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Simulating Aftershocks for an On Site Inspection (OSI) Exercise

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INTRODUCTION

In addition to an international monitoring system (IMS) and an international data center (IDC), on site inspection (OSI) is one of the important verification elements of the Comprehensive Nuclear Test Ban Treaty (CTBT – also referred to here as the Treaty). In November and December of 2014 the OSI Integrated Field Exercise (IFE14), was carried out in Jordan to simulate a CTBT OSI. Included in the exercise were passive seismic methods to detect and locate aftershocks from an explosion. United States and Russian experience with underground nuclear explosion (UNE) testing revealed that, as is the case with earthquakes, aftershocks typically occur following underground nuclear explosions UNEs(Ford and Labak, 2015). The magnitude and number of these aftershocks decay rapidly with time after the detonation; this fact is what drives Treaty requirements for an inspection team (IT) to arrive at the inspection area (IA) as soon as possible in order to possibly detect aftershocks. The reason that aftershock detection is so important is that the IA can be up to 1000 km^2 in size – this presents a challenge to the inspectors who are trying to narrow the scope of the inspection to a much smaller area, on the order of a few km^2.

For IFE14, a Scenario Task Force was formed in order to create and plan a "credible and scientific" noncompliant (a UNE had been carried out) scenario for the exercise. Because a real explosion could not be used for the exercise, aftershocks had to simulated in some way so that the IT could exercise the seismic aftershock measurement system (SAMS). In addition, aftershock simulation was intended also to be used as a way to control the exercise, since detection of aftershocks would help to focus the IT efforts in a particular part of the IA. Two approaches were considered to simulate aftershocks: use of small (10 kg) explosive charges and use of a weight drop apparatus. Both methods were considered and planned, but during the exercise only the explosive charges were used. Three charges were set off during an early part of the exercise at locations within a few kilometers of the simulated ground zero of the explosion that triggered the simulated inspection.

Several difficulties were involved with the use of explosives (in addition to the obvious safety considerations) to simulate aftershocks. Firstly, holes had to be drilled before the start of the exercise for placement of the charges – this meant that their locations were pre-determined as part of the scenario. Secondly, the charges had to be detonated at night, when the IT was not in the field and in a way that the explosions could only be discovered by means of SAMS and only at a time when a SAMS station had been deployed by the IT close enough to detect the (explosive) aftershock. Finally, when the explosive was actually detonated, the IT members of the SAMS analysis team instantly recognized the event as an explosion because the seismic wave arrivals at the seismic array were followed by an easily identified (by its velocity) air wave. In this case, the Control Team for the exercise had to "inject" the information to the IT that the detected explosion was in fact an aftershock, thus diminishing the realism of the exercise.

The experience of IFE14 emphasizes the need for a better way to simulate aftershocks during an OSI exercise. The obvious approach is to develop a digital model of aftershocks that can be used either for a real field exercise or for a computer simulation that can be done in an office, for training for example. However, this approach involves consideration of several aspects, such as how and when to introduce waveforms in a way that maximizes the realism of the data and that will be convincing to a savvy, experienced seismic analyst. The purpose of this report is to outline a plan for how this approach can be implemented.

Simulating Aftershocks – the Phenomenology

The objective for simulating aftershocks for an OSI exercise is to determine, based on credible scientific sources, the rate and magnitude of aftershocks from a hypothetical clandestine underground nuclear explosion that is the triggering event in the exercise scenario. The magnitude (m_b) of the triggering event determines the rate and magnitude of aftershocks from real explosions (Ford and Walter, 2010, and Ford and Labak, 2015); their formalism is can be used to estimate the aftershock characteristics that would be expected from a real event.

The formalism is based on several well-known characteristics of aftershocks:

The Omori Law gives the number of aftershock events per unit time:

$N(t) = Kt^{-p}$, where K and p are constants and t is time in days.

The Gutenberg-Richter relationship gives the number of events at a given magnitude, M:

$N(M) = A*10^{-bM}$, where A and b are constants

Combining these expressions, the aftershock rate equation is obtained:

$L(t,M) = 10^{a+b(Mm-M)}t^{-p}$, where Mm is the magnitude of the main shock and a is related to aftershock productivity:

$a = \log_{10}(K)-b(M_m - M_{min})$, where M_{min} is the magnitude of the aftershock being considered.

From this, we find that $K = 10^{(a+b(Mm - Mmin))}$.

From Ford and Labak (2015) we have the following values for the parameters a, b, and p for different kinds of rock:

model		a	b	P
NTS soft		-4.01	1.36	1.7
NTS hard		-4.05	1.4	1.44
STS hard		-2.39	0.95	1.1

In the above, “NTS soft” refers to alluvium and tuff typical of media where underground nuclear tests were conducted at the former U.S. test site in Nevada. “NTS hard” refers to harder welded tuff typical of media where underground nuclear tests were conducted at the former U.S. test site in Nevada. “STS hard” refers to hard rock of the former Soviet Union test site in Kazakhstan. These are the type of geology units that the aftershock studies are calibrated against.

Based on the table and expressions above, for a given aftershock magnitude (M_{min}) and rock type, we can calculate the number of aftershocks of a given magnitude that can be expected versus the number of days of elapsed time after the triggering event explosion. As an example, M_m, the triggering event magnitude for the IFE14 scenario, was assigned a value of 4.0. The charts below indicate the number of aftershocks per day, for a given magnitude, to be expected, after the initial explosion.

NTS hard rock model:

	M_{min},	M_{min}	M_{min}	M_{min}	M_{min}	M_{min}
	-2	-1	0	1	2	3
Time, days	# per day	# per day	# per day	# per day	# per day	# per day
2	8251	328	13	1	0	0
4	3041	121	5	0	0	0
6	1696	68	3	0	0	0
8	1121	45	2	0	0	0
10	813	32	1	0	0	0
12	625	25	1	0	0	0
14	501	20	1	0	0	0
16	413	16	1	0	0	0
18	349	14	1	0	0	0
20	300	12	0	0	0	0

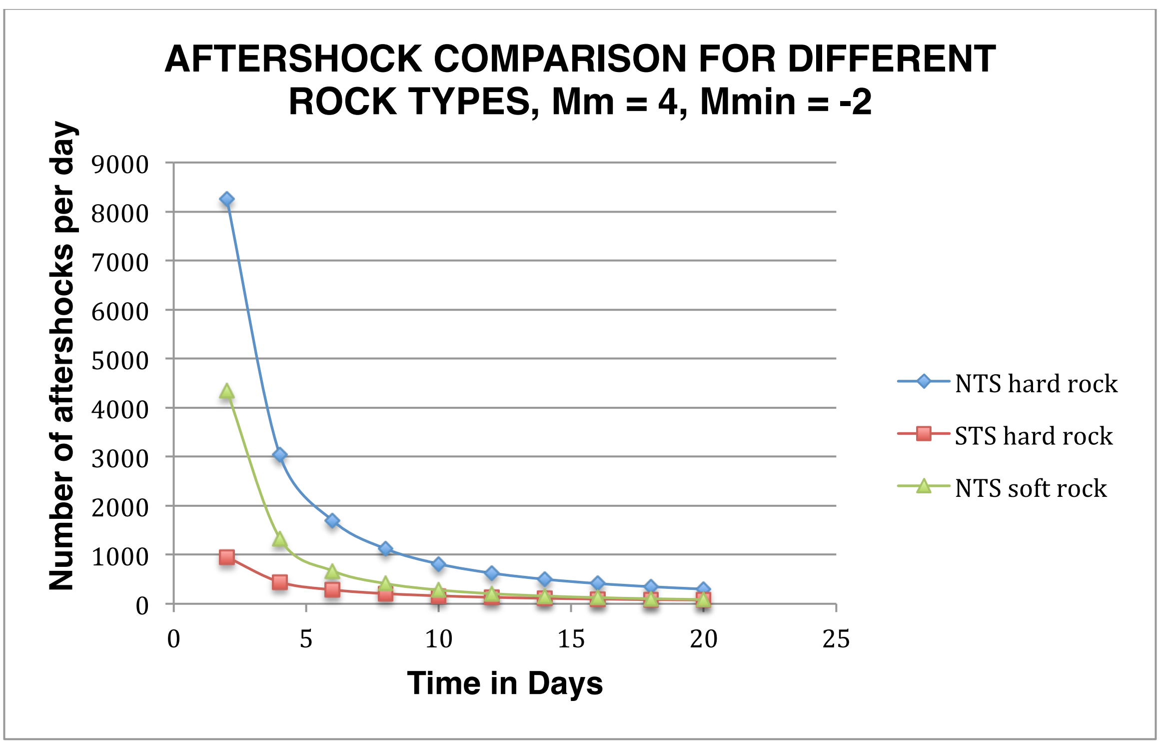
In the scenario time line for IFE14, it was about 10-14 days after the explosion occurred before the inspection team (IT) could be on site in the inspection area (IA) and begin to record aftershocks. Thus the IT could expect to see numerous magnitude -2 and -1 events initially at the site, but larger magnitude aftershocks would be rare for this geology.

STS hard rock model:

	$M_{min,}$	M_{min}	M_{min}	M_{min}	M_{min}	M_{min}
	-2	-1	0	1	2	3
Time, days	# per day	# per day	# per day	# per day	# per day	# per day
2	953	107	13	1	0	0
4	444	50	5	0	0	0
6	284	32	3	0	0	0
8	207	23	2	0	0	0
10	162	18	1	0	0	0
12	133	15	1	0	0	0
14	112	13	1	0	0	0
16	97	16	1	0	0	0
18	85	14	1	0	0	0
20	76	12	0	0	0	0

For this rock type, the decay rate is somewhat faster, but there are a few more events of larger magnitude that occur early after the main shock. Again, at a time of about 10-14 days after the triggering event, there will be numerous events of magnitude -2 and -1, but larger events will be rare.

Results for the NTS soft rock geology follow a similar pattern, as shown in the plot below:



The result for the purposes of planning the aftershock scenarios is that it doesn't matter very much which rock type model is used; the end result is that there will be a large number of magnitude -2 and -1 events and very few larger events. The seismic aftershock measurement system (SAMS) of the PTS is designed to detect a magnitude -2 event at a distance of about 5 km. Thus a dense spacing of sensors is needed to detect and locate such small events. The current SAMS system available to the Provisional Technical Secretariat (PTS) of the CTBT Organization (CTBTO) (and deployed at IFE14) consists of equipment that can be deployed at 50 stations, in order to have minimal coverage of magnitude -2 events over an area of 1000 km^2. A chart of the detection capability of the current SAMS system and a diagram of a typical array layout is show below.

A1.3.7. Illustrative examples of mini-array estimated detection limits are given in Table A1.3-1 (exact configurations are decided at the time of deployment; radius of detection depends on the seismic attenuation characteristics of the area).

Table A1.3-1. Mini-Array Expected Detection Limits

Magnitude (Ml)	Radius of Detection	Coverage Area	Number of Arrays	3-C[a] Sensors in Arrays	1-C[b] Sensors in Arrays
–2	2.5 km	19.6 km^2	50	50	150
–1.5	3.5 km	38.5 km^2	35	35	105
–1	5 km	79 km^2	15	15	45

[a] Three component seismometers. [b] Single component seismometers.

A1.3.8. A typical mini-array geometry and configuration are shown in Figure A1.3-1.

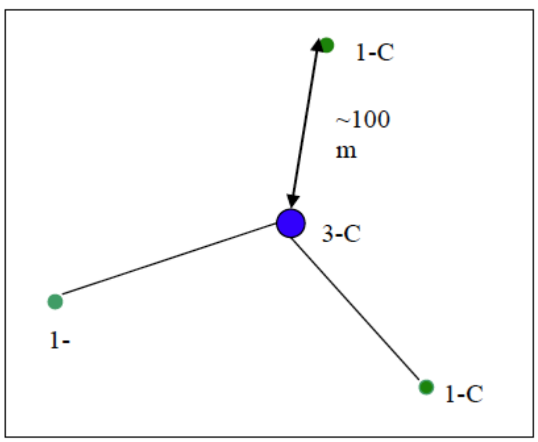
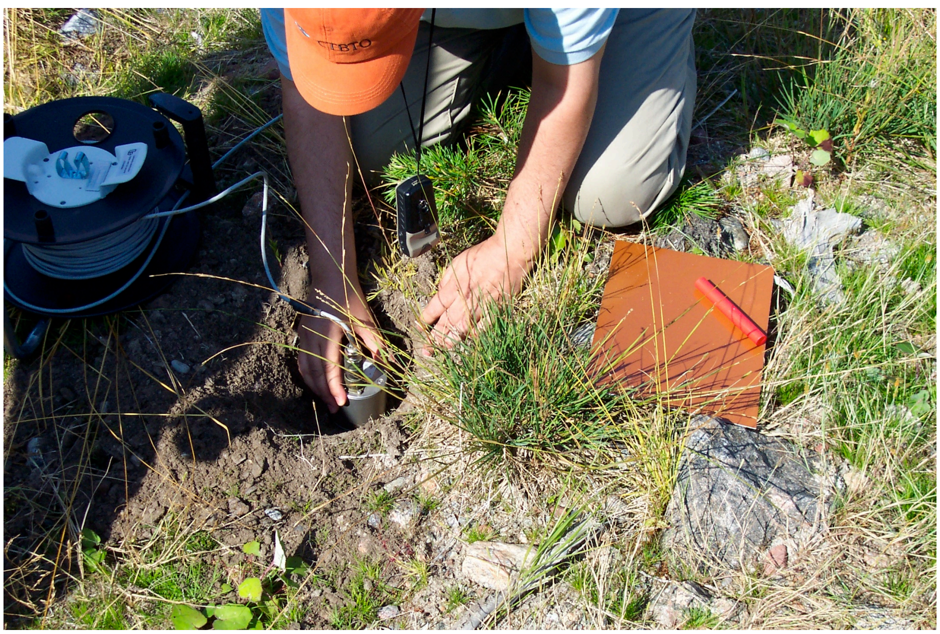


Figure A1.3-1. Mini-array with central three component seismometer and three satellite one component seismometers with the same characteristics. The distance to the satellite 1-C seismometers is nominally ~100 m, but smaller aperture arrays (e.g. 50 m) may be useful for more careful characterization of a source of aftershocks.

The photos below show details of how the seismometers are deployed in the field (taken during a field exercise in Finland in 2009).



The simulated events should be designed to occur within a radius of a few hundred meters of the detonation point, in a random pattern. The timing of the events would also be random. The timing of simulated aftershock events would follow the above formalism and these would be combined with a location model, depending on whether an explosion source (elliptical, with a long vertical axis, or spherical distribution at random distance from the hypocenter) or an earthquake source (planar distribution, depending on fault orientation) is modeled.

Network Configuration Issues

For a given exercise, free play will dictate the deployment of seismic mini-array stations by the IT. The IT will follow the inspection team functionality procedures and daily current information to guide the deployment locations for the stations. The number of stations deployed will depend on access, logistics, and strategy decisions by the IT. In order to produce synthetic waveform aftershock data for the IT, the locations of all deployed and operating stations will have to be known by the control team in order to calculate the travel time and attenuation of the waveform for a designed aftershock. This requires the use of a travel time and attenuation model appropriate for the IA. The control team will have to constantly monitor the locations and status of the deployed stations via the integrated information management system (IIMS) in order to plan the design of aftershock waveforms.

Waveform Models

In order to inject simulated aftershocks into an exercise scenario, typical aftershock waveforms will have to be produced. Two types of aftershock waveforms have been identified as typical of UNEs – impulsive and emergent (Smith, 1998). Impulsive events have a sharp onset of the initial P wave and are probably caused by stress relief and development of new fractures near the explosion cavity. Emergent events have a much slower onset of the P wave and are representative of shifting of rubble within the collapse zone or with an initial cavity collapse event.

Thus the desired types of waveforms can be obtained from representative examples of previously recorded aftershocks or other seismic data. Once the waveform type has been selected, then the waveform must be scaled by yield and attenuation based on the distance to a specific deployed mini-array. The next step will be to adjust the waveform model for each element (center three component instrument, and three outlying vertical instruments) of the mini-array. Again, the configuration of each deployed mini-array (location of each element) will have to be obtained from the Integrated Inspection Management System (IIMS). Adjusting the waveform model for elements of the array will require very precise travel time adjustments to be consistent with each deployed array.

Finally, the injected waveform data will only be believable if the waveforms are embedded within realistic noise. The preferred method to add noise to the waveforms would be to merely add the waveform signal to the existing noise of each element of the mini-array. Hopefully, then, the field seismic analyst, when he views the data in the working area of the IIMS, will observe a small seismic event that look like real data and, when analyzed will be consistent with an aftershock of an impulsive or emergent type that occurs at the place and time designed by the control team.

Insertion of Data into the IIMS

The concept for the exercise is that the control team will insert the aftershock waveform data into the IIMS some time after the relevant data for the day when the aftershock is designed to occur has been entered by the IT into the IIMS. This will have to occur before the data is available to the IT for analysis in the work area. The current system used by the PTS incorporates SD data cards that are collected every one or two days from the field and then loaded into the IIMS at the end of the field activity day. For that approach, injection of control team data should not be difficult. However, should the PTS eventually incorporate telemetry into the SAMS system, injection of aftershock data will be more time intensive, although even data collected via telemetry will have to be observed by the Inspected State Party (ISP) before it is entered into the IIMS.

Summary -- Sequence of events for injecting aftershock data:

1. Determine the scenario.
    a. Triggering event
    b. Other sources (e.g. mining, fluid injection, cultural)
2. Based on the triggering event (event time, magnitude, rock type), carry out a probability analysis to determine probability of an aftershock of a given magnitude for each day beginning with time of first SAMS deployment.
    a. Generate a table of number of events per day
    b. Generate a model of random distribution of aftershocks around initial hypocenter
    c. Generate a table of aftershock event locations for each day starting with deployment of SAMS
3. Generate waveforms for seismic events in the table.
4. For each day of SAMS deployment, determine location and configuration of each SAMS mini array.
5. Generate waveforms for each element (seismometer) of the array, taking into account distance from source to mini array, velocity structure along the path, and attenuation and magnitude of the event. [This can be done with a simple, 1D velocity model.]
6. Alternative is to generate a single waveform for each array location, without going into the configuration [which includes timing of arrival on each arm of the array] of the mini arrays (this is less realistic).
7. Waveforms must be consistent with timing and location of the event for all arrays deployed at a given time. This could be done on a day-by-day basis, or based upon when the IT gathers data from the field sites.
8. Waveforms will be inserted into the IIMS without the knowledge of the IT, for later analysis. Data will be inserted into the relevant field data as part of a continuous stream consisting of background noise that will also contain some teleseismic events from outside the IA.

Note that items 5. – 8. can only be done during the exercise, so a capability needs to be developed to generate the waveforms for the simulation in [near] real time. The IT has the capability to deploy up to 50 arrays with the current SAMS system.

Waveforms must be consistent (e.g. P and S phases of proper relevant amplitudes and shapes) with the nature of the source: earthquake or explosion or some kind of collapse, stress relaxation, or cultural event.

Given the complexity of the waveforms, it would be desirable to use real data recorded under conditions similar to those expected for the types of events and geology of the area where the exercise takes place.

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