3D acoustic and microseismic location of collapse events in complex, 3D geological structures

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3D Acoustic and Microseismic Location of Collapse Events in Complex, 3D Geological Structures

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Passive microseismics is a well developed technique that has gained importance in petroleum exploration operations as well as in geohazard assessment. When applied in complex geological environments, it requires advanced processing capabilities to ensure useful accuracy in the source location and characterization.
Here we investigate a fast marching method to determine the travel-time field, rays and ray take-off angles in complex 3D media, for application with a direct-search event location method. We then illustrate and discuss the potential of the chosen methodology in the mining context. This methodology allows improvements in acoustic monitoring of large-scale underground mines by taking into account the intrinsic characteristics of propagation of the acoustic waves. Ongoing work on a dataset collected during the monitoring of a large-scale salt cavern collapse is also discussed. We expect that the use of an evolving 3D model will help to reduce the location errors and improve the dataset analysis, improving risk management for time-varying collapse events.

Introduction

Passive microseismics is a well developed technique that has been widely used since the 1970s and 1980s in active underground mines to monitor stress changes around the workings and in geothermal fields to image fracture networks activated during production and injection. In addition, application of this technique to petroleum characterization has been increasing in the past decade following its successful use on the Barnett Shale in the Fort Worth basin, Texas (Maxwell et al., 2010). Real-time microseismic monitoring and more recently acoustic monitoring of underground silent voids is also often included in early-warning systems dealing with geohazards (Contrucci et al., 2010a; Nadim et al., 2010).

Event location is of primary importance to accurately identify the zones of rupture and determine source characteristics such as magnitude or moment tensor. For a mine geometry, this location requires taking into account complex velocity models with direct-search event location methods. For the case of acoustic monitoring it can be assumed that the acoustic waves do not transmit through the host rock, so their propagation is governed by reflection and diffraction at the cavity boundaries. This leads to a complex travel-time field that can be modelled based on the same algorithms as those used currently in microseismics.

In this extended abstract we first present a fast marching method to determine the travel-time field, rays and ray take-off angles in complex 3D media, for application with direct-search event location methods. We then present a series of examples to illustrate the potential of the chosen methodology using a 2D model based on the geometry of an abandoned salt mine instrumented with dual microseismic – acoustic stations. Finally, we discuss further applications on 3D complex structures.

Event location in 3D complex media with a few numbers of sensors

Among the three basic classes of methods to calculate travel-times and rays (full-waveform methods, ray methods, and eikonal and shortest-path, graph-based methods), the eikonal fast-marching method (FMM) is one of the most efficient and stable when considering complicated 3D velocity structures. FMM solves the wavefront propagation problem through numerical solution of the eikonal equation for ray propagation, with repeated application of Huygen's principle while taking into account causality - that is to say that information only flows forward in time (Sethian, 1999). This condition makes the method unconditionally stable in the presence of shadow zones, diffractions and caustics, and also makes it applicable to 2D and 3D regular and irregular grids.

In addition to the generation of the travel-times from one point in a gridded velocity model to all others points in the model, FMM also permits the calculation of ray-paths and take-off angles through post-processing of the travel-time field using finite-differences to follow the local time gradient back from the receiver to the source. This is of great importance for improving microseismic locations when using only a small numbers of sensors. Take-off angles measured at a 3D receiver are useful to constraint direct search event location method, especially in limited-aperture situations like borehole monitoring.

Application to the case of an abandoned salt mine

An abandoned room and pillar salt mine located below an urbanized area has been instrumented in 2005 by INERIS (Nadim et al., 2010). The mine can approximately be circumscribed into a 300 meters * 350 meters area with regular and large galleries (~17 meters wide and 6 meters high), with an approximated total of 360 pillars (~15 meters large * 15meters wide) cut by around 20 km of cumulated intersecting galleries and an extraction ratio close to 75%.

Three dual acoustic-microseismic stations have been set up in different locations with the aim of detecting precursory signals of fracturing that may lead to a roof collapse process. Each station is composed of a highly sensitive microphone installed in a gallery and of a geophone clamped above in the solid part of the roof, both sensors being equipped with built-in amplifiers. The objective of the monitoring system is to alert if a significant event occurs between two inspection visits, triggering then an extra inspection.

To analyze acoustic wave propagation and assess the resolution of FMM along with the Oct-Tree direct-search location method (Lomax and Curtis, 2001) in the context of the abandoned salt mine, we consider various virtual geometries of sensors and collapse events.

First we consider an ideal situation with a dense and regular receiver distribution (acoustic sensors are placed at every second gallery intersection). In Figure 1 (left), the reverse travel-time field is computed for a receiver in the third gallery from the West and first gallery from the South; the acoustic travel-time field is constrained to not transmit into the host rock (pillars). It shows that the travel-time field is almost circular, due to the regular geometry of the mine and large proportion of void space however, the diffractions around the pillars are visible as cusps and perturbations in the travel-time field (Figure1-Left).

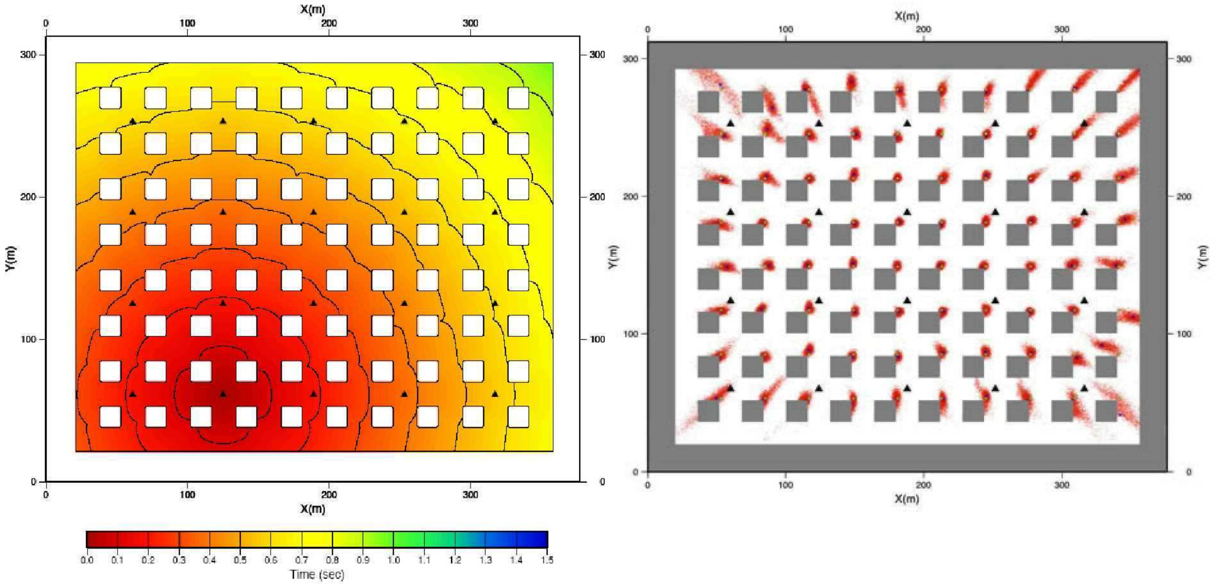

Figure 1. *Left) Travel-time field computed when considering a receiver placed in the third gallery starting from the West and first gallery from the South. Right) Location of events throughout the site obtained using the ideal array geometry. Stations are represented by black triangles, true and calculated locations are represented respectively by green and blue symbols; the location pdf is shown in red (red cloud of points).*

Then, given this ideal geometry and synthetic arrival-times with 0.01s noise corresponding to events throughout the site, we observe a good ability to relocate correctly the synthetic events: stations are available at a wide range of distances and directions enabling good constraint on the location (Figure1-Right). At the boundaries of the site the *pdf* locations can be elongated or irregular, with some significant mislocations, due to the absence of stations outside of the modeled area and consequent poor station coverage.

In general, within the station network the maximum likelihood hypocenter is very close to the theoretical hypocenter almost every time, with close coincidence near the centre of the network.

Practically, for costs and technical reasons, monitoring devices often comprise only a few numbers of receivers, sometimes positioned far away from the area of interest due to difficult access conditions. Thus the receiver distribution is often very poor.

When relocating a theoretical event while considering a poor receiver distribution with few stations near the source, the location *pdf* increases in volume (Figure 2-left). Besides, a discrepancy in the relocation is observed: the event is located in a gallery intersection adjacent to the intersection where the theoretical event was placed.

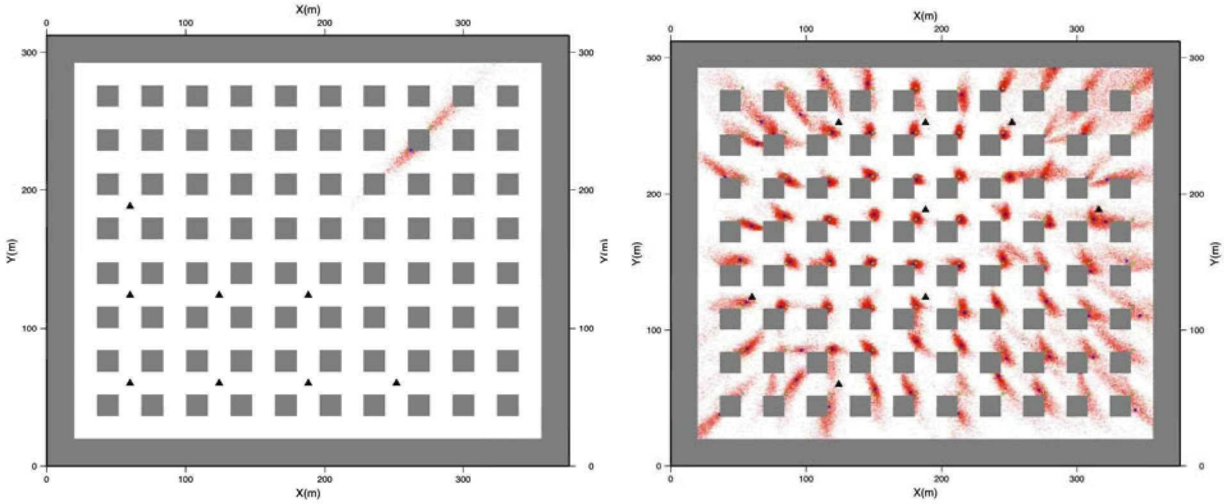

__Figure 2.__ Left) Location of an event occurring in the upper right corner of the site obtained using a poor receiver distribution. Right) Several locations using a dispersed and irregular receiver distribution. Stations are represented by black triangles, true and calculated locations are represented respectively by green and blue symbols; the location pdf is shown in red (red cloud of points).

When considering few stations irregularly dispersed across the site (Figure 2-Right), the *pdf* locations remain quite well constrained in areas surrounded by receivers, thanks to the aperture of the available stations. The *pdf*s increase in volume and become more complex for events occurring outside of the network (southeast corner for example) indicating low confidence in event location: in some configurations, it becomes difficult to locate the source at the scale of the mine quarter.

Further application: the monitoring of a large-scale cavern collapse

Between 2005 and 2009, a solution mine was instrumented in order to monitor a large-scale cavern collapse (see Figure 3 and Contrucci et al., 2010b for full detail). It allowed the recording of the unique microseismic database comprising more than 60 000 events, including 30 000 events during the last three days preceding the collapse.

Until now, a 1D velocity model was used to process the data and locate the events. This velocity model was estimated using a series of calibration shots made on the surface at the beginning of the experiment in 2005. For computational convenience, the model was taken as fixed during the whole experiment.

The geology of the site however considerably evolved along with the cavern extension, leading to a for more complex velocity model. First, massive roof falls occurred due to the failure of the indurated anhydrites overlying the salt layer allowing vertical propagation of cavern dome the towards the surface. Second, the rupture of a massive and competent bed of dolomite overlying the cavern at ~120 meters depth led 24 hours later to the general collapse of the overburden (Contrucci et al., 2010b).

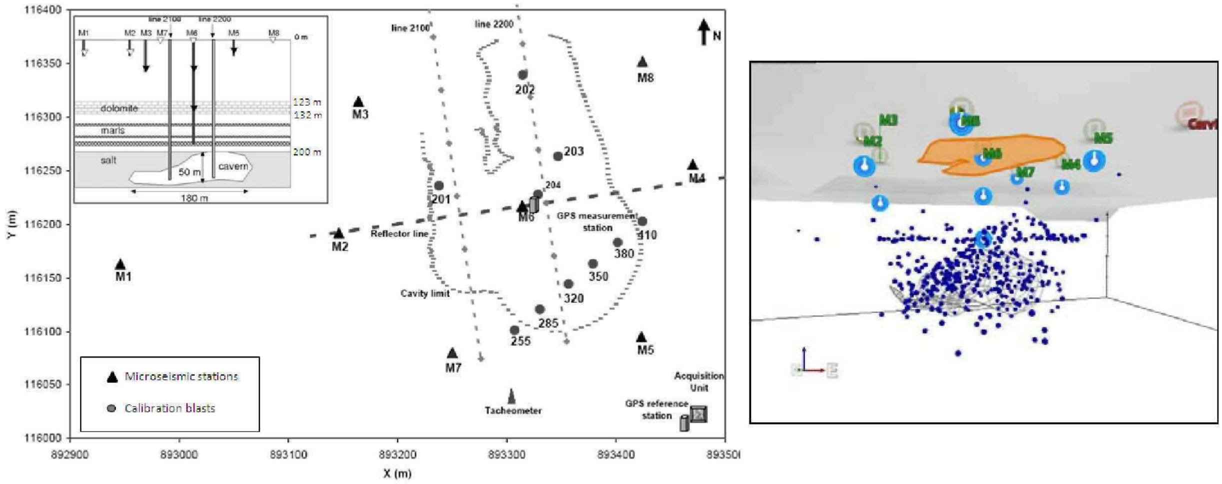

__Figure 3.__ Left) Location of the multi-parameter monitoring network and simplified E-W geological section showing the position of the 3D microseismic probes (black symbols) and 1D (unfilled symbols) with depth. Right) 3D view of the microseismic events location a few days before the collapse.

The fixed velocity model assumption undoubtedly leads to strong location errors, especially during the last days of the experiment. Also, it almost prohibits the use of S-arrivals in the location process, since the computed travel-time field does not take into the increasing volume of brine in the cavern which clearly affects S-wave propagation.

Thus the possibility of using an evolving, 3D model would help to reduce the location errors and improve the analysis

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