MIIC – Monitoring and Imaging based on Interferometric Concepts

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1. Overview

Recent years have witnessed the emergence of a new field in seismology (Courtland, 2008). New concepts from mesoscopic physics have dramatically changed the seismologists' view on ambient noise and seismic coda. Being disturbing signals that hinder the detection of earthquakes only six years ago these wave fields become a major source of information that is used with seismic interferometry.

The goal of MIIC is to develop new imaging and monitoring strategies that are based on these new concepts to make use of scattered waves and ambient seismic noise in a broader set of applications that extends beyond seismology. We will develop an analysis tool that integrates real time data handling, interferometric processing and novel simulation and inversion strategies to combine the monitoring and imaging approaches into a dynamic tomography that gives 4D information about the structure of the target and its temporal changes. This concept is illustrated in figure 1.

With this tool we will provide the opportunity to use the advantages of seismic interferometry in many disciplines that are concerned with elastic waves.

The special requirements of the interferometric concepts in the data acquisition will be met by optimized instruments that will be developed within the project. From the combination of active and passive seismic techniques with new imaging and monitoring technologies

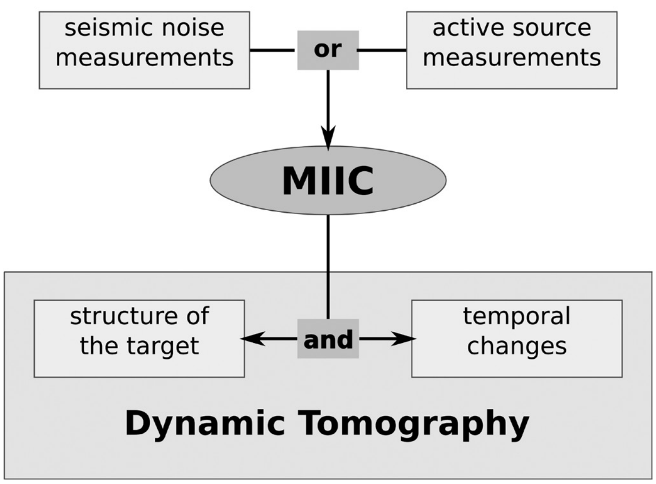

Figure 1: Illustration of the concept of MIIC. The use of interferometric concepts allows to simultaneously retrieve information about the structure of the target and its temporal changes resulting in a dynamic tomography (4D).

that will be developed in the project we expect progress that is strongly required in the fields of building-ground investigation (seismic risk, Eurocode 7), subsurface monitoring (mining safety and subsurface storage) and geo-hazard evaluation (volcano and landslide monitoring).

2. Goals of the project

MIIC is a joint effort of research institutes, a university and private companies. It combines scientific and technical goals with the economic goal of commercially usable results.

Scientific goals

- Detailed investigation of the potential of seismic interferometry for monitoring material changes on different scales and in different environments
- Comprehensive understanding of the effects of localized changes in the propagation medium on phase shifts, de-correlation of the wave form and amplitude variations of the scattered wave field
- Inversion of phase shifts and wave form changes in the scattered seismic wave field for the location and amplitude of spatially localized changes in the target material
- Utilization of seismic three-component data for joint inversion of Rayleigh and Love waves from ambient noise
- Utilization of stationary non-synchronized noise sources for imaging and monitoring
- Investigation of the benefit of a structurally coupled inversion of surface wave dispersion measurements with seismic refraction and geoelectric measurements

Technical goals

- Development of a software for the integrated analysis of seismic noise and scattered waves from active sources for monitoring and imaging
- Implementation of an inversion routine to locate medium changes based on variations of the scattered wave field
- Application and test of the software with data from various environment that are candidates for later commercial application of the methodology
- Development of seismic sensors for continuous recording with wireless real time access to the data and integration in the software for real time analysis.

3. Project Structure

The workload in the joint project MIIC is divided into two activities reflecting different approaches to the ultimate goal of the a 4D dynamic tomography.

3.1 Activity I: From Monitoring to Dynamic Tomography

State of research

Monitoring with acoustic or seismic waves has been limited to the monitoring of sources for a long time. In nondestructive testing the acoustic emissions can yield information about the damaging process and earthquake locations studied in seismology picture the tectonically active features in the earth's crust. Temporal changes in the wave propagation have generally been neglected since these variations are usually very weak, i.e. smaller than the spatial variability. However, changes of the wave velocity or attenuation may provide valuable information about ambient stress changes, the opening and development of cracks, temperature changes or chemical alteration. The key to detect these temporal variations of the wave field is to use interferometry of scattered waves. This provides an accuracy that is far superior to traditional travel time measurements. During the long time that scattered waves propagate, they accumulate the effects of changes in the medium (e.g. phase delays due to velocity changes). Figure 2 illustrates this advantage.

The concept of detecting temporal changes with interferometry of scattered waves in seismic coda was presented by Poupinet et al. (1984) under the term Moving Window Cross

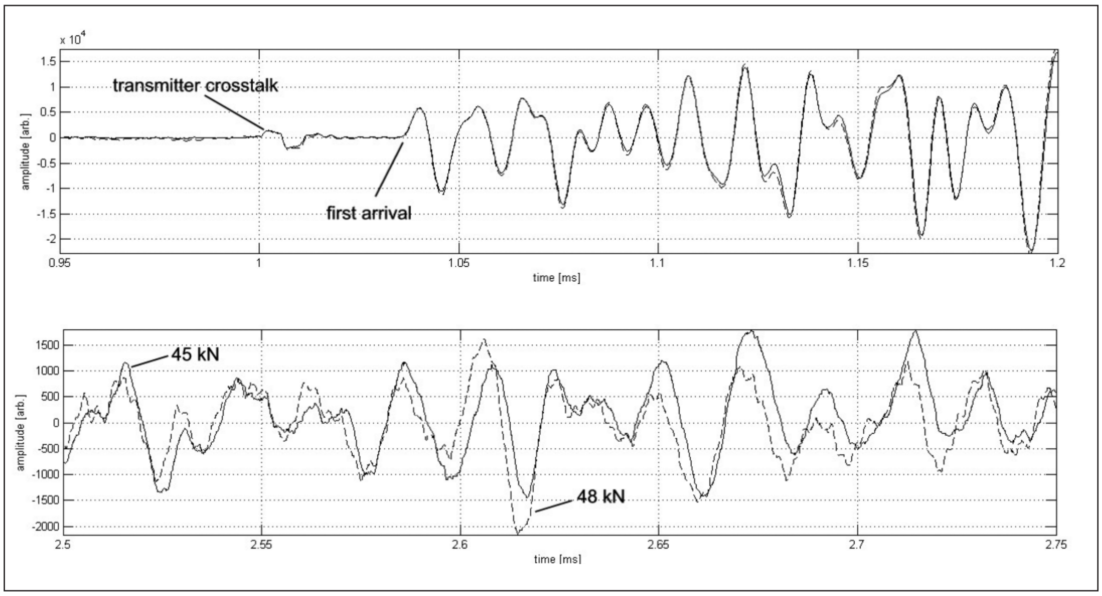

Figure 2: Ultrasonic transmission through concrete sample at different loads. Straight line : 45 kN load, dotted: 48 kN load. The slight load change has almost no effect on the time of flight of the direct wave (top) but in the coda a clear phase shift can be observed (bottom). From Stähler et al. (2009)

Spectral Analysis. A number of studies applied this technique to identify temporal changes in fault zones and volcanoes. Snieder et al. (2002) presented some more theoretical consideration of this approach and coined the term Coda Wave Interferometry (CWI). Following this, CWI was applied to monitor velocity changes in the medium, movement of scatterers, and differences in source locations. The concept was also used with active source experiments e.g. Nishimura et al. (2005). Grêt et al. (2006) reported on stress induced changes in a mining environment that were detected with CWI. These investigations suffered from the irregular temporal sampling induced by uncontrolled or expensive sources. In Sens-Schönfelder and Wegler (2006) we introduced a new concept termed Passive Image Interferometry (PII) that revolutionized the research on temporal changes. We demonstrated the possibility to retrieve scattered waves from ambient noise. This allowed to continuously monitor temporal changes with ambient noise independent of irregular or expensive sources. The method was applied to data from Merapi Volcano (Indonesia) were the changes of the local ground water level were observed on a daily basis. Figure 3 shows the Green's functions that are retrieved from noise on Merapi. The temporal changes in the medium result in the variable travel time of the coda phases in figure 3. In combination with independent precipitation data our modeling proved the applicability of the concept. In Wegler and Sens-Schönfelder (2007) and Wegler et al. (2009) we applied the method to the fault region of a Japanese earthquake and could estimate a clear co-seismic velocity drop. To increase that accuracy of the interferometric measurements, we presented a new technique based on dilatation and compression of the coda time axis that considerably stabilizes the measurements (Sens-Schönfelder and Wegler, 2006). In Sens-Schönfelder and Larose (2008) we analyzed temporal changes in the lunar crust that are induced by variations of the surface temperature. Based on our developments Brenguier et al. (2008b) observed pre-eruptive velocity changes at Piton de la Fournaise volcano. At the San Andreas fault Brenguier et al. (2008a) observed the post-seismic relaxation after two earthquakes. These prominently published applications helped to initiate investigations in seismology around the world. This approach is a completely new area of research.

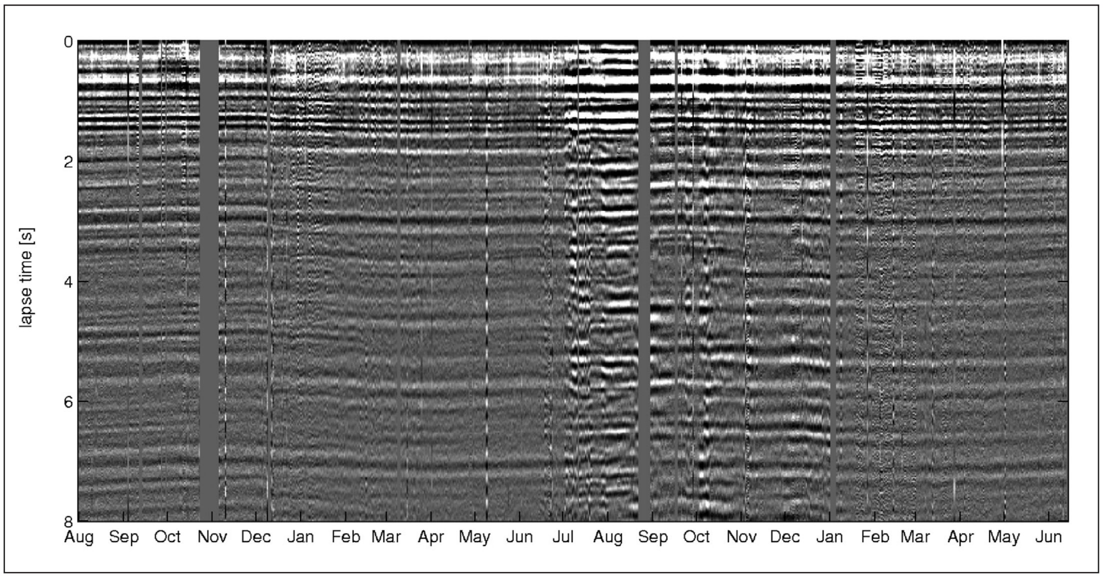

Figure 3: Noise retrieved Green's functions from Merapi volcano for each day as used by Sens-Schönfelder and Wegler (2006). Travel time is on the vertical, time of the year on the horizontal axis and amplitude is color coded. The change in the medium is reflected by the variable travel time of the coda phases, e.g. at 7 s lapse time.

The only theoretical approaches to the problem of locating velocity variations via travel time perturbations in the seismic coda were presented by Pacheco and Snieder (2005) for diffuse waves and by Pacheco and Snieder (2006) for single scattered waves. Brenguier et al. (2008b) used a heuristic regionalization concept that is not based on the physics of wave propagation to assign detected travel time changes to some region.

In Sens-Schönfelder and Wegler (2006) we presented the first approach to detect spatially heterogeneous velocity changes with scattered waves. In Sens-Schönfelder and Larose (2008) we modeled the heterogeneous velocity change in the lunar soil. The application of interferometric methods is not limited to geosciences. As Larose and Hall (2009) as well as Stähler et al. (2009) have pointed out, the concept can for example be applied in non-destructive testing of concrete and other materials.

Work plan

Activity I will focus on monitoring techniques with seismic coda waves because they provide superior temporal resolution of variations from relative measurements. Use of this advantage is currently limited to the scientific community. Also the type of change in the coda of seismic signals that is analyzed for medium changes is currently restricted to phase shifts which correspond to changes of propagation velocity. Finally the superior sensitivity and temporal resolution of monitoring with scattered waves comes at the cost of difficulties to locate the changes. This defines the main goal of activity I:

– The experience based development of software that allows the easy application of the interferometric methodology in the geophysical, geotechnical- and engineering communities.
– The application of the methodology to a number of targets ranging from seismological monitoring of volcanoes over geotechnical sites like mines or tunnels to nondestructive testing of concrete samples to investigate the potential of interferometric processing in different ares.
– Comprehensive study of the relation between changes of different wave field properties (amplitude, de-correlation) and their underlying variations of the propagation medium with theoretical modeling, lab experiments, and field data.

– The development of a tomographic approach to image the temporal changes. This will be fundamentally different from traditional tomography with direct waves. By adding spatial resolution to the monitoring technique we will approach the aim of a dynamic (4D) tomography starting from the temporal variations.
– The validation of analysis and inversion tools with model experiments

The activity is divided into four work packages. In work package 1.1 the processing and analysis software is developed that is used by the other work packages. Work package 1.2 is devoted to a broad interdisciplinary application of the monitoring technique. In work package 1.3 we will develop methodology for localizing the changes that are measured with scattered waves. With the model experiments that are performed in work package 1.4 we will validate and calibrate analysis and inversion strategies.

3.2 Activity II: From Imaging to Dynamic Tomography

State of research
During the last few years, the analysis of seismic noise recorded by arrays has been found to be particularly successful in deriving the S-wave subsoil structure below an investigated site. Innovative tools based on seismic noise analysis have been developed and tested in a broad set of targets and proved to be particularly suitable for the urban area, and especially Megacities. In particular, using just a few minutes of seismic noise recordings and combining this with the information coming from the well known horizontal-to-vertical spectral ratio, it was shown by Parolai et al. (2005) that it is possible to investigate, with a sufficient resolution, the average 1D velocity structure below an array of stations in urban areas to depths that would be prohibitive with active source surveys, and hence avoiding very expensive invasive measurements (boreholes). After successful applications of this method to several urban areas (e.g. Istanbul, see Picozzi et al., 2009 b), the possibility of deriving 3D structures by simply using some minutes of seismic noise recordings is now to be explored.
The pioneering work of Shapiro et al. (2005) showed that seismic interferometry from seismic noise recording in the frequency band below 0.5 Hz allows the retrieval of the 3D structure of the Earth at regional scales. Following applications of this Ambient Noise Tomography (ANT) were presented also in exploration geophysics (e.g. Bakulin and Calvert, 2006), focusing generally on noise above 10 Hz, and therefore a portion of subsoil of few meters.
Recently, Picozzi et al. (2009 a) applied the ANT technique for engineering seismology purposes (frequencies between 0.2-10 Hz), aiming to fill the gap between the seismological and exploration geophysics scales in the subsoil characterization. Please note that the change of frequency range from seismology to engineering seismology scale does not imply a trivial scaling. In fact, in the frequency range between 0.2-10 Hz, seismic noise sources are different (mainly anthropic), the attenuation in the considered material is larger and the distance between stations is much shorter with respect to the wavelength of the signal, complicating the estimation of the propagation time. The results obtained, showed that with just a few tens of minutes of seismic noise recording, it is possible by seismic interferometry to obtain 3D images for few tens of meters of the subsoil structure. As it can be imagined, this technique might result in a small revolution in geophysical investigations of shallow geology. Differently from the standard active source method, it allows obtaining images of the subsoil mechanical properties and the possibility of continuously monitoring also at sensible site like landslides and megacities.
A crucial point of ANT applications is that a large number of stations to be deployed in the field is required. This opens some main issues: (1) the costs of the standard seismological equipment to be used would be very high; (2) the dimension, weight and function of the

standard seismological equipment make it not suitable for this kind of experiment; and (3) the analysis of data is generally performed only in a post-survey timeframe, which represents a severe drawback for some applications, as for example the landslides monitoring and early warning. For these reasons it is necessary that the equipment (i.e. hardware and software) we can dedicate to this kind of experiment is at the same level of excellence as the methodology we proposed.

Therefore, during the project, it will be necessary to develop and tests ad-hoc equipment. For this purpose, we can take advantage of the experience gained in building up wireless sensing instruments for the SOSEWIN Early Warning System for Istanbul, Turkey (Fleming et al., 2009), which have been developed by the Helmholtz-Zentrum Potsdam GFZ German Research Centre for Geosciences and Humboldt University of Berlin (HUB) within the framework of the European projects Seismic eArly warning For EuRope (SAFER, http://www.saferproject.net) and Earthquake Disaster Information systems for the Marmara Sea region, Turkey (EDIM, http://www.cedim.de/EDIM.php).

In the surroundings of construction sites or other industry, non-synchronized sources like vibrations of machinery may be used for imaging. Indeed they have to be used because dominant stationary sources destroy the random character of the ambient noise and hinder the use for ambient noise tomography. Seismic imaging with the noise of a tunnel boring machine or with drill bit noise are examples of taking advantage of the non-synchronized but known sources (Ashida, 2001). Non-synchronized means here that the source signal is unknown but the position of the source is known. This possibility can be extended by purposeful generating noise. Such an approach was used by Gouédard et al. (2008) for a surface survey. They worked with a continuously recording array and used human steps as non-synchronized sources. These records can be used similarly to the noise records in ANT. From cross-correlation between the signals from two sensors the impulse response can be obtained as if one receiver was a source. The advantage of using the active (non-synchronized) sources compared to ambient noise is the better convergence towards the Green's function since the "noise" can be generated in line of the receiver pair which is preferable for the cross-correlation.

Besides the improvement of the seismic methods a further possibility to improve the subsurface imaging is the combination with other geophysical methods. Irrespective of the kind of geophysical data they all have their common origin in the geological structure under investigation. This allows to couple independent geophysical data via a common subsurface structure and jointly invert and interpret the measurements. Compared to a separate inversion with subsequent common interpretation, the significant advantage is the unique structure that is used to explain the different data sets. It may significantly improve the subsurface image by combining advantages of different methods e.g. abilities of resolve layer properties (seismic surface waves, electrical measurements) or abilities to locate interfaces (seismic reflection or refraction measurements).

Work plan

Activity II will approach the dynamic tomography by augmenting imaging techniques with temporal resolution. The new concept of small scale seismic imaging with noise or non-synchronized sources is advantageous if active sources are prohibitive as in megacities or on landslides or in the presence of strong active non-synchronized sources of vibrations like machinery. The application of this new approach requires new field equipment and new analysis tools that are developed in activity II. It has the following goals:

- The development of wireless 3-component seismic sensors for continuous data acquisition and real-time transmission.
- The development of analysis software for small scale ambient noise tomography of 3-component data.

– The development of a tool for small scale subsurface investigations with seismic waves emitted from non-synchronized sources.
– The integration of an approach for the structurally coupled inversion of seismic surface wave dispersion curves with other geophysical measurements.

Activity II is divided into two work packages. Field instruments will be developed in work package 2.1. that allow real time data transmission of continuous recordings. New approaches of interferometry for better constraining underground models by using Love waves and estimating attenuation will be developed. Repeated imaging will open the possibility to detect temporal changes. In work package 2.2 we will develop a new approach to use seismic interferometry in combination with active non-synchronized sources. This will result in an easy-to-use tool for surface wave analysis of the shallow subsurface. It will be integrated in an algorithm for the structurally coupled inversion with other geophysical methods.

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