# Simulation of Random 3-D Trajectories of the Toxic Plume Spreading over the Terrain

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## The objectives of examination of aerial toxic discharges propagation

In the early phase of an accident the cloud is drifting over an observed area and noxious agents (e.g. radionuclides) are depleted due to the various removal mechanisms. The primary quantity of interest is 3-D distribution of harmful admixture concentration in the air on basis of which all other values in a respective release phase can be derived. Important indirect derived variables are for example *time integral of the radioactivity concentration in ground-level* of the air and *radioactivity deposited on the ground*. Both quantities can be perceived as a certain projection of the primary 3-D concentration field into 2-D and on their basis health risk on population is estimated. The submission resumes an advance in modeling practice and experience from perspective of transition from former deterministic methodology in direction to *probabilistic approach* of consequence prognoses and *data assimilation*. The latest result of investigations is development and application of a pivot algorithm constituting a kernel which is repeatedly recalled during the sampling process of random trajectory realizations. It provides a proper bases for:

- **Sensitivity study** – enables ranking of random model parameters according to their importance
- **Uncertainty analysis** – providing the model error covariance structure with further extension to probabilistic approach in an accident consequence assessment
- **Data assimilation of model predictions with real observations from terrain** – computationally tractable even for extensive online Bayesian tracking of the plume trajectory progression.

## Segmented Gaussian Plume model (SGPM) of aerial transport

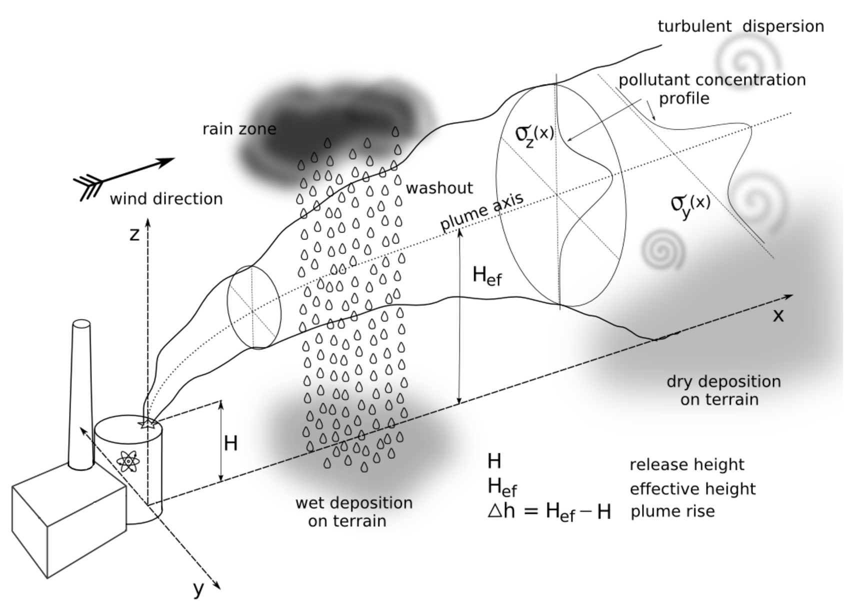


**Figure 1.** *Illustration of complex phenomena during propagation of harmful substances discharged into atmosphere.*

Synchronization of release dynamics with meteorological forecast is accomplished. Real dynamics of accidental release is transformed into an equivalent number G of homogeneous 1-hour segments. Movement of each segment is driven by short-term meteorological forecast for corresponding hour of propagation. Shape of the segment spreading is simulated by "'Gaussian droplet"' coming out from simplified solution of diffusion equation. Total movement of partial Gaussian segment within one-hour interval is modeled as a sequence of K partial elemental shifts $k$ ($k \approx 30 \div 50$). Decrease of activity concentration within the elemental shift $k \rightarrow k+1$ of the droplet can be described schematically by separation of pure dispersion component $C^{disper}$ and so called source depletion factors:

$$\Delta C\,(k \rightarrow k+1) = \Delta C^{disper}\,(k \rightarrow k+1) \times \times \Delta f_R^{k \rightarrow k+1} \times \Delta f_F^{k \rightarrow k+1} \times \Delta f_W^{k \rightarrow k+1} \qquad (1)$$

Depletion factors with indices $R, F, W$ stand for radioactive decay, dry deposition (fallout) and potential washout due to atmospheric precipitation. Each hourly segment g is consecutively modeled in its all hourly meteorological phases f (f=1,...,F(g) ) and output vector $s_{TOTAL}$ of values of interest is superposed from the particular segment-phase outputs $s^{\{g;f\}}$ as:

$$s_{TOTAL} = \sum_{g=1}^{g=G} \left[ \sum_{f=g}^{F(g)} s^{\{g;f\}} \right] \qquad (2)$$

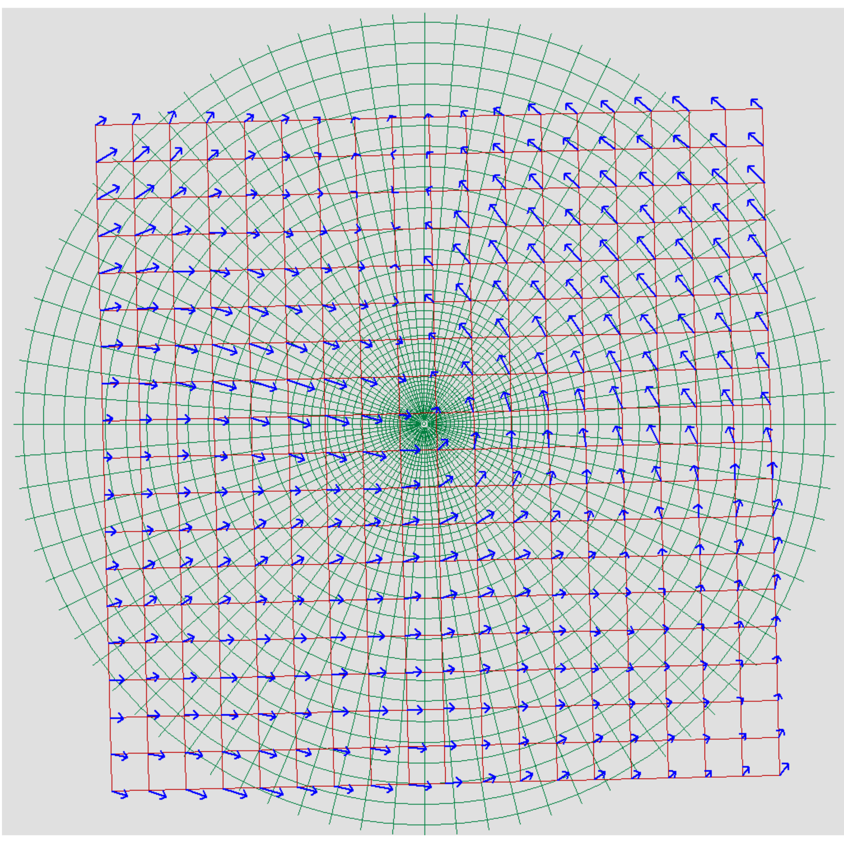

**Figure 2.** *3-D meteorological forecast of wind field in vicinity 160 × 160 km around a hypothetical source of pollution.*

## From deterministic calculations to probabilistic approach

Recent trends in risk assessment methodology insist in transition from deterministic procedures to probabilistic approach which enables to generate more informative probabilistic answers on assessment questions. Corresponding analysis should involve uncertainties due to stochastic character of input data, insufficient description of real physical processes by parametrization, incomplete knowledge of submodel parameters, uncertain release scenario, simplifications in computational procedure etc. Simulation of uncertainties propagation through the model brings data not only for the probabilistic assessment (see next figures 4 and 5), but also for another main task of analysis called assimilation of the model predictions with real measurements incoming from terrain.

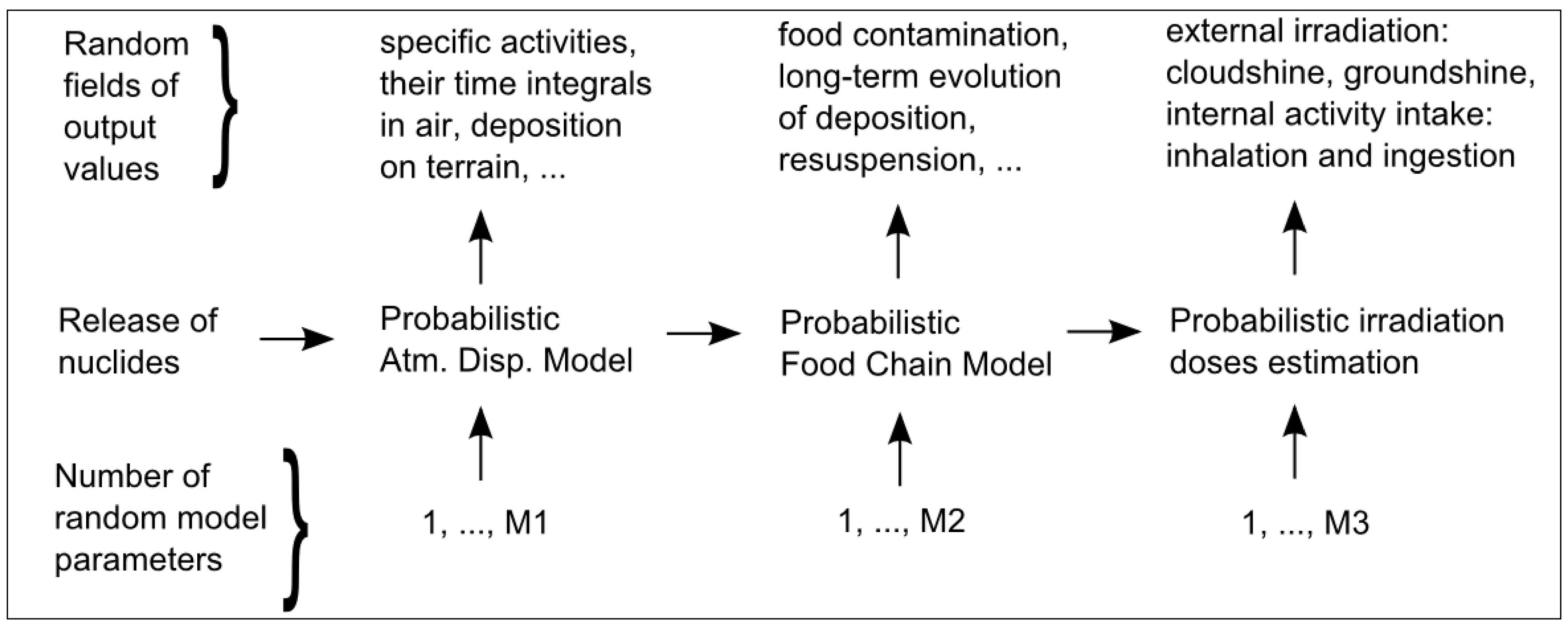


**Figure 3.** *Model chain for probabilistic estimation of random quantities of interest.*

Computational simulation $\Re^{SGPM}$ based on $SGPM$ approach enables to express random 3-D trajectory $\mathbf{X}_{Tr}$ ("particle", sometimes called also background vector) according to the parametrization: $\mathbf{X}_{Tr} \approx \Re^{SGPM}(\Theta_1, \Theta_2, \ldots, \Theta_K; [\alpha_j^{fixed}]_{j=1,\ldots,J})$. $\alpha_j$ are fixed parameters. For atmospheric dispersion model, the random parameter vector $\Theta$ is specified as:

$$\mathbf{X_{Tr}}(t = t(G,F)) = \Re^{SGPM} \left( \begin{bmatrix} q_{g=1} \\ q_{g=1} \\ q_{g=3} \\ \vdots \\ q_{g=G} \end{bmatrix}; \sigma_y;\ v_g;\ \begin{bmatrix} (u,\varphi)_{f=1} \\ (u,\varphi)_{f=2} \\ (u,\varphi)_{f=3} \\ \vdots \\ (u,\varphi)_{f=F} \end{bmatrix}; \ldots \right) \qquad (3)$$

The parameters have physical meaning. $q_g$ stands for radioactivity released during hourly segment $g$ $[Bq.hour^{-1}]$, plume horizontal dispersion is proportional to $\sigma_y$ $[m]$, $v_g$ describes dry deposition velocity $[m.s^{-1}]$, $(u,\varphi)_f$ represents wind speed and direction forecast for hour $f$ after the release start.

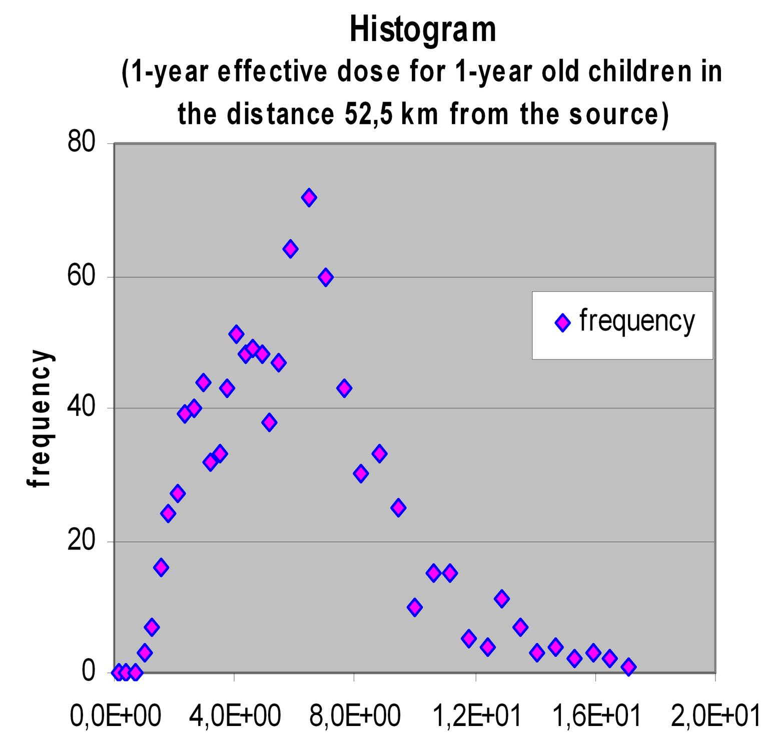


Fig. 4: Frequency of dose [ mSv / year]

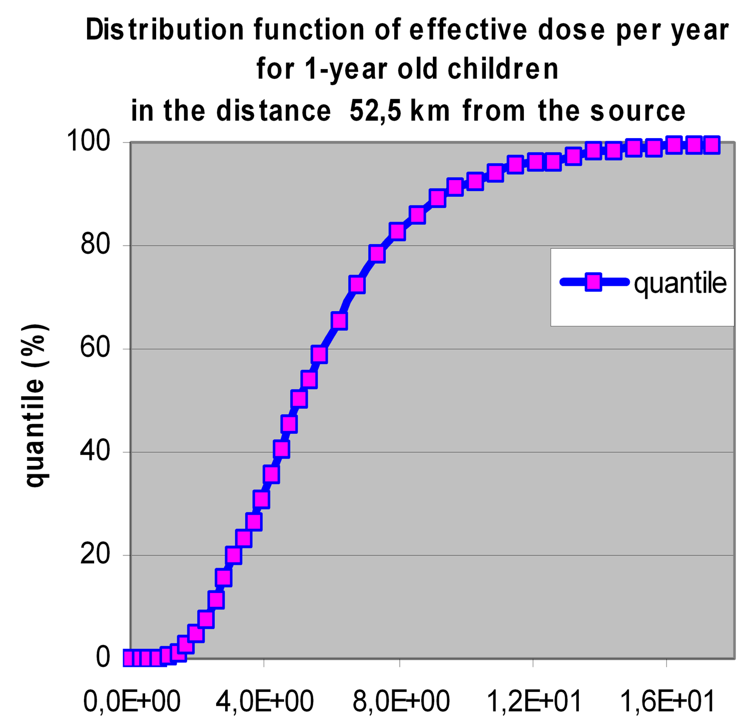


Fig. 5 : CDF of dose [ mSv / year]

## Data assimilation (DA): From model to reality

Detailed predictions of pollution infiltration into the living environment and propagation of uncertainties through the model is inevitable prerequisite for application of advanced statistical methods for assimilation of observations incoming from terrain with model results. The techniques are based on **optimal blending** of all information resources including prior physical knowledge given by model, observations incoming from terrain, past experience, expert judgment and intuition. Advanced DA techniques account for time evolution of forecast and model error covariance structure.

Real scenario of radioactivity dissemination represents complex problem, which requires a good degree of understanding and ad hoc developments. The most complicated is assimilation process during the early phase of radiation accident when advanced statistical techniques have to be applied (e.g. particle filtering method mentioned in the next paragraph).

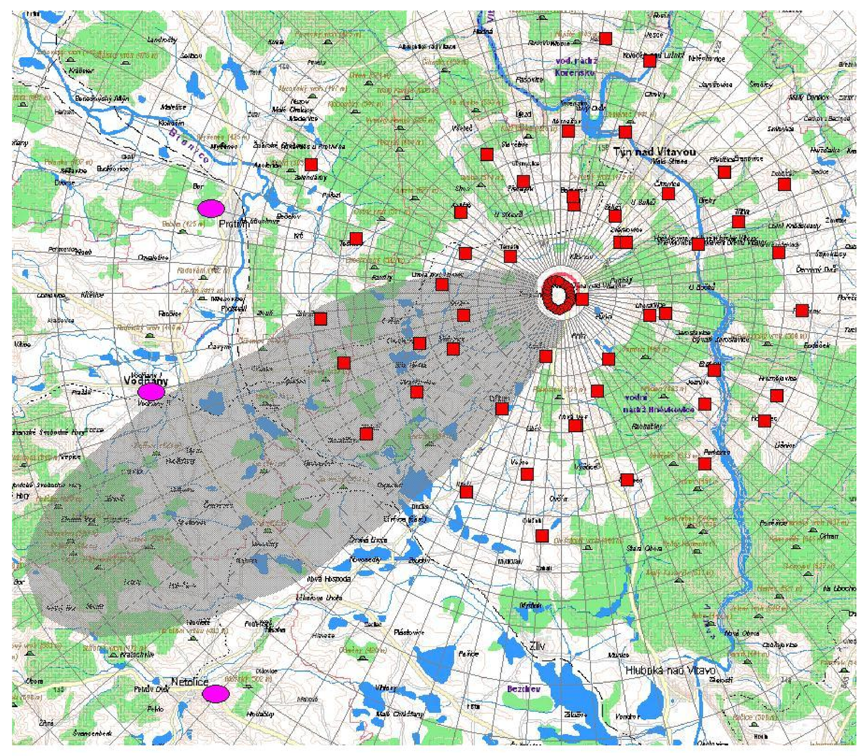

**Fig. 6: Parts of Radiation Monitoring Network around NPP Temelin**

inner teledosimetric circle on NPP-fence (24 sensors) · outer II. circle of receptors · randomly located mobile stations

## Bayesian tracking of the plume in the early stage of accident

Tracking in Bayesian concept insists in recursive evaluation of the state posterior probability density function (pdf) based on all available information. Ex post retrospective analysis for atypical meteorological situation is presented in the article. For selected date March 31, 2009 and $^{131}I$ release started at 10.00 CET has been found, that the real meteorological measurements and short term forecast are not in a good agreement. Deterministic model prediction 2 hours forward with "'best estimate"'values of model parameters is given in Fig. 7, left (short term meteorological forecast is used). Repeating the same calculation for meteorological values measured in the first 2 hours, the deposition will be located inside shadow contour in Fig. 6. The differences are evident. The following steps of assimilation in the same beginning of release are proposed:

- The assimilation process is initialized by estimation of prior pdf (probability density function) $p(X(t_1 = 2hours))$ standing for just 2 hours after the release start, but so far no measurements are available. The expectations of the prior pdf are given in Fig. 7, right.
- Assuming the measurements $y(t_1)$ incoming from terrain just at t=2 hours , the marginal posterior density $p(X(t_1)|y(t_1))$ using Bayes rule and PF resampling algorithm is simulated. The expectations of the posterior distribution illustrated in Fig. 8 are evidently approaching close to the observation trajectory (see also the shadow contour in Fig. 6), which was selected for generation of "'artificial"' measurements (the principle is known as twin experiment).

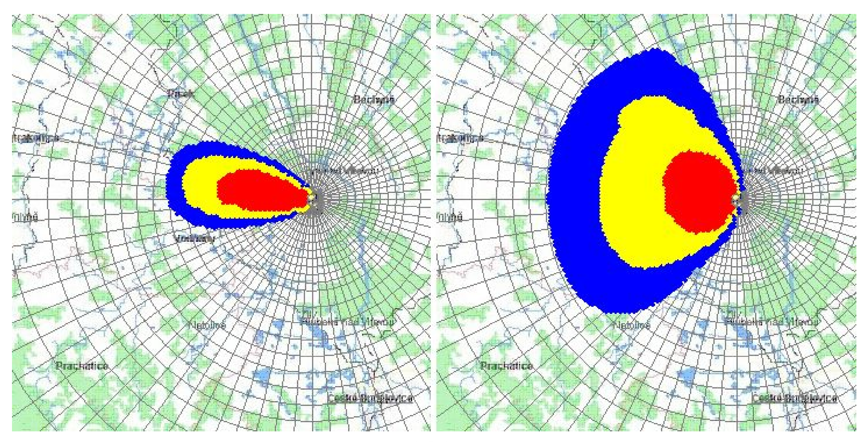

Figure 7: *Deposition of $^{131}I$ on terrain just 2 hours forward. Best estimate prediction (left), expectations of prior pdf (right - estimated on basis of samples of random parameter vector $\Theta$).*

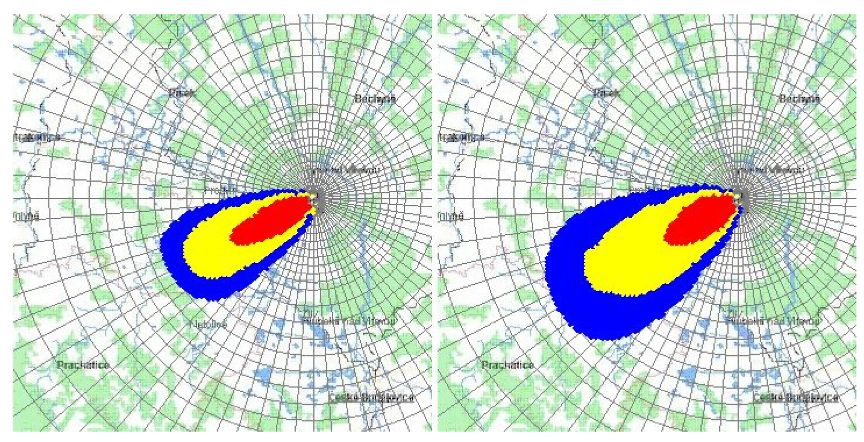

Figure 8: *Expectations of posterior pdf after measurements assimilation in hour 2. Small measurement errors (left), higher measurement errors (right).*

### Acknowledgment

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