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ADVANCES IN DEVELOPMENT OF GEOPHYSICAL SEISMIC AND NON-SEISMIC TECHNIQUES FOR CTBT ON-SITE INSPECTION

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ABSTRACT

On-site inspection (OSI) is the final verification measure of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). According to paragraphs 69(e), 69(f) and 69(g) of Part II of the Protocol to the CTBT, an OSI may involve the following seismic and non-seismic geophysical techniques to search for, locate and characterize underground anomalies associated with a nuclear explosion: passive seismological monitoring for aftershocks; resonance seismometry and active seismic surveys; magnetic and gravitational field mapping; ground penetrating radar; and electrical conductivity measurements.

In preparation of the CTBT's entry into force, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is actively developing OSI capabilities. Most recent advances in passive seismological monitoring include upgrade of the telemetry system for data transmission and development of the data processing software to accommodate topographically challenging environments. To assess current OSI geophysical imaging capabilities for the other geophysical techniques and for deep site characterization applications in an integrated manner, an extensive field test was conducted in September 2022 in the Austrian Ybbstaler Alps in a topographically challenging environment. Resonance seismometry and active seismic surveys, magnetic and gravitational field mapping, as well as electrical conductivity measurements were performed along three profiles over a cave system at 40-350 m depth mimicking underground cavities produced by an underground nuclear explosion. This was the first field test of a newly acquired active seismic data recording system, with the aim of developing OSI methods for active seismic surveys. Out of all geophysical techniques, active seismic surveys have the potential of providing the highest resolution for deeper site characterization.

Other recent advances include the development of forward models to characterize the magnetic anomalies created by complex geometric bodies simulating different OSI-relevant observables. As a follow-up of this project, a series of multi-level magnetic surveys (ground, near surface and airborne) were conducted in central Italy to further develop magnetic field mapping workflow in an OSI.

We present these recent advances in development of the CTBT OSI regime for geophysical techniques, with specific focus on aspects that are also applicable in the wider context, for example for site characterization of potential nuclear waste repository sites.

INTRODUCTION

Upon entry into force of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) [REFERENCE 1], an on-site inspection (OSI)—the final verification measure of the CTBT—may be launched with a request from a State Party to the CTBT based on a suspicious event detected by the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) or on data generated through national technical means. The purpose of an OSI is to clarify whether a nuclear weapon test explosion or any other nuclear explosion has been carried out in violation of the CTBT and, to the extent possible, to gather any facts which might assist in identifying any possible violator. According to paragraphs 69(e), 69(f) and 69(g) of Part II of the Protocol to the CTBT, the inspection team may during an OSI use the following geophysical techniques to search for, locate and characterize underground anomalies associated with a nuclear explosion:

- ✓ Passive seismological monitoring (PSM)
- ✓ Resonance seismometry surveys (RES)
- ✓ Active seismic surveys (ACT)
- ✓ Magnetic field mapping (MAG)
- ✓ Gravitational field mapping (GRV)
- ✓ Ground penetrating radar (GPR)
- ✓ Electrical conductivity measurements (ECM)

Technical development of PSM for OSIs aims to establish capabilities required to detect aftershocks of suspected nuclear explosions in order to localize the search area and facilitate determination of the nature of these events in accordance with the provisions of the CTBT. The development of PSM capabilities for OSI was first addressed in 1997, during the first OSI Workshop [REFERENCE 2]. This shows the relatively long history of technical development of PSM by the Provisional Technical Secretariat (PTS) of the CTBTO. The historical development of the rest of the geophysical techniques for OSI purposes started and up until recently focused on the detection of shallow observables (within the uppermost 20-30 meters) by using relatively simple equipment and conducting geophysical activities on areas with a gentle topography. In the past few years, the PTS has also conducted field tests of geophysical techniques for the detection of OSI-relevant deeper observables, but always on a relatively flat terrain and primarily using instrumentation rented from external contractors [REFERENCE 3]. The success of the geophysical techniques to detect OSI-relevant deeper observables—e.g., cavities, rubble zones, artifacts—depends on many factors that include inter alia the dimensions of the observable, the characteristics of the surrounding geology, the design of the geophysical surveys and the topography.

As a part of the 2022-23 OSI Programme of Work [REFERENCE 4], and as a practical validation of the conclusions from the Expert Meeting and Tabletop Exercise on OSI in a Mountainous Environment conducted by the PTS in June 2022 [REFERENCE 5], the latest OSI development work for the geophysical techniques has focused on building OSI capacity for challenging mountainous environments. In terms of the PSM, the most recent advances include upgrade of the telemetry system for data transmission and development of the PSM data processing software to accommodate topographical variations imposed by mountainous environments. To assess the current geophysical imaging capabilities in mountainous environments for the rest of the geophysical techniques and deeper OSI-relevant observables, the PTS conducted a field test in the Austrian Ybbstaler Alps in September 2022 with observables of OSI interest (cave system) at 40-350 m depth [REFERENCE 6]. The field test was intended to assess and validate the functionality and specifications of hardware, software, and procedures for some of the inspection techniques listed in paragraphs 69(f) and 69(g) of Part II of the Protocol to the CTBT in an integrated manner, namely: RES; ACT; GRV; and electrical resistivity tomography (ERT) and frequency-domain electromagnetics (FDEM), which are subgroups of methods covered under the generic term ECM. Except for a seismic source used for ACT, the field test was fully conducted with equipment owned by the PTS. This field test was the first OSI activity where an ACT data recording system owned and operated by the PTS was deployed. Additionally, a MAG survey was conducted as a trial activity to test the OSI data flow and functionalities within the newly developed Geospatial Information Management system for OSI (GIMO).

Over the past few years, development of airborne MAG for OSIs has been separately addressed in a series of projects. In 2019, a project was launched to document the state-of-the-art of airborne MAG for OSI purposes. The project included a review of hardware and software, a compilation of case studies, analysis of limitations and recommendations on optimal configuration for an OSI airborne MAG platform. In the next stage, forward models were developed to characterize magnetic anomalies created by complex geometric bodies simulating different OSI-relevant observables. Finally, as a follow-up of the desk studies, a series of multi-level magnetic surveys (ground, near surface and airborne) were conducted in central Italy to further develop MAG workflow in an OSI.

RECENT ADVANCES IN THE DEVELOPMENT OF GEOPHYSICAL TECHNIQUES FOR OSI

Recent Advances in Passive Seismological Monitoring (PSM)

The conduct of an underground nuclear explosion may generate a broad range of signatures, e.g., a cavity which is likely to collapse within days after the explosion [REFERENCE 7]. When this collapse happens, the cavity is filled with debris and a rubble-filled chimney is created. The rearrangement of underground rocks to form the chimney and the relaxation of stress within the rock mass surrounding the detonation point will create seismic aftershocks that may be detected using PSM. To detect and locate aftershocks down to magnitude -2, OSI utilizes a mini-array approach with a central three-component (3C) seismometer in the middle and three one-component (1C) satellite elements 100 m away from the central component. 50-75 mini-arrays with a spacing of a couple of kilometres should be sufficient for covering the entire inspection area, with a set maximum size of 1000 km^2 by the CTBT, in order to detect and locate the small aftershock events.

The OSI telemetry system used for data transfer of the PSM data is a private telemetry (LTE) infrastructure provided by Motorola Solutions. The PSM digitizers are connected to the telemetry system with an LTE modem and data sent to the CTBTO application server via a VPN tunnel on the LTE network. The original system was procured in 2017, and now the upgrade involves hardware update with new security features and better cell range.

Earthquake location in the OSI PSM software package is based on the Nanoseismic Suite of Sonicona GbR, Germany. The software uses 1D ray tracing, i.e., event location with an Earth model of flat layers with laterally homogeneous velocities, which is common for most earthquake location programs. The advantage of 1D ray tracing is its simple mathematics. To increase model complexity for mountainous regions (without compromising the computational advantages of 1D modelling) the latest update of the software by Sonicona GbR consisted of inclusion of topography into the 1D layering. This was implemented by extending the uppermost layer to the elevation of the highest station, with the topography for the rest of the stations realized as ‘pseudo boreholes’; building on earlier implementation of subsurface stations. Additionally, the update consisted of a possibility to define a local underground correction for each station which, combined with the ability to handle topography, will help to accommodate some aspects of laterally varying velocities.

Field Test of OSI Geophysical Techniques for Deep Applications in a Mountainous Environment

The field test in the Austrian Ybbstaler Alps was the first OSI field test in a mountainous environment. The OSI relevant observable at the site is a cave system called Bärwies-Eishöhle [REFERENCE 8], mimicking tunnels and underground cavities produced by a nuclear explosion. The cave system has a total mapped length of almost 7 km. It is embedded in the Dachstein limestone and dolomite, with karst voids with a diameter of about 5-15 m at depths of 40-350 m (horizontal floors at about 40, 110 and 330-350 m below the surface).

The RES, ACT, GRV and ECM surveys were conducted in different combinations along three 300-600 m long 2D profiles over the cave system. Profile 1 followed a mountain road, with cave targets at about 40 m and 350 m depths beneath the surface. Profile 2 followed partly road segments, partly ran in the forest to form as straight profile as possible over cave targets at about 40 m depth and the widest cave target at about 330 m depth. Profile 2 had a gap between distances of 178 m and 240 m along the profile because of steep changes in topography. Profile 3 followed an opening in the forest at the western edge of the known cave system. Profile 3 was designed to investigate possible unmapped continuation of the cave system.

It was expected that not all the geophysical techniques would be able to detect and characterize the OSI-relevant observables present in the field test area; however, the overall goal was to identify operational lessons and to test procedures in an integrated manner. During the field test, full OSI data workflow for geophysical techniques was tested using current functionalities within the GIMO. On the first day of field activities, a small-scale MAG survey was used as a trial activity to ensure that GIMO was working properly before starting the data flow processes for the rest of the techniques.

During the field test, a workflow was tested for marking and positioning the survey profiles, with the goal to create consistent procedures across the geophysical techniques and to provide high-accuracy positioning data for needed topography corrections. The RES, ACT and ECM survey locations were positioned using a Leica GS18 survey-grade GNSS RTK rover, with a Leica AR10 multi-purpose GNSS antenna as a GNSS base station to perform the RTK positioning. GRV requires the highest positioning accuracy, especially for the relative elevation changes along the profile. A Leica TRCP1205 motorized auto target total station was used for GRV.

Resonance Seismometry Surveys (RES)

Resonance is a physical phenomenon that can generally be defined as the increase in the amplitude of oscillation in a system exposed to a specific force with frequency equal or very close to the natural frequency of the system. RES may include both active and passive seismic methods to search for, locate and characterize underground anomalies related to a nuclear explosion, including, e.g., cavities and rubble zones [REFERENCE 7].

Active development of RES for OSIs started after the 2014 OSI Integrated Field Exercise (IFE14) [REFERENCE 9]. So far, the work has focused on development of passive RES methods. Recent advances indicate that the phenomenon of seismic resonance in the vicinity of a cavity caused by an underground nuclear explosion may be detected by analyzing spatial distribution of spectral power of the seismic ambient noise [REFERENCE 10]. The size of the area where this signature is detectable could be up to ~1 km around “ground zero”, depending on the depth and size of the cavity. The increase of amplitudes in the close vicinity of the epicenter (≤100 m) is in the frequency range of ~2 to at least 30 Hz. Furthermore, recent results also indicate that regional and teleseismic earthquake data may reveal cavity-related propagation changes by differences in time and amplitude [REFERENCE 11]. Based on these advances, an OSI concept of operations (ConOps) for RES was drafted in 2020 [REFERENCE 12].

RES data were collected as a part of the 2022 field test along profiles 1 and 2 to assess the draft ConOps in a topographically challenging environment. So far, the equipment used for RES has been the same that the PTS operates for PSM. The RES stations consisted of a Lennartz 3C seismometer connected to a Reftek 130 high-resolution digitizer with a global positioning system (GPS) antenna providing timing. The mountainous environment provided an opportunity to learn valuable operational lessons for further development of RES. Data processing and interpretation is currently ongoing, including analysis of ambient noise as well as regional seismic event and teleseismic data, considering the full depth range of cave targets and the effect of topographical variations on the results. The results will be used to further develop the RES ConOps and workflows.

Active Seismic Surveys (ACT)

Out of all the OSI geophysical techniques, ACT methods, in particular seismic reflection surveys, have the potential of providing the highest resolution for deeper site characterization. The data acquisition and processing workflows can be adjusted according to the specific target. The ACT surveys of the field test were conducted using a cable-free light-weight nodal Geospace GSB-3 3C seismic data recording system and 5 Hz 3C geophones procured by the PTS for testing and training purposes in 2022, just before the conduct of the field test. This field test was the first activity where an ACT system owned and operated by the PTS was deployed. The seismic source used for the ACT surveys was an accelerated weight drop (AWD) source with a United Service Alliance AF450 hammer mounted on an IC35 crawler. The source was rented for the conduct of the field test. The source system was equipped with Geospace source decoder recorder (SDRX) which provides GPS time stamps for the sources in a format readily compatible with the Geospace GSB-3 data recording system. For areas with a more difficult access (source points in the forest), a 5 kg sledgehammer source was used together with a Geospace SDRX owned by the PTS.

During the 2022 field test, ACT data were collected along profiles 1 and 2. The ACT surveys were planned primarily considering the deeper cave targets located at about 330-350 m below the surface. The ACT measurements were designed to collect P-wave reflection seismic data; however, the data were also used for P-wave refraction tomography. With the used survey layouts, the depth extent of the refraction tomography results is about 100 m and the depth extent of the reflection seismic sections about 1 km. The challenging terrain limited the location and length of the profiles, and it was not possible to have optimal receiver and source coverage over the targets. During data processing, careful corrections to accommodate for the topographical variations were needed. Generally, caves filled with air can be expected to significantly lower the seismic velocities and acoustic impedances (product of seismic velocity and density), physical properties to which refraction and reflection seismic surveys respond, respectively. However, detection of the targets depends on many factors, e.g., on the surrounding geological and noise conditions, and fundamental resolution limits of the survey design. The initial data processing results indicate attenuation of the reflection amplitudes in the reflection seismic section, and slightly lower seismic velocities associated with the caves in the refraction seismic results. Overall, the field test results will be used to develop OSI workflows and documentation for ACT.

Electrical Conductivity Measurements (ECM)

A range of methods can be applied under the general umbrella of the ECM methods, e.g., electrical resistivity tomography (ERT) and frequency-domain electromagnetics (FDEM) implemented during the field test. Generally, the ECM methods have a long history of OSI development [REFERENCE 3], with already well-established workflows. In the case of ECM, the field test in a mountainous environment provided new operational lessons for further development of the procedures for challenging environments.

ECM/ERT data were collected with ABEM Terrameter LS2 system along profiles 1 and 3, and ECM/FDEM data with IRIS Promis instrument along profile 1. The ECM methods were planned with the shallower cave targets in mind, with the expected depth penetration of the methods within the range of about 50 to 150 m depending on the specific survey layout and data acquisition parameters used on each profile. It should be noted that a cave (high electrical resistivity) within limestone (also high electrical resistivity) is not an optimal target for electrical conductivity measurements, and especially not for the IRIS Promis instrument.

The known cave targets at about 40 m depth are not distinguishable as specific anomalies on the ECM/ERT results of profile 1, however, they are related to a lower-resistivity, fractured bedrock (Dachstein limestone) area at the southern end of the profile. Profile 3 does not cross any known cave targets. However, profile 3 shows high-resistivity areas that are interpreted to be associated with previously unmapped caves (air-filled voids) at about 15-30 m depth. The final inversion results of the ECM/FDEM data show lower-resistivity areas in a higher-resistivity Dachstein limestone. The location of the largest low-resistivity area corresponds to the near-surface low-resistivity area observed on the ECM/ERT results of profile 1 and interpreted as finer weathered sediments.

Gravitational field mapping (GRV)

Prior to the field test, GRV was previously tested during IFE14 [REFERENCE 9]. The GRV measurements were conducted along profile 1 using the CG-5 gravimeter of the PTS. Only the cave tunnels at about 40 m depth beneath profile 1 were considered as targets for GRV. However, detecting the small micro-gravity signal associated with the caves would require a very precise GRV workflow for accurate correction of other factors affecting the measurements, the scale of which may be several orders of magnitude larger than the sought-after anomaly. While detecting the target caves was considered unlikely, the GRV survey was conducted to assess the suitability of the current equipment for micro-gravity surveys, and to make recommendations for the build-up of OSI GRV workflow. The practical goal was to document the GRV survey and consequent data processing to a fine detail to make full use of the lessons learnt in the next steps of the development of GRV for OSI.

Recent Advances in Magnetic Field Mapping (MAG)

Since 2019, development of airborne MAG for OSIs has been separately addressed in a series of projects. These projects have had two major outcomes: MAG portfolio of magnetic signatures created by OSI-relevant observables and the conduct of a series of magnetic surveys at different altitudes (ground, near surface and airborne) over the same area of interest in Fucino Basin in central Italy, with shallow man-made objects (e.g., water wells) that can be used as examples of OSI-relevant observables. Airborne MAG can contribute to the detection of observables related to an underground nuclear explosion, especially when using remotely controlled platforms for the conduct of near-surface surveys. Remotely controlled platforms can fly at low altitudes, with narrow line spacing, following regular grids, using minimal resources, and increasing the probability of detecting relevant observables.

CONCLUSIONS

The OSI PSM mini-array approach has been designed to detect small aftershocks over an area of 1000 km^2. The recent advances in data transfer via new telemetry system and ability to accommodate topographical variations in data processing make the OSI PSM approach more robust to also accommodate challenging environments.

The OSI 2022 field test allowed to collect valuable operational and technical experience on application of the full range of OSI geophysical techniques for deeper site characterization in a challenging mountainous environment. The field test results will be used for further development of the OSI hardware, software, and procedures to accommodate for variable topography conditions. Joint interpretation of the field test results demonstrates the range of subsurface aspects imaged by the different OSI geophysical techniques, namely the RES, ACT, GRV and ECM techniques tested during the field test. Looking at only one dataset might lead to a different interpretation than putting all the evidence together. A rock fall area identified based on a combination of high electrical resistivity, low seismic velocity, and lower-frequency seismic reflection response on profile 1 is a good example of this. It should be emphasized that the inability of some of the methods to produce useful data for the detection of the cave targets (e.g., ECM/FDEM and GRV) is not a failure of the technique but rather an element of the local geology and conditions. This is also to be expected during an OSI that can take place anywhere in the world, and it is the reason why there are many different geophysical techniques designated in the CTBT. The objective is to use methods which are most appropriate for the local field conditions and likely to provide results, the same as for any geophysical application for any purpose.

The recent series of projects to develop OSI airborne MAG approach illustrates the power of forward modeling for understanding the expected signatures and interpreting collected data correctly. Similar forward modeling projects are planned for all OSI geophysical techniques. Furthermore, new remotely controlled platforms offer a means to conduct detailed surveys in a time-efficient manner. OSI will continue to investigate the use remotely controlled platforms for the implementation of the OSI geophysical techniques.

All these recent advances in development of OSI geophysical techniques have a wide range of applications also outside the OSI context and can be used, e.g., for extensive site characterization studies at potential nuclear waste repository sites.

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