resolution, and characterize the coherence of the data. Theory and implementation issues merge.
- In **Optimal Subspace and Illumination** selection is computationally intensive but makes a huge difference.
Concluding remarks

Imaging in its many forms is at the center of modern applied mathematics.

- It is naturally interdisciplinary
- It is profoundly mathematical
- It has to deal with large data sets
- It has to deal with statistical issues
- It has to deal with optimization issues


3. Wave propagation and time reversal in randomly layered media, Fouque, Garnier, Papanicolaou and Solna, Springer, 2007. The first five chapters cover basic wave propagation in layered media. Chapter 6 is a self-contained treatment of asymptotics for stochastic equations as it is used in the rest of the book. Chapter 7 is a basic, mathematical treatment of waves in one-dimensional random media.

5 Transport equations for elastic and other waves in random media, Ryzhik L V, Papanicolaou G C and Keller J B, 1996, Wave Motion, vol 24, 327-370. A more mathematical treatment of topics found in the previous reference

References for the lectures


More references

5 Edge illumination and imaging of extended reflectors, Liliana Borcea, George Papanicolaou and Fernando Guevara Vasquez, SIAM Journal on Imaging Sciences, vol 1 (2008), pp. 75-114. Use of SVD in edge illumination and imaging


7 Stable iterative reconstruction algorithm for nonlinear travel time tomography Berryman J, 1990, Inverse Problems, vol 6, 21-42. Basic reference for travel time tomography

8 Adaptive interferometric imaging in clutter and optimal illumination Borcea, Papanicolaou, and Tsogka, 2006, Inverse Problems, vol 22, 1405-1436. Paper on which Lectures IX and X are based, plus Tsogka’s lectures


References for cross correlations continued


