Nesting of Data Assimilation Cycles into the Recursive Model Predictions

Petr Pecha [1] , Petr Kuča [2]

[1] Institute of Information Theory and Automation of the ASCR, Prague
[2] *National Radiation Protection Institute, Prague, Czech Republic*
pecha@utia.cas.cz
petr.kuca@suro.cz

Abstract

The paper addresses the important problem of model errors impact on attempts for realistic modelling of pollution propagation in the atmosphere. The mathematical model always remains only a simplification of the complex physical phenomena and a significant extent of the uncertainties involved can degrade credibility of the model predictions. The article itemizes particular sources of the model errors and illustrates the influence of variability of the most important meteorological inputs. Stochastic character of the task calls for introduction of advanced statistical assimilation techniques based on merging of all available associated information including real observations incoming from terrain.

Keywords: *radioactivity propagation, meteorological forecast, data assimilation, filtering*

1. Introduction

Typical transport periods of radioactive cloud drifting according to atmospheric conditions over the terrain are several hours or a few tens of hours. Within this short interval of the early stage of accident the prompt launching of protective actions should be activated. The primary interest of a decision maker is to be provided immediately by realistic picture of radiological situation and its short term forecast [5]. Introduction of urgent countermeasures on population protection in case of erroneously anticipated areas can have fatal health and social consequences. Then, reliable and up to date information represents basic inevitable condition for effective management of intervention operations targeted on consequence mitigation during emergency situations.

Physical model of pollution propagation through the living environment affords valuable prior knowledge. An experience accumulated in physical models by hundreds of years of refinement of theories brings significant contribution to the system state description. But fundamental limitations of a physical model exists. For instance Jean-Philippe Drécourt in [1] explains:

*...”Until the beginning of the XXth century, it was believed that models could become so precise and so complex that it would be possible to predict the behaviour of any system, simply by calculating for long enough. The use of mechanic calculation and the improvement of scientific knowledge made people extremely confident in the power of mathematics and what we call today **deterministic modelling** to reach any level of precision. Lately it became clear that we would not be able to describe the world at any level of precision. The models, that we were so proud, proved to be too simple to represent the behaviour of a world that is in all its aspects fractal and chaotic. It is impossible to get a clear picture of the whole system either because it is hidden, or the system is so complex that we cannot model it without making assumptions that have negative impact on the accuracy of the model”...*

Within the frame of applied dispersion models, many uncertainties related to imperfections of both conceptual model (parameterization errors, uncertain submodel parameters, stochastic nature of some input data) and computational scheme (step of computation net, averaging land-use characteristics, averaging time for dispersion parameters, uncertainty in release scenario etc) are involved. In consequence of the inherent uncertainties the output radiological quantities have a random character.

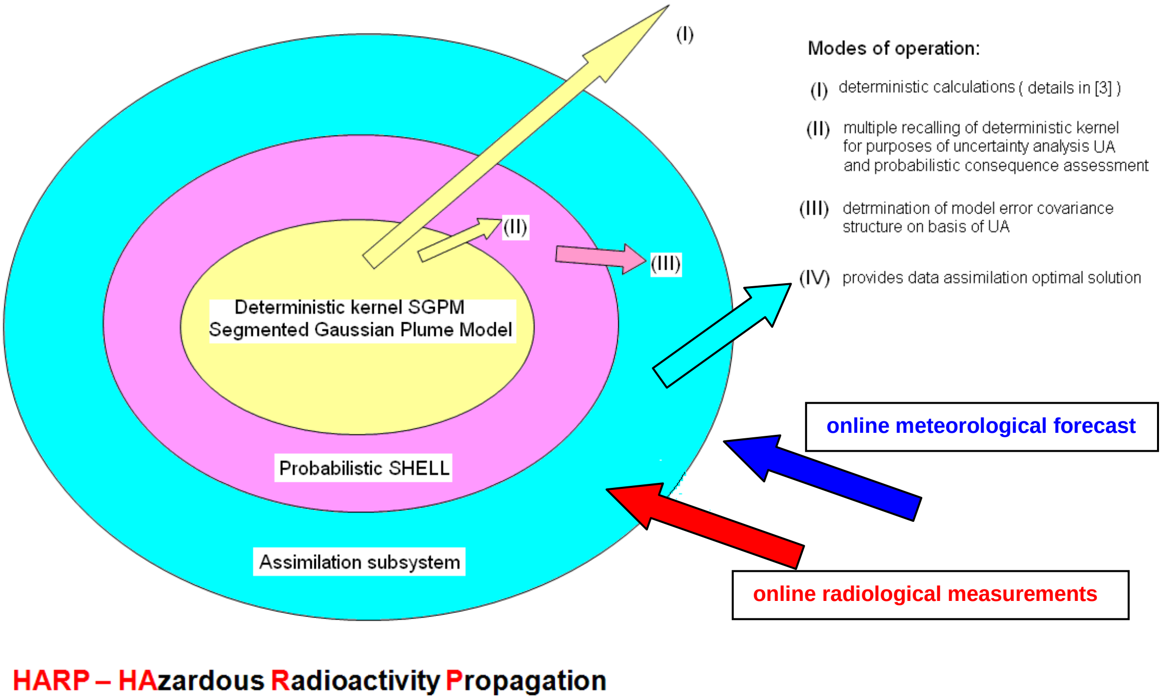

Image No. 1 Scheme of the environmental model HARP [2]

Here we are introducing advanced environmental software HARP [2] (see Image 1) incorporating assimilation subsystem which brings together all available information. Several important sources of information which can improve predictions of the system state comprises the basic physical knowledge provided by the physical model (e.g. time and space evolution of radioactivity concentration in the air, activity deposited on the ground, propagation through the food chains towards human body). Assumptions related to the random characteristics of the model inputs or assessment criteria can be supported by some kind of expert judgements. Substantial benefit can result from accessibility of data incoming from terrain. Each such resource can be known on a certain degree of details (e.g. a level of sophistication of the environmental model, dense or rare measurements in space and time, cases with indirect observations, complete or only partial knowledge of model error covariance structure). Merging of all these contending resources for purposes of improvement of predictions is a principle of assimilation and had shown to be very promising in many branches of contemporary Earth sciences.

2. Multi-purpose application of the environmental code HARP

The main objective of development and application of the environmental system HARP is **improvement of reliability of the model predictions** on basis of assimilation with measured data incoming from terrain and further information. Specifically, the progression is now accomplishing in UTIA AV ČR under auspices of the project of Safety Research provided by Ministry of the Interior of the Czech Republic, project No. VG20102013018. System is tested in close cooperation with National Radiation Protection Institute (SÚRO) in Prague using archived data (2009-2010) for both meteorological forecasts and radiation measurement. At the same time, an ability of the system to use on-line meteorological forecast and radiation measurements from the Early Warning Network (part of the Radiation

Monitoring Network of the Czech Republic) available in SÚRO in case of an emergency situation is also tested.

Besides the main purpose, the deterministic kernel of the code can provide various kinds of outputs, specifically:

- Standalone deterministic analysis of certain important accident scenarios (**worst-case analysis**, design bases accident (DBA) examination, analysis of various postulated accidents necessitated for Safety reports, calculations for comparative procedures with other codes etc.). In [3] is published WVA study (Weather Variability Assessment) belonging to a special application from the domain of **PSA-Level 3 analysis.**
- Within the uncertainty analysis the kernel is recalled many times with concrete sets of realizations of random model parameters. The final statistical processing of output realizations provides a rational basis for **probabilistic consequence assessment**.
- The product is presented here from viewpoint of its utilization such a **training tool** for decision support staff. User-friendly interface for input definitions of the task is offered both for atmospheric dispersion and ingestion parts. Interactive graphical subsystem enables to present wide range of results. The algorithm is logically partitioned to the time-consuming early stage analysis of an accident and interactive late stage consequence estimation. Easy interactive way for entering alternative options is offered to user for testing the effect of variability of some input parameters thus providing decision-making staff to improve their perception of the problems.

The software product development is oriented to needs of potential users from both business or institutional sphere. The system is approved by Assessing board No. 6 of SUJB for the product application in the field of nuclear safety. Within the project of Safety Research provided by Ministry of the Interior of the Czech Republic mentioned above the product can be acquired by easy and inexpensive way. The user can utilize full functionality or only particular functions above-mentioned, support and maintenance of the system is ensured.

3. Uncertainties in meteorological input – primary reasons of erroneous model predictions

Air born admixtures are drifted by the surrounding ambience and, precisely, the equation describing the pollution transport should be solved simultaneously together with the equations describing the state of atmosphere. In its full formulation, the system of equations for atmospheric state has stochastic character and describes the dynamic chaos. As a consequence, the predictability of evolution of the weather conditions is limited. The solution is provided by the data assimilation procedures applied in the field of meteorology. Because of the practical infeasibility, the pollution transport is analyzed separately whereas the meteorological fields enter the calculations externally as input. Analytical solution of respective diffusion equation can be found only under the drastic simplifications and for simple initial and boundary conditions. Our approach is based on Gaussian dispersion modelling using further modifications of a certain numerical scheme making approximate account for accounting for the real situation. A basic idea insists in stepwise synchronization of available short-term meteorological forecast (48 hours forward for each hour) provided by the Czech meteorological service with release dynamic of harmful substances discharged into the atmosphere (equivalent homogenous one-hour release consecutive segments).

In this chapter we shall illustrate an impact of deficient meteorological inputs on expectation values of output radiological situation. At the same time, the further improvements of the data are declared. Using deterministic kernel of the HARP system and real time series of archived historical measurements and forecast data some drawbacks have been revealed:

A) Point versus giridded short-term meteorological forecast

Two kinds of short-term meteorological forecasts are available:

- „Point data“: Short--term meteorological forecast for location of a source of pollution is generated. Hourly data for the next 48 hours are available belonging to analysis period 12 hours. The quartets of values forecasted for each hour comprise wind direction, wind speed, category of atmospheric stability according to Pasquill, atmospheric precipitation. The modelling is constrained to be *time dependant, spatially constant.*
- Gridded 3-D meteorological data for mesoscale region 160 $\times$ 160 km around source of pollution in HIRLAM format. Resolution of the rectangular grid is 9 $\times$ 9 km. Multilevel data are delivered for 13 vertical levels. Forecast on the next 48 hours are updated every 12 hours and transferred to ORACLE database. Modelling can be fully *time dependant and spatially dependant*

In Image No. 2 is demonstrated deposition of ^{131}I on terrain. It relates to one-hour release with total activity of 1.91E+11 Bq, release start at 00.00 CET , meteorological conditions relates to the real situation from Dec 10, 2009.

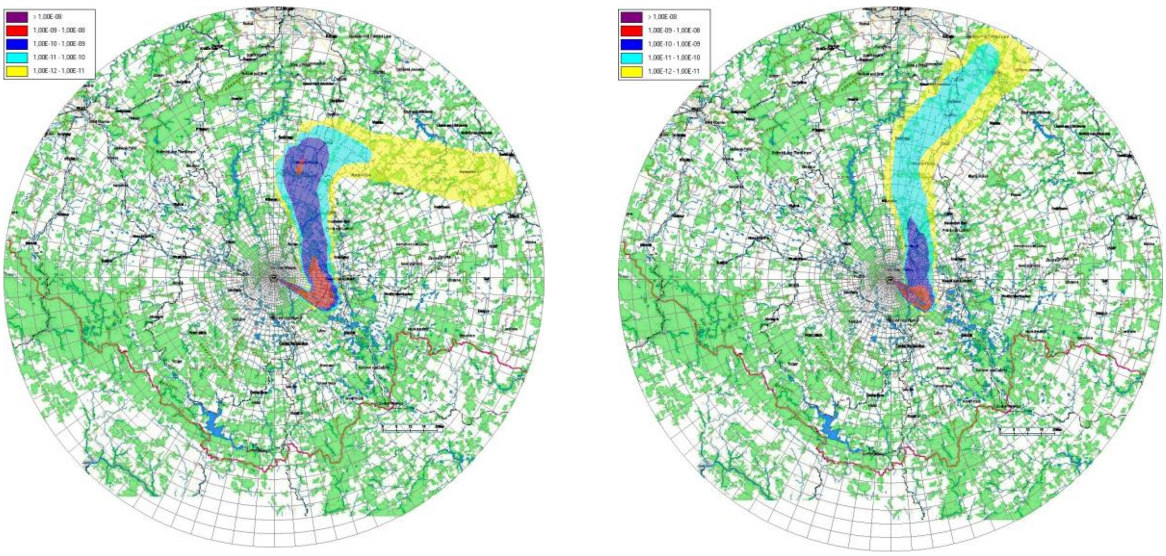

Image No. 2 Deposition of ^{131}I. Release start at 00.00 CET on Dec 10, 2009. Left: Simple “point” meteorological forecast; Right: More detailed 3-D gridded meteorological forecast in HIRLAM format

<u>The main resume from previous image No.2</u>: Point forecast can sometimes lead to wrong prediction of affected areas at longer distances causing implementation of protective actions here to be ineffective and likely having adverse consequences in the really impacted areas. Left picture shows situation after 15 hours of the release propagation. The small red point in the middle of the trace is caused by precipitation anticipated for the 11th hour after the release time. Even if the atmospheric precipitations are predicted for the single point of the source, this forecast propagates to the whole region. Thus, for model prediction at longer distances from the source, more precise 3-D meteorological forecast is necessary.

B) The data analysis term should be as close as possible to the next analysis term.

In Image 4 is described commencement of summer storm at May 26, 2009. Left is displayed the situation just before the storm when one-hour release of ^{131}I starts at 13.00 CET. Right is situation just two hours later. It means, that one-hour release of ^{131}I starts at 15.00 CET. But both scenarios come out from the same sequence of short-term forecast relating to the meteorological data analysis time at midnight. It means that “time distance” of the short term meteorological forecasts are 13 respective 15 hours. We can recognize fast changes in the trace of deposited radionuclide and presume the uncertainties involved due to imprecise forecast will grow with that "time distance" from the up to date analysis of the basic meteorological model.

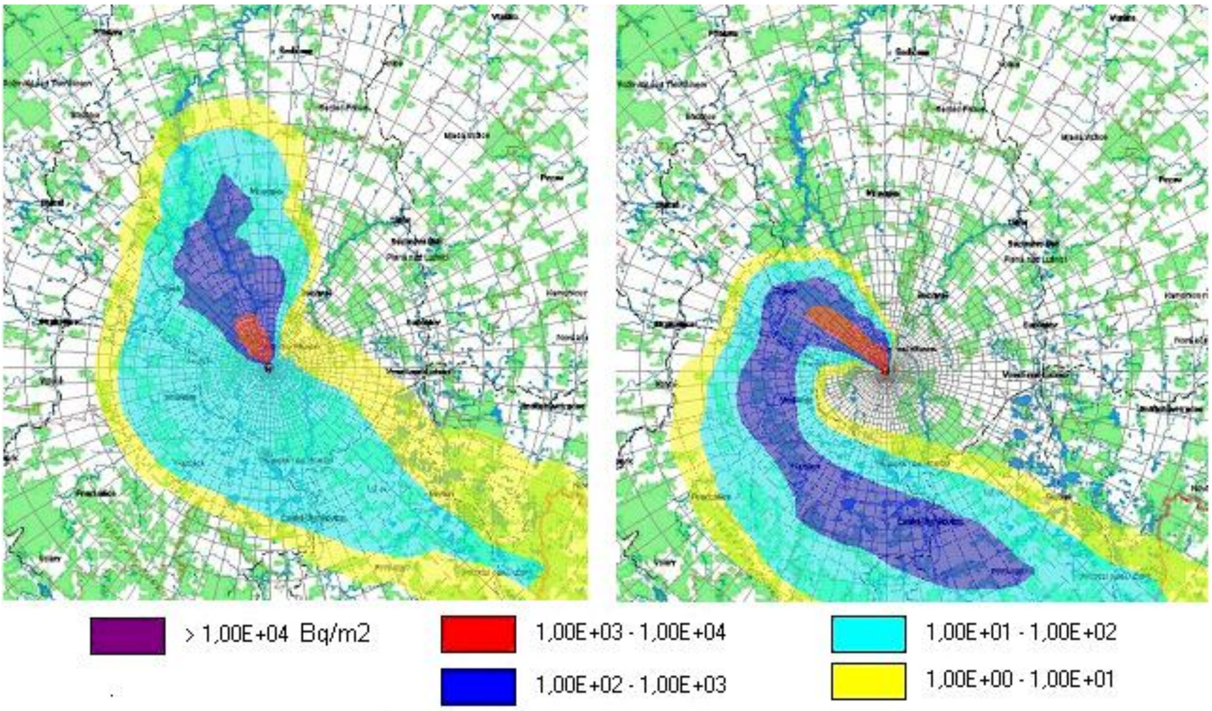

Image No. 3 Deposition of ^{131}I. Total amount of one hour release is 1.91E+11 Bq. In both cases is used midnight basic meteorological analysis time stamp. Left: Release start at 13.00 CET on Dec 10, 2009. Right: Release start at two hours later at 15.00 CET.

<u>The main resume from previous image No.3</u>: One way how to reduce the uncertainties involved due to imprecise forecast is to reduce the "time distance" between two analysis of the basic meteorological model. So far the distance is 12 hours (due to final pre-processing, the midnight or midday analysis is delivered with further delay about 5 hours) but in relation with increasing computer power in ČHMÚ is expected be reduced to 6 hours and short term meteorological analysis will be published every 6 hours per day.

C) Partial disproportion between measured data and HIRLAM forecast at the point of the source pollution

Periodically incoming meteorological measurements and meteorological forecast are stored in database in SURO and can be pre-processed by meteorological pre-processor of the HARP system. Following ex post analysis can give a retrospective view on the atypical actual situations (their occurrence rate is surprisingly not negligible) when measurements and forecast at the initial point of radioactivity release disagree in some extent resulting into the situation when the decision maker is not provided by fully clear and unambiguous information. The evolution of emergency situation from the same beginning of an accident is usually so far varied and complicated that specific ad hoc solutions have to be introduced. One of these problems is to decide initial stage of wind field on the basis of comparison of measurements and forecast. Possible discrepancies can be smoothed by DA techniques.

One of the integral criterion of agreement of meteorological measurements and forecasts is illustrated in Image No. 4. Annual wind direction statistics are constructed from measurements and forecasts for each of 8395 hours of the 2008 year at the initial point of release.

Partial resume from image No.4: We can hardly expect perfect agreement of the local wind measurements and short term forecast data in HIRLAM format. The reasons follow from local measurements conditions, measurements errors, measurement dating and averaging, influence of fluctuation on one hand and forecast model error, computation grid size etc. on the other hand. As the first step we shall try to gain more detailed model HIRLAM forecast on fine grid. Current situation offers forecast on grid 9 $\times$ 9 km, final stage is assumed to be 3 $\times$ 3 km.

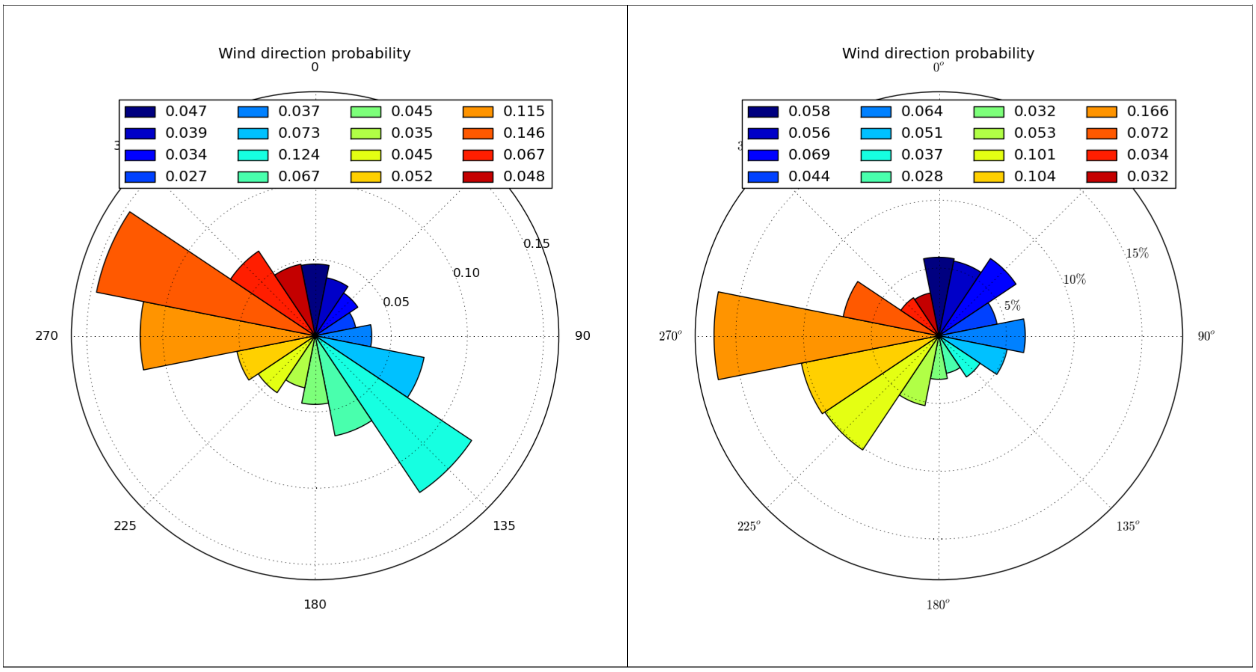

Image No. 4: Annual (2008) wind direction statistics for the site of NPP Temelin. Left: generated from archived 3-D HIRLAM data; Right: generated from meteorological measurements at the observatory close to the NPP. Sense of direction: from where the wind blows.

4. Data assimilation: two weakness produce one good result

Let empathize the initial decision-maker situation. He is responsible for generation of as reliable as possible prediction of time and space evolution of the contamination. According to these prognoses the urgent emergency actions have to be considered and launched in the most impacted areas in zones of emergency planning. The similar importance has information related to anticipation of radioactivity propagation in medium range distances for purposes of warning. The polluted plume drifting depends on meteorological conditions and corresponding duration of traveling above the monitoring areas can last from a few hours to several tens of hours (calm situations with a small velocity of the flow).

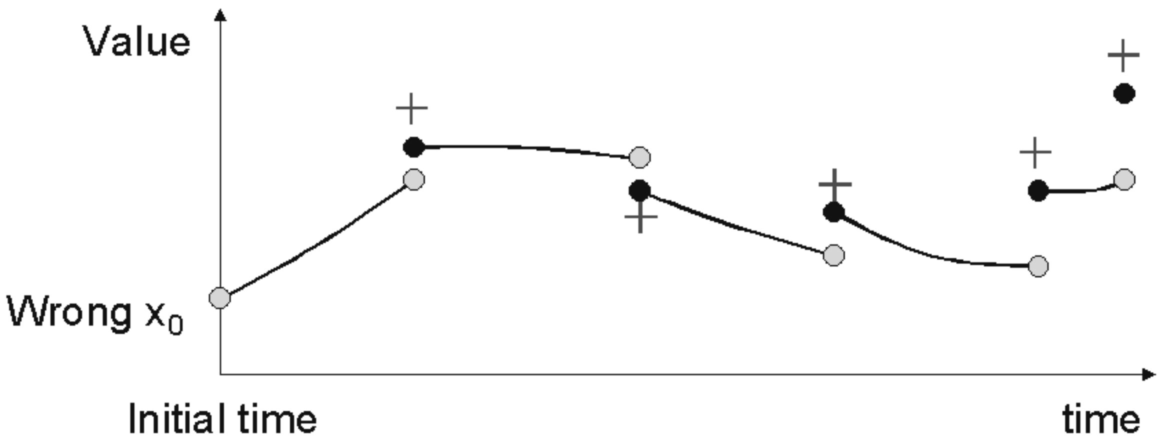

Image No. 5: Sequential data assimilation approach. When an observation *is* available(+), the model forecast (grey dot) is updated to a value closer to the observation (black dot) that is used to make the next model forecast. Reprint from [1].

The first reasonable predictions on regional or national scale should be available as soon as possible. The merging is accomplished by optimal blending of all information resources including prior physical knowledge given by model, observations incoming from terrain, past experience, expert judgment and intuition. The optimal blending is realized thought the advanced statistical assimilation techniques accounting for both model error and observation error covariance structure. Thus, erroneous measurements and imperfect model predictions provide through the DA techniques new corrected predictions having higher information worth.

From all possible advanced DA techniques was chosen particle filtering (PF) convenient to our SGPM trajectory model. In Image 5 is illustrated scheme for sequential data assimilation usually realised by the Bayesian recursive process of Bayesian filtering. It describes the real principle of the data assimilation cycles nesting into the model predictions. Prior model forecast (grey dot) is updated to a value closer to the observation (black dot – posterior system state) when minimizing the analysis error covariance. The resulting optimal solution shows a tendency to lean inversely related to the errors magnitudes of either model predictions or real measurements [4].

The PF originating from the sequential Monte Carlo method is applied here for simulation of the posterior distribution of the system state. The 3-D trajectories represent the “particles” (in fact, the 3-D trajectory is a model realization for one concrete set of parameters realization from their random distributions) and during the re-sampling, those particles having small weights with regard to the measurements are eliminated.

ACKNOWLEDGMENTS

These activities are supported thanks to grant project No. VG20102013018, Ministry of the Interior of the Czech Republic.

References

[1] Drécourt Jean-Philippe : Data assimilation in hydrological modelling. Thesis, Technical University of Denmark, 2004. ISBN 87-89220-84-6,

[2] “HARP – HAzardous Radioactivity Propagation" : A Software Tool for Fast Assessment of Radiological Consequences of Radiation Accident.“ http://havarrp.utia.cas.cz/harp/

[3] Hofman R., Pecha P.: Application of Regional Environmental Code HARP in the Field of Off-site Consequence Assessment. PSA 2011 International Topical Meeting on Probabilistic Safety Assessment and Analysis, Am. Nuclear Society. Wilmington, NC, USA, March 13-17, 2011

[4] Pecha P., Hofman R, and Šmídl V. "Bayesian tracking of the toxic plume spreading in the early stage of radiation accident," *Proceeding of European Simul. and Modelling Conference ESM*, Leicester, 2009.

[5] Pecha P., Hofman R., Kuča P. : Lessons learned from former radiation accidents on development of software tools for effective decision making support , Present and future of crisis management - 2009, 11th International Conference on Present and Future of Crisis Management 2009, (Praha, CZ, 23.11.2009-24.11.2009) (2009)