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DIRECT AND INVERSE MODELLING OF ATMOSPHERIC DISPERSION AND GAMMA RADIATION IN THE CONTEXT OF CRISIS MANAGEMENT OF ACCIDENTAL OR DELIBERATE RADIOACTIVE RELEASES: THE TERRIFFIC PROJECT

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Abstract: TERRIFFIC, a disaster-resilience project funded under the H2020 Framework Programme, aims to deliver a step change in the effectiveness of first responders during the first hours of a Radiological, Nuclear, explosive (RNe) incident. Ecole Centrale de Lyon (ECL) develops the plume software which is one of the TERRIFFIC system components. This software aims to characterize the RNe source (position, release rate, radionuclide type) and estimate the safety zones associated. This information is of prime importance in order to efficiently manage the control zone and first responder's actions. The plume software is composed of two main building blocks: a direct model and an inverse model.

The direct model aims to estimate and forecast the impacts (fluence/dose rate field) based on the source characteristics. The model consists in a stochastic Lagrangian atmospheric dispersion model (SLAM), coupled with a gamma radiation model (Model for Atmospheric Radiation Indoor & in Environment – MARIE). SLAM calculates the transport and dispersion of radioactive particles. MARIE enables to evaluate the fluence/dose rate from radioactive material emitting gamma rays. The performances of MARIE have been evaluated against effective dose rate values provided by Dewji et al. (2018) and against equivalent dose rate values presented in IRSN data sheets. The results show a good agreement with the *reference* values.

Conversely, the inverse model, called ReWind, aims to characterize the RNe source from the fluence/dose rate measured by sensors mounted on drones and robots. The inverse approach consists in evaluating the characteristics of the source which minimizes the difference between the observed and predicted dose rates at the receptors. A sensibility study shows that the higher is the number of measurements, the lower is the error on the source position.

Key words: Atmospheric dispersion modelling, Gamma radiation modelling, Inverse modelling, RNe incident.

INTRODUCTION

The first hours of the response to a Chemical, Biological, Radiological, Nuclear, explosive (CBRNe) incident, and especially a radiological one, are critical. Responders want to contain the most severe consequences, halt the ongoing threat, save victims, manage the crime scene and organise an effective response as quickly as possible. It is also when they are most at risk as the extent and intensity of the contamination is still unknown and there may be secondary devices or contaminated objects.

The TERRIFFIC (Tools for early and Effective Reconnaissance in cbRne Incidents providing First responders Faster Information and enabling better management of the Control zone) project tackles these issues. Ecole Centrale de Lyon (ECL) develops the plume software, one of the TERRIFFIC system components, which aims to characterize the RNe source and estimate the safety zones associated. All this information are of prime importance in order to efficiently manage the control zone and first responder's actions.

This study presents the TERRIFFIC project and focuses on the plume software component.

THE TERRIFFIC PROJECT

TERRIFFIC, a disaster-resilience project funded under the H2020 Framework Programme, aims to deliver a step change in the effectiveness of first responders during the first hours of a Radiological, Nuclear, explosive (RNe) incident. TERRIFFIC will enrich the European response to RNe events by integrating a set of complementary, interconnected and modular software and hardware components into an integrated system (**Figure 1**). These components include new detectors, algorithms, drones, robots, dispersion models, information management software and decision support systems. In addition, advanced mixed reality technology will be leveraged to provide first responders with ad-hoc available and continuously updated information during operations.

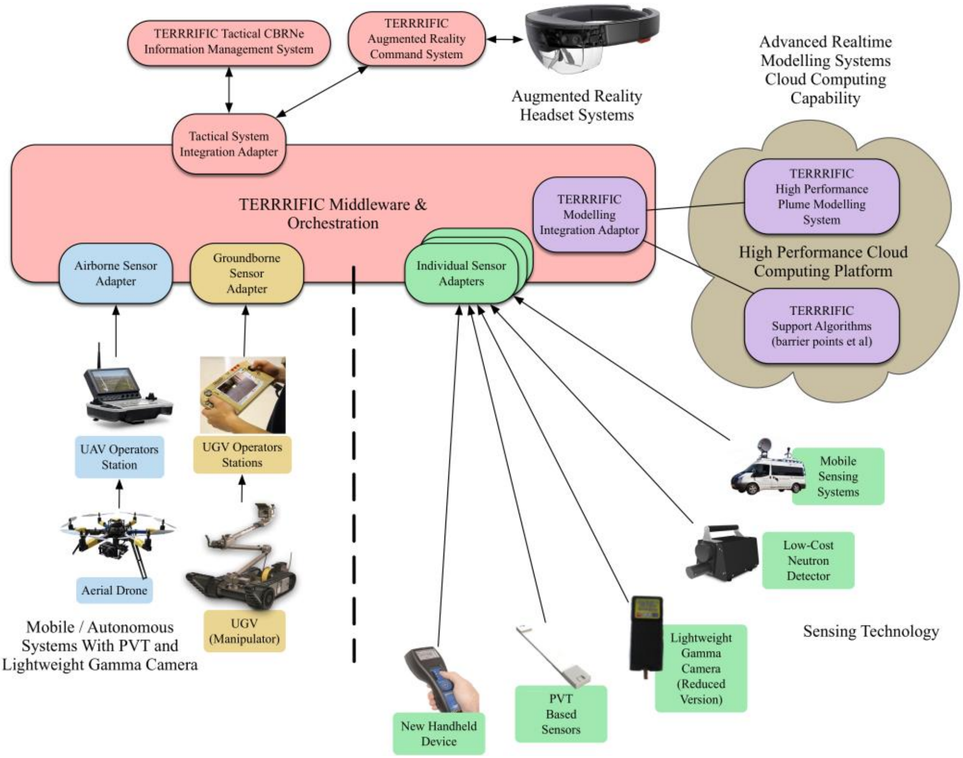

Figure 1. Components of the TERRIFFIC system

PLUME SOFTWARE

The plume software aims to characterize the RNe source (position, release rate, nuclide type) and estimate the safety zones associated. All this information are of prime importance in order to efficiently manage the control zone. The plume software is composed of two main building blocks: a direct model and an inverse model.

Direct model

The direct model aims to estimate and forecast the impacts (fluence/dose rate) fields based on the source characteristics. The direct model consists on an atmospheric dispersion model, called Safety Lagrangian Atmospheric Model (SLAM), and a gamma radiation model, named Model for Atmospheric Radiation Indoor & in Environment (MARIE).

SLAM is a stochastic particle dispersion model, based on the tracking of Lagrangian trajectories of individual particles. The temporal evolution of the Lagrangian velocity of each particle is estimated with the equation:

$$U_i(t) = \overline{U}_i(t) + U_i'(t) \text{ with } U_i'(t+dt) = U_i'(t) + dU_i' \quad (1)$$

where $\overline{U}_i$ is the mean velocity of the flow. The evolution of the fluctuating velocity U_i' is determined by the stochastic differential equation (Thomson, 1987):

$$dU_i' = a_i(\boldsymbol{X}, \boldsymbol{U}', t)dt + \sum_j b_j(\boldsymbol{X}, \boldsymbol{U}', t)d\xi_j \quad (2)$$

where a_i and b_j are expressed in terms of standard deviations of the velocity fluctuations σ_{u_i} and of the Lagrangian times $T_{L,i}$. Once the cloud of particles has been transported using the previous equations, the concentration/volume activity are calculated by dividing the sum of the mass/activity of all the particles present in a grid cell, by the volume of this grid cell. SLAM has been validated against wind tunnel experiments (Vendel et al., 2011) and has been used in several studies (Foucher et al., 2018, Armand et al., 2014, Marro et al., 2014, Dubourg et al., 2013, Sadek et al., 2011, Vendel et al., 2010).

MARIE estimates the radiation field, especially the fluence rate (photon.m^{-2}.s^{-1}) and the dose rate (Sv.s^{-1}) fields, caused by radiological and nuclear source(s) emitting gamma rays. The fluence rate is calculated with the equation:

$$\Phi(E) = \sum_{source\ i} \frac{B(E, \mu r_i)}{4\pi r_i^2} \exp(-\mu r_i) I Q_i \quad (3)$$

where E [eV] is the energy of the gamma ray, $\Phi(E)$ [photon.m^{-2}.s^{-1}] is the fluence rate, r_i [m] is the distance to the source i, μ [m^{-1}] is the linear attenuation coefficient, $B(E, \mu r_i)$ is the build-up factor, which takes into account absorption/reemission by the medium of propagation, I is the intensity (branch ratio) of the gamma ray with the energy E, and Q_i [Bq] is the activity of the source i. The dose rate is then calculated with:

$$D(E) = \Phi(E)\alpha(E) \quad (4)$$

where $D(E)$ is the dose rate and $\alpha(E)$ [Sv.m^{-2}] is the dose rate coefficient by fluence rate. The *total* fluence rate and the *total* dose rate are calculated by summing the contributions of all the gamma rays emitted by the source(s). To evaluate this model, the effective dose rate received in a semi-infinite cloud (of nuclides) have been calculated for several nuclides and compared with those provided in Dewji et al. (2018) (**Figure 2**). Likewise, the equivalent dose rate received from a punctual source at different distances (mainly 0.1, 0.3 and 1 m) have been estimated for several nuclides and compared with those provided in IRSN data sheets (**Figure 2**). The results show a good agreement with the *reference* values provided by Dewji et al. (2018) and IRSN data sheets.

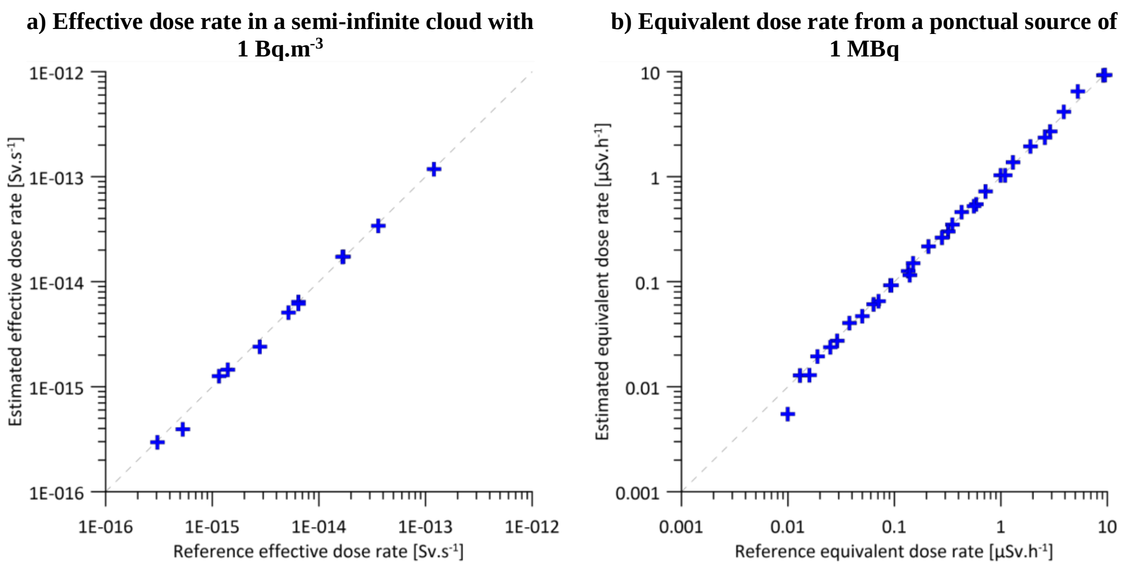

Figure 2. Comparison of modelled (with MARIE) dose rate with reference values from Dewji et al. (2018) (a) and from IRSN data sheets (b) for several nuclides

Inverse model ReWind

ReWind aims to characterize (localisation, release rate, nuclide type) a RNe source based on fluence/dose rates measured by sensors. Once the source characteristics are determined with ReWind, these data are provided as input to the direct model to estimate and forecast the fluence/dose rate field.

ReWind assumes that the fluence/dose rates measured by sensors are linearly link to the source rates. Thus, the source rates are estimated by resolving the linear equation system:

$$\begin{pmatrix} ATC_{11} & \cdots & ATC_{1n} \\ \vdots & \ddots & \vdots \\ ATC_{m1} & \cdots & ATC_{mn} \end{pmatrix} \begin{pmatrix} Q_1 \\ \vdots \\ Q_n \end{pmatrix} = \begin{pmatrix} C_1 \\ \vdots \\ C_m \end{pmatrix} \quad (5)$$

where C_m is the measured fluence/dose rate relative to the m^{th} observation, Q_n is the release rate of the n^{th} source and ATC_{mn} is the so-called *Atmospheric Transfer Coefficient* (ATC) from the n^{th} source to the m^{th} observation. The ATC matrix is the mathematical operator that models the physical mechanisms that are responsible for the *transfert* of concentration or fluence/dose rate in the atmosphere. Concretely, the ATC_{mn} value corresponds to the concentration or the fluence/dose rate at the (*position* of the) m^{th} observation considering only the n^{th} source with an unit release rate. The values of the ATC matrix are evaluated with the direct model.

When only the source rate is unknown, the linear equation system (5) is solved directly to estimate it. If the position and/or the nuclide type are also unknown, an iterative algorithm is applied to test different sources locations and nuclide types. The characteristics (location, release rate, nuclide type) that minimise the discrepancies between modelled and measured radiations are defined as the most probable. ReWind and the inversion approach have been developed during the PhD of N. Ben Salem and have been the object of several scientific articles (Ben Salem et al., 2014a, Ben Salem et al., 2014b). We have assessed the sensibility of this algorithm for the evaluation of the source position according to the number of measurements and the measurement errors. This assessment has been carried out on a test case which consists in characterizing a solid radioactive source from synthetic measurements (data constructed with the direct MARIE model). The **Figure 3** shows that the lower is the measuremens errors, the better is the source position estimate. Likewise, the higher is the number of measurements, the lower is the error on the source position. However, the results also suggest that the error on the source position is less sensitive to the number of measurements from a certain value.

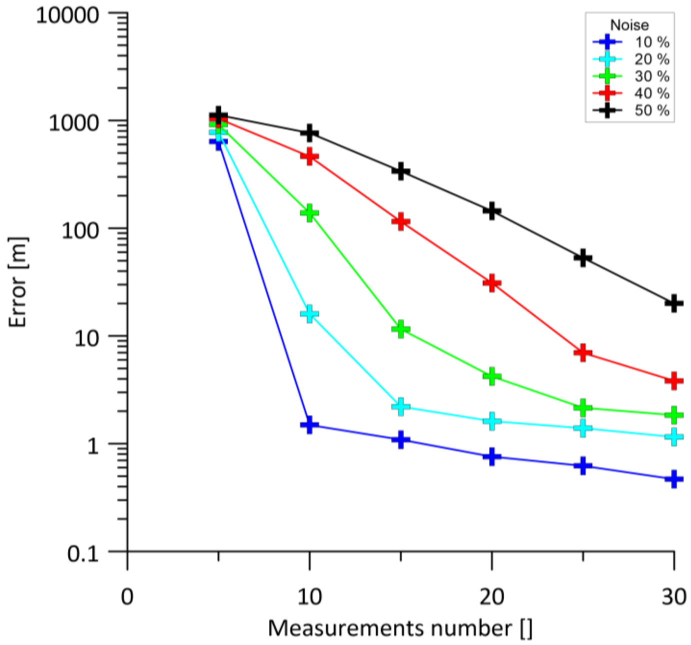

Figure 3. Error on the source position according to the number of measurements and measurements noise (for each number of measurements, the error on the source position is averaged on 10 000 simulations)

CONCLUSION

This study presents the TERRIFFIC system, focusing on the plume software component. The plume software is composed of two main building blocks: a direct model and an inverse model.

The direct model consists in a stochastic Lagrangian atmospheric dispersion model (SLAM), coupled with a gamma radiation model (Model for Atmospheric Radiation Indoor & in Environment – MARIE). The performances of MARIE have been evaluated and the results show a good agreement with the reference values.

The inverse model, called ReWind, consists in evaluating the characteristics of the source which minimizes the difference between the observed and predicted dose rates at the receptors. A sensibility study shows that higher is the number of measurements, the lower is the error on the source position.

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