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Models and Measurements: Complementary Tools for Predicting Atmospheric Dispersion and Assessing the Consequences of Nuclear and Radiological Emergencies

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Models and Measurements: Complementary Tools for Predicting Atmospheric Dispersion and Assessing the Consequences of Nuclear and Radiological Emergencies[1]

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Abstract

Since its inception over 26 years ago[3], NARAC (the National Atmospheric Release and Advisory Center) has used measurement data to update model predictions of radioactive releases from *known* origins. NARAC continues to routinely participate in emergency response drills with organizations that collect air concentration, ground deposition, and radiation exposure measurements. From a complementary perspective, NARAC is now developing an advanced capability to combine models and data from monitoring systems to characterize and forensically reconstruct atmospheric release events of *unknown* origin.

Keywords: atmospheric dispersion modeling, source term estimation, measurement data assimilation, real-time modeling systems, event reconstruction

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[3] As ARAC, the Atmospheric Release Advisory Capability

1 Introduction

The National Atmospheric Release Advisory Center (NARAC), located at Lawrence Livermore National Laboratory (LLNL), provides emergency support services, real-time assessments, detailed studies, and planning assistance for incidents involving a wide variety of airborne hazards, including radiological, chemical, biological, and natural emissions (Bradley, 2005; Nasstrom et al., 2005). When hazardous materials are accidentally or intentionally released into the atmosphere, NARAC provides plume predictions and consequence assessments to emergency managers quickly enough for them to protect the affected population. NARAC provides 24x7 support for US Department of Energy (DOE) facilities, DOE emergency response teams, and the Department of Homeland Security (DHS) Interagency Modeling and Atmospheric Assessment Center (IMAAC).

NARAC supports its customers with easy-to-use, real-time access to critical information, enabling them to rapidly determine hazard areas and affected population. The NARAC system provides reach-back access to the advanced, three-dimensional model predictions, and to the global meteorological and geographical databases at the central NARAC facility. It also provides stand-alone modeling and geographical information tools on remote users' personal computers. When a nuclear or radiological emergency occurs, the remote stand-alone capability calculates initial plume estimates for on-scene personnel within less than one minute. Within 5 to 15 minutes, the reach-back capability delivers a higher-fidelity, *initial* plume prediction from NARAC.

2 Using Models and Measurements to Optimize Plume Predictions for Atmospheric Releases of Known Origin

2.1 The Synergism between Models and Measurements

NARAC'S initial plume predictions form the basis for early interpretations of potential consequences. Although usually quite accurate, they can be further improved by blending in radiological measurements. Because of limitations and uncertainties in input data (e.g., source term estimates), particularly during emergencies, and due to other modeling assumptions, it is important to incorporate field measurements into predictions and assessments of dose as soon as possible during an incident or accident. For nuclear power plant accidents, it may be possible to make credible estimates of the source term based on plant conditions, inventories, or data from a monitored stack. However, refinement of these estimates requires additional data. For terrorist scenarios (e.g., a radiological dispersion device, RDD) on the other hand, little may be known about the characteristics of the dispersed and airborne material. In this case, an idealized gas or aerosol source with a unit amount of material can be used to initially predict the downwind area in which to focus air- or ground monitoring activities.

Integration of measurements of radioactive contamination, airborne or on the ground, is particularly valuable in the early and intermediate phases of an event. Even if only sparse measurement data are available, they can be used to calibrate initial model predictions to more accurately predict what areas potentially need protective actions (such as sheltering, evacuation or relocation). NARAC predictions, in turn, can help guide field teams to potentially contaminated areas that need to be monitored. Models can then be used to provide a geographically complete picture of radioactive contamination, by interpolating between measurements and extrapolating beyond areas that have been monitored by measurement teams. By using this approach to the problem, low levels of contamination that are difficult to measure can be simulated more accurately. This methodology also can aid in helping guide crop and food field sampling teams to areas in which contamination might result in an ingestion-pathway dose that exceeds regulatory limits.

2.2 NARAC's Proven Procedure for Iterative Modeling and Measuring

Typically, the first plume model prediction for a radiological incident or exercise at a NARAC-supported facility would be run by on-site personnel using the simple Gaussian plume model included with the NARAC iClient software package (see Figure 1a). The Gaussian model runs in approximately one minute or less. The purpose of this initial calculation is to quickly plan an immediate response strategy. As previously mentioned, rather than assuming a worst-case scenario, a credible guess of the source would be used, based on knowledge of the facility and its inventories. Typically the site would notify NARAC of the incident and run the Gaussian model within approximately 10 minutes of the time that the incident occurred ($T_{incident}$+10 minutes).

The same input data used for the Gaussian model would be automatically relayed to NARAC and used as input for the initial NARAC "reach-back", three-dimensional, higher-fidelity simulation. The plume prediction from this simulation will be available to the on-site personnel within about 10 minutes of the time the request is received by NARAC (see Figure 1b).

Initially guided by the locally run Gaussian model plume prediction, and by first-hand knowledge of the real-time weather conditions at the facility, the local teams would deploy by approximately $T_{incident}$+10 minutes to take the first radiological measurements. At approximately $T_{incident}$+20 minutes (10 minutes after NARAC was notified) the local teams would receive the initial, fully automated NARAC plume prediction over the NARAC iClient and/or NARAC Web communications systems. The measurement teams would relocate, if so indicated by the initial NARAC prediction, to fine-tune their search for radioactivity under NARAC's predicted plume path. If they already had measurement data, the teams would send those data to NARAC using the iClient.

Meanwhile, the NARAC Staff would be doing a thorough quality-control check of the input data (source term, meteorological data, etc.) of the automated NARAC prediction and, if necessary, would make adjustments to the input data and other aspects of the simulation (model domain size, grid structure, etc.) to optimize the accuracy of the initial prediction. A second NARAC predication (see Figure 1c), incorporating those modifications, would be sent to the facility where the event or exercise occurred. The on-site measurement team would once again refine the search area, based on the quality-controlled NARAC calculation.

Within approximately 30 minutes to one hour after the time of the incident, the on-site teams would use the iClient to send NARAC a set of radiological measurements (perhaps a dozen or so), which NARAC would use for the first refined (source-scaled) calculation (Figure 1d). NARAC scientists would visually and statistically compare measured and computed values for each monitoring location point. A useful statistic is the average ratio of measured and computed values. These ratios provide good statistical measures for values that can vary over many orders of magnitude, and can be used to scale the airborne source amount assumed in the model. A range of values for uncertain model input data (in particular wind data from several possible sources, and release heights for buoyant releases) are analyzed to determine the input data that result in the best-fit model predictions, as measured by the measured-computed ratios. As the response to the event continued, NARAC's iterative process of modeling and measuring would continue until the plume's path and the deposition pattern were adequately mapped.

For major radiological emergencies, more comprehensive measurements are provided by the Federal Radiological Monitoring and Assessment Center (FRMAC), an interagency organization with representatives from federal, state, and local radiological response organizations. The FRMAC coordinates all federal off-site radiological monitoring and assessment activities during a radiological emergency. Guided by NARAC's initial plume predictions (Figure 2a), deployed FRMAC assets – including the Radiological Assistance Program (RAP) and the Aerial Measurement System (AMS) – take detailed radiological measurements in the affected area (see Figures 2b and 2c). Data are collected, assessed, and stored in FRMAC databases, and then electronically transmitted to NARAC[4]. In an iterative process, NARAC would continue to use the FRMAC measurements to further refine its calculations, and use its calculations to guide the measurement teams. After all measurements are completed, NARAC would calculate a final refinement of the radiation pattern over the affected area, and assess the long-term consequences.

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[4] An Extensible Markup Language, or XML, file is being developed to electronically tranfser measurement data from FRMAC databases to the NARAC modeling system. XML has proven to be a simple, flexible, self-describing text format for this use. Data are stored with necessary metadata, such as units of measure, time of measurement, type of instrument, type of radiation or isotope.

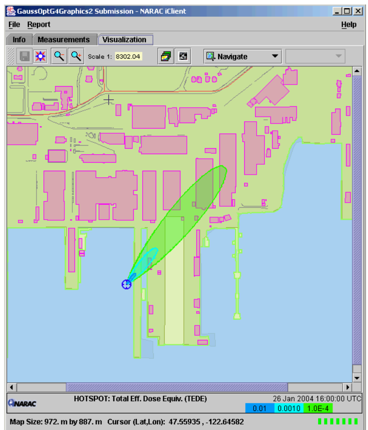

Fig. 1a. Initial 2-D local model prediction runs at the supported facility in approximately 1 minute.

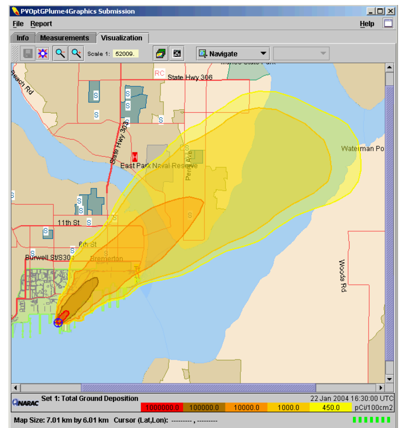

Fig. 1b. Initial NARAC “reach-back” 3-D model prediction is fully automated and is available at the supported facility in approximately 10 minutes.

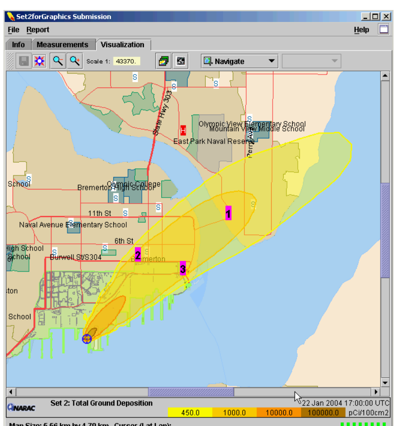

Fig. 1c. Quality-assured NARAC 3-D model prediction is available within approximately 30 minutes.

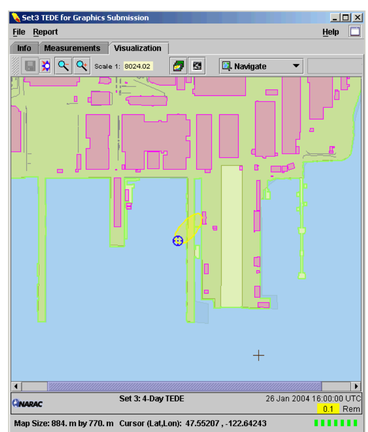

Fig. 1d. Refined NARAC 3-D model prediction is scaled by field measurements and typically is available within less than two hours.

Figure 1. The NARAC phased response concept of operations.

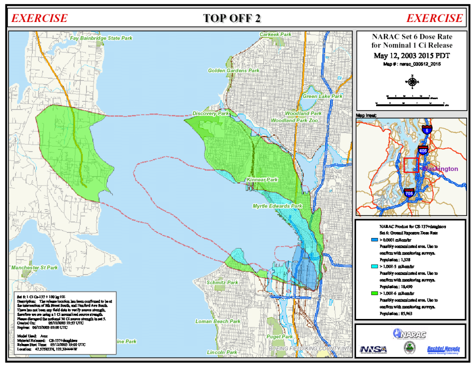

Fig. 2a. Initial NARAC plot for an exercise

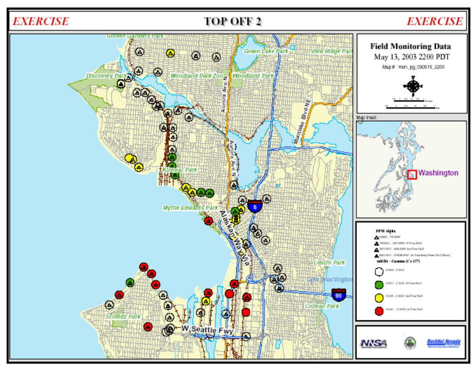

Fig. 2b. Locations of simulated ground-based measurements

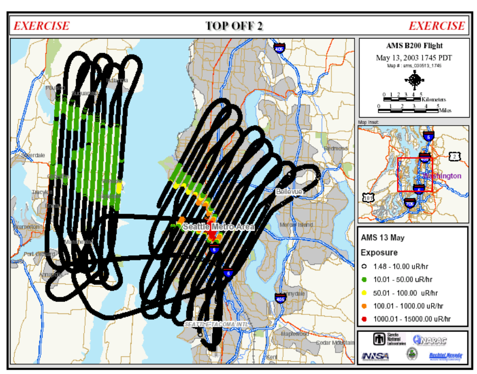

Fig 2c. Aerial Measurement System flight path

Figure 2. The U.S. Department of Energy's NARAC, RAP, and AMS use models and measurements to support the FRMAC. See text for more details.

2.3 Examples of actual Events for which NARAC has used the Model-Measurement Iteration Procedure

Examples of NARAC's use of field measurements to update model predictions and estimate source terms include the Uranium Criticality accident at Tokaimura, Japan, in 1999, and the accidental melting of a Cesium medical radiation source at a steel-processing facility in Algeciras, Spain in 1998 (Vogt et al., 1999).

3 Using Models and Measurements to Forensically Reconstruct Atmospheric Releases of Unknown Origin

3.1 The Motivation for an Event Reconstruction Capability

NARAC is developing a new capability, complementary to those described above, that will use models and data from monitoring systems to characterize and forensically reconstruct the details of atmospheric releases of unknown origin. When a hazardous plume is detected by an instrument network, but there is no knowledge of an atmospheric release, an *event reconstruction* capability must answer the critical questions: "*How much material was released?", "When?", "Where?",* and "*What are the potential consequences?"* Current methods rely on first responders or analysts to estimate source characteristics, which are then used as input to predictive models to analyze the impacts of the release. Inaccurate estimation of the source term can lead to errors and/or time delays in the response to a crisis. NARAC is developing a data-driven event reconstruction capability, which seamlessly integrates observational data streams with predictive models to provide high-quality estimates of unknown source term parameters, as well as optimal and timely situation analyses consistent with both models and data.

Traditional approaches to atmospheric release event reconstruction such as manual inversion, adjoint methods, or optimization have proved problematic. These approaches fail when applied to a general event reconstruction problem due to inherent complexities of the problem, high-dimensionality and non-linearity of the underlying dynamical system, and error processes and uncertainties characterized by non-Gaussian distributions. Often they can provide only a single "best" answer and are difficult, if not impossible, to solve for large non-linear systems. These methods have particular weaknesses for sparse (poorly-constrained) data problems, as well as the high-volume (potentially over-constrained) and diverse data streams anticipated in the future.

Expensive detection, warning, and incident characterization systems need to derive the maximum possible information from potentially limited and/or even contradictory data. Recent real-world detection events and exercises have exposed the limitations of the current event reconstruction approach that relies on manual inversion procedures. The atmospheric release problem provides an ideal application for the development of general data-driven simulation methods, because it is a multi-scale, high-dimensional, non-linear, time-dependent problem characterized by inherent stochastic behavior due to natural fluctuations in forcing and turbulence.

Automated techniques for optimizing model simulations using air- and ground-contamination measurements hold promise for faster refinement of uncertain model input variables, such as the source term. The development and operational use of event reconstruction tools is now becoming feasible due to the convergence of numerical modeling approaches, remote and deployable sensor technologies, high performance computing, and operational deployments of detector networks. These technologies are at the forefront of a revolutionary new paradigm for treating dynamic complex problems, which involve mutual optimization of sensor data and models (the use of data to steer models and of models to guide data collection). A variety of approaches are being pursued, including heuristic methods (backward trajectories, ensemble simulations), Bayesian-inference stochastic sampling algorithms, and non-linear optimization. These techniques can greatly aid an effective response to an unexpected radiological event that requires rapid quantitative estimation of the source term(s) based upon the available data, in order to provide the best possible predictions of agent transport and the resulting health risks to the exposed population and emergency responders.

3.2 The Development of an Event Reconstruction Capability at NARAC

NARAC scientists are developing a flexible and robust data-driven event reconstruction capability and a supporting computational framework that will be suitable for operational integration. NARAC's approach couples data and predictive models with Bayesian inference and stochastic sampling to provide backward analyses to determine unknown source characteristics, optimal forward predictions for consequence assessment, and dynamic reduction in uncertainty as additional data become available (Johannesson 2005; Kosovic, et al., 2004, 2005). The new capability uses stochastic sampling methods to solve source inversion problems and compute source term parameters taking into consideration measurement errors and forward model errors. Stochastic sampling methods are suitable even for the problems characterized by non-Gaussian distribution of source term parameters and when the underlying dynamical system is non-linear. NARAC scientists have demonstrated a Markov Chain Monte Carlo (MCMC) event reconstruction capability using data from the Prairie Grass (Barad, 1958) and Copenhagen (Gryning, 1981) tracer field experiments. By using data from a subset of sensors and NARAC's operational Lagrangian particle dispersion model, LODI (Nasstrom et al., 2000), the source location and source release rate can be identified. Using the MCMC capability NARAC has demonstrated source inversion with a three-dimensional, building-resolving, computational fluid dynamics code (Chow, et al., 2005a, 2005b). NARAC scientists also have demonstrated a multi-source release reconstruction based on synthetic data. To assimilate data dynamically as they become available, NARAC has developed and implemented a Stochastic Monte Carlo (SMC) methodology and has demonstrated its source inversion capability for a synthetic moving source.

The coupling of Bayesian inference with stochastic sampling methodologies provides a powerful alternative approach to the event reconstruction problem. Bayesian methods address the “inverse” problem via an efficient sampling of an ensemble of predictive simulations, guided by statistical comparisons with observed data. Predicted values from simulations are used to estimate the likelihoods of available measurements; these likelihoods in turn are used to improve the estimates of the unknown input parameters. Bayesian methods impose no restrictions on the types of models or data that can be used. Thus, highly non-linear systems and disparate types of concentration, meteorological and other data can be simultaneously incorporated into an analysis.

This approach will enable the development of a unique and robust event reconstruction framework for a viable operational tool. The results could be very different from those provided by conventional methods. They will include a mapping of the relative probabilities of all possible outcomes of the problem. This information will allow decision makers to weigh various courses of action or determine what new data should be obtained. It will reduce uncertainties in situation awareness and facilitate informed decision-making to help emergency managers take the most effective actions to protect the affected population (e.g., evacuation, sheltering-in-place, medical treatment). The project directly leverages on the investments being made at LLNL and other institutions to develop sensors, real-time data acquisition and communication systems, predictive models, and high performance computing.

3.3 An Example of Event Reconstruction for an Intermediate-Scale Tracer Field Experiment

In the Copenhagen field experiment, releases were from an elevated source at 120m above the ground. Three twenty-minute time-averaged concentrations measurements were available for each one-hour release period, and the domain was about 100 km^2. Figure 3 shows the results of the event reconstruction process using MCMC based on measurements from only nine sensors. The experimental setup is shown in Figure 3a; the source is located at the coordinate (0, 0), sensors are denoted with circles, and the length of the bars represent average concentrations measured by particular sensors while their orientation indicates the mean wind direction. The probability distribution of the source location obtained from event reconstruction using MCMC is shown in Figure 3b. The actual source is within the fifty-percentile confidence region. Figure 3c shows the reconstructed source release rate (blue line), computed as a mean of the four Markov chain reconstructions, compared to the actual release rate (red line). The MCMC algorithm successfully reconstructed both the release rate and the source location given the errors in measurements and model predictions of plume dispersion.

Fig. 3(a)

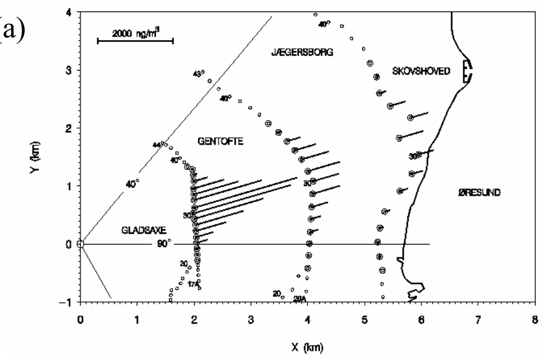

Fig. 3(b)

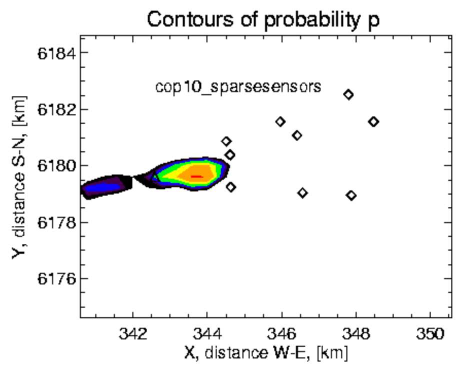

Fig. 3(c)

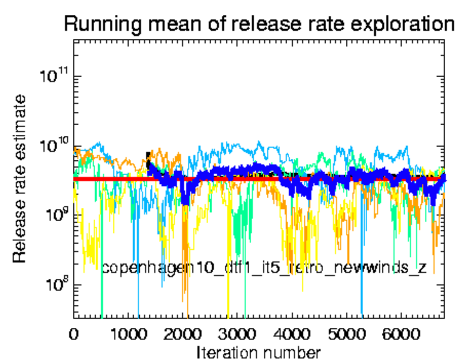

Figure 3. Event reconstruction with MCMC algorithm and LODI dispersion code for the Copenhagen experiment. The circles in frame (a) shows sensor locations and the bars represent one-hour integrated concentrations. The event reconstruction probability distribution of source location is shown in frame (b) and a comparison of the reconstructed (blue) vs. actual (red) release rates is shown in frame (c). See text for more details.

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