RADIOACTIVE MATERIAL RELEASE RATE ESTIMATION

THROUGH DATA ASSIMILATION OF GAMMA DOSE RATE MEASUREMENTS

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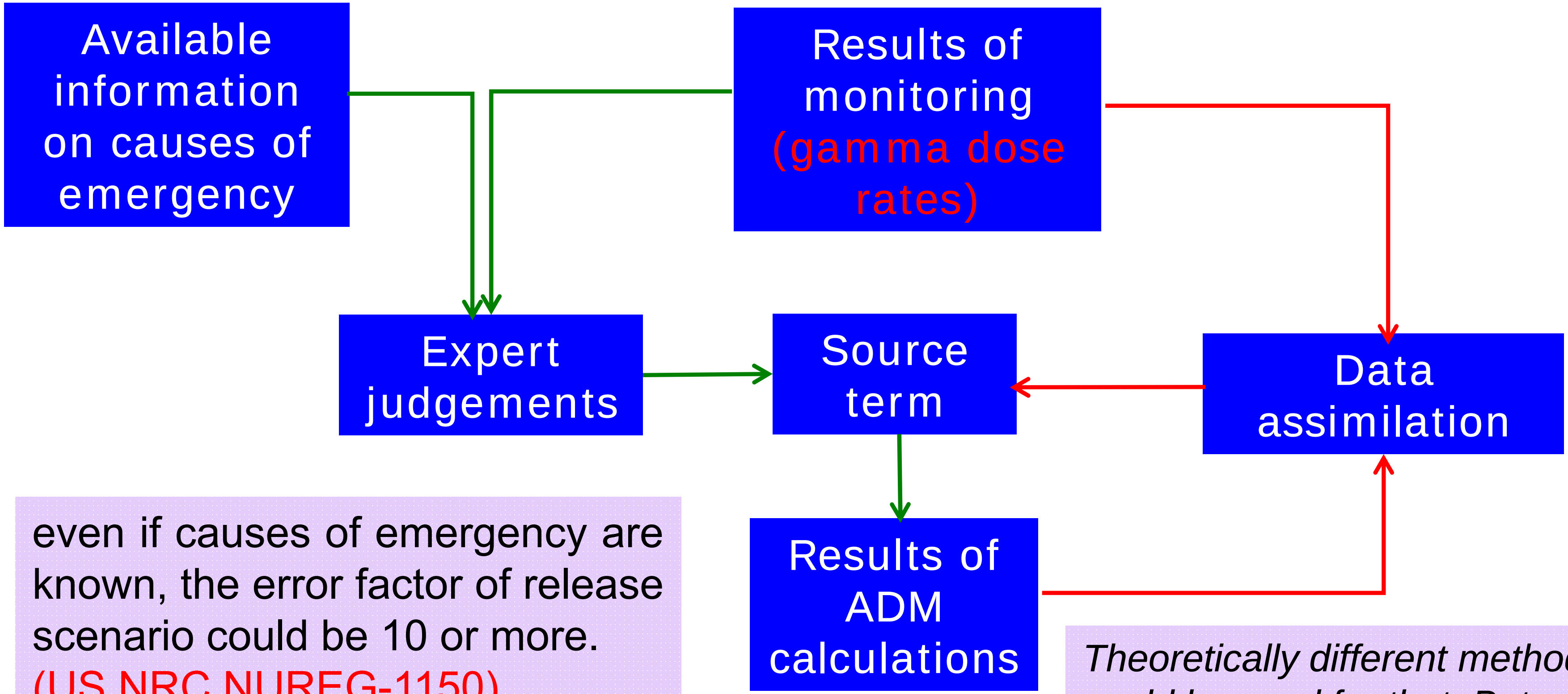
Source term assessment in emergency phase

- If a nuclear accident occurs, estimation of radionuclide dispersion should be produced immediately. In order to do this one has to **specify the source term**

- It is known that in emergency phase uncertainty in source term could be very large and dominates all other uncertainties.

Source term assessment in emergency phase



even if causes of emergency are known, the error factor of release scenario could be 10 or more. (US NRC NUREG-1150)

atmospheric dispersion model could be used in data assimilation mode in order to improve the input source information.

Theoretically different methods could be used for that. But because of complexity of the problem still very few emergency response systems have such methods implemented operationally.

Objective of the study

To **evaluate** 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 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 RODOS, the real-time European nuclear **emergency response system** (ERS).

Description of the DIPCOT

Stochastic version (Lagrangian puff) (Andronopoulos, et.al., 2009)

Particles are assumed to follow the mean and fluctuating wind flow

$$x_i^{n+1} = x_i^{n} + \left(\overline{u_i} + u_i'\right)\tau$$

Turbulent velocity fluctuations are based on the assumption that turbulent diffusion can be modelled as a Markov process, using Langevin equation

Concentration calculations: Gaussian-shaped density kernel (Yamada and Bunker 1988)

$$C(x_o, y_o, z_o, t) = \frac{1}{(2\pi)^{3/2}} \sum_{i=1}^{N} \frac{q_i \tau \exp\left(-\lambda\left(t-(i-1)\tau\right)\right)}{\sigma_x \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\frac{(x_i - x_o)^2}{\sigma_x^2}\right)$$
$$\exp\left(-\frac{1}{2}\frac{(y_i - y_o)^2}{\sigma_y^2}\right)\left\{\exp\left(-\frac{1}{2}\frac{(z_i - z_o)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2}\frac{(z_i + z_o - 2z_g)^2}{\sigma_z^2}\right)\right\}$$

Gamma dose calculation :

$$\dot{D}_\gamma = \sum_{n=1}^{N_p} \sum_{nu=1}^{N_{nucl}} \sum_{ig=1}^{4} f_{ig,nu} \frac{\mu_{\alpha,ig} E_{\gamma,ig,nu}}{\rho} \Phi_{n,nu,ig}$$

$$\Phi_i\left(0,0,h_i\right) = \frac{1}{4\pi} \frac{Q_i}{\sigma'_{xi}\sigma'_{yi}\sigma'_{z_i}} \frac{1}{\mu}\left(A_1 + \kappa A_2\right)$$

Data assimilation algorithm

Variational formulation of DA

1.Control variables: source rates at release time of each puff

$$\mathbf{q} = (q_1, q_2, \ldots, q_{NP})^T$$

2.Cost function to be minimized:

$$J_1 = \sigma_B^{-2}(\bar{q} - \bar{q}^b)^T(\bar{q} - \bar{q}^b)$$

$$J_2 = \sigma_O^{-2}(\bar{d}^o - \underline{\underline{G}}\bar{q})^T(\bar{d}^o - \underline{\underline{G}}\bar{q})$$

$$J = r_{rel}(\bar{q} - \bar{q}^b)^T(\bar{q} - \bar{q}^b) + (\bar{d}^o - \underline{\underline{G}}\bar{q})^T(\bar{d}^o - \underline{\underline{G}}\bar{q})$$

$$r_{rel} = (\sigma_O / \sigma_B)^2$$

Subject to $\bar{q} \geq 0$

- **The first part describes** the distance of the analyzed source function (which we want to find) from the first guess (or background) estimation.

- **The second part describes** the distance of the calculated gamma dose rates from the measurements.

- **Both parts** are weighted with the corresponding errors of measurements and of the background estimation.

Data assimilation algorithm

It could be easily established that gamma dose rates are linearly related to vector of source rates. Therefore exists the <G matrix> which could be multiplied on <q> to give vector of gamma dose rates.

Calculation of elements of the matrix G:

The *following formula for the elements of that G-matrix could be derived from the corresponding relationship for gamma dose rates calculations which was presented above.*

$$g_{li} = \frac{1}{4\pi}\sum_{ig=1}^{4} f_{ig}\,\frac{\mu_{\alpha,ig}E_{\gamma,ig}}{\rho\mu}\,\frac{\left[\tau\exp\left(-\lambda\left(t_l-(i-1)\tau\right)\right)\right]}{\sigma'_{xi}\sigma'_{yi}\sigma'_{zi}}\left(A_{1,ig,i,l}+\kappa_{ig}A_{2,ig,i,l}\right)$$

Then is used in minimization procedure with standard minimization software in order to find the optimal vector of source rates.

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** is used.

Control vector reduction

The basis of this technique is the observation that when source function is specified for every reasonable release scenario it is assumed to be constant through large enough release intervals roughly varying from 10 minutes to 10 hours. But time interval between puff's releases is much smaller and it varies from less than 1 s to 100 s.

In operational practice: $\Delta t \sim 10^3 \div 10^4 s$ $\tau \sim 0.1 \div 100 s$ → $\Delta t / \tau = \Pi >> 1$

- Puffs could be combine in P=N_p/Π groups so that all puffs were released with the same release rate.
- Control vector $\underline{\tilde{q}}$ of release rates could be reduced to the the size P.
- Elements of $\underline{\tilde{q}}$ represent source rate for each group of puffs.
- Formula for calculating the reduced G-matrix $\underline{\underline{G}}^r$ from the original G-matrix could be easily established:

$$g_{lj}^r = \sum_{m=1}^{\Pi} g_{l((j-1)\Pi+m)}, \forall l, 1 \le l \le N_o K, 1 \le j \le P$$

From Central Limit Theorem and following the condition Π>>1 elements g_{lj}^r of the reduced G-matrix converge to statistically stable values

Results of validation against the field measurements

- We validated our data assimilation procedure against measurements from the atmospheric dispersion experiment of Ar-41 carried out at the Australian Nuclear Science and Technology Organisation's (ANSTO) previous research reactor, HIFAR, located in Sydney, Australia.
- 16 different cases are simulated that cover winter and summer periods of the years 2002 and 2003

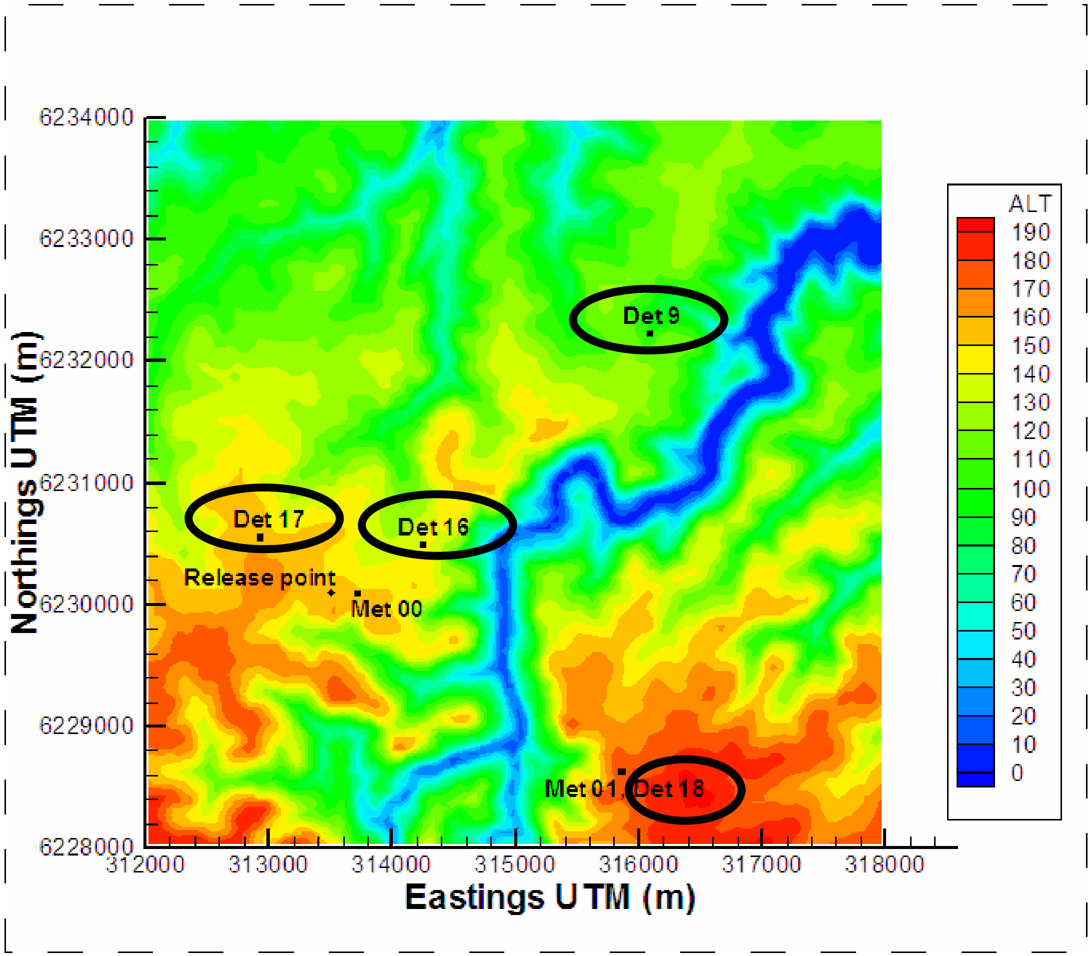
Available measurements

- measured ^{41}Ar emission rate from the stack
- meteorological data by a weather mast
- Data of the gamma radiation field

Basic setup of DIPCOT

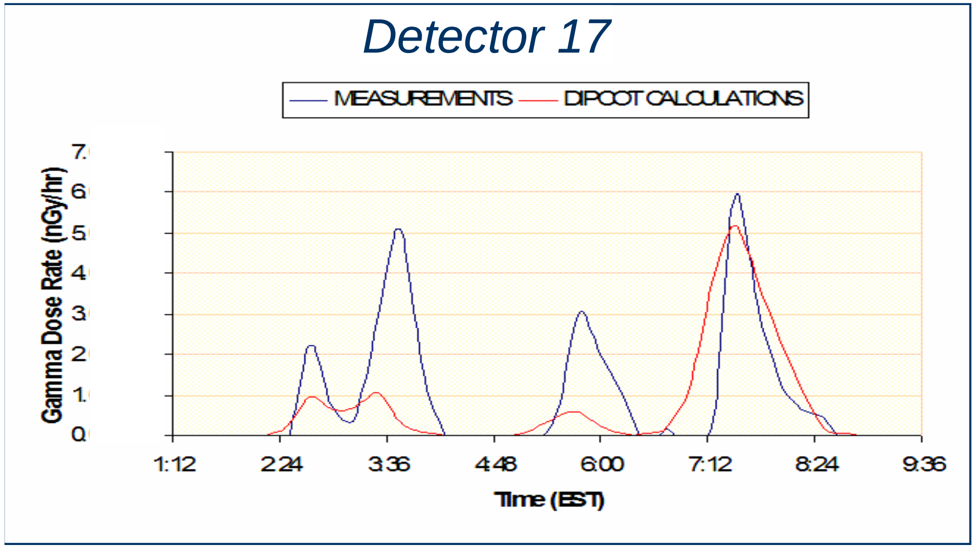
- In DIPCOT runs puffs were released each 2 and 4 seconds.
- First guess source function was by the factor of 10 greater than the true;
- Data assimilation runs with stochastic version of DIPCOT were performed and the number of groups <P> representing source functions varied.

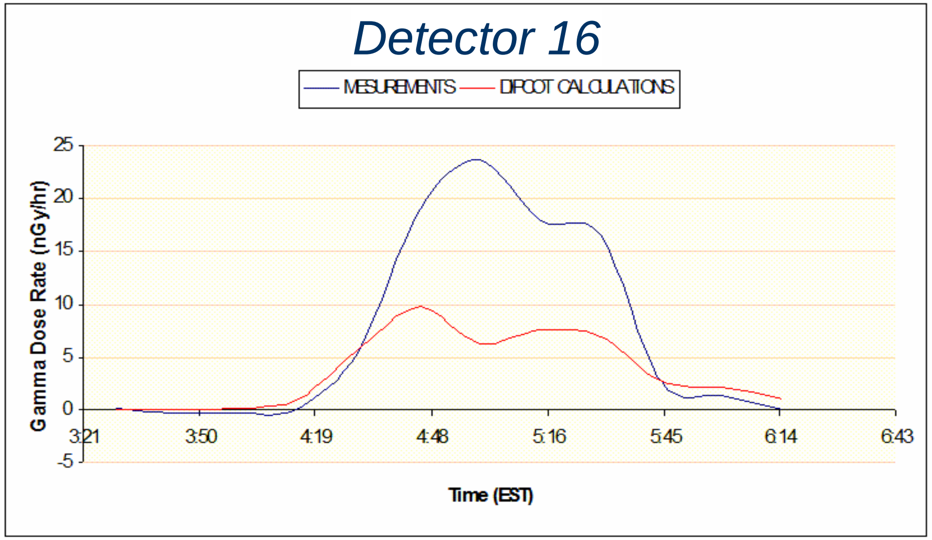
Map of Sensors locations in ANSTO experiments

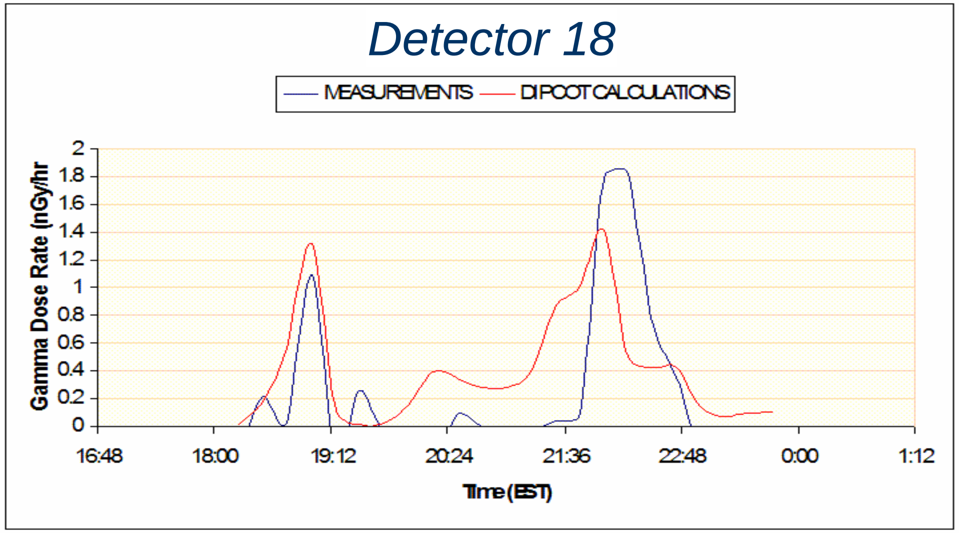


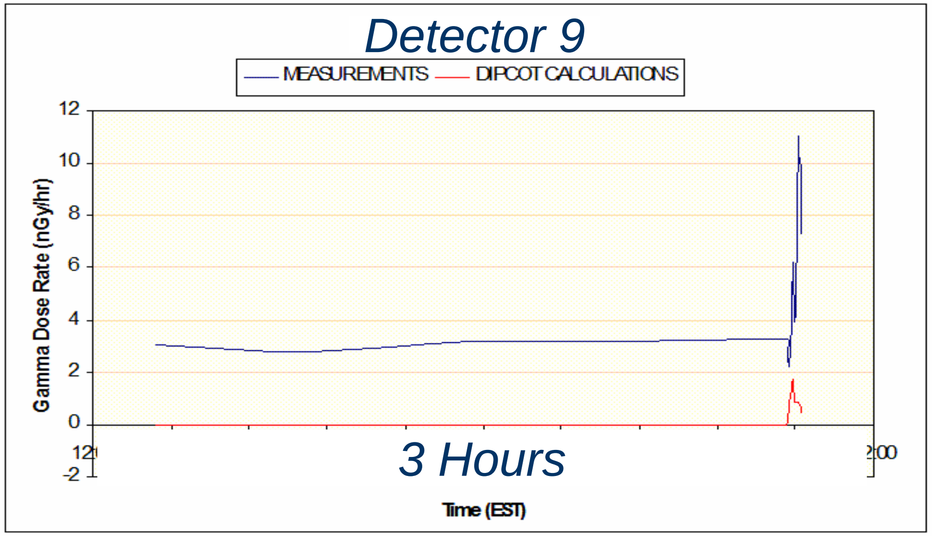
- The computational domain with terrain elevation contours
- The Ar-41 release location
- The meteorological stations (Met00, Met01)
- The gamma dose rate detectors (Det9, Det16, Det 17, Det18)

Comparison of Dipcot gamma dose rate calculations in forward run against measurements.









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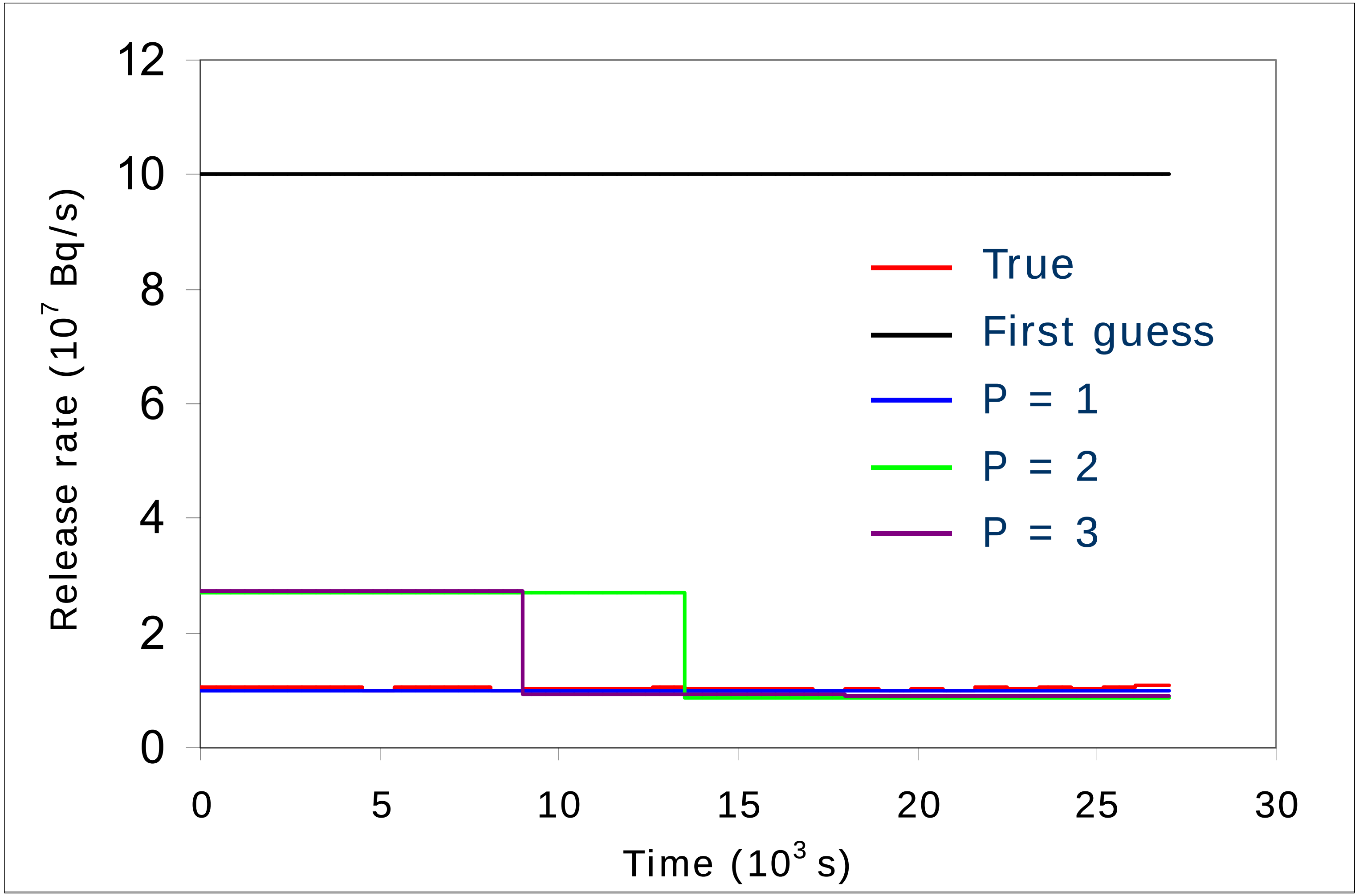
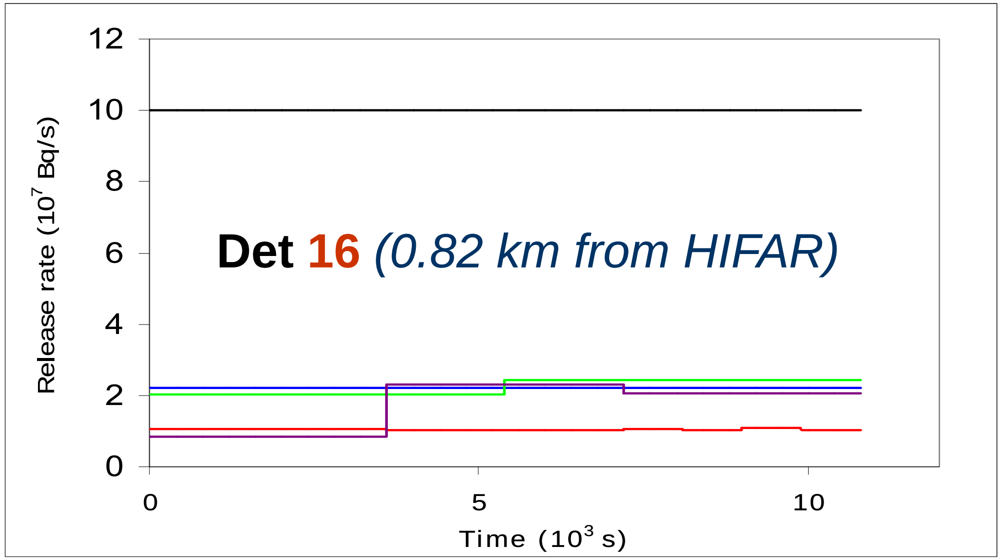
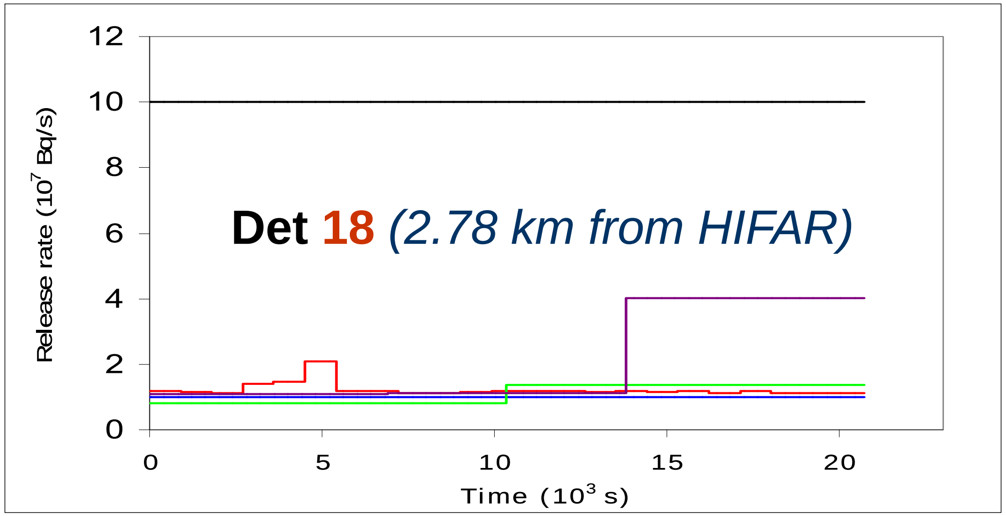
Source rate estimations as result of assimilation of gamma dose rate – Det 17 *(0.73 km from HIFAR)*



Source rate estimations as result of assimilation of gamma dose rate

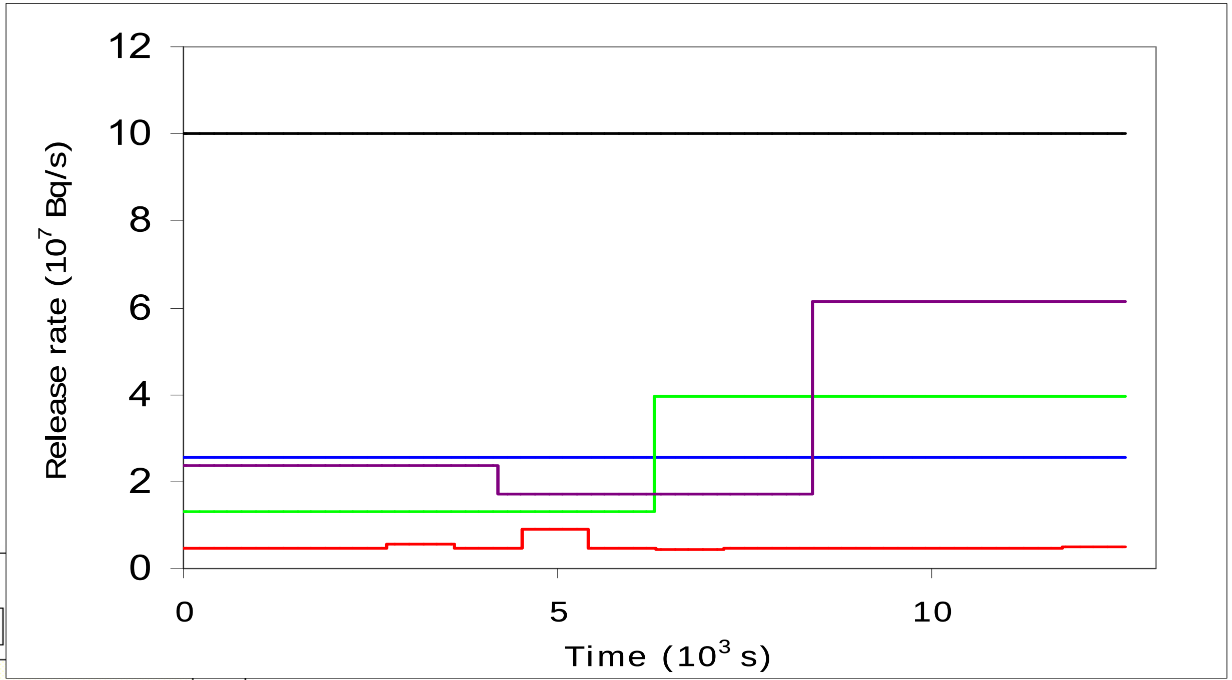


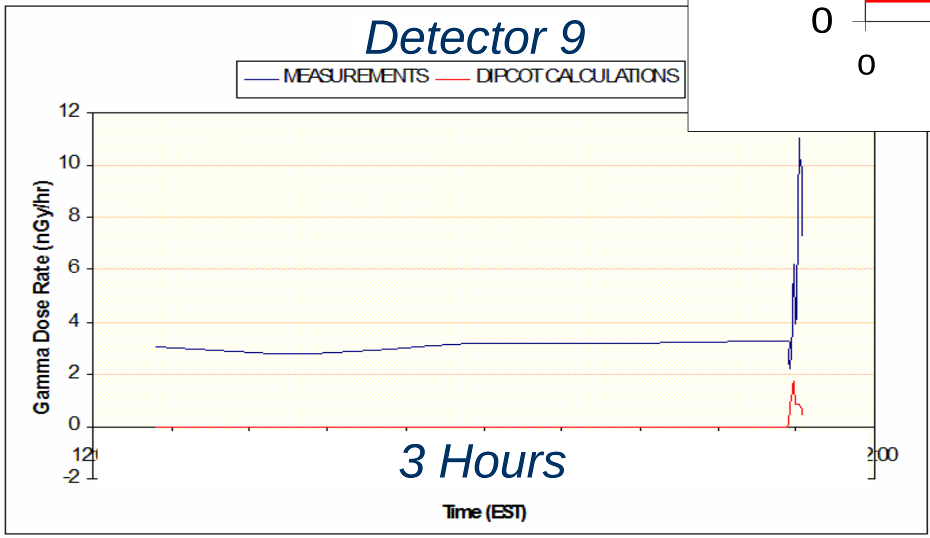


True
First guess
P = 1
P = 2
P = 3

The results obtained for detectors 16 and 18 reveal the same level of improvement of the analyzed source function in comparison with the first guess.

Source rate estimations as result of assimilation of gamma dose rate – Det 9 *(3.33 km from HIFAR)*





Even in this worst case the algorithm improves the source rate.
DIPCOT in forward run, no satisfactory forecast

Statistical indicators of errors in s.f. estimation

Qualitative conclusions are supported with the statistical indicators of errors

$$MAE = \langle |q^a - q^t| \rangle / \langle q^t \rangle$$

$$MRB = \langle q^a - q^t \rangle / \langle q^t \rangle$$

Detector point 17

P	MAE	MB
First guess	9.0	9.0
3	0.62	0.46
2	0.86	0.71
1	0.06	-0.06

Detector point 16

P	MAE	MB
First guess	9.0	9.0
3	0.80	-0.67
2	1.12	1.12
1	1.12	1.12

Detector point 18

P	MAE	MB
First guess	9.0	9.0
3	0.88	0.70
2	0.28	-0.09
1	0.17	-0.17

The statistical indicators of the analyzed source function as compared to measured were calculated

The errors of the first guess estimation is also presented in tables

Detector point 9

P	MAE	MB
First guess	9.0	9.0
3	5.33	5.33
2	4.11	4.11
1	3.92	3.92

As it follows from the data in Tables in all cases level of improvement of the source function with data assimilation is good.

Conclusions

- The data assimilation method that has been recently developed in NCSR Demokritos for estimating an unknown emission rate of radionuclides in the atmosphere was evaluated.

- 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 with less satisfactory results for the detector 9 with small sample size.

- The data assimilation method is evaluated against a complicated case, under a range of atmospheric stability conditions having data from only one gamma dose detector each day. Therefore, the DA method allows for substantial improvement of source rate.

Thank you for your attention!