NEMOS – A software framework to simulate the response from nuclear explosion detection networks

Anders Ringbom, Peter Jansson, Sofie Liljegren, Per Andersson, Oscar Björnham, Jon Grumer, Leif Å Persson, Daniel Vågberg

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INTRODUCTION AND MAIN RESULTS

A software framework - Nuclear Event Monitoring Simulator (NEMOS) has been developed to simulate the response of sensor networks to nuclear explosions and other events. NEMOS simulates the response from seismic sensors, infrasound detection sensors, and several types of radioactivity instruments. The response models are used in combination with a nuclear source vector and atmospheric transport modelling. Network responses from a large set of simulated explosions are used in a statistical analysis to evaluate different network configurations with respect to verification capability.

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P3.4-517

Introduction

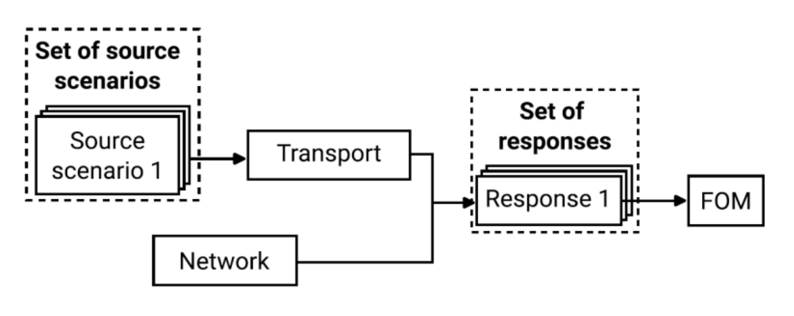
Global or regional sensor networks for timely *detection*, *identification*, and *location* of nuclear explosions and other nuclear events are important for international treaty verification and national security. Depending on the purpose of the network, requirements may vary. Since these kind of networks are major investments, it is important to have a good knowledge of the expected capability before they are established, and have answers to key questions like:

- Does the network detect the events with high enough probability?
- What is the reporting time?
- Which sensors detected the event?
- Can the system differentiate between nuclear explosions and other (nuclear) events?
- How well is the event location estimated?
- How well can the yield and height of an explosion be estimated?
- What network configuration is the most cost effective?

The software package NEMOS (Nuclear Event Monitoring Simulator) [1] was developed with the end goal to find answers to these, and other questions, for a variety of network configurations using a combination of sensors technologies.

[1] FOI report: FOI-R--5626—SE, 2024.

General methodology



NEMOS takes information about a nuclear event and combines with a sensor network configuration and simulates the system response. The procedure is performed for multiple source scenarios and network figure of merits (FOMs) are calculated from the set of responses. Assuming that the network consists of a seismic (S), an infrasound (I), and a radionuclide network (R), the following FOMs are calculated, *inter alia*:

- **Detection power**: The fraction of events resulting in at least one detection in S, I, or R.
- **Location power**: The fraction of events resulting in a location error less than *x* and *y* km, for a seismic and infrasound detection, respectively.
- **Reporting power:** The fraction of events resulting in a reporting time less than t_r (case dependent).
- **Nuclear Explosion Identification Power:** The fraction of explosions resulting in an identified nuclear explosion.

Simulated sensors

Sensor type	Observable	Sensitivity	Typical reporting time
Seismic network	Ground motion	High	minutes
Infrasound network	Air pressure difference	High	1-5 hours
GM tubes	Dose rate	Low	T+~10 min
NaI-detectors (air)	Spectroscopic	Medium	T+~1 h
NaI-detectors (ground)	Spectroscopic	Medium	T+~1 h
NaI-detectors (filter)	Spectroscopic	Medium	T+~1 h
Filter station with HPGe	Spectroscopic aerosols	High	T+~72 h
SAUNA III	Spectroscopic xenon	High	T+~12 h
SAUNA CUBE	Spectroscopic xenon	High	T+~20 h

T = transport time for radioactive plume.

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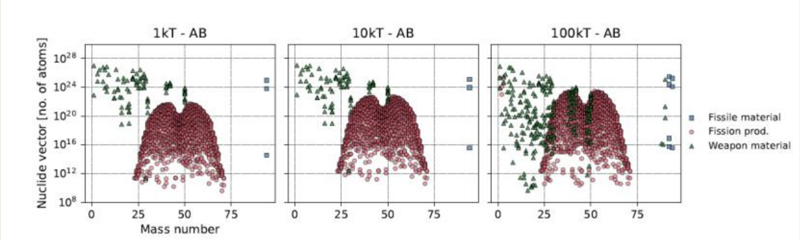
Nuclear explosion source scenario

A nuclear source scenario is defined in NEMOS by:

- **Nuclide vector:** Nuclides created at time zero.
- **Explosion yield**: weapon type and yield.
- **Position and height**: lat, lon and height or depth of burial.
- **Environment:** Above or in ground or water.



The figure shows the nuclide composition following three different explosion scenarios (all air bursts conducted at heights to maximize damage from shock wave):

- 1 kT fission weapon (^{239}Pu)
- 10 kT fission weapon (^{239}Pu)
- 100 kT fission-fusion (50/50%). The primary contains ^{235}U, ^{238}U, and ^{239}Pu as fissile material.

The model [2] includes fission and activation products in weapon-, air-, and ground material. The actual geometric distributions in the weapon is not modelled. Neutron flux is assumed isotropic, and the weapon material evenly distributed around the neutron source.

[2] Per Andersson, FOI report FOI-D--1296—SE, 2024.

Atmospheric dispersion calculations and radioactive decay

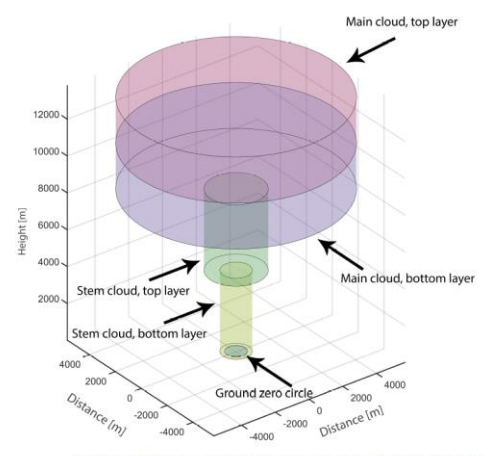


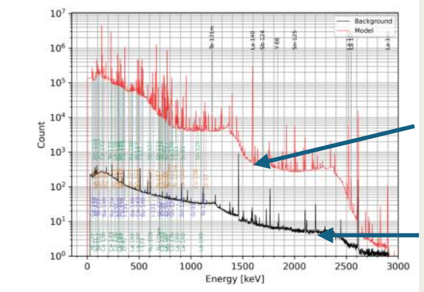
Illustration of the main sections of a mushroom cloud as modelled by NWSWAMP for an 80 kt bomb with 50% fission that explodes on the ground surface. A base surge cloud only appears for underground explosions which is not the case here.

The aerosol source term for atmospheric explosions is made with the model NWSWAMP, which is based on KDFOC3 [3], with the addition of small-sized particles and inert gases to allow for long-range dispersion. The main sections in the model is shown above. The dispersion is made using the model PELLO [4]. Results include both air and ground deposition. Noble gas releases are calculated using HYSPLIT [5] (only air dispersion). The nuclide vector is decayed assuming ingrowth from all precursors using a Bateman solver, and the result is combined with the dispersion calculation results. The results is then used as input to the different radionuclide detector response models.

[3] T. Harvey, et.al., UCRL-52338, LLNL, 1992.
[4] J. Lindqvist. FOA report FOA-R-99-01086-862-SE, 1999.

Responses from radiation detectors

- **GM tubes:** Effective dose rate to adult humans are estimated based on the calculated nuclide-specific activity concentration in air or on ground. The count rate is modelled using the dose rate scaled with a calibration factor.
- **NaI detectors:** The different measurement geometries are simulated using Geant4, and the calculated measured energy spectra are, together with a typical background analysed using a simplified ROI technique.
- **Aerosol stations:** HPGe response is simulated using Geant4, and combined with the dispersion calculations to yield spectra, analysed using standard analysis software.



Example of an energy spectrum and the corresponding background energy spectrum produced by the HPGe aerosol model. Peaks identified by UniSAMPO that are also on the list of CTBT-relevant nuclides are marked.

Spectrum caused by simulated nuclear explosion.

Background

- **Radioxenon systems:** SAUNA III and SAUNA CUBE responses are modelled using the dispersion results and Poisson statistics, assuming typical system response parameters.

[5] A. F. Stein, et. al.,Bull. Am. Met. Soc. 96(12) 2059-2077, 2015.

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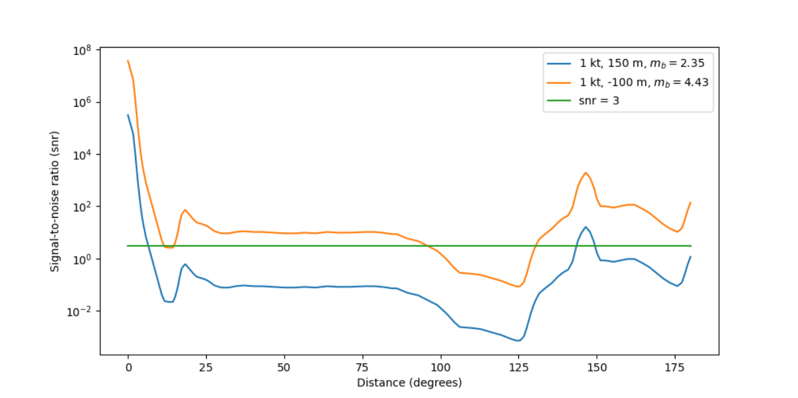
Responses from seismic sensors

The seismic detection process uses P-waves only. Magnitude and resulting amplitude is calculated using relationships from previous underground nuclear tests together with a decoupling factor, obtained from [6]. The decoupling factor depends on height or depth of burial. The magnitude is also corrected for sensor-event distance using a published model [7]. The seismic noise was estimated using data from the Swedish IMS-station in Hagfors, calculated between 0.8 and 2.2. Hz. For arrays, the noise was reduced by $\sqrt{N}$, where N is the number of elements.



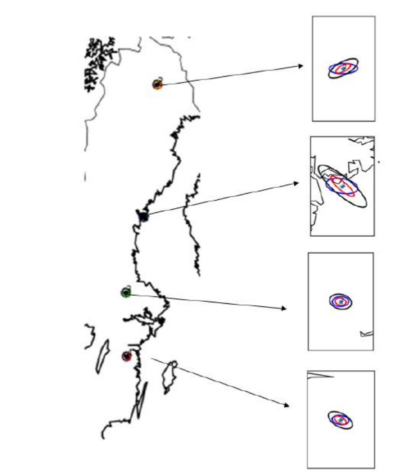
The resulting SNR for two explosion cases (1 kT, 150 m above ground and 100 m below, respectively) are shown above. The model required an SNR ≥ 3 for detection.

[6] M. W. Edenburn, et. al., SANDIA report SAND-97-2518, 1997.
[7] P. K. Gaebler and L. Ceranna, PAGEOP, 178(7) 2419-2436, 2022.

The seismic localization is simulated using travel times [8] for different P-phases, depending on angular distance. The observed travel times are calculated by perturbing the theoretical travel time with an uncertainty taking into account pick time and model error, according to [6]:

$$\sigma_i^2 = 0.75^2 + \left(\frac{0.15}{SNR_i - 1}\right)^2$$

The localization is performed using grid-search of 100 Monte-Carlo histories, assuming σ_i is normally distributed, and the 90% error ellipse is calculated from the resulting distribution. The model is to be considered as a first approximation, but were found to agree reasonably well compared to real events analysed by the Swedish National Seismic Network (SNSN):

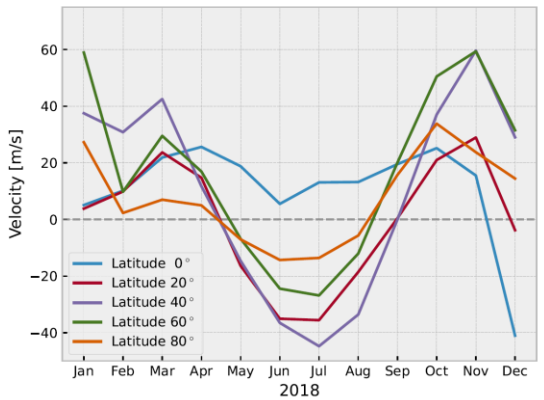


Comparison of 90% error ellipses created using the model (in blue) and real data analyzed using SesiComp with the LOCSAT module. Data was analysed with manual picking of P-phases only (in black), and using both P-and S-phases (in red).

[8] Kennett and Engdahl, Geophys. J. Int. 105(2):429-465, 1991.

Responses from infrasound sensors

The infrasound detection process is essentially modelled using the approach from [6], where the signal amplitude pressure difference is described by a parameter equation containing the effective yield (which depends on the height of the explosion) and event-sensor distance. The average wind velocity vector V along the signal trajectory at 50 km altitude is used to correct the signal amplitude by a factor given by $10^{0.0173V}$. The wind vector was calculated using monthly average wind fields for 2018 [9].



Monthly averaged wind velocity at 50 km altitude above the equator and at four different latitudes at the northern hemisphere. Data was obtained from [7].

The infrasound localization was modelled using a similar approach as was used for seismic sensors, with an arrival time uncertainty of 2% of the travel time, and the bearing uncertainty varying from 2.8 to 27.5 degrees, depending on event-sensor distance.

[9] GMAO, 2015, MERRA-2,
DOI: 10.5067/V92O8XZ30XBI.

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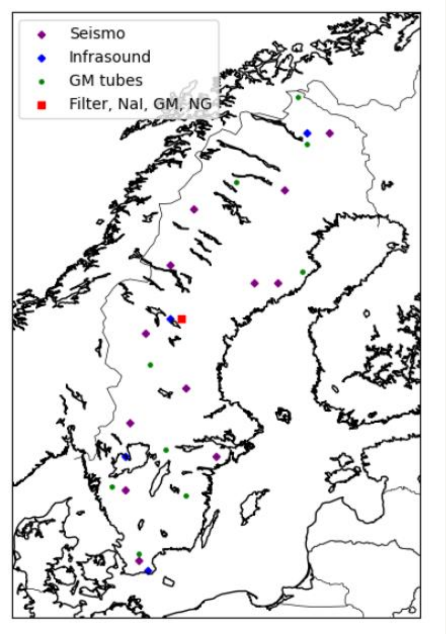
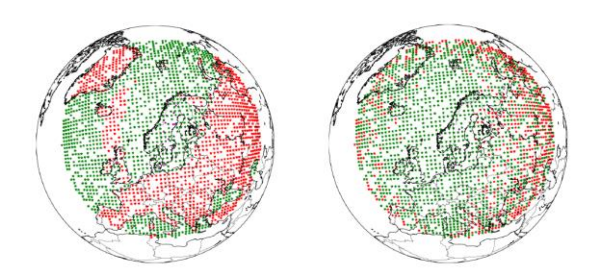
Some results for a hypothetical network



Layout of a hypothetical sensor network in Sweden used to exemplify NEMOS results.

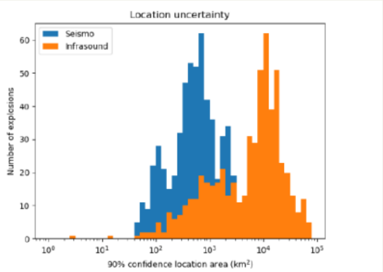
To illustrate NEMOS functionality, we show some results from a fictitious network in Sweden (see map above), containing 12 seismic and four infrasound stations, 10 GM tubes, and one multi-detector radionuclide site equipped with an aerosol station with a HPGe detector and an additional NaI detector monitoring the filter on-line, one stand alone NaI, one GM-tube and two noble gas systems (SAUNA III and SAUNA CUBE).

The network was investigated using different explosion sets. One set contained 3650 explosions (1kT at 150 m height) occurring at ten random start times per day during a year (2018) at coordinates randomly chosen from a rectangular grid covering Europe. Seismic and infrasound detection patterns are shown below (green means detected, and red not detected by the sub-network).



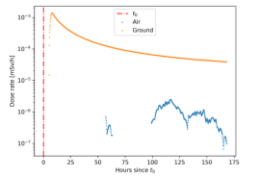
(a) Seismic detection pattern (b) Infrasound detection pattern

The seismic detection capability is clearly affected by the stronger coupling above water. The infrasound signals can be detected at larger distances, but are affected by high-altitude wind patterns, and have, as expected, considerably higher location uncertainty:

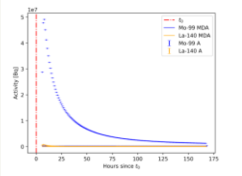


Measured dose rates and examples of isotope-specific detections from one of the explosions are shown below.

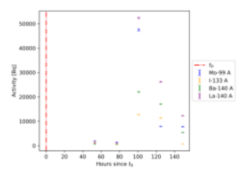
GM-tube



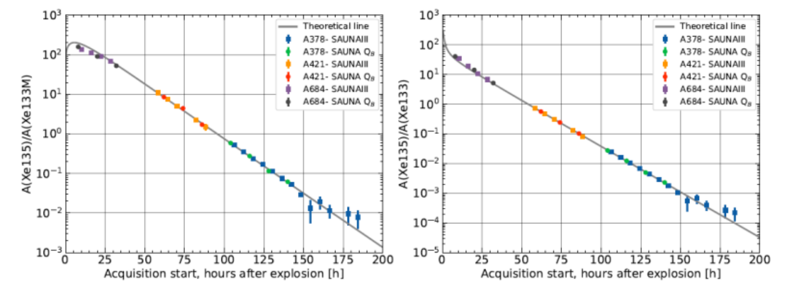
NaI



HPGe



Simulated measurements of radioxenon isotopic ratios from three of the explosions are shown below:



As illustrated, NEMOS produces a wealth of results that allows for an in-depth analysis of the performance of multi-technology sensor networks. NEMOS could also be used to produce detector spectra and other material for exercises, such as the NDC Proficiency Experiments (NPEs) organized by the CTBTO.

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