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Assimilation of the spatio-temporal distribution of radionuclides in the early phase of a radiation accident

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Applying the Bayesian approach, the input parameters are modelled as random quantities, estimated based on available measurements. The method, as well as providing a picture of the radiological situation improved based on measurements, gives an estimate of the atmospheric dispersion parameters whose accuracy improves with increasing number of measurements. The algorithm was tested on a simulated scenario of the release of ^{41}Ar.

1. INTRODUCTION

When radioactive pollutants are released into the atmosphere, a radioactive plume is passing over the terrain. The released radioactive material causes pathway specific irradiation of the population. Chernobyl accident was the worst nuclear power plant disaster in history and the only level 7 event on the International Nuclear Event Scale. It resulted in a severe release of radioactivity into the environment which had detrimental effects on population health. Although we hope that this will never happen again, there is still nonzero probability of less severe releases caused by either emergency or regular operation of nuclear power plants. In order to ensure efficiency of countermeasures introduced in case of an accident, it is necessary to predict spatial and temporal distribution of the pollution. This is the purpose of so called decision support systems (DSS) exploiting complex mathematical models of radionuclides propagation in the environment. Performance of current DSSs (in terms of reliability of radiation situation predictions) can be significantly improved by taking into account data provided by existing radiation monitoring network and employing data assimilation (DA) in the decision support process [5]. DA is the optimal way how to exploit information from both the measured data and expert-selected prior knowledge to obtain reliable estimates of radiological quantities of interest. It can be used for improvement of predictions both in early and the late phase [2]. This paper presents exploitation of advanced statistical DA methods in the early phase of a radiation accident, when a radioactive cloud is passing over the terrain.

2. ASSIMILATION SCENARIO

Radiation situation in the early phase is modeled via atmospheric dispersion models (ADMs) with many inputs regarding the source of release and actual conditions of the atmosphere and the surrounding environment. In the proposed assimilation methodology we focus on the inputs and exploit the fact that given the inputs, the predictions are given deterministically (up to the stochastic terms of atmospheric turbulence) by the used model. Exact values of the inputs are uncertain due to the stochastic nature of the dispersion, lack of accurate information, etc. Typically, their choice is subject to an expert opinion. Their subjective choice can introduce significant errors into the predictions and thus decrease the positive impact of the countermeasures. To avoid this, we apply Bayesian approach and treat the parameters as random quantities. Their early identification is essential for reduction of uncertainty in the radiation situation predictions. In this paper, particle filter [1] is used to evaluate posterior distributions of estimated parameters and improve their estimates on-line as the plume is passing over the stationary measuring sites.

Let's assume that there is an aerial release of a radionuclide from a source. Let the radiological quantity of interest is the activity concentration in air. We assume, that there is a radiation monitoring network present around the source which provides measurements of gamma dose rate. For propagation of the puff is used statistical approximation of the 3-D advection-diffusion equation, the Gaussian puff model (GPM), see [1], [3]. GPM gives us analytical expression for evaluation of activity concentration in an arbitrary spatial location and its simplicity allows for good insight into obtained results.

A group of the most significant input parameters affecting the dispersion process was selected using available sensitivity and uncertainty studies performed on dispersion models [3]. We attempt to estimate the four parameters: magnitude of release, wind speed, wind direction and the rate of horizontal dispersion of the puff in terms of dispersion coefficients.

To estimate the parameters we employ Bayesian approach to filtering. It is based on representing uncertainty via probability distribution. This has many advantages in contrast to "classical" estimation methodologies, which usually provide us only selected moments of distribution of the estimated quantity. Drawbacks of the Bayesian approach is the fact, that evaluation of the optimal solution is in the most of real scenarios computationally prohibitive. It involves multidimensional integration over complex spaces and thus we have to adopt some suboptimal approach. In this paper we use particle filters [1].

Assimilation process can be summarized as follows: We have got an ADM for evaluation of activity concentration in air in a set of grid points, measurements of the gamma dose rate and a group of the most significant model parameters. We want to on-line estimate the state comprising of the activity concentration in air on the computational grid and the selected parameters as the cloud is passing over stationary measuring sites. Using posterior distribution of parameter, we want to predict future evolution of the radiation situation. For the details see [3].

3. NUMERICAL EXPERIMENT

The algorithm is tested on a simulated scenario with an instantaneous release of Ar-41. This isotope is not dominant source of irradiation in case of an emergency release. It was chosen because of its good physical and chemical properties for purposes of algorithm testing [3]. Experiment is conducted as a twin experiment when the measurements are simulated via a twin model and perturbed. We developed integral observation operator converting the activity concentration in air in *Bq/m*^{3} to the gamma dose rate in *Gy/s* [3], [4]. It is evaluated by the means of numerical integration method of the Gaussian quadrature. Twin model for simulation of measurements assumes that the "real" release was smaller in magnitude, with lower wind speed, directed by 37 deg anticlockwise and the puff dispersed more than was a priori assumed. Convergence of assimilated prediction to the twin model is in the *Fig. 1*. Results are visualized in terms of time integrated concentration (TIC). In *Fig. 1* top left is the expected TIC without the DA. In *Fig. 1* top right is the expected TIC evaluated by the twin model. Expected value of prediction of TIC displayed in *Fig. 1* bottom left is just after the first assimilation step. Even at this stage, the wind direction was correctly recognized, however

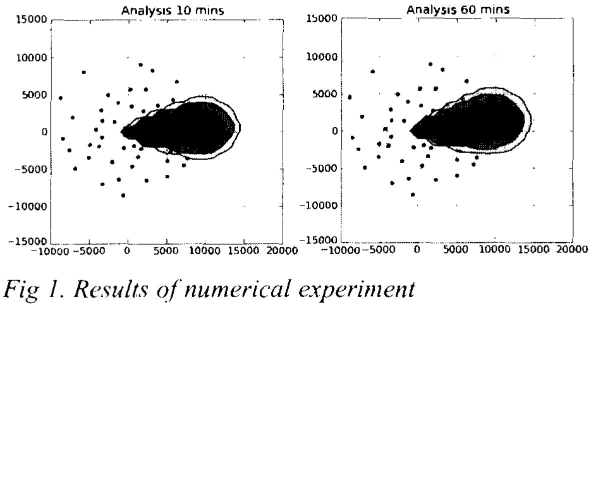

Fig 1. Results of numerical experiment

other parameters, are still too uncertain and the prediction differs from the twin model.

With increasing time the measurements provide enough information and the expected values of TIC converge to the twin model, see *Fig. 1* bottom right.

For more details on the dose rate calculation, simulation of measurements and details of the experiment see [3].

4. CONCLUSION

The method gives us a joint estimate of spatio-temporal distribution of activity concentration and parameters of the dispersion model. Thus, we obtain improved estimate of the radiation situation on the terrain and a way how to easily extend this estimate to prediction on an arbitrary time horizon. Introduced Bayesian methodology has very interesting properties suitable for the solved problem. However, a lot of work is required to incorporate the method into the existing decision support systems. We foresee the core of the future work in development of more realistic models of the state evolution and the measurements. For example, more realistic scenarios should consider a mixture of radionuclides and extended set of uncertain variables. Proposed methodology also offers a tool for assessment of the influence of measurements. This can be useful for purposes of designing the topology of the radiation monitoring network and determination of sufficient number and density of measuring stations.

Asimilace časoprostorového rozložení radionuklidů v časné fázi radiační nehody

Příspěvek pojednává o využití data asimilačních metod v časné fázi radiační nehody. V případě úniku radioaktivních škodlivin do ovzduší se utvoří radioaktivní vlečka postupující nad terénem. Uniklé radionuklidy představují zdravotní riziko. Pro plánování a nastolení co nejefektivnějších protiopatření je nutná znalost budoucího časoprostorového vývoje distribuce radionuklidů v prostředí. Předpovědi se tvoří pomocí numerických disperzních modelů. Tyto modely mají mnoho vstupů a jejich výstupem je předpověď radiační situace pomocí radiologických veličin. Přesné hodnoty vstupních parametrů jsou často neznámé. To je dáno náhodným charakterem turbulentních procesů v atmosféře, nedostatkem informací o nehodě a zdrojovém členu atd. Subjektivní (expertní) volba vstupních parametrů může vyústit v chybné předpovědi, na jejichž základě není možno plánovat efektivní protiopatření. Proto navrhujeme použití Bayesovského přístupu a modelujeme vstupní parametry jako náhodné veličiny, které odhadujeme na základě dostupných měření. Navrhovaná metodika nám poskytuje nejen odhad radiační situace vylepšený na základě informace poskytnuté měřeními, ale zároveň nám s přibývajícími měřeními dává zpřesněný odhad parametrů atmosférického disperzního modelu. Tyto zpřesněné parametry mohou být využity pro predikování dalšího vývoje na libovolném horizontu. Algoritmus je testován na simulovaném scénáři úniku radionuklidu Ar-41.

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Bayesian modeling and prediction of solar particles flux

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Deskriptory *INIS*: MATHEMATICAL MODELS; SOLAR ACTIVITY; SOLAR FLARES; SOLAR FLUX; SOLAR PARTICLES

The paper deals with the prediction of the flux of subatomic particles ejected from the upper atmosphere of the Sun. The Bayesian approach to this issue is presented and a method capable of taking available expert knowledge into account is introduced.

1. INTRODUCTION

Besides the spacecraft systems, manned space-flights and launchers, the exposition to space weather has effects on high-altitude air flights, where the penetrating particles must be taken into account as well. The solar particles may pose problems both on human beings and the electronic devices installed in modern airplanes, where the potential malfunctions might be very dangerous. These effects comprise the SEE (Single Event Effects), arising from ionising interactions of the solar particles and leading to both soft errors involving single or multiple bits and hard errors like burn-outs [4].

During the last two decades or so, the researches of the effects of ionisation on aircrew and frequent flyers were undertaken. The increasing awareness of the health risks lead in Europe to Directive 96/29/EURATOM, which specifies the demands posed on the aircraft operators in connection with the exposure to the ionising energy.

In face to this facts, the mathematical modeling of the particles flux becomes still more significant, because it would allow to issue early warnings on its grow and the increase in the health and SEE risks. There already exist several methods, e.g. [5][6][7]. However there still exists a challenge in the prediction of the Solar Energetic Particle (SEP) events, when the flux intensity is significantly higher. We can take advantage of the known physical facts, e.g. that higher intensity solar X-ray flares are more likely accompanied by Coronal Mass Ejection (CME) [3]. Andrews statistical study [1] shows that all the X-class flares (peak burst intensity $I \geq 10^{-4}\ Wm^{-2}$) in his samples were associated with CME, however it this is not a rule for lower intensities. The hardening of the spectrum is observable approximately one day before the Earth is hit by the intensified solar wind, which allows us to tune the mathematical model to catch the changes in the flux development.

2. BAYESIAN MODEL

For our purpose, the basic underlaying model describing the evolution of the particles flux measured by Particle Flux Units (*pfu*, [particles/cm^2-s-sr]) is given by the autoregression model

$$pfu_t = \sum_{i=i}^{n} a_i pfu_{t-i} + k + e_t \qquad (1)$$

where the new flux value is expressed as a combination of the values in the previous time instant t-i weighted by model parameters a_i and an absolute term k. The model order n has to be determined to sufficiently catch the evolution of the flux, $n = 2$ seems to be adequate. The autoregressive property of the flux seems to be obvious, because under general conditions and with the exception of SEP events each new value follows from the last data. The fluctuations around the mean value can be interpreted as the noise effect e_t caused e.g. by the sensor contamination and the non-homogeneity of the environment. The noise is often supposed to be white and normally distributed with zero mean and variance σ^2, $e_t \sim N(0, \sigma^2)$.

The Bayesian methodology employs probability distributions of the model parameters evaluated by mea-