Accepted for publication in the International Journal of Environment and Pollution

Radiation Source rate estimation through Data Assimilation of gamma dose rate measurements for operational nuclear emergency response systems

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Abstract: This paper presents an 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 the 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. In this paper the algorithm is evaluated against a more complicated case than others used in previous studies. There was only one monitoring station available each day. The area surrounding the reactor is characterized by moderately complicated topography and varying land cover. Overall the estimated release rate approaches the real one to a very satisfactory degree as revealed by the statistical indicators of errors.

Keywords: radiation source rate estimation, data assimilation, variational method, Lagrangian model, nuclear accidental releases

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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 or 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. (2011), and Tsiouri et al., (2012). In the latter work (Tsiouri, et al., 2012) 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 Ar-41 routine releases 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 Ar-41 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 the 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 the 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., 2011 and Tsiouri, V. et al., 2012). The main objective of the DA method is the minimization of the following cost function with respect to the control vector $\bar{\psi}$ which consists of the source rates corresponding to times of releases of puffs: $\bar{q}$.

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

Here $\bar{\psi}^b$ is the first guess estimation of the control vector, $\underline{\underline{O}}$, $\underline{\underline{B}}$ are the covariance matrices of the errors of the observations and the background errors respectively; the vector $\bar{d}^o \in R^{N_O K}$ consists of the gamma dose rates $d^o(n,k)$, measured on each time interval Δt_n by the 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 the stochastic Lagrangian atmospheric dispersion models, the control vector reduction technique explained in detail in Tsiouri V. et al, (2012) is used. This technique is based on the assumption that during small enough time interval Δt, the source rate can be considered as constant with sufficient accuracy. Then the 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 the 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 the 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 the source rate is assumed to be constant during the whole release interval. Instead of initial problem of minimizing equation (1) with respect to the control vector $\bar{q}$ consisting of the 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

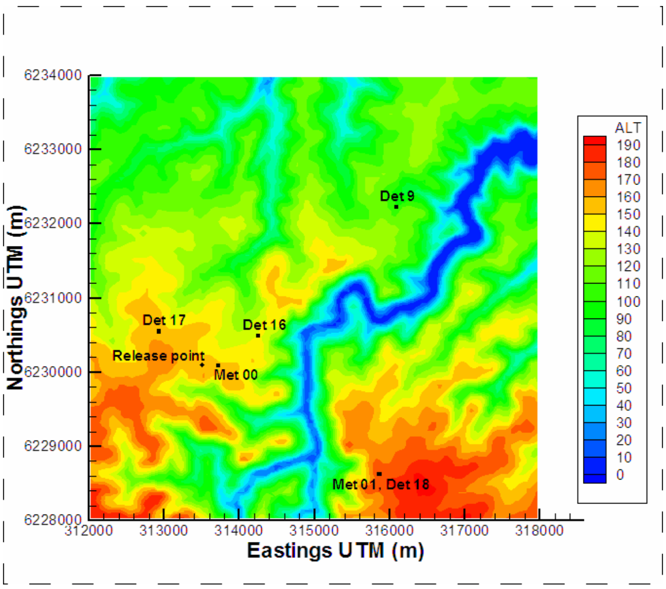
In the present work data assimilation runs are performed and the data assimilation algorithm is evaluated against the measured release rate from the Ar-41 database developed at the Australian Nuclear Science and Technology Organisation's (ANSTO) previous research reactor, HIFAR, located in Sydney, Australia. 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 Ar-41data base used for the 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 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 the DIPCOT model 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 the 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. A detailed description of the simulations is given in Table 1.

Table 1 The detailed description of the simulations.

Case (date)	**Station name/**	**Detector Point (Station #)**	**Distance from HIFAR(km)**	**Case details**	Tested Value of **P** /corresponding values of time intervals **(Δt)** during which the source rate is assumed to be constant
Day 1 (06/06/03)	Waste Services (WS)	17	0.73	Winter, unstable conditions	1,2 and 3/ Δt ~450,225,150 min
Day 2 (17/12/2002)	Main Gate (MG)	16	0.82	Summer, stable conditions	1,2 and 3/ Δt ~180,60,30 min
Day 3 (22/06/2003)	Boys Town (BT)	18	2.78	Winter, stable conditions	1,2 and 3/ Δt ~405,202,5,135 min
Day 4 (09/07/2003)	Barden Ridge (BR)	9	3.33	Winter, stable conditions	1,2 and 3/ Δt ~210,105,70 min

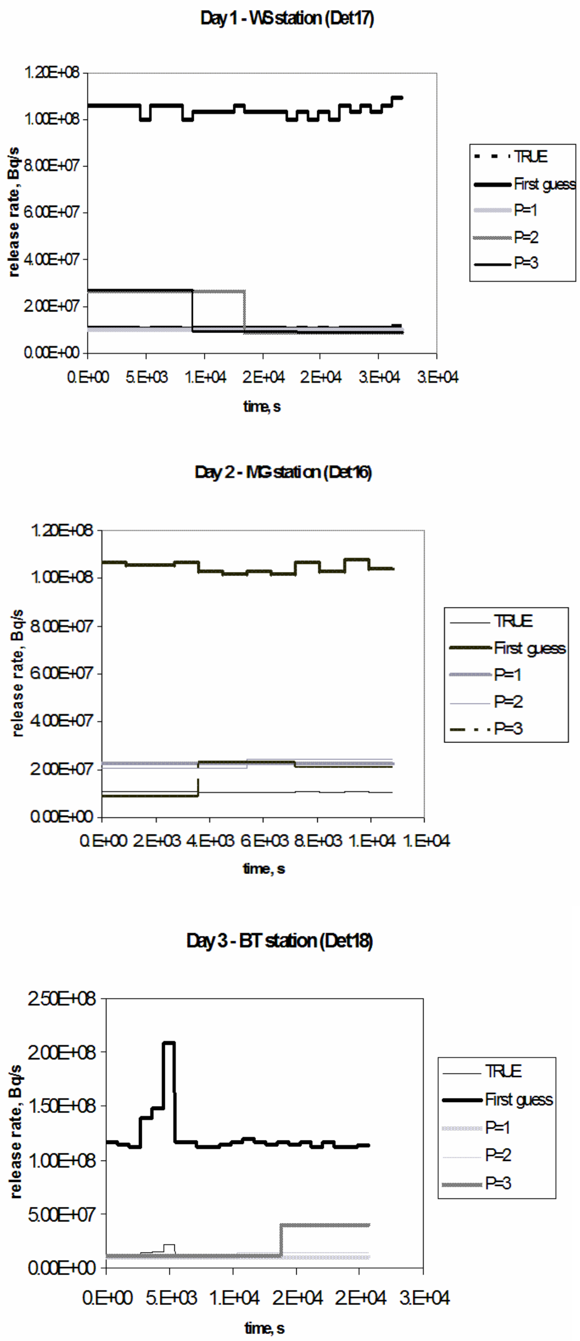
Figure 1 The computational domain with terrain elevation contours, the Ar-41 release location, the meteorological stations (Met00, Met01) and the gamma dose rate detectors (Det9, Det16, Det 17, Det18)

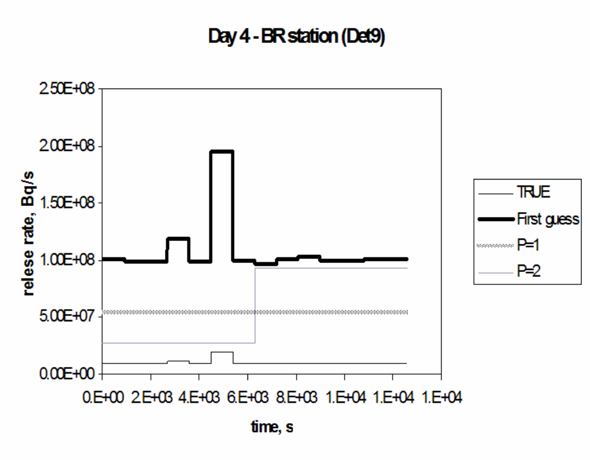


How efficient is the Dipcot model in estimating the unknown source rate with the implementation of the data assimilation algorithm can be clearly seen in Figure (2). Figure (2) presents the source emission rate estimations as result of the assimilation of gamma dose rate data for the cases of Day 1, Day 2, Day 3 and Day 4 in case of the stochastic version of DIPCOT against time. The source rate is estimated at fixed intervals over the release period of time depending on the tested value of P. Results with different number of groups P in control vector reduction procedure are presented. The true source rate is known but we supposed we don't know it and an arbitrary value of it was taken (10 times more). As it can be seen from figure (2) the algorithm managed to estimate the unknown source rate. 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 Day 1 (Det 17), Day 2 (Det 16) and Day 3 (Det 18) cases under all stability conditions. For Day 4 (Det 9) because of the small sample size the results are less satisfactory, but even in this worst case the algorithms improves the source rate. It is important to refer that 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.

This qualitative result is confirmed with the results of the mean relative absolute error (MAE) and the mean relative bias (MRB) presented in the Table 2 ($MAE = \langle |q^a - q^t| \rangle / \langle q^t \rangle, MRB = \langle q^a - q^t \rangle / \langle q^t \rangle$), where q is the source function, $\langle \ \rangle$ means averaging, superscripts 'a' and 't' denote the analyzed and the true source function respectively). The results obtained by the stochastic version of DIPCOT at a time interval $\tau \approx 2s$ for Day 1, Day 2, Day 3 and Day 4 cases and with different values of the CVR parameter P are presented in the Table 2. The Results by setting the time interval that the puffs were released to $\tau \approx 4s$ are also presented for the Day 1. Generally as follows from these results in all cases the analyzed source rate in the assimilation runs is much better than the first guess function even if in the forward run (e.g. Day 4) 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 2 (for Day 1 case).

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





Conclusions

The innovative 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 Ar-41 routine releases 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 Ar-41 data base that is used for the purposes of the study covers various seasons during 2002-03. The method is based on the 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. Even for the Day 4 (Det 9) with small sample size the algorithm improves the source rate. 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.

Table 2 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.

Case	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

Title

Acknowledgments

This paper is a revised and expanded version of a paper entitled [Radioactive material release rate estimation through Data Assimilation of gamma dose rate measurements] presented at the 14th International Conference on *Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Kos (Greece), October 2-6, 2011."

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