The following small scale experiment (ultrasounds in concrete) shows how coda waves might allow us to monitor weak changes in the internal structure of the earth (temperature or pressure). Such a technique could be useful to keep a watch on volcanoes and faults, or could interest companies for concrete structures and application to monitoring weak changes.

The experiment was conducted in summertime when outside temperature was increasing from 17°C (night) to 32°C (day). This resulted in noticeable variations of the concrete temperature, from 20°C to 30°C.

The velocity increases at night and decreases with solar warming.

This experiment takes advantage of multiply scattered and/or reflected coda waves. The more scattered, the more precise we get for \( v \). From the delay estimation we calculate that the thermal dilation rate of concrete velocities is 0.15%/°C.

This technology has been used by several researchers, in particular by the team of B. Anache at Grenoble University, France. They were interested in multiple scattering of kHz vibrations and possible applications to seismology.

**A. TIME CORRELATION OF FIELD AND WEAK CHANGE MONITORING**

**1. Physical principle**

A thermal change \( \Delta T = \theta - \theta_0 \) of the medium results in a change in the wave velocities:

\[
\begin{align*}
\epsilon_P &= \epsilon_0 + \Delta \epsilon_P \\
\epsilon_S &= \epsilon_0 + \Delta \epsilon_S
\end{align*}
\]

At first order it corresponds to a temporal dilatation of the impulse response:

\[
h(t) = h_0(1 + \epsilon)
\]

with \( \epsilon \) the dilation rate. It is related to a delay around time \( t \) given by

\[
\tau = \frac{k}{\Delta \epsilon} \Delta T = \frac{\epsilon}{\epsilon_0} \Delta T
\]

It is a good approximation as long as the waveforms are weakly modulated.

**2. Experimental setup and data processing**

The experiment is conducted on the second floor of a concrete structure.

**3. Results**

The experiment was conducted in summertime when outside temperature was increasing from 17°C (night) to 32°C (day). This resulted in noticeable variations of the concrete temperature, from 20°C to 30°C.

The velocity increases at night and decreases with solar warming.

This experiment takes advantage of multiply scattered and/or reflected coda waves. The more scattered, the more precise we get for \( v \). From the delay estimation we calculate that the thermal dilation rate of concrete velocities is 0.15%/°C.

**4. Conclusion**

The phase correlations reveal the mean free path \( \lambda \). Experiments are in preparation.

**B. SPATIAL CORRELATION OF PHASE**

We concentrate on a theoretical study of the information contained in the phase. In seismology one can measure directly the field and not only the intensity (like in optics). The large wavelength (\( \lambda \approx 4m \)) allows us to obtain the phase and its spatial derivatives without much difficulties with data processing. The advantages are: additional information and a data processing without need for calibration.

**1. Spatial field correlation**

In the presence of multiple scattering the spatial field correlation function is related to the Green function between two points [5]:

\[
C(x, y; t) = \langle \Phi(x, t) \Phi(y, 0) \rangle \approx \exp(-2|t|/\lambda)
\]

Behaviour:

- the exponential decay is due to dephasing from scattering;
- the oscillations on the scale of the wavelength \( \lambda \) are due to a superposition of plane waves incident with arbitrary directions but with equal amplitude.

**2. Phase derivative correlation**

The wrapped phase \( \Phi \) is defined as the complex phase of the wave function \( \Phi = \exp(\Phi) \). Using the hypothesis of gaussian statistics for the multiply scattered field, one can obtain [6]:

\[
C_{\Phi}(x > \lambda) \approx \langle \Phi(x)\Phi(x') \rangle \approx \left\{ (2\pi/\lambda) \exp(-2|t|/\lambda) \right\} 
\]

3D: the asymptotic value varies only logarithmically with \( d \).

**3. Unwrapped phase correlation**

The unwrapped phase \( \Phi_{\text{uw}} \) is defined as the complex phase of the wave function \( \Phi = \exp(\Phi_{\text{uw}}) \) corrected for its discontinuous jumps of 2\( \pi \).

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\[
C_{\Phi_{\text{uw}}}(x) = \iint d^2x' \int dz \Phi_{\text{uw}}(x', z)
\]

**4. Conclusion**

The phase correlations reveal the mean free path \( \lambda \). Experiments are in preparation.

References


