How can we determine the origin of radionuclide observations? Presenting the Bayesian source reconstruction algorithm "FREAR"

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Abstract:
Radionuclide observations made by the International Monitoring System are an important part of the CTBT verification regime, as it allows to discriminate between conventional and nuclear explosions. In this poster, the Bayesian source reconstruction tool FREAR is presented. The FREAR tool allows to determine source parameters based on radionuclide observations and source-receptor-sensitivities; the latter can be calculated by an atmospheric transport model and are routinely provided by the CTBTO. Detections and instrumental non-detections are taken into account, and the possibility of false alarms and misses is considered too. The Bayesian approach inherently takes into account uncertainties. Furthermore, a method to determine model uncertainties, based on an ensemble, is presented.
FREAR in a nutshell:

- Forensic Radionuclide Event Analysis and Reconstruction
- Flexible tool that combines ATM and radionuclide observations to determine unknown emission parameters (such as release location and release amount)
- Written in R
- Can run on a laptop
- Requires open source software only
- Available under the GPL v3 on GitLab: [https://gitlab.com/trDMt2er/FREAR](https://gitlab.com/trDMt2er/FREAR)
How can we determine the origin of radionuclide observations? 

Presenting the Bayesian source reconstruction algorithm “FREAR”

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1/ Detections and non-detections

FREAR can use both detections and instrumental non-detections; it takes into account the possibility for misses and false alarms (see Fig. 1)

2/ Uncertainty quantification

The Bayesian inference approach provides an estimate on the uncertainties in a natural way. Furthermore, an ensemble of atmospheric transport modelling can be used to better estimate model uncertainty

3/ Several source parameterizations are available

Users can select the most appropriate source parameterization for a given problem, and can add their custom source parameterization if needed

4/ Bayesian approach vs cost optimization approach

Two separate methods are available to determine source parameters: (i) a Bayesian Markov Chain Monte Carlo method and (ii) a cost function optimization approach

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**Fig 1:** Decomposition of the likelihood as a function of the simulated activity concentration \(c_{mod}\) for a detection \(c_{det}\) below the minimum detectable concentration (MDC). The likelihood considers the possibility that the detection was a false alarm. See De Meutter et al. (2021) for details
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**Fig 2:** (Example output) posterior distribution for the source parameters “longitude”, “latitude” and “accumulated release”.

**Fig 3:** (Example output) source location probability map.

Disclaimer: The views expressed on this poster are those of the author and do not necessarily reflect the view of the CTBTO.
In order to perform a source reconstruction using FREAR, we need to know the model uncertainties (uncertainties associated with the atmospheric transport modelling).

1. Since we do not know the true model error, we replace it by a distribution. We use an inverse gamma function with three parameters (initial noise estimate $s$, the scale parameter $\alpha$ and the shape parameter $\beta$): 

   $$
   \psi(\sigma_{\text{mod},i}|s_i, \alpha_i, \beta_i) = 2\alpha_i^{\beta_i} \Gamma(\beta_i) \left( \frac{s_i}{\sigma_{\text{mod},i}} \right)^{2\beta_i} \exp \left( -\frac{\alpha_i}{\sigma_{\text{mod},i}} \right) \frac{1}{\sigma_{\text{mod},i}}
   $$

2. These parameters can be sample-specific (observation-specific) (Fig. 5, next slide)

3. The parameters can be given as input, or derived from an ensemble of SRS to better represent the model uncertainties (Fig. 4)

4. These model uncertainties have an impact on the source characterization (Fig. 6, next slide)
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**Fig 5:** (a): Model uncertainties are observation-dependent; (b): Model uncertainties increase when going forward in simulation time (here: backwards in time); the errors oscillate according to the diurnal cycle.

**Fig 6:** Example of a source location map using (a) fitted model uncertainty parameters from an atmospheric transport model ensemble. (b) the average from multiple source reconstructions using several *a priori* choices for the model uncertainty.

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1/ What is FREAR?
FREAR is a flexible tool that combines ATM and radionuclide observations to determine unknown emission parameters

Available on Gitlab under GPL3.0, written in R:
https://gitlab.com/trDMt2er/FREAR

2/ Features
Can deal with instrumental detections and non-detections

Model uncertainty is represented by an inverse gamma function, which fits well with an atmospheric transport modelling ensemble

3/ We welcome your feedback to improve the tool!

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Technical references


See also
Testing the Forensic Radionuclide Event Analysis and Reconstruction Tool (FREAR), Ian Hoffman et al (P3.5 – 407)