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# SOLUTION OF THE SOURCE IDENTIFICATION PROBLEM WITH USING THE JRODOS MATCH

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## Introduction

In frame of the EU FP7 NERIS-TP and HARMONE-OPERRA projects the meteorological forecasting system based on WRF mesoscale model was developed and integrated with the JRODOS nuclear emergency response system [1] so that JRODOS user can compute weather forecast at nearly every location over the world and use it for atmospheric dispersion calculations by the local scale atmospheric dispersion models of JRODOS (beyond 800 km). Complementary to that system the software tools were developed which enabled JRODOS far range atmospheric dispersion model MATCH running on the output data of WRF or freely available NWP data of the Global Forecasting System (GFS) [2, 3]. Possibility to run MATCH on global NWP (GFS) data opens opportunities to use MATCH model not only for forward atmospheric dispersion calculations but also for backward calculations in order to establish possible sources of radioactive pollution following it's detection and provided that corresponding measurements were available to the user of the JRODOS system. The corresponding algorithm was developed and it is presented in this work.

## Formulation of the algorithm

For the solution of source identification problem when increased levels of pollution are detected following releases from the unknown sources the inverse modelling approach based on adjoint equations could be used (e.g. [4]). The forward atmospheric dispersion problem in Eulerian formulation (which is the case of MATCH model) is expressed by the equation:

$$\partial c/\partial t + u\,\partial c/\partial x + v\,\partial c/\partial y + w\,\partial c/\partial z + Diff(c) = S, \qquad (1)$$

where c – is concentration of pollutant, u, v, w – are horizontal and vertical velocity components, Diff – is the diffusion operator, S – is the source term. The forward problem is solved during certain time interval ($t_{min}$,$t_{max}$).

The inverse (adjoint) atmospheric transport problem will be the solution of equation:

$$-\partial c^*/\partial t - u\,\partial c^*/\partial x - v\,\partial c^*/\partial y - w\,\partial c^*/\partial z + Diff(c^*) = p_n, \qquad (2)$$

where $c_*$ - is adjoint concentration, $p_n$ =1 in n-th measurement point during time interval when increased concentrations were detected.

The adjoint equation (2) could be integrated backward in time from $t_{max}$ to $t_{min}$. This could be done using JRODOS MATCH by changing velocity components in NWP data (u, v, w) → (-u, -v, -w) and by changing times to which NWP files are attributed:

$$\begin{aligned} &NWP^{(u,v)}(0) \to NWP^{(-u,-v)}(N_{\max}),\\ &NWP^{(u,v)}(1) \to NWP^{(-u,-v)}(N_{\max}-1),\\ &\ldots\\ &NWP^{(u,v)}(N_{\max}) \to NWP^{(-u,-v)}(0) \end{aligned} \qquad (3)$$

In (3) $NWP^{(u,v)}(i)$ denotes file with NWP data corresponding to i-th forecast hour. The operator denoted by arrow means that after changing the direction of the velocity components in file corresponding to analysis (zero) time it is attributed to the last (Nmax) forecast hour. Analagous

procedure is done for the files corresponding to the other forecast hours. It could be easily seen that solving forward dispersion problem (1) after suggested substitution (3) is equivalent to solving adjoint equation (2) without substitution (3).

**Condition No. 1.** The distribution of adjoint concentrations resulting from the solution of the inverse model correspond to the domain where the source of release could be located. When there are several places of registration of radioactive pollution the release is located at the intersection of the areas of adjoint concentrations resulting from the solutions of the equations (2) with the locations of the releases of adjoint concentrations corresponding to different locations of pollutant detection. At the same time, addition of adjoint plume from the points were detected concentrations were very low helps further decreasing domain of possible release location (Fig. 1).

**Condition No. 2.** Additional constraint for the location ($\bar{r}_s$) and time ($t_s$) of the potential release is that ratios of ajoint concentrations calculated from different inverse runs should correspond to ratios of the detected activities ($A$):

$$\frac{c_1^*(\bar{r}_s,t_s)}{c_2^*(\bar{r}_s,t_s)} \approx \frac{A(\bar{r}_1,t_1)}{A(\bar{r}_2,t_2)} \quad . \tag{4}$$

Here $\bar{r}_1,\bar{r}_2,t_1,t_2$ are locations and times of two measurements for which inverse runs 1 and 2 were performed and adjoint concentrations $c_1^*,c_2^*$ were calculated. The relationship (3.9) follows from the well known relationship: $c_i^*(\bar{r}_s,t_s)\cdot q_s = A(\bar{r}_i,t_i)$ (e.g. [4]).

Source identification is performed using four conditions (restrictions) that allow narrowing of the wide set of potential sources to unique solution as described below. +The conditions which should be satisfied by the solution are described as follows.

**Condition No. 3.** Next restriction on the solution which allows to reduce the size of area where release location could be potentially located is selection for the analysis only those grid nodes where adjoint concentration is greater than certain level. More exactly, the necessary condition for the inclusion of the potential release point located in node $\bar{r}_s$ and at the time $t_s$ in the list of potential sources is that the following inequality holds:

$$c_i^*(\bar{r}_s,t_s) > \frac{\max(c_i^*)}{IL} . \tag{5}$$

Here IL – is the 'inclusion level'. The greater is IL the wider set of possible locations will be included in analysis.

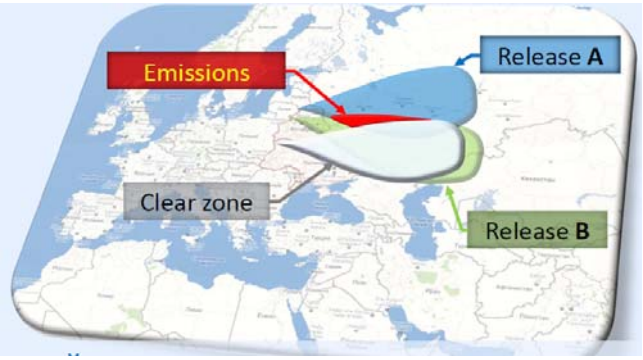



**Fig. 1.** Intersection of plumes of adjoint concentrations released from different measurement points with addition of adjoint plume from the points were detected concentration was very low

**Condition No. 4.** Finally source of release could not appear in any place. We consider only releases from nuclear installations, i.e. enterprises dealing with radioactive materials (NPPs and other). Deliberate releases and releases from transportation accidents for now are not considered. If the map of nuclear installations is available then only those grid nodes were nuclear installation exist are considered in the analysis.

After identification of the release location and time, source rate is identified by performing forward simulation with constant release amount $Q_0$ (in case of instantaneous releas) and then

it's multiplication on the average ratio of calculated/measured concentrations: $Q = Q_0 \left\langle A_{meas_i} / A_{calc_i} \right\rangle$.

**Example of application for discovering source of I-131 in October, 2016**

During 10-25 October 2016 footprints of iodine (exceedance of lower limit of detection) were found over Europe as presented in Fig. 2. The filters at each place were installed for a period of about 1 week therefore it was impossible to precisely identify plume arrival time. Therefore a series of inverse simulations were performed which identified the most probable regions of releas locations shown in Fig. 3. One of regions is Moscow region, in which 3 places with nuclear installations which could be sources of iodine are present: in Moscow, Dubna and Obninsk

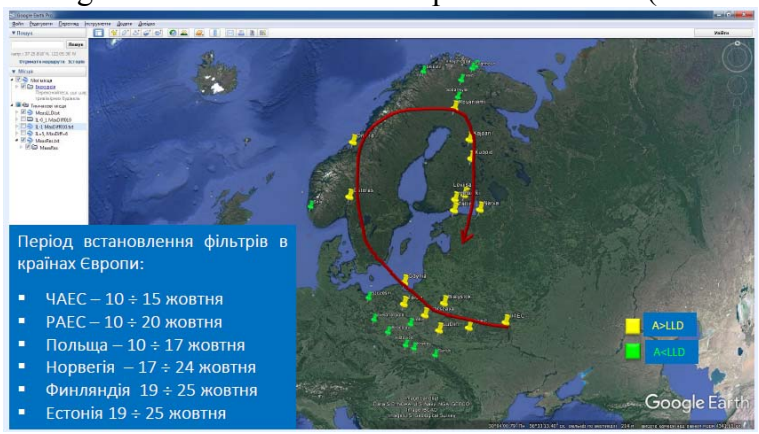



**Fig. 2.** Footprints of I-131, found over Europe in October, 2016: Chernobyl NPP (10-15.10), Rivne NPP (10-20.10), Poland (10-17.10), Norway (17-24.10), Finland (19-25.10), Estonia (19-25.10)

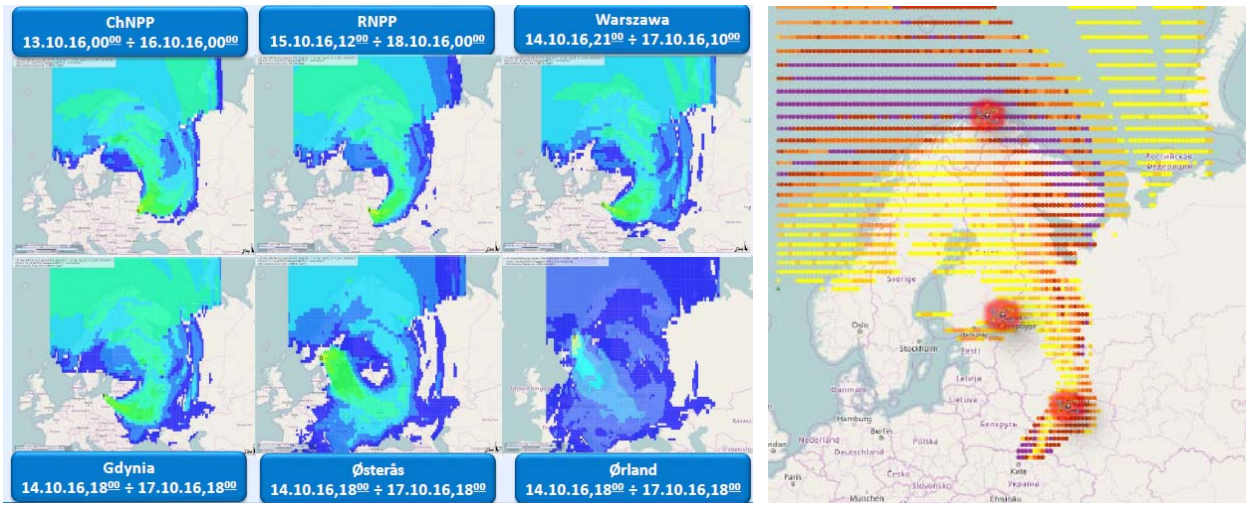
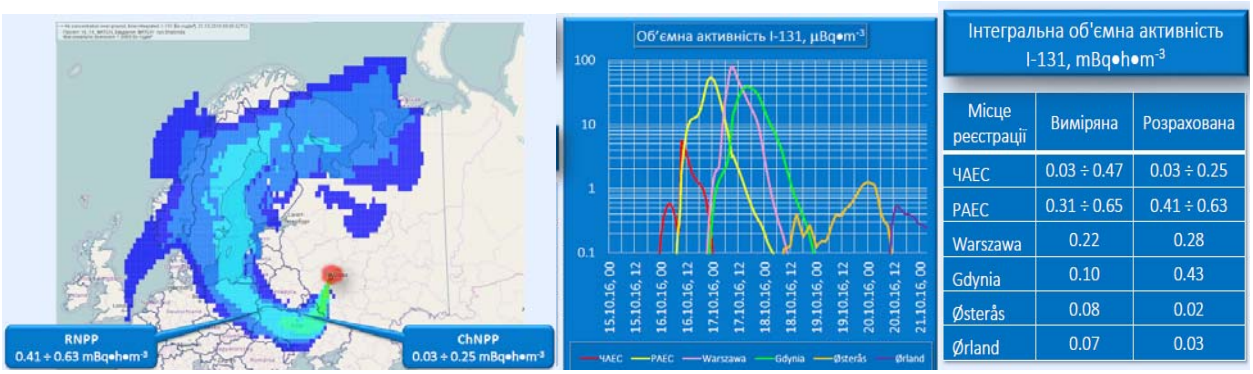



Fig. 3. (left) - the 'inverse' plumes calculated by solving (1)-(3); (right) – the most probable release locations identified in red

The results of forward dispersion calculations following release scenario from Obninsk, Moscow region are shown in Fig. 4. With estimated total inventory 108 GBq released on 14.10.2016, between 07:00-08:00, the calculated average concentrations agree fairly well with corresponding measurements. However, it should be stressed out, that this is only one possible source of release. Additional measurements were to be processed to identify source with greater certainty. However there were only those measurements available to authors which are presented at Fig. 2 and those measurements are located far from possible source. Note that similar detection of iodine footprints happened over Europe in 2011 [5] and due to international collaboration of institutions responsible for monitoring (the so-called 'Ring of 5') with the aid of source inversion methods such as described in [5] it was established that the source was the Institute of Isotopes, Budapest, which produces I-131 for healthcare.




Інтегральна об'ємна активність I-131, mBq•h•m-3

| Місце реєстрації | Виміряна | Розрахована |
|---|---|---|
| ЧАЕС | 0.03 ÷ 0.47 | 0.03 ÷ 0.25 |
| PAEC | 0.31 ÷ 0.65 | 0.41 ÷ 0.63 |
| Warszawa | 0.22 | 0.28 |
| Gdynia | 0.10 | 0.43 |
| Østerås | 0.08 | 0.02 |
| Ørland | 0.07 | 0.03 |

Fig. 4. (left) Integral concentration of I-131 released from Obninsk on 14.10.16, released inventory – 108 GBq; (middle) – time histories of instantaneous iodine concentrations (uBq/m$^3$) at different sites; (right) – comparison of measured and calculated average concentrations at different sites according to presented release scenario. Averaging times correspond to Fig. 2

**Conclusions**

A methodology has been developed which allows usage of the JRODOS far-range atmospheric dispersion model MATCH for the solution of the problem of identification of the unknown source location following radioactivity detection by the measurement stations. In the proposed approach it is assumed that radioactive release happens from one of the nuclear installations while releases from transportation accidents and deliberate releases are not considered. The developed method was applied the case of $^{131}$I detection in Europe in October, 2016. It is shown that the areas of the most likely locations of the potential release could be identified by the developed tool. More precise results can be achieved on the basis of the data measured in larger amount of locations for which international cooperation in the monitoring of environmental radioactivity is crucial. For the successful usage of the proposed method it is also necessary that the map of nuclear installations (which could be potential sources of radioactive pollution) would be available to the users of the JRODOS system.

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