Monitoring and Imaging Based on Interferometric Concepts

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MONITORING AND IMAGING BASED ON INTERFEROMETRIC CONCEPTS

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ABSTRACT

Utilization of coherent phase information in complex wave fields forms the basis of interferometric time series analysis. The concept is known since decades, but until about 15 years ago there have been no practical implementations. Meanwhile seismic interferometry is used in a wide range from investigations of the earth's deep crust to engineering applications. Focused on monitoring and imaging the MIIC (Monitoring and Imaging based on Interferometric Concepts) project as part of the German GeoTechnologien program has contributed to this development. Special attention was given to the transfer of methodology to different length scales that range from centimeters, in laboratory applications, over geotechnical scales to even kilometers in seismological applications. General purpose methods and open source software was developed, which can be used on all scales. The core of the MIIC software is a Python library organized in different modules for various processing tasks. A graphical user interface facilitates the creation of processing routines by visualizing connections and dependencies of variables and by checking the consistency of data types. Example applications have included carbon sequestration, salt mine and railroad embankment monitoring as well as imaging changes in concrete constructions.

KEYWORDS : *Ultrasound, Seismics, Interferometry, Monitoring, Tomography*

INTRODUCTION

The detection, localization and interpretation of subtle changes in a medium are central tasks in many scientific and engineering disciplines. The idea of using actively or passively generated elastic waves is quite old. Practical application has until recently limited to time of flight measurements of elastic waves, eventually combined with tomographic approaches or the localization/characterization of seismic/acoustic events. Both approaches have their limitations, e.g. the lack of sensibility to small, continuous changes in the medium.

Utilization of coherent phase information in complex wave fields forms the basis of interferometric time series analysis. The concept is known since decades, but until about 15 years ago there have been no practical implementations. Meanwhile seismic interferometry is used in a wide range from investigations of the earth's deep crust to engineering applications (e.g. [1]). Focused on monitoring and imaging the MIIC (Monitoring and Imaging based on Interferometric Concepts) project as part of the German GeoTechnologien program has contributed to this development. Our Focus was to develop general purpose, open source algorithms and software to foster the application in various disciplines. Special attention was given to the transfer of methodology to different length scales that range from centimeters, in laboratory applications, over geotechnical scales to even kilometers in seismological applications. Another task was to improve the localization capabilities of the algorithms by tomographic concepts.

1 MONITORING AND LOCALIZATION OF CHANGES BASED ON CODA WAVES

1.1 Theory

The theory of coda wave interferometry uses the scattered elastic wave field in a heterogeneous medium to observe the effect of subtle changes in the medium. It was described e. g. by [1]. In connection with passive data it was first used by [2] to obtain a continuous observation in situations without controllable sources like seismology. A strategy to obtain spatial information about changes in the investigated medium was described by [3]. As suggested by [2] the perturbations in the wave field are measured based on the cross-correlation of the recorded time series versus a reference time series, which is compressed or extended in time by a sufficiently small factor ν, corresponding to a relative velocity change:

$$CC(\nu) = \frac{\int_0^T h_i(t \cdot (1-\nu))\, h_o(t)\, dt}{\sqrt{\int_0^T h_i^2(t \cdot (1-\nu))\, dt \int_0^T h_0^2(t)\, dt}} = \max .$$

The highest crosscorrelation value CC marks the average velocity change in the medium. A similar approach based on shifting parts of the reference in time is used by [1].
The first localization approach used in this project is based on sensitivity kernels originally developed by Pacheco and Snieder [4][5]. The kernels include the effect of reflections at an objects boundary. This approach was used to generate the tomography of the concrete specimen shown in section 2.2. Meanwhile a new approach based on energy transfer theory was developed and validated [6]. As it includes the effect of direct waves it leads to better solutions especially in the vicinity of the sensors. This approach was used to calculate the tomographies shown in [10].

1.2 Software

One of the main tasks in MIIC was the development of a general purpose library for interferometric data processing. The algorithms have been implemented in Python, partially based on or inspired by the existing seismological library obspy (www.obspy.org).
The library contains routines for:

- Data import (popular seimic data formats (obspy and many others).
- Preprocessing in time and frequency domain.
- Correlation and deconvolution for Green's function retrieval.
- Reorganization of Green's functions to correlation matrices to detect temporal changes.
- Processing of correlation matrices in time and frequency domain to detect temporal changes.
- Imaging of the spatial distribution of changes.

To simplify the application of these developments a graphical user interface was implemented using the BlockCanvas system (Figure 1). It allows the visual connection between different algorithms and processing steps including the generation of workflows.

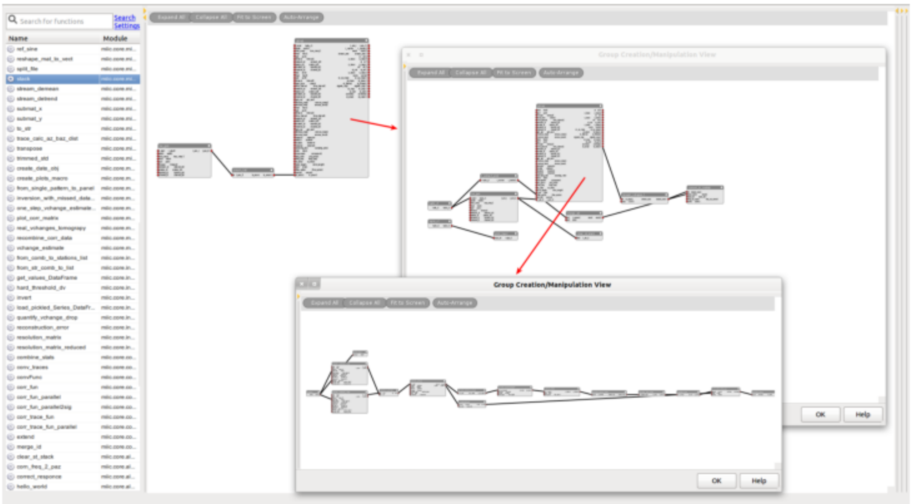

Figure 1: Generation workflows for the MIIC library using the BlockCanvas system.

2 APPLICATIONS IN GEOLOGY AND MINING

The methods and concepts developed in MIIC have been applied to various datasets from geology and mining. Among them are signals acquired at the volcano Piton de la Fournaise [7] and at a major landslide (www.grosshang.de). Two other examples are shortly described below.

2.1 Carbon sequestration

Even if it has lost some impetus recently, the idea of storing CO_2 underground is thought to be one possible solution to reduce global warming. But as for fracturing in the shale gas business there are environmental concerns, especially in the local population at storage sites. West of Berlin a pilot facility is maintained, where among many other issues several geophysical monitoring techniques are evaluated.

Seismic noise has been recorded at various three component surface stations (distance to injection borehole few meters to five km) between 2008 and 2011. The experiments and data evaluation is described in detail in [8]. Using interferometric concepts velocity changes have been determined which are low (>0.5%) but significant and show a one year period (Figure 2). This period can neither be correlated with CO_2 injection activities nor with changes in the activity of the major seismic noise source, a nearby wind park. In contrary, there is a strong correlation with seasonal changes in the water table, which is just a few meters underground in this case.

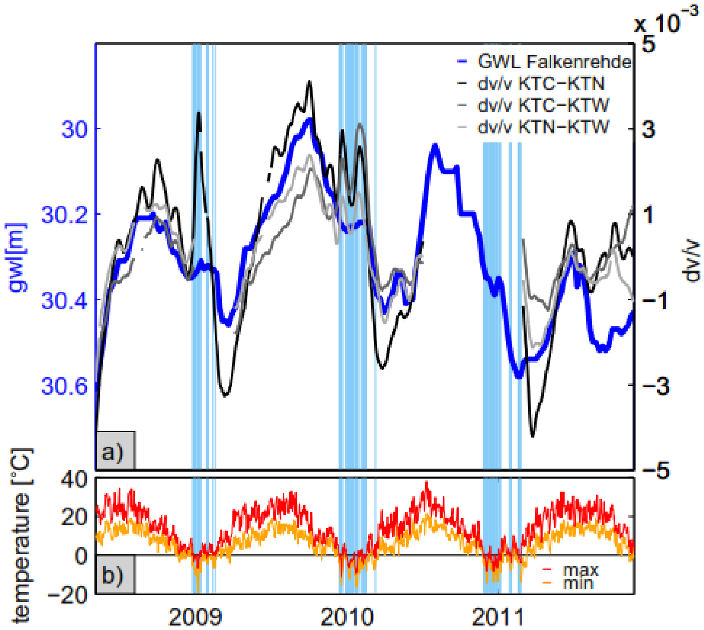

Figure 2: Velocity changes for three station pairs at the CO_2 storage site compared to environmental parameters. The strong correlation with the changes in groundwater level (gw, in blue, axis in m above sea level) is obvious.

To support this interpretation the average velocity changes were calculated using different time window positions, corresponding to different depths. Figure 3 shows, that the velocity changes happen to be dominant in the early (near surface) part of the signals indicating a process at shallow depth as cause of the changes.

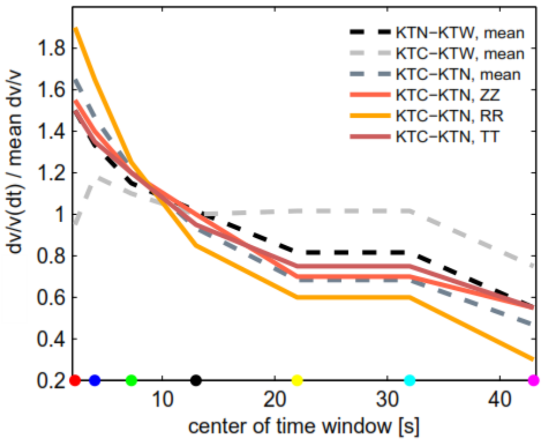

Figure 3: Velocity changes in for various time windows.
Later time windows correspond to larger penetration depths.

2.2 Salt Mine

Active and abandoned mining areas have to be monitored for seismic events and geometrical changes to prevent damage to the mines themselves but also to the population and constructions above. Many mining operations are already using seismic networks. One of them is installed in a

partially active salt mine in central Germany. The acquisition system was modified for the purpose of MIIC to record continuous waveforms. 16 stations (two of them above the surface) have been used. Distance between stations ranges between 0.5 and 8 km.
Figure 4 shows the result for noise correlations between station pairs, separately for different (partly abandoned) areas of the mine. In one part ("Ostfeld", abandoned) the correlation level is significant lower and shows more variation than in others, maybe due to a different geological setting or noise excitation here. The variations in velocity are generally low. Anomalies can be mostly aligned with changes in the instrumentation. There is no obvious correlation with the microseismic activity.

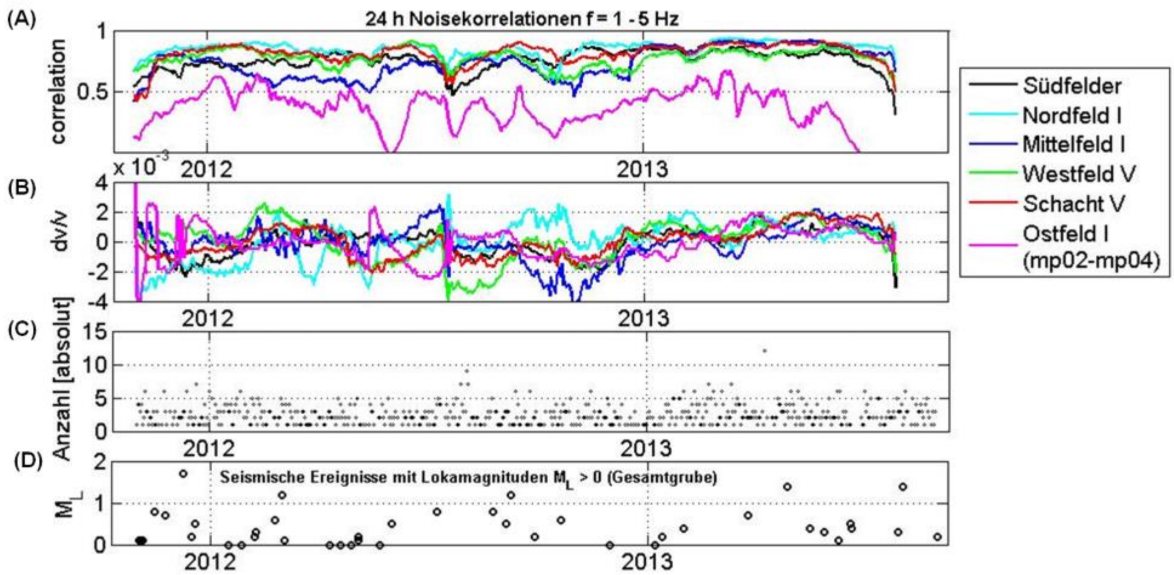

Figure 4: Seismic monitoring results for the salt mine. A) mean correlation between noise records, separately for different parts of the mine, B) corresponding velocity changes. C) microseismic event count (total). D) Magnitude of larger events.

3 APPLICATIONS IN GEOTECHNICAL AND CIVIL ENGINEERING

3.1 Monitoring of a Railway Embankment

A significant amount of Germany's railroad embankments has been constructed on soft layers including peat and/or peat clays and have to be enforced for high-speed trains. These soft sediments often induce dynamic movements to the embankment whenever a train is passing. On a long term the stability might be affected. Formalised in the German industry standard DIN 45672-1, respective tracks are under control and their dynamic stability is quantified by measuring the vibration displacement in particular frequency bands from vibrations excited by passing trains. In addition to these vibration measurements, seismic crosshole investigations are a useful tool to estimate the distribution and extension of soft layers within or underneath the embankment. In the frame of MIIC an embankment in north-eastern Germany was monitored by active and passive seismic experiments. Only the active experiment is described in short in this paper.

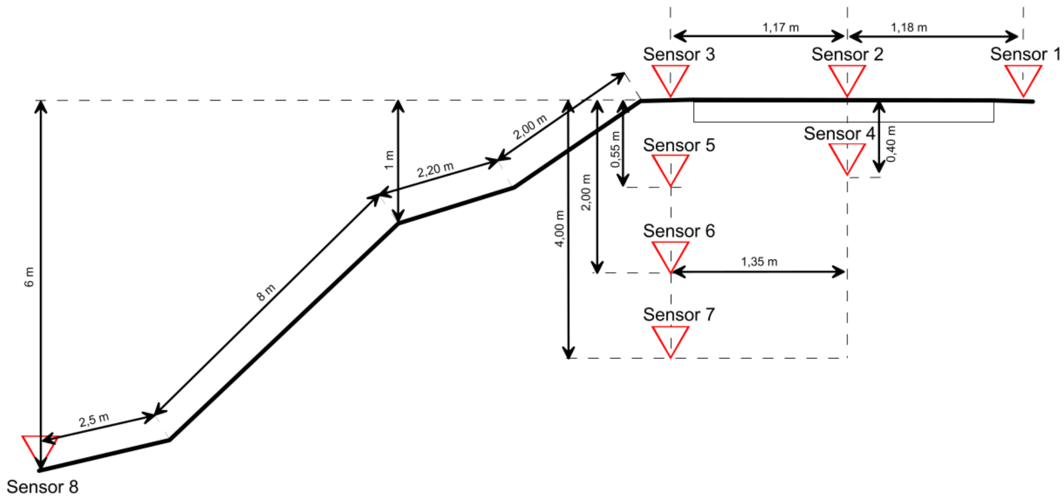

Figure 5: Cross section of the railroad embankment including schematic sensor arrangement (surface and buried). From [9].

A 10 kg drop weight close to sensor 8 (Figure 5) has been used and stacked ten times to generate signals which were recorded for 3.5 s. These signals were generated in 2 min time steps over a period of approximately 15 min. The acquisition started immediately after the train passed. The aim was to monitor the relaxation process of the embankment. Vertically oriented 4.5 Hz geophones have been used as sensors. The application of coda wave interferometry on the actively generated signals yields slight velocity changes (Figure 6) compared to the mean value. Data from the near surface sensor 5 shows a slight velocity drop directly after the train passage. The velocity recovers to its previous level after about 15 minutes. Sensor 7, which is buried 4 m below the track, shows no significant trend. The velocity values are floating with minor variations around the reference level. This kind of experiments, which are much more sensible than traditional seismic time of flight measurements, will be helpful to determine the impact of train vibration in time and space.

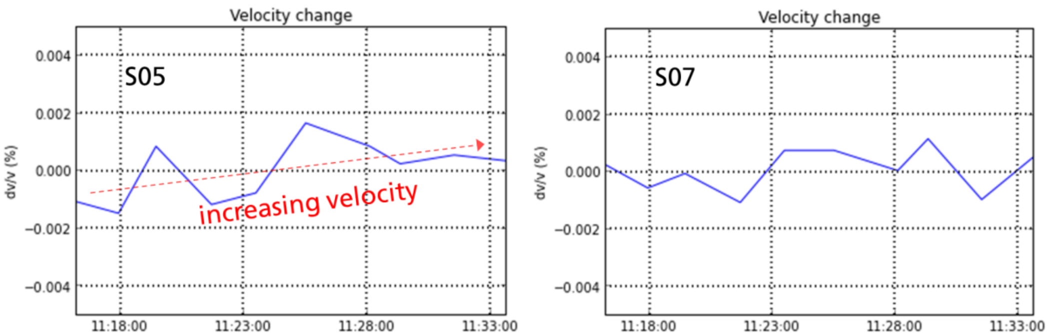

Figure 6: Relative velocity changes after train passage from active experiments and coda wave analysis for a sensors close to the surface (S05, left) and a sensor 4 m below the tracks (S07, right). From [9].

3.2 Concrete Specimen

Concrete is known to be a strong and durable material. However, several degradation mechanisms, triggered by chemical attack and/or physical stress may lead to serious damages to constructions and might endanger the users. Most of the degradation mechanisms start slowly without visible indications. Sensible monitoring methods, which are not limited to the specific location of the

sensors, would be of great value. The topic and experiments in the frame of MIIC are described in more detail in[10] in the same volume.
Figure 7 shows the result of an experiment which was done to validate the localization algorithms described in section 1.1. It resembles a similar setup used earlier by Larose et al. **Error! Reference source not found.**. A few ultrasonic sensors, which can be used as transmitters as well as receivers, were placed on the upper surface of a homogeneous concrete block (size 1×1×0.25 m³) without reinforcement. Signals for all possible transmitter and receiver combinations were recorded. A small vertical borehole vertical was drilled from the lower surface and the ultrasonic experiment was repeated. Figure 7 displays the decorrelation values imaged in the concrete specimen using the methods described in section 1.1. Taking into account the low number of sensors the borehole was mapped with a sufficient accuracy.

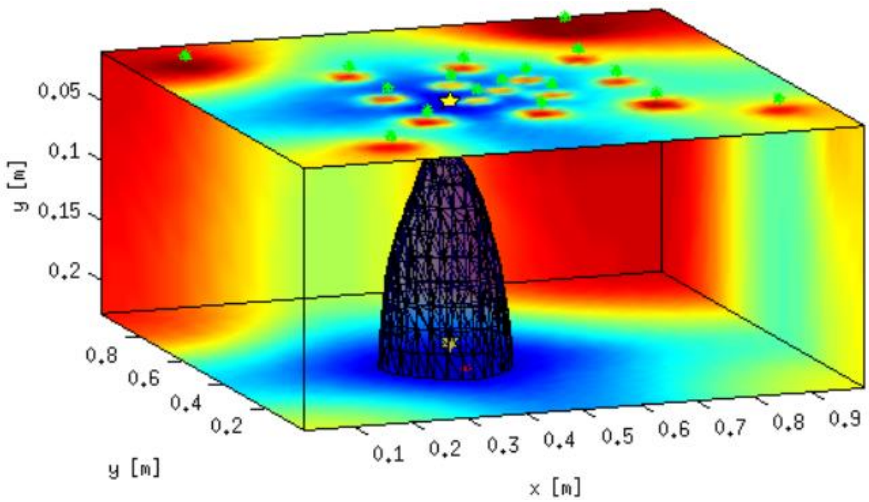

Figure 7: Imaging defect localizations in a concrete specimen. Red: low damage probability, blue: high damage probability. Yellow star: Estimated point of defect and its projection to the upper surface. Red point: true position of borehole. Green triangles/stars: sensors on upper surface.

CONCLUSION

In the frame of MIIC various algorithms for interferometric processing of seismic and ultrasonic date have been developed. They were proved to be valuable for various applications independent of scale. The results have been demonstrated at various test sites, ranging from a volcano to concrete specimen. Parts of the software are currently used in continuing the monitoring of the salt mine and more practical oriented experiments on concrete constructions. While the BlockCanvas user interface was useful in the design phase of experiments and processing schemes it was discarded for most practical applications to allow the integration of interferometric processing into existing systems.

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