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Distributed framework for modeling and reconstruction of nuclear accidents

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1. Introduction

Application of advanced Bayesian methods in the field of radiation protection, e.g. Monte Carlo methods, requires high computational power. To ensure sufficient computational resources without extensive investments we attempt to develop a framework for construction of distributed computational environments using a large number of common personal computers connected to the internet. It can be used for construction of systems dedicated to a single extensive task or as a computational base for multiple concurrent users.

The developed framework and the following applications based on the framework are briefly presented:

- Bayesian data assimilation (inverse modeling)
- Evaluation of monitoring networks
- Web interface to an atmospheric dispersion model for multiple concurrent users

1.1 Architecture of the system

The framework is based on the client-server architecture, Fig. 1. Its core components are:

- Server providing web pages with user interface for configuration of tasks (simulation runs of a model etc).
- Document-oriented (NoSQL) database for storage of various data in different formats (user data, model data etc.).
- Workers—task-specific computer codes run on remote machines.
- Task scheduler for assigning tasks to workers.

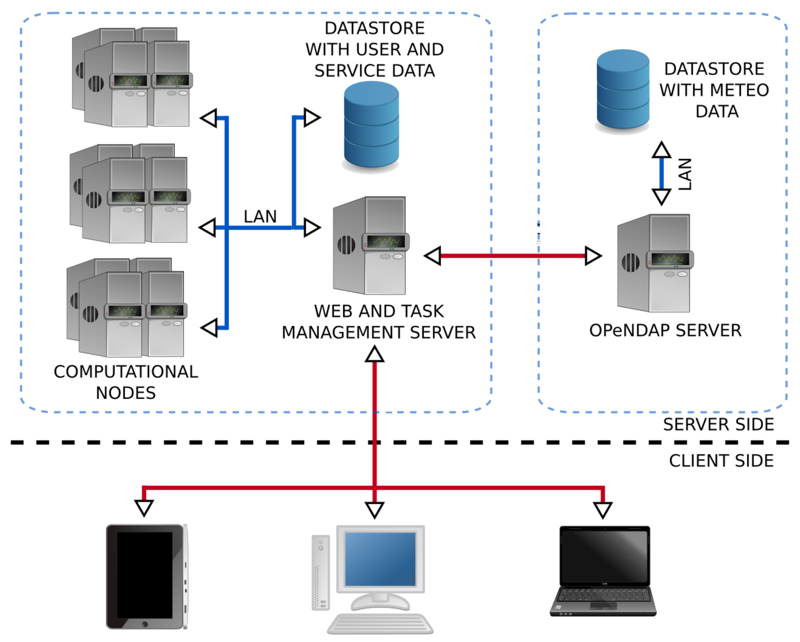

Figure 1: Architecture of the framework.

Tasks are configure by users via a client application and stored in a queue implemented using a database on the server. Workers repeatedly query the queue for free tasks. If a new task is inserted into the queue, an idle worker is assigned to it. Task input is sent to the worker over the internet. When the computation is done the worker sends output back to the server where it is further processed.

Worker list List of all workers registered to the system

No.	Username	Machine	IP address	System	Worker's state	Activity
1	worker_5	kolotoc	147.231.15.159	Linux	IDLE	OK
2	worker_0	dss.utia.cas.cz	147.231.16.143	Linux	BUSY	OK
3	worker_3	thinker.utia.cas.cz	147.231.12.248	Linux	IDLE	OK
4	worker_2	thinker.utia.cas.cz	147.231.12.248	Linux	IDLE	OK
5	worker_4	thinker.utia.cas.cz	147.231.12.248	Linux	DOWN	N/A
6	worker_6	kolotoc	147.231.15.159	Linux	IDLE	OK
7	worker_1	thinker.utia.cas.cz	147.231.12.248	Linux	BUSY	OK

Figure 2: List of workers with indication of their state [IDLE, BUSY, DOWN].

This design offers a good scalability and almost seamless extension of computational resources. As a side effect we obtain a robust solution where the functionality of the system is not influenced by unavailability or a failure of a subset of workers. Since workers communicate over http protocol, they can run without any special need of configuring firewalls etc.

2. Bayesian data assimilation

The fundamental task of data assimilation in the case of a radiation accident is reduction of uncertainty in the source term and possibly meteorological and other inputs to an atmospheric dispersion model (ADM). This is achieved by systematic comparison of modeled radiological quantities and those observed via Radiation Monitoring Networks (RMN). Improved estimates of the source term and other inputs may in turn be used in different short- and long-range models, with a view to increasing the reliability of decision-making resulting in higher efficiency of countermeasures. Our goal is to develop a decision support system for modeling and reconstruction of radiation accidents localized for Czech conditions, i.e. NPPs Temelin and Dukovany and their RMNs.

2.1 Real time estimation of source term

- We aim to develop an autonomous data assimilation system for screening assessment of radiation situation during the early phase of an accident when gamma dose rate measurements from receptors in the vicinity of NPP are available.
- Our goal is to process this stream of measurements from RMN and analyze radiation situation in real time.
- We focus on sequential Bayesian methods which are suitable for real-time processing of incoming measurements and representation of uncertainty [1], [2].

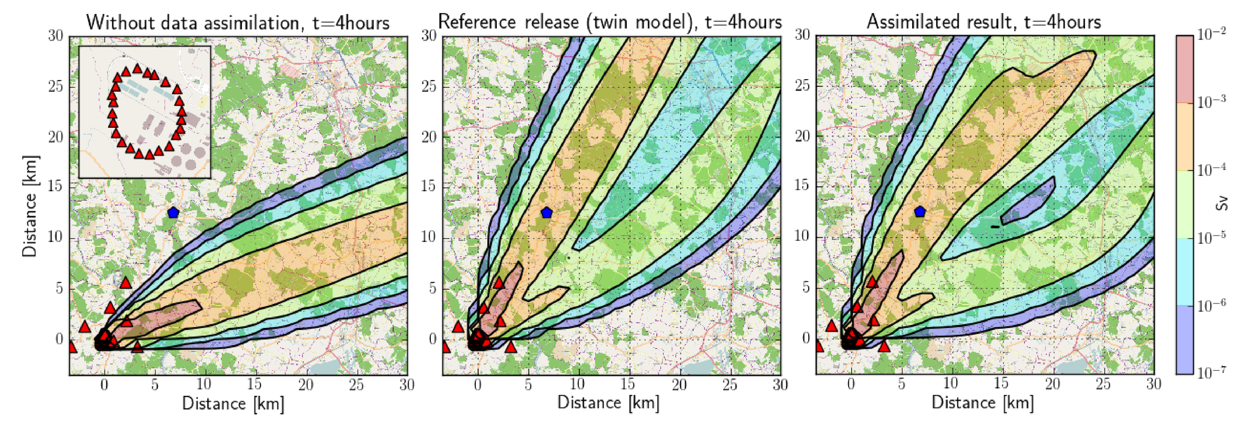

Figure 3: Experiment with simulated release of ^{41}Ar and real topology of RMN around NPP Temelin. **Left:** Cloudshine dose based on simulation with nominal data (without data assimilation). **Middle:** Reference model representing the true release. **Right:** Expected value of dose after data assimilation. Blue pentagon is a point of interest (POI), an inhabited place where want to estimate the dose distribution and use it for countermeasures planning. RMN is denoted by red triangles, detail of the first ring of receptors is in left top corner of the left figure.

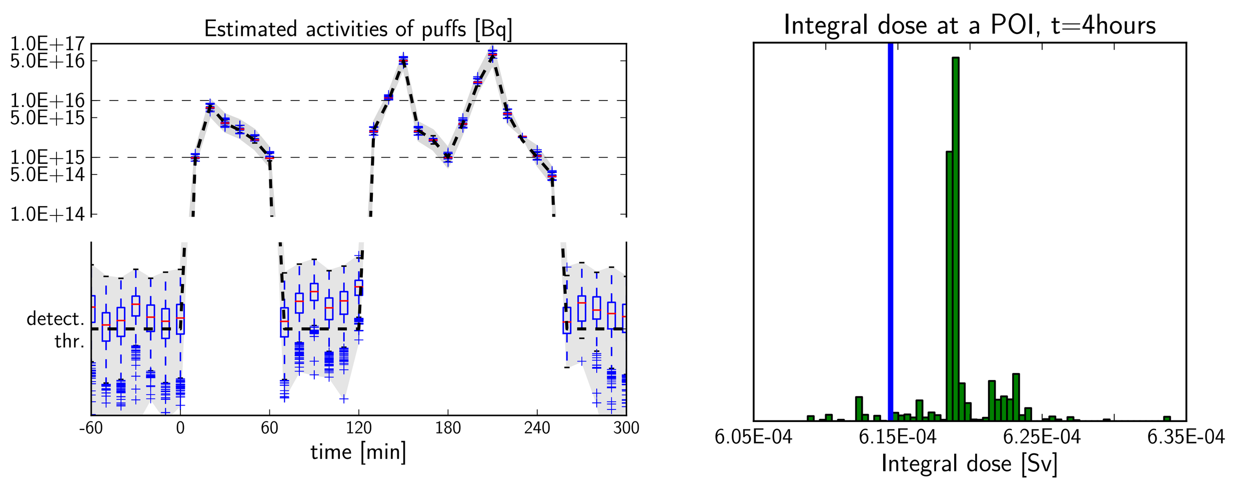

Figure 4: Left: Estimates of released activity during continuous monitoring. The estimates (blue boxplots) are in good agreement with the true values (black dashed line). Time t=0 denotes release start. **Right:** Empirical distribution of dose at POI.

2.2 Work to be done

The system was demonstrated on an artificial scenario with release of a single pollutant. For successful application in radiation protection it must be extended for source terms with multiple nuclides in different physical forms. This will require: (i) external assumptions on the expected accident-specific ratios of nuclides (otherwise the number of estimated variables would be computationally infeasible); and (ii) modification of observation operator for calculation of cloud- and groundshine gamma dose rates. These modifications will increase the computational complexity which suggests further improvements of effectivity of the method.

3. Evaluation of monitoring networks

Performance of a RMN is typically evaluated via a Monte Carlo study simulating all potential events [3], [4]. However, the ability of the network to help the decision makers strongly depends on the quality of assimilated results. This aspect is often overlooked and networks are optimized using very simple assimilation procedures, in order to keep reasonable computational cost.

- We do not search for optimal positions of receptors but we evaluate performance of a set of fixed network configurations. The aim is to provide a tool that allows the decision makers to compare the proposed configurations from various points of view.
- Data assimilation procedure providing an empirical posterior distribution of parameters is run for each network configuration for different weather and release conditions.
- The quality of the network is then evaluated as an expected value of several loss functions with respect to the empirical posterior distribution.

3.1 Experimental Results

- A study involving an ensemble of simulated releases from NPP Temelin under 150 different meteorological episodes from year 2009.
- Comparison of three radiation monitoring network configurations: RMN 1, 2 and 3 (Fig. 5).
- For all combinations of meteorological situations and networks a sequential data assimilation of gamma dose rate measurements from cloud- and groundshine was performed.
- Performance of a network is assessed using loss functions evaluated point-wisely in terms of dose rates. Alternatively, grid-point values are weighted by the number of inhabitants living in vicinity of the point.
- Following loss functions were assumed:
  - **Factor of two:** $FA2 = \frac{N(0.5B_i < A_i < 2B_i)}{N}$, $\{i | A_i B_i > 0\}$, where $N(\cdot)$ is the number of grid points (no. of inhabitants living on a corresponding grid cell) satisfying condition in the argument. N is total number of grid points (inhabitants).
  - **Mean square error:** $MSE = \frac{1}{N}\sum_{i=1}^{N}(A_i - B_i)^2$.

Here, A_i and B_i denote dose rates from assimilated and reference models in grid point i, respectively.

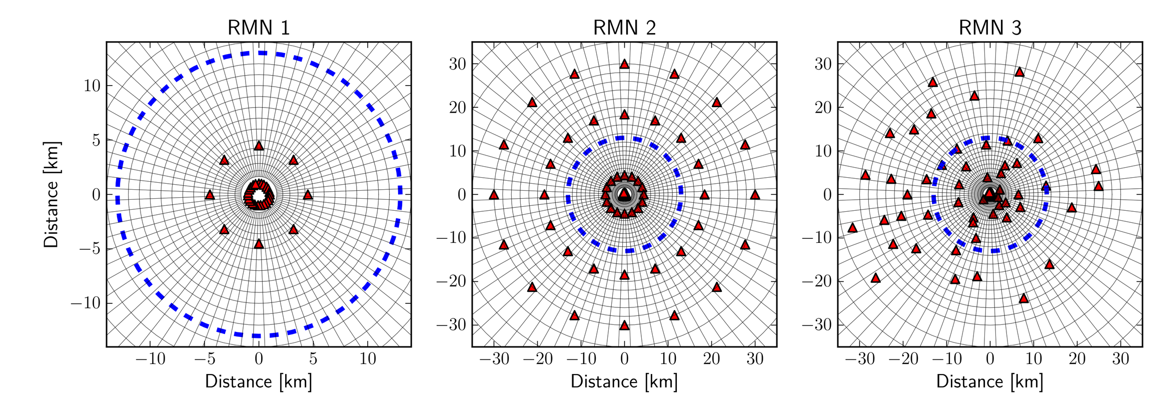

Figure 5: Tested radiation monitoring networks. RMN 1 approximates the current monitoring network of NPP Temelin. RMN 2 and RMN 3 are possible extensions of RMN 1 (with equal number of receptors) with regular spatial coverage and coverage of inhabited places, respectively.

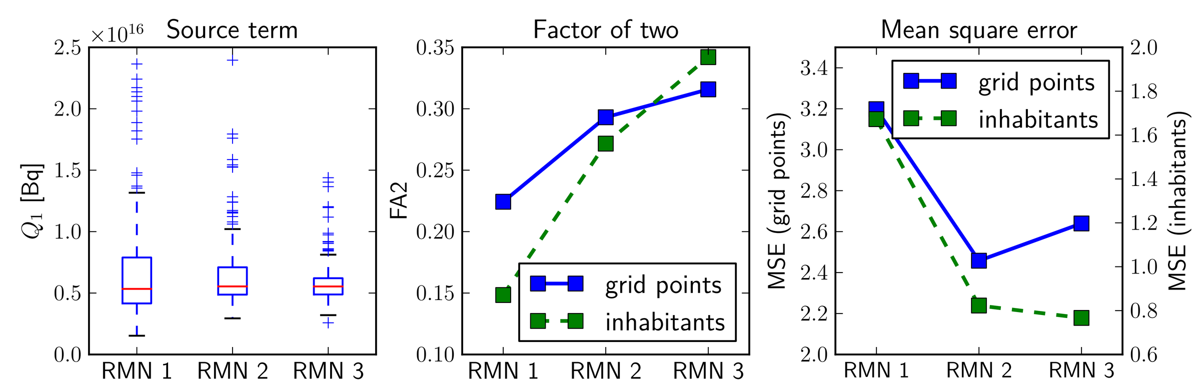

Figure 6: Left: Boxplots of estimated magnitudes of release given by the ensemble for all three monitoring networks. We observe that median for all networks is sufficiently close to the true value 5.0E+15 Bq of ^{137}Cs. **Middle-Right:** Values of loss functions. RMN 2 with regularly spaced receptors attained higher value of FA2 (grid points) over FA2 (inhabitants). RMN 3 with receptors placed in the inhabited sites attains higher value of FA2 (inhabitants).

4. Web interface to dispersion model HARP

- The trend of providing different tools as web-based services is evident also in the field of emergency decision support, e.g. International Exchange Program hosted by NARAC, Lawrence Livermore National Laboratory (*https://ixp.llnl.gov*).
- Our goal is to develop an easy-to-use web interface to the atmospheric dispersion model HARP (HAzardous Radioactivity Propagation) which is a segmented Gaussian plume model certified for emergency use in the Czech Republic [5]. The system should enable:
  - Running model simulations with different source terms and meteorological conditions for multiple concurrent users at a time.
  - Viewing results as transparent overlays on Google Maps.
- The main application domains are education and training in the field of atmospheric dispersion of radioactive pollutants and consecutive decision making.

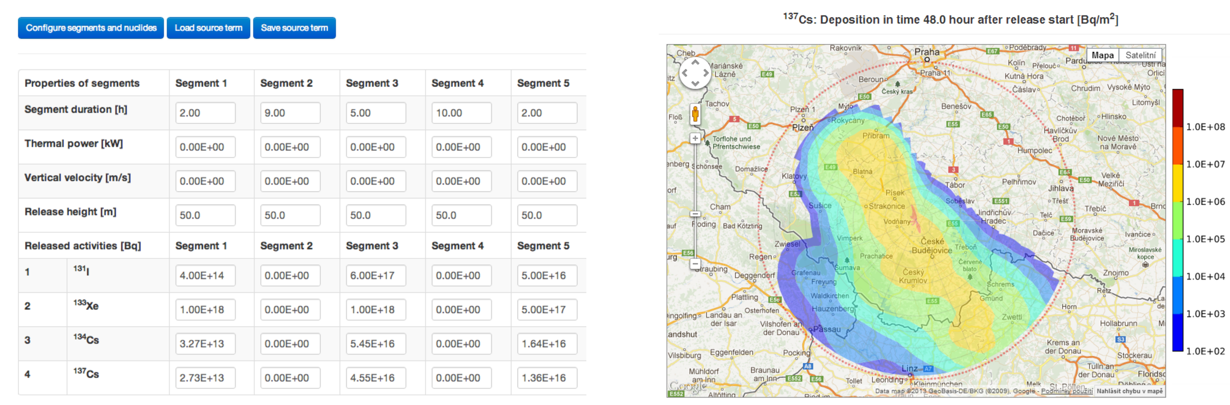

Figure 7: Illustration of web graphical user interface to dispersion model HARP. **Left:** panel for configuration of the source term. **Right:** Visualization of results on map background. The red circle delimits the area of model range—100km from the source.

The web version of the model is not intended to be a fully-fledged alternative to the desktop application. Contrary to the desktop version it has some limitations, e.g. the limit on the maximum number of nuclides. This is given by the chosen client-server architecture and the need to transfer rather large amount of data over internet. However, we hope that the ease-of-use will be attractive for both present and new users of the model.

In the next development we want add new features and improve overall user experience. The priority will be given to switching from point-wise to gridded meteorological inputs. It will require an on-line access to a database of historic and possibly operational meteorological data (as indicated in Fig. 1).

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Built with...

python mongoDB CherryPy NumPy SciPy matplotlib

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