CAMI-AFT : a scientific field experiment to calibrate real-time monitoring systems dedicated to the management of post-mining risks

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CAMI-AFT: A SCIENTIFIC FIELD EXPERIMENT TO CALIBRATE REAL-TIME MONITORING SYSTEMS DEDICATED TO THE MANAGEMENT OF POST-MINING RISKS

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ABSTRACT: *The CAMI-AFT experiment was performed to calibrate the physical parameters of real time microseismic systems installed at sites affected by post-mining instabilities, in the Lorraine iron basin (France) and to improve the processing tools as well as the data analyses. Blasts in the mine bottom, with known locations and energy release, were carried out at 6 instrumented sites. The recorded seismograms were used to test and calibrate numerical procedures to determine signal polarization - azimuth and incidence angle - by wave rotation methods. The data were also used to determine a multi-layered velocity model of the geological cover from a global inversion of P-wave arrival times. The performance of the 3D location program was tested by relocating the blasts using wave arrival times and polarisation angles in the determined, multi-layered velocity model. The data analysis for each site allowed the definition of an empirical law relating the source energy to the sensor energy.*

KEYWORDS: *Microseismic monitoring, Post-mining risks.*

RESUME : *les objectifs de l'expérimentation CAMI-AFT étaient de caler les paramètres physiques des dispositifs de télésurveillance microsismique en temps réel déployés sur des zones à risque d'instabilité post-minière du bassin ferrifère Lorrain (France) et d'améliorer les outils numériques utilisés pour l'analyse des données microsismiques enregistrées. Des tirs d'explosifs en fond de mine, parfaitement connus en termes de localisation et d'énergie à la source, ont ainsi été réalisés sur 6 sites instrumentés. L'analyse des sismogrammes enregistrés a permis de tester et calibrer la procédure d'analyse des angles de polarisation des signaux - azimut et pendage des rais incidents - par la méthode de rotation d'onde. Les données microsismiques ont été également utilisées pour caler un model de vitesse multi-couches du recouvrement géologique, à partir d'une méthode inversion globale des temps d'arrivée des ondes P. L'efficacité du programme de localisation 3D a été testée pour retrouver la position des tirs à partir des temps d'arrivée des ondes et des angles de polarisation, mais aussi, grâce à l'utilisation d'un model de vitesse multi-couches. L'analyse des sismogrammes enregistrés a permis également de définir, pour chaque site, une loi empirique permettant d'estimer l'énergie à la source à partir de l'énergie au capteur.*

MOTS-CLEFS : *Surveillance microsismique, Risques après-mine.*

1. Introduction

INERIS has deployed more than 30 microseismic real-time monitoring networks covering the most hazardous areas of the Lorraine iron-basin region of Eastern France (Figure 1-a). In this region decades of iron ore mining have left extensive underground cavities beneath or in the vicinity of urban areas. To ensure public safety, INERIS has developed, tested and validated a microseismic monitoring technique as a volumetric method for detecting underground microseismic activity that may occur before a collapse (Bennani et al., 2004 ; Couffin et al., 2003 ; Senfaute et al., 2000).

This monitoring method was deployed after the major collapse in 1996 at Auboué located in the Lorraine iron-basin region. Since then, no major collapse has occurred in any of the monitored areas. Though most of the monitored sites show little microseismic activity, small microseismic events are recorded and form a background, underground noise level. Usually recorded by single 3D probes, the associated seismograms show very low amplitude (~10^{-6}mm/s), corresponding roughly to negative magnitudes for sources at the mine level. The small size of the events and recording on single probes causes difficulties for reliable automatic analysis, especially source location, a fundamental parameter for any appropriate analysis and understanding of stability analysis (Driad et al., 2005).

In this context a specific experiment, named CAMI-AFT, was initiated in 2005 for six instrumented zones. The experiment consisted of sequences of small blasts in underground mine pillars accurately controlled in terms of location, orientation and energy of the explosive source. This unique database of underground events was then used to calibrate procedures to estimate the 3D hypocenter location and the source energy.

This paper describes the design of the field experiment and the main characteristics of the induced events, as well as the method used to process and analyse the recorded data. Preliminary scientific results are then presented and discussed.

2. Experiment design

The field experiment was performed between October 2005 and May 2006. A total of 70 blasts were shot, with explosive mass ranging from 0.5 to 12 kg (see Table 1 for details, Figure 1-a), leading to more than 1200 high quality seismograms.

Small isolated dynamite blasts were shot in mine pillars located at a depth ranging from 50 m down to 250 m depending on the site. Each site is monitored by microseismic stations (Figure 1-b), which are composed by a 1D surface probe, a 1D probe located at ~15 m depth, and a 3D probe located at ~ 50 m depth (Figure 2). To produce a relevant microseismic database, location, size, orientation and energy of the explosive sources had to satisfy mainly three requirements, which are :

- source locations must ensure the best possible coverage in terms of offset and azimuth and dip angles of the incident microseismic signals, taking into account constraints related to accessibility and safety.
- the size and energy of the explosive sources were chosen, based on empirically predicted amplitudes, in order to optimise signal-to-noise ratio to get usable waveforms while avoiding saturation.
- all stations of a same site had to be triggered.

Specific local source patterns (for example: successive blasts of varying energy or orientation in a same pillar; blasts in upper and lower excavated layers in case of superposed layers etc.) were also designed to study source effects and test capabilities of numerical routines to discriminate and quantify them.

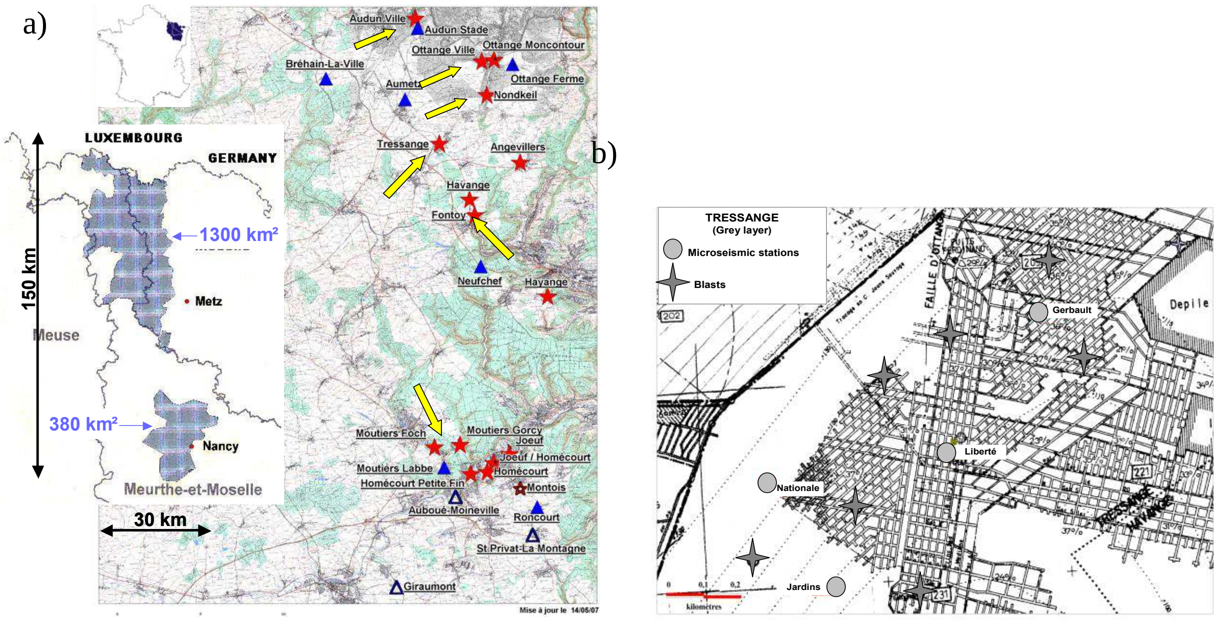

Figure 1: a) general location map of the CAMI-AFT experiment sites. b) mining map of the Tressange site. Grey spots represent the microseismic stations. Dark crosses represent the blasts.

Table 1: Basic parameters of CAMI-AFT experiment layout.

Site	Number of blasts	Mass of explosives	Number of seismograms
Fontoy	13	3.0kg – 12.0kg	130
Tressange	13	2.0kg – 5.0kg	260
Audun-le-Tiche	11	2.0kg – 9.0kg	165
Nondkeil	10	0.5kg – 2.0kg	140
Ottange	18	2.0kg – 10.0kg	468
Moutiers	5	1.0kg – 5.0kg	115
TOTAL	**70**	**0.5kg – 12.0kg**	**1278**

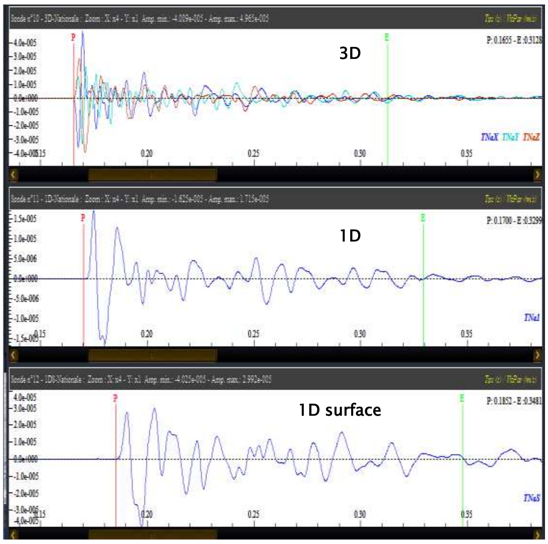

Figure 2: Seismograms of a blast recorded by a microseismic station of the Tressange network (amplitude in mm/s versus time in s). The 3D probe is the deepest one; the 1D surface probe is the shallowest one.

3. Data analysis

The data analysis of the 3D seismograms strategy is the following :

- systematic analysis of all seismograms per site and microseismic station in terms of amplitude and energy is undertaken in order to assess data quality;
- polarization analysis to check consistency between measured incident angles and expected values. These values are of the utmost importance, given their role in source location when dealing with a very limited number of P or S-wave arrival times;
- velocity model determination by minimizing errors on estimated P and S wave travel times using a global inversion;
- automatic location procedure, based on numerical inversion of P and S wave arrival times, incident angles and an appropriate velocity model, is tested for performance assessment.
- empirical determination of a source energy, depending from the source-to-sensor distance and sensor energy. This work has already been presented in a previous paper (Tastet et al., 2007); for further details about the method, please refer to this paper.

3.1. Wave polarisation analysis

The polarisation analysis consists in the calculation of incident P-wave angles (azimuth and incident angles) giving the direction of propagation at the 3D sensor (Figure 4-a). The computation was performed assuming a homogeneous medium with straight ray paths between blast source and oriented 3D microseismic probes. This information, when obtained through careful polarization analysis of 3D seismograms, represents a unique means of constraining an ill-conditioned 3D localization problem due to the lack of P or S arrival times or other a priori information.

The polarization formulation currently used (Dodo Amadou, 1998; Abdul-Wahed et al., 2001) was improved by introducing automatically calculated quality and uncertainty factors to assess reliability of the numerical analysis, such as rectilinearity and polarization index functions (Tarantola and Valette, 1982; Lomax 2005).

For most of the stations, calculated and measured azimuth and incidence angles show a very good agreement. The average azimuth error is found to be less than ± 5° with no bias, except for sub-vertical ray paths for which sensitivity to azimuth errors is numerically expected. The average error on the measured incidence angles is found to have a bias of 7° deeper inclination, most likely due to the straight ray paths assumption. A multi-layered velocity model could probably correct this bias, at least partially.

The good quality of these results can be attributed to (1) all 3D microseismic probes are fully grouted 50 to 70 m deep avoiding most of the perturbations introduced on primary front waves by free surface effects or tube waves from boreholes; (2) geological overburden, although clearly stratified sub-horizontally, remains globally homogeneous when considering seismic wave length and short distances of propagation.

Note that for a few 3D microseismic stations, calculated and measured azimuth angles showed an important bias most likely corresponding to an error of measurement during the grouting of the buried probe (Figure 4-b). In that case, the apparent bias may be introduced as a definitive correction factor.

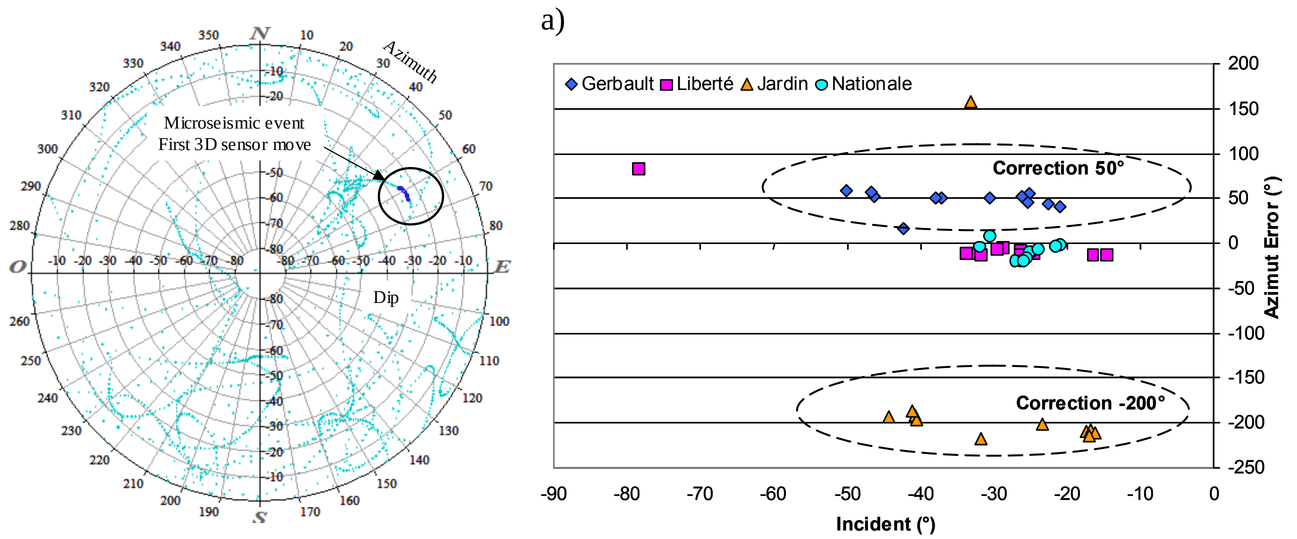

Figure 4: a) stereographic representation of azimuth and incidence angles for one 3D probe. b) Plotting azimuth errors versus incidence angles for 4 microseismic stations, Gerbault station show a systematic bias of ~ 50° and Jardin station a systematic biais of ~–200°.

3.2. Optimisation of velocity models

A specific routine was developed in order to invert measured arrival times, through an inclined multi-layered velocity model, from well-known hypocenter coordinates to well-known station coordinates (Contrucci et al., 2007). Monte-Carlo simulations were then performed, resulting in distribution of solutions per velocity class, for each layer (Figure 5).

For a numerical, multi-layered, inclined velocity model in such a sedimentary geological context is to improve the accuracy of hypocenter determination, requires comprehensive knowledge of the lithology. In the case of the CAMI-AFT field experiment, detailed geological description was largely available in many mining data files.

Table 3 shows the best average values obtained for the Tressange site. Velocities are found to be consistent and in good agreement with other sites located in the same geological context. Although the velocity model inversion has not been run on all sites, intermediate results obtained show that, low contrast is found between the different geological strata, except for the altered surface layer, which is poorly constraint numerically.

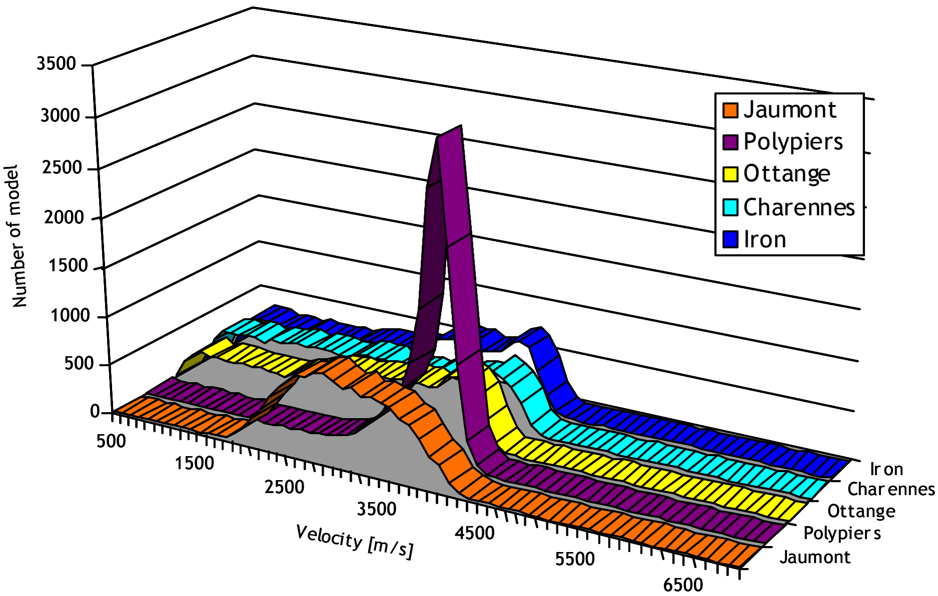

Figure 5 : distribution of solutions per velocity class for each layer of the Tressange Site.

Table 3: P-wave velocities and standard deviation (m/s) obtained for each layers of the Tressange site.

	Jaumont limestone	Polypiers limestone	Ottange limestone	Charennes marl	Iron formation
V_P [m/s]	2780	3560	3250	3230	3500
Std-Dev [m/s]	550	290	950	1020	1060
Layer thickness [m]	14	85	54	28	-

3.3. Source localization

Most of the microseismic events recorded by the Lorraine monitoring systems are usually detected by only one single 3D station. This configuration, one 3D station and only P-wave arrivals, is unfortunately inefficient to locate microseismic event, except if the microseismic event is supposed to come from the mine works, which is a strong hypothesis. To circumvent this problem, a new algorithm was developed, which integrate polarization parameters (incident and dip angle), in addition to the P and S waves arrival times. Tests were performed to check the robustness and the capacities of this algorithm to locate a microseismic event with a few numbers of stations. Multi-layered velocity models were, as well, integrated into the location procedures (Figures 6 and 7).

The available microseismic data for the blasts, where the locations are known, were used to test the precision of the new localization algorithm. An absolute localization was performed on the Tressange site, using a numerical homogenous velocity field and P-wave arrival times and the incident and dip angles, recorded by 4 stations at the same time. The results showed an estimated hypocentral error in XYZ is ~ 70 m (Figure 6). Using a multi-layered velocity model the location error is improved of about 20 % (Figure 7). Indeed, a multi-layered velocity model takes into account the real ray path, reducing localization errors.

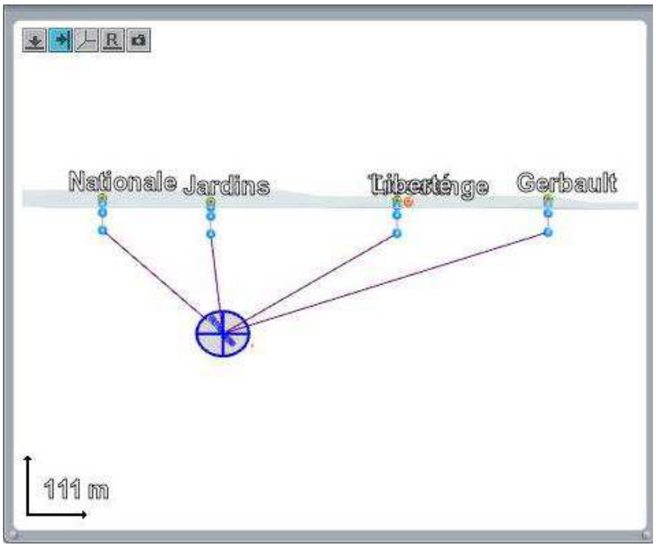

Figure 6 : localization using an homogenous velocity model, example of the Tressange network.

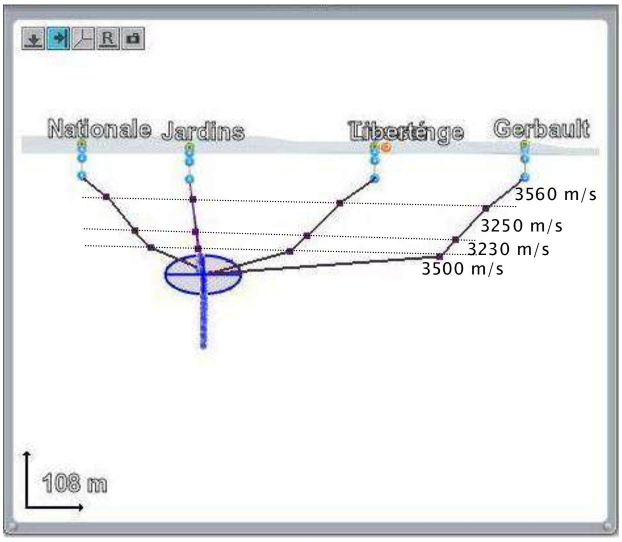

Figure 7: Localisation using a multi-layered velocity model, example of the Tressange network.

4. Conclusions

This experimentation contributes to quantifying the sensitivity of the monitoring systems as well as to improving and validating the processing tools. The results benefit from the referenced database composed of the 1200 "induced-blast" seismograms. The CAMI-AFT data processing allows to : (1) validate the polarization analysis tool ; (2) calculate P-waves velocity models of each site ; (3) validate the 3D localization approach ; (4) construct an empirical source energy law from the sensor energy for each experimental site (see Tastet et al. 2007 for details).

The final objective of this experiment is to improve the quality and reliability of the operational real-time monitoring of the French National Monitoring Centre for Ground and Underground Risks (CENARIS) of INERIS. The developed tools will improve and generalize the operational procedures for the characterisation of post-mining instabilities events. Furthermore, the developments will improve decision-making aid for crisis management.

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