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RADIOACTIVE MATERIAL RELEASE RATE ESTIMATION THROUGH DATA ASSIMILATION OF GAMMA DOSE RATE MEASUREMENTS

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Abstract: This paper presents evaluation of an innovative data assimilation method that has been recently developed in NCSR Demokritos for estimating an unknown emission rate of radionuclides in the atmosphere, with real-scale experimental data. The efficient algorithm is based on assimilation of gamma dose rate measured data in the Lagrangian atmospheric dispersion model DIPCOT and uses variational principles. The DIPCOT model is used in the framework of the nuclear emergency response system (ERS) RODOS. The evaluation is performed by computational simulations of dispersion of Ar-41 that was emitted routinely by the Australian Nuclear Science and Technology Organisation's (ANSTO) previous research reactor, HIFAR, located in Sydney, Australia. The area surrounding the reactor is characterized by moderately complicated topography and varying land cover. The first guess source emission rate has been set by a factor of 10 greater than the true one. Overall the estimated release rate approaches the real one to a satisfactory degree as revealed by the statistical indicators of errors.

Keywords: *nuclear emergency response, inverse problems, data assimilation, radionuclides emission rate estimation, gamma radiation dose rate, atmospheric dispersion, complex terrain*

INTRODUCTION

In nuclear power plant accidents that involve release of radionuclides in the atmosphere, the emission rate of radioactive material is usually unknown. During the emergency phase the estimated source term can differ from the true one by the factor of 10 and more (US NRC, 1990). Therefore improving source rate estimation is of primary importance. A way to assess the release rate is data assimilation of gamma dose measurements which are typically available around every nuclear power plant. In this respect an innovative computational method has been recently developed in NCSR Demokritos for estimating the unknown emission rate of radionuclides in the atmosphere. The algorithm is based on assimilation of gamma dose rate measured data in the Lagrangian atmospheric dispersion model DIPCOT (Andronopoulos, et al., 2009) used in the framework of the nuclear emergency response system (ERS) RODOS (Raskob W., 2007) and uses variational principles. The method is described in Tsiouri, et al. (2011a), and Tsiouri et al., (2011b). In the latter work (Tsiouri, et al., 2011b) the method was successfully evaluated against the fluence rate measurements in field experiment of Ar-41 atmospheric dispersion in Mol, Belgium (Drews, et al., 2002). In the present work the method is evaluated against a more complicated case using gamma dose rate measurements from the atmospheric dispersion experiment of Ar-41 that was carried out at the Australian Nuclear Science and Technology Organisation's (ANSTO) previous research reactor, HIFAR, located in Sydney, Australia. In this experiment the area around the research reactor is characterized by moderately complex topography and spatially varying land cover. The experimental data base that is used for the purposes of the study covers various seasons during 2002-03 and includes measured gamma radiation dose rates from 4 monitoring stations located in a radius of 5 km around the research reactor. There are 16 days of gamma radiation dose measurements but only one monitoring station is available each day. Therefore the challenge for improving the source rate in this case is the assimilation of gamma dose rate measured data from only one monitoring station and the complex terrain of dissected plateaus and valleys that surrounds ANSTO.

METHODOLOGY

Model description

DIPCOT (Andronopoulos, S. et al., 2009) is a 3-dimensional model, which simulates atmospheric dispersion estimating particle (puff's) trajectories. It has been comprehensively validated against numerous field and laboratory experiments on atmospheric dispersion (e.g., Andronopoulos, S. et al., 2010a) and it is included in the European RODOS (Real-time, On-line, DecisiOn Support) system for nuclear emergencies. In DIPCOT there are two modes of particles /puffs movement, the stochastic mode (SM) and the deterministic mode (DM). In deterministic mode puffs are transported by average wind field and grow in size according to well-known Pasquill-type relationships. In stochastic mode puffs are transported also by wind fluctuations based on Langevin equation, formulated for stationary homogeneous isotropic turbulence at the horizontal direction, and on inhomogeneous Gaussian turbulence for the vertical direction, i.e., particles' equations of movement become stochastic. Concentration C (activity concentration of nuclides in air) and gamma dose rates at a particular location and time are calculated by summing the contribution of all neighbouring puffs. A description of the gamma dose calculation methods used in DIPCOT is given in Andronopoulos, S. et al., (2009) and in Andronopoulos, S. et al., (2010a).

Data assimilation algorithm

An innovative and efficient methodology based on variational data assimilation (DA) is used for estimating the unknown emission rate (Tsiouri, V. et al., 2011a and Tsiouri, V. et al., 2011b). The main objective of the DA method is the minimization of the following cost function with respect to control vector $\overline{\psi}$ which consists of source rates corresponding to times of releases of puffs: $\overline{q}$.

$$J = J_1 + J_2,\ J_1 = \left(\overline{\psi} - \overline{\psi}^b\right)^T \underline{\underline{B}}^{-1} \left(\overline{\psi} - \overline{\psi}^b\right)$$
$$J_2 = \sum_{n=1}^{N_O} \sum_{k=1}^{K} \sigma_O^{-2} \left(d_k^o\left(t_n\right) - \tilde{d}\left(\overline{r}^k\right)\right)^2 = \left(\overline{d}^o - \underline{\underline{G}}\overline{\psi}\right)^T \underline{\underline{O}}^{-1} \left(\overline{d}^o - \underline{\underline{G}}\overline{\psi}\right) \quad (1)$$

Here $\overline{\psi}^B$ is first guess estimation of the control vector, $\underline{\underline{O}}$, $\underline{\underline{B}}$ are covariance matrices of the errors of observations and background errors respectively; vector $\overline{d}^o \in R^{N_O K}$ consists of gamma dose rates $d^o(n,k)$, measured on each time interval Δt_n by k -th station. The elements of d^o are ordered sequentially as follows: $d_l^o = d_{(n-1)K+k}^o = d^o\left(n,k\right)$.

For substantial improvement in numerical efficiency and accuracy and to enable using the DA method also in the framework of stochastic Lagrangian atmospheric dispersion models, the control vector reduction technique explained in detail in Tsiouri V. et al, (2011) is used. This technique is based on the assumption that during small enough time interval Δt, source rate can be considered as constant with sufficient accuracy. Then particles could be joined in $P = N_p / \Pi$ groups with Π particles in each group being characterized by the same source rate: $q_{(j-1)\Pi+1} = q_{(j-1)\Pi+2} = ... = q_{j\Pi} = \tilde{q}_j, 1 \le j \le P$. Here $\tilde{q}_j$ are the values characterizing source rate of the $j-th$ group of particles, which form the reduced control vector: $\underline{\tilde{q}}$ of size P. Clearly the value of P depends on the choice of the time interval Δt during which source rate could be considered as constant and thus it is a free variable that depends on the expert judgment of the user. Note that if P=1, then source rate is assumed to be constant during the whole release interval. Instead of initial problem of minimizing equation (1) with respect to control vector $\overline{q}$ consisting of release rates of individual particles the 'reduced' minimization problem is solved in which the same function is minimized with respect to the reduced control vector $\underline{\tilde{q}}$. The cost function (equation 1) with constraint of positive control vector values is minimized using the IMSL ® package (IMSL Inc., 1987).

APPLICATIONS – RESULTS

In the present work data assimilation runs are performed and the data assimilation algorithm is evaluated against the measured release rate from the atmospheric dispersion experiment of Ar-41 that was carried out at the Australian Nuclear Science and Technology Organisation's (ANSTO) previous research reactor, HIFAR, located in Sydney, Australia. Specifically 16 different cases are simulated that cover winter and summer periods of the years 2002 and 2003 and include all the atmospheric stability conditions. The experimental data base used for method evaluation include the Ar-41 stack emission rate, measured meteorological data from 2 stations and measured gamma dose rates from 4 monitoring stations located in a radius of 5 km around the reactor. All the above data were available in 15-min time intervals. The terrain elevation and the land cover were available on a grid of 25 m resolution for the area of interest around the site. Figure 1 shows the computational domain with terrain elevation contours, the Ar-41 release location, the meteorological stations and the gamma dose rate detectors. The terrain is moderately complicated with hills of about 190m height and a valley that transverses the domain. The land cover is varying, including urban (south-east part), suburban (central part), woods (along the river) and low vegetation (north and south-west part) areas. The available meteorological measurements included wind speed, wind direction and temperature at the levels of 10 and 49 m for the station Met00 and wind speed and direction at 18.5 m for the station Met01 (figure 1). The atmospheric stability has been determined by the pre-processors for each 15-min time interval from the temperature gradient between 10 and 49 m and from the wind speed. The raw wind velocity data of 1 min sampling at heights 69 m and 78 m have been averaged on 10 min intervals to drive the dispersion model, together with the Pasquill-Gifford stability categories given in 10 min intervals in the experimental data base. The meteorological data were pre-processed by the meteorological pre-processor FILMAKER of the RODOS system to prepare input meteorological fields for the DIPCOT model.

Simulations with DIPCOT have been performed with the following set of parameters. The puffs were released at a time interval $\tau \approx 2s$ and at a time interval $\tau \approx 4s$. Simulations have been performed in stochastic mode of DIPCOT operation. The first guess source emission rate was set by a factor of 10 greater than the true rate. Different number of source time intervals (parameter P of CVR technique) has been used in different runs. For the case of 06/06/03 experiment (Day 1) that concerned Detector 17 (0.73 km from HIFAR - station WS) and was a winter case with stable conditions for first two peaks that turned to unstable at 7am EST for 3rd peak different values of P=1, 2, 3 have been used corresponding to the following values of time intervals during which source rate is assumed to be constant: $\Delta t \approx 450, 225, 150\,\text{min}$ respectively. In case of 17/12/02 experiment (Day 2) that concerned Detector 16 (0.82 km from HIFAR – station MG) and was a summer case with stable conditions, the tested values of P were: 1, 2, and 3 corresponding to the values of $\Delta t \approx 180, 60, 30\,\text{min}$ respectively. In case of 22/06/03 experiment (Day 3) that concerned a more distant station, Detector 18 (2.78 km from HIFAR – station BT) and was a winter case with stable conditions, the tested values of P were: 1, 2, and 3 corresponding to the values of $\Delta t \approx 405, 202.5, 135\,\text{min}$ respectively. In case of 09/07/03 experiment (Day 4) that concerned the most distant station, Detector 9 (3.33 km from HIFAR – station BR) and was a winter case with stable conditions, the tested values of P were: 1, 2, and 3 corresponding to the values of $\Delta t \approx 210, 105, 70\,\text{min}$ respectively.

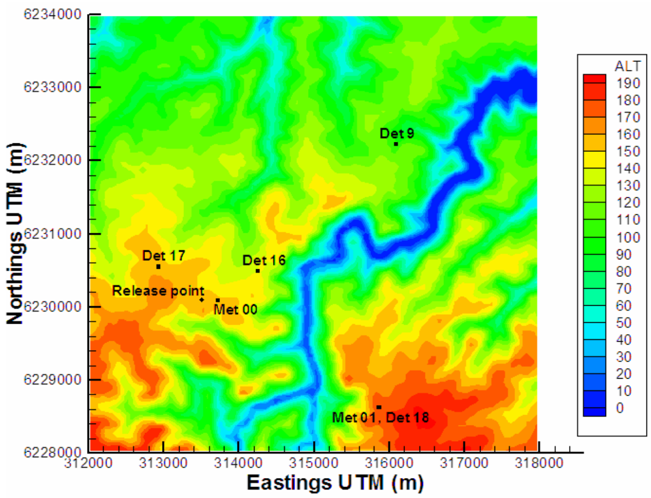

Figure 1. The computational domain with terrain elevation contours, the Ar-41 release location, the meteorological stations (Met00, Met01) and the gamma dose rate detectors (Det9, Det16, Det 17, Det18).

Figure (2) presents source emission rate estimations as result of assimilation of gamma dose rate data for the case of Day 1, Day 2, Day 3 and Day 4 experiments in case of stochastic version of DIPCOT. Results with different number of groups P in control vector reduction procedure are presented. As it is evident from Figure (2) results improve with decreasing P and the adjusted source functions in all cases are much better than the first guess source function. Overall the estimated release rate approaches the real one to a very satisfactory degree for the near flat stations MG and WS and for complex terrain towards station BT under all stability conditions. For the most distant station BR with undulating terrain and small sample size the results are less satisfactory.

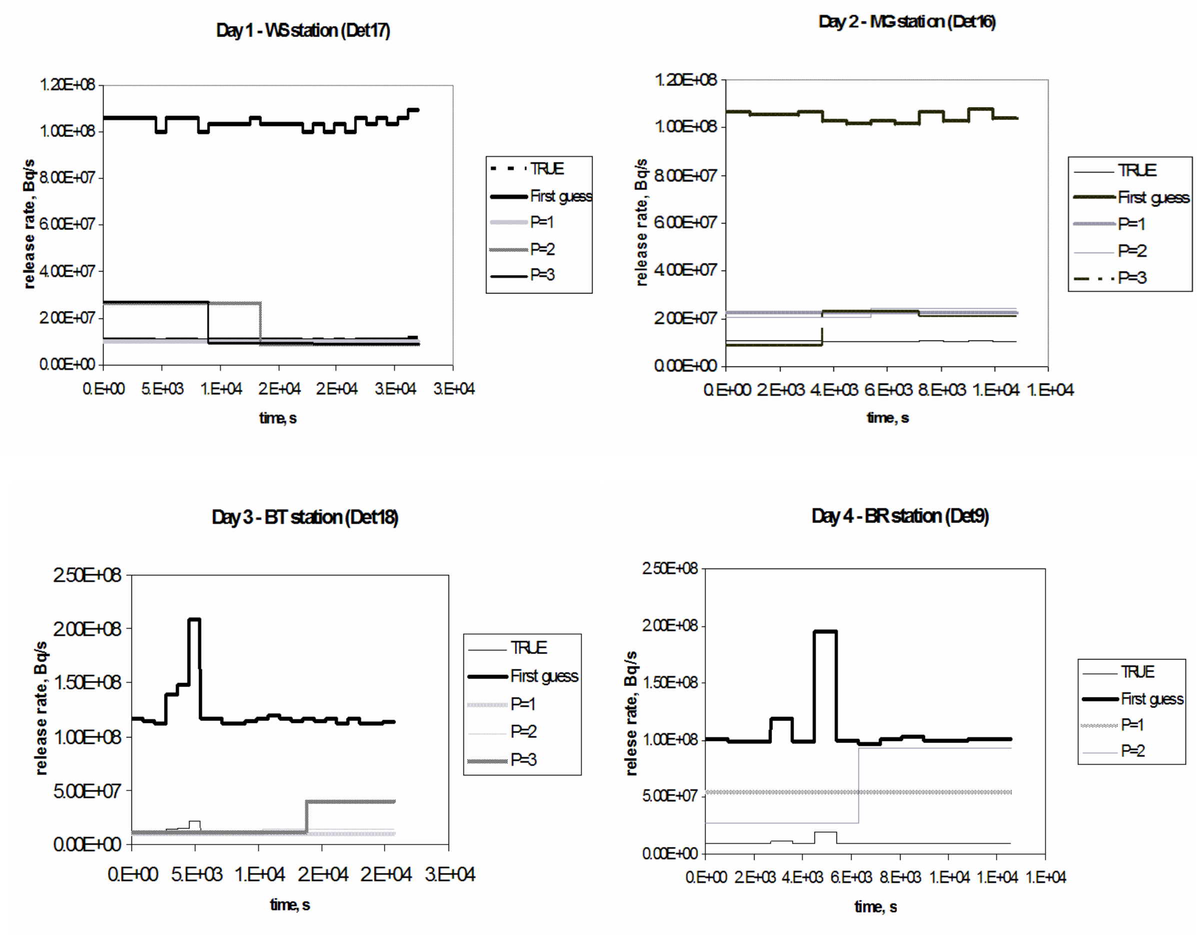

Figure 2. Release rate estimations as result of gamma dose rate assimilation, for Day 1, Day 2, Day 3 and Day 4 experiments.

This qualitative result is confirmed with the results of mean relative absolute error (MAE) and mean relative bias (MRB) presented in Table 1 ($MAE = \langle |q^a - q^t| \rangle / \langle q^t \rangle, MRB = \langle q^a - q^t \rangle / \langle q^t \rangle$) , where q is source function, $\langle \ \rangle$ means averaging, superscripts 'a' and 't' denote analyzed and true source function respectively). The results obtained by stochastic version of DIPCOT at a time interval $\tau \approx 2s$ for Day 1, Day 2, Day 3 and Day 4 experiments and with different values of the CVR parameter P are presented in Table 1. Results by setting the time interval that the puffs were released to $\tau \approx 4s$ are also presented for Day 1. Generally as follows from these results in all cases the analyzed source rate in assimilation runs is much better than the first guess function even if in forward runs for Day 1 and Day 2 the model did not succeed in attaining the suggested satisfactory performance as reported in Andronopoulos S., et al. (2010b). Satisfactory results also obtained even if we reduce the no. of puffs to half as it can be easily seen in table 1 (Day 1 experiment).

Table 3. Mean absolute relative error (MAE) and mean relative biases (MRB) of calculated source function as compared to measured source function. Errors of the first guess source function as well as the errors of source functions corrected in assimilation runs with different values of CVR parameter P.

Experiment (date)	**Station name**	**Detector Point Station #**	**No.of puffs**	**P**	**MAE**	**MRB**
(Day 1)	Waste Services (WS)	17	13500	First guess	9.0	9.0
(Day 1)	Waste Services (WS)	17	13500	3	0.62	0.46
(Day 1)	Waste Services (WS)	17	13500	2	0.86	0.71
(Day 1)	Waste Services (WS)	17	13500	1	0.06	-0.06
(Day 1)	Waste Services (WS)	17	6300	First guess	9.0	9.0
(Day 1)	Waste Services (WS)	17	6300	3	1.3	1.14
(Day 1)	Waste Services (WS)	17	6300	2	1.12	1.02
(Day 1)	Waste Services (WS)	17	6300	1	0.02	-0.01
(Day 2)	Main Gate (MG)	16	5400	First guess	9.0	9.0
(Day 2)	Main Gate (MG)	16	5400	3	0.80	-0.67
(Day 2)	Main Gate (MG)	16	5400	2	1.12	1.12
(Day 2)	Main Gate (MG)	16	5400	1	1.12	1.12
(Day 3)	Boys Town (BT)	18	10344	First guess	9.0	9.0
(Day 3)	Boys Town (BT)	18	10344	3	0.88	0.70
(Day 3)	Boys Town (BT)	18	10344	2	0.28	-0.09
(Day 3)	Boys Town (BT)	18	10344	1	0.17	-0.17
(Day 4)	Barden Ridge (BR)	9	6300	First guess	9.0	9.0
(Day 4)	Barden Ridge (BR)	9	6300	2	4.58	4.58
(Day 4)	Barden Ridge (BR)	9	6300	1	4.11	4.11

CONCLUSIONS

The innovatite and efficient data assimilation (DA) method that has been recently developed in NCSR Demokritos for estimating an unknown emission rate of radionuclides in the atmosphere is evaluated using gamma dose rate measurements from the atmospheric dispersion experiment of Ar-41 that was carried out at the Australian Nuclear Science and Technology Organisation's (ANSTO) previous research reactor, HIFAR, located in Sydney, Australia. The area around the research reactor is characterized by moderately complex topography and spatially varying land cover. The experimental data base that is used for the purposes of the study covers various seasons during 2002-03. The method is based on assimilation of gamma dose rate measured data in the Lagrangian stochastic atmospheric dispersion model DIPCOT and uses variational principles. The DIPCOT model is used in the framework of the nuclear emergency response system (ERS) RODOS. In the DA runs performed in this study, the first guess source emission rate has been set by a factor of 10 greater than the true one. In all cases of DA runs the statistical indicators of errors of the estimated source emission rate as compared to the measured one were reduced. In all cases the estimated release rate approaches the real one to a very satisfactory degree as revealed by the statistical indicators of errors under all stability conditions except the most distant station BR with undulating terrain and small sample size where the results are less satisfactory. The data assimilation method is successfully evaluated against a complicated case, under a range of atmospheric stability conditions. There was only one monitoring station available each day, therefore even with assimilation of gamma dose rate measured data from only one monitoring station the DA method allows for substantial improvement of source rate. Therefore, the presented results demonstrate the potential of the developed data assimilation algorithm for application in operational nuclear emergency response systems.

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