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Local-Scale Hazmat Dispersion Modelling for First Responders Based on High-Resolution Computational Fluid Dynamics - an Overview of CT-Analyst Hamburg

Bernd Leitl[*a], Frank Harms[a], Eva Berbekar[a], Jay Boris[b], Gopal Patnaik[b], Keith Obenschain[b], Susanne Fischer[c]

[a]Universität Hamburg, Meteorologisches Institut, Bundesstrasse 55, 20146 Hamburg, Germany
[b]Naval Research Laboratory, Advanced Computational Physics Lab, 4555 Overlook Ave, Washington DC 20375-5344, USA
[c]City of Hamburg Ministry of Interior and Sports, Johanniswall 4, 20095 Hamburg, Germany
bernd.leitl@uni-hamburg.de

Accidental and deliberate releases of harmful substances pose a tremendous challenge to first responders because of the large number of possible casualties and the resulting potential environmental and economic damage in densely populated areas. Within minutes after a release, countermeasures must be taken to protect the population and environment adequately. This requires the exposed area, travel time of pollutants and possible exposure levels to be known in advance with sufficient accuracy in complex urban and industrial terrain where accidental releases are possible. This paper introduces an innovative and efficient concept for a more reliable local-scale hazmat dispersion modelling in the context of emergency response, developed at NRL. Using the current implementation of this approach for first response professionals in the city of Hamburg as an example, an overview of the emergency response tool CT-Analyst Hamburg is presented. Unique features of the tool such as source location reconstruction based on available measured data or the simulation of pollutant retention time in built-up terrain are discussed. The extensive efforts undertaken to carefully and reliably validate the first responder's tool are described. Both, the underlying CFD-LES simulations as well as the CT-Analyst tool have been validated extensively using high-resolution test data sets generated in special boundary layer wind tunnel facilities and available field test data.

1. Motivation and basic concept of the tool

Reliable airborne hazmat dispersion modelling is a critical core component of efficient and adequate emergency response. Major challenges in airborne hazard dispersion modelling include the requirement for instant availability of meteorological information, of sufficiently high quality for dispersion modelling close to the ground and a sufficiently accurate characterization of the release source to be simulated. Even if qualified meteorological data and emission source information is available, atmospheric dispersion modelling remains a big challenge particularly at local scale. In this local scale, covering the first few kilometers distance from the source, individual flow obstacles have a direct impact on dispersion patterns resulting from puff or plume releases. Exposure is characterized by extreme concentration fluctuations and a permanent variability of plume or puff dispersion parameters. At the local scale, obstacle-resolving flow and dispersion modelling is mandatory for sufficiently accurate prediction of dispersion patterns and realistic threat assessment. Only such fast and reliable dispersion modelling avoids the need for excessive safety factors contradicting, for example, evacuation concepts in densely populated areas from a logistic point of view.

In principal, qualified advanced flow and dispersion modeling tools such as Large Eddy Simulation already exist. However, they cannot be used in a case of emergency because calculations are too laborious and time consuming and the interpretation of results is not a straight forward task. In an emergency, first results are needed within a minute or two and evolving information on the scenario should be considered continuously, as it becomes available, in simulation efforts. A fundamentally different approach is needed, if high-resolution dispersion modeling is intended to be used in the context of time-sensitive, local-scale emergency response.

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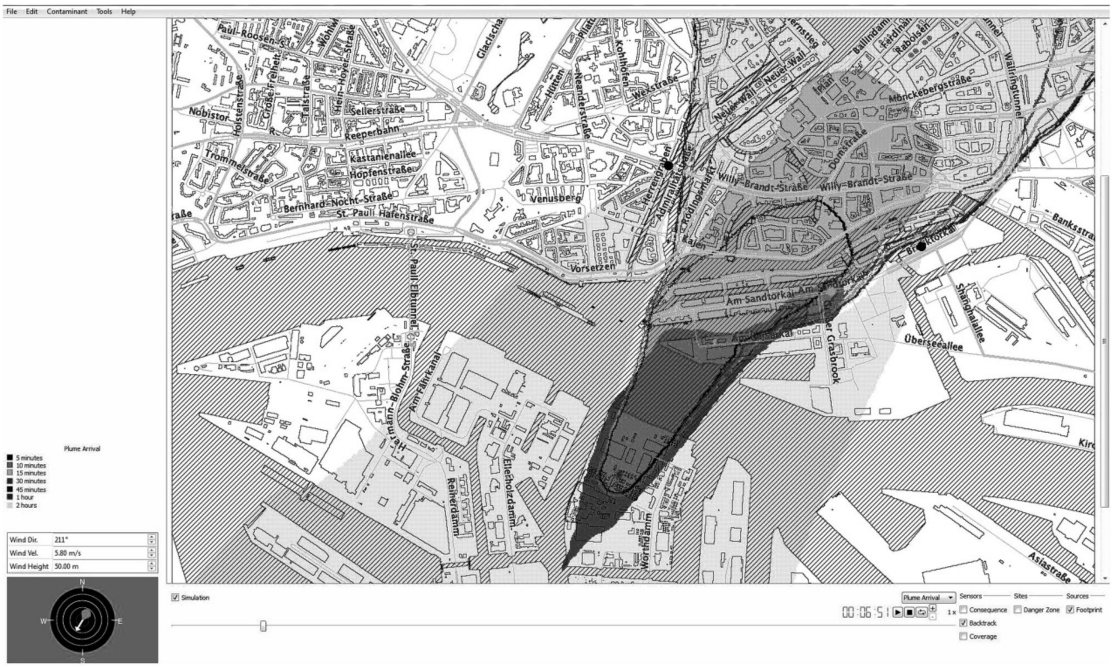
The CT-Analyst approach, developed at the U.S. Naval Research Laboratory, is providing a simulation methodology delivering reliable plume dispersion results based on advanced computational fluid dynamics in built terrain instantly and at a comprehendible level of complexity, first responders can deal with immediately. Amongst others, the concept has been implemented in the emergency response management of the city of Hamburg and is used on an operational level by the Hamburg Fire Brigade.

The fundamental concept of CT-Analyst is to use an extensive amount of pre-calculated systematic high-resolution wind field data for the given urban geometry to derive essential parameters driving the geometrically accurate dispersion process for the current real-time wind field. In case of an emergency, the first responder's tool CT-Analyst then constructs the area possibly affected by a certain release as well as features like pollutant travel time and possible health effects with reference to chosen exposure levels. The big advantage of this two-step approach is that time-consuming sophisticated flow simulations can be carried out in advance, but the actual reconstruction of puff or plume releases is carried out in milliseconds even on affordable hardware like handheld tablet devices or personal computers while the effect of complex urban or industrial structures on the dispersion pattern is still maintained in the response tool.

For systematic wind flow simulations the monotonically integrating Large Eddy Simulation (LES) software Fast3D-CT is used (Patnaik et al., 2010 and references therein, Leitl et al. 2013). Like other computational fluid dynamics code packages, Fast 3D-CT simulates the transient wind flow patterns in complex urban and industrial structures by solving the system of relevant conservation equations numerically. Whereas standard LES models use subgrid-scale turbulence models to consider the effect of turbulence not explicitly resolved in the model, Fast 3D-CT uses a more efficient monotonic turbulence integration scheme. This enables substantially larger computational domains to be simulated at sufficient resolution even on ordinary computational hardware within a reasonable amount of time. In a preceding pilot study an area of 192 km^2 was treated in the software, a current implementation of CT-Analyst covering the whole city of Hamburg comprising approximately 760 km^2, is processed on a server with 4 six-core CPUs and 128 GB RAM.

The physically motivated data reduction leads to compact maps of bounds defining the maximum area a possible release can cover. Deriving these so called Nomografs is also a part of the tool generation and carried out before the use of CT-Analyst. A detailed description of the Nomograf generation can be found in Boris et al. (2011). The computational effort for calculating Nomografs is less than for the flow simulations but still substantial if a large domain needs to be covered. One of the unique features of the Nomograf approach also is that large areas of interest can be subdivided in several smaller patches. Flow simulations and Nomograf generation are carried out at patch sizes the available hardware can handle and results can subsequently be merged at the Nomograf level. This enables the basis of the first responders tool CT-Analyst to be updated as necessary, when the building structure is changed substantially due to urban development, changes in the layout of an industrial site occur, or the coverage region is expanded. There is no need to re-calculate the whole domain, lowering costs for tool maintenance and allowing more frequent updates. Furthermore, the patch-like approach allows subareas to be resolved with higher local resolution and embedded in the whole domain seamlessly. In this way, computational and modelling efforts can be spent where actually necessary, for example close to more complex obstacle arrangements or in areas requiring higher protective measures.

Finally, the CT-Analyst tool provides an intuitive, easy to use interface where first responders can interactively drop sources and sensor locations on a map and receive, at virtually no delay, information on the area affected by a release, on pollutant cloud travel time, or on health risk levels for a chosen hazardous material. The required representative wind speed and wind direction driving the dispersion process could be provided automatically via linked measurement stations or meteorological now-casting and can be adjusted interactively by the tool operator. Incorporating sensor readings, as they might be available from standard monitoring stations or mobile units regularly deployed during accidental releases, allows “back-tracking” to unknown source locations as easily and quickly as the dispersion predictions are provided. As with other hazmat dispersion modeling tools, CT-Analyst can handle numerous sources and sensors in one scenario simultaneously, with no relevant loss in performance. Simulating the temporal behavior of a release is easily possible while moving the source, which enables automated tracking of possible sources like hazmat trucks or ships. Furthermore, all dispersion simulation results can be exported for display/overlay in standard mapping applications like GIS or GoogleEarth. Figure 1 shows a typical screenshot of the tool as it is currently used by first responders in Hamburg.



Wind Dir. 211°
Wind Vel. 5.80 m/s
Wind Height 50.00 m

Figure 1: Screenshot of the first responders tool CT-Analyst, predicting the affected area that results from an instantaneous release at an industrial site. The circular dots represent sensor locations for which readings (cold/hot) are available for backtracking the source location.

2. Tool validation

As in any modelling effort, the CT-Analyst tool involves abstraction or simplification from the usually more complex reality. Thus, a fundamental requirement for any tool is its application-specific testing and validation. As far as CT-Analyst Hamburg is concerned, the task was (a) to validate the LES model Fast3D-CT specifically for application in typical European urban environments and (b) to validate the results of the CT-Analyst tool specifically implemented for the city of Hamburg. Both tasks can be handled independently as long as the underlying flow simulations are validated first to ensure that the CT-Analyst results are right for the right reasons. The following paragraphs briefly summarize extensive model and tool validation efforts.

Validating flow and dispersion models specifically for use in the context of local-scale emergency response is a non-trivial task. As outlined in model validation protocols existing for micro-scale meteorological modelling or as proposed explicitly for local-scale emergency response modelling (Andronopoulos et al., 2015), model validation requires first of all application-specific reference data of sufficient quality. Availability of such data is still very limited. In complex urban geometries it is nearly impossible to generate qualified representative validation data based on field measurements. As far as general measurement data quality is concerned, test datasets must contain sufficient information on wind flow to both derive all required input boundary conditions to run a certain flow model and to sufficiently validate predicted flow patterns within the corresponding model domain. In the context of local-scale emergency response, the situation is complicated further by the fact that mean flow patterns are almost irrelevant at local-scale. Due to the turbulent nature of wind flows driving local-scale dispersion in complex environments, instantaneous wind fields and fluctuations in wind speed and direction must be simulated and validated correspondingly.

2.1 Fast3D-CT model validation for a European city

In the work presented here, Fast3D-CT results were compared with results from systematic boundary wind tunnel measurements in a detailed model of parts of the city of Hamburg (Hertwig, 2013). The model validation was carried out as a blind test which means results of numerical simulations were delivered before the experiments in the wind tunnel were completed. At several hundred measurement locations within the reference area, statistically representative time- and component-resolving wind flow measurements were captured and analysed. The results were compared with corresponding Fast3D-CT wind flow time series regarding mean turbulence statistics as well as transient flow phenomena. Figure 2 documents the excellent reproduction of mean horizontal wind speed even within very complex urban structures for 3 typical measurement locations. Similarly good agreement was found for comparison of wind direction and turbulence intensity profiles. For a more detailed comparison of turbulent features of the modelled flow, among others the spectral distribution of turbulent kinetic energy was compared. Figure 3 shows again a good agreement between simulation results and the measured data, providing confidence that all relevant wind flow fluctuations are well replicated by the Fast3D-CT model. The spectra indicate the expected fall off in turbulent kinetic energy for eddy sizes in the order of resolution of the computational grid or smaller. From the entire validation effort it could be concluded that Fast3D-CT flow simulations deliver at least sufficiently accurate wind flow data to generate Nomografs from.

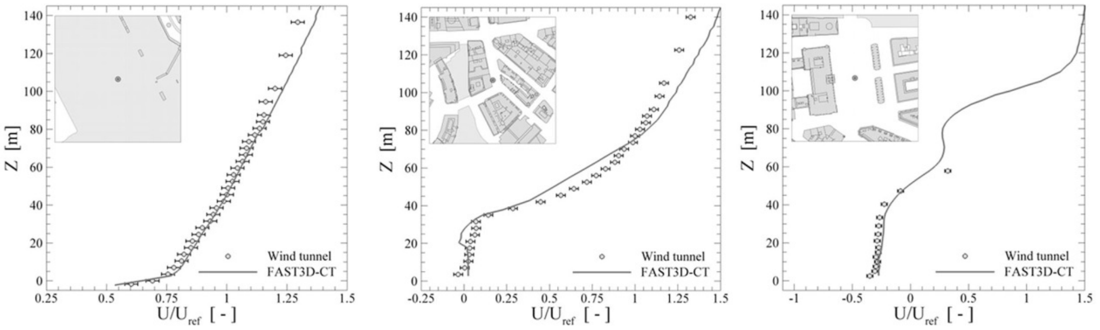


Figure 2: Comparison of normalized horizontal mean wind speed measured in the wind tunnel (symbols) with corresponding Fast3D-CT results (solid line) for three typical locations.

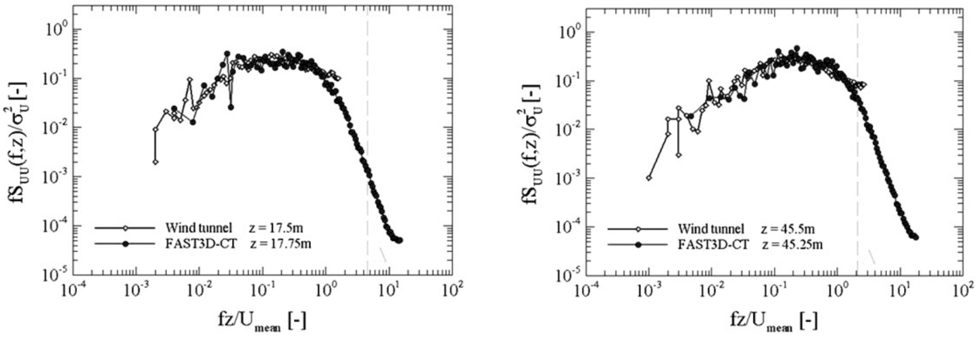


Figure 3: Comparison of non-dimensional turbulent kinetic energy spectra calculated from wind tunnel measurements (open symbols) and corresponding Fast3D-CT wind velocity time series (solid symbols).

2.2 Validation of the CT-Analyst first responders tool

As a second stage validation, the predictions of the CT-Analyst tool were systematically validated using corresponding time-resolved dispersion measurements from boundary layer wind tunnel modelling and using a single release field trial in Hamburg as reference cases. In the laboratory experiments, several emission scenarios in different release environments were measured, enabling the performance of the tool to be evaluated for releases in relatively open terrain on a river and in industrial environments as well as in densely built-up urban regions. As the tool predicts essentially three major quantities (1) the affected area, (2) the travel time of released material and (3) concentration levels used for health effect assessments, different dedicated reference measurements were required.

For verification of the predicted impact area, continuous releases were simulated in the wind tunnel. The edge of the exposed area was identified by recording very long concentration time series in order to detect possible momentary occurrences of tracer/pollutant at a given location. Depending on the assumed full-scale wind speed, the length of the time series recorded in the laboratory corresponds to at least several hours full-scale. Surprisingly sharp bounds of the exposed area were found for most of the simulated release scenarios. A possible explanation for this behaviour is the effect of buildings guiding the flow close to the ground. Figure 4 illustrates the validation for a typical release scenario. On the corresponding CT-Analyst map, the shaded area is representing the predicted danger zone where released hazardous material can be expected. The square symbols indicate locations, where in the corresponding laboratory experiment at least one occurrence of released tracer was detected. Locations where no tracer signal was recorded within a period of several hours are marked by triangles. The predicted danger possible exposed area agrees within a few meters with the corresponding measurements.

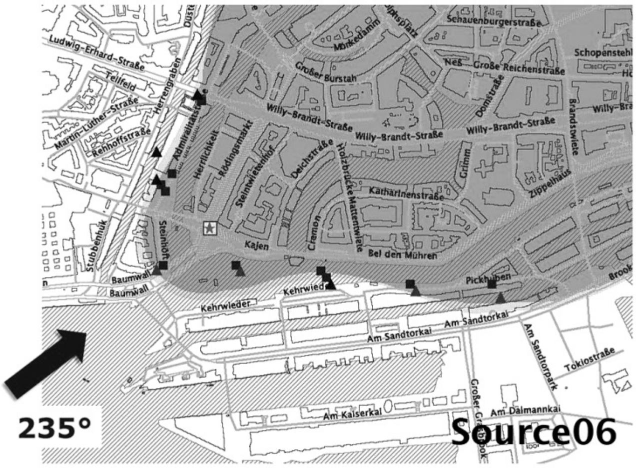


Figure 4: CT-Analyst exposure area validation: the star symbol marks the release location, the shaded area corresponds to the predicted danger zone, square symbols indicate locations where at least momentary exposure was detected and triangles indicate locations where no pollutant was detected within several hours in the reference experiments.

For validating predicted pollutant cloud travel times, instantaneous releases were simulated in the laboratory experiment. Release durations of substantially less than a second in the wind tunnel correspond to approximately two minutes at full-scale for typical wind speeds. For each release scenario and several measurement locations per case, more than 300 individual puff releases were simulated. This ensured statistically representative ensembles of reference data for the inherently variable results caused by turbulence. In Figure 5, a typical example shows for just one out of more than 30 test locations the frequency distribution of cloud travel times measured in the laboratory and the arrival time as predicted by CT-Analyst. Again, a remarkably good performance of the tool is documented, considering that CT-Analyst should also be providing 'conservative' results as far as cloud travel time is concerned.

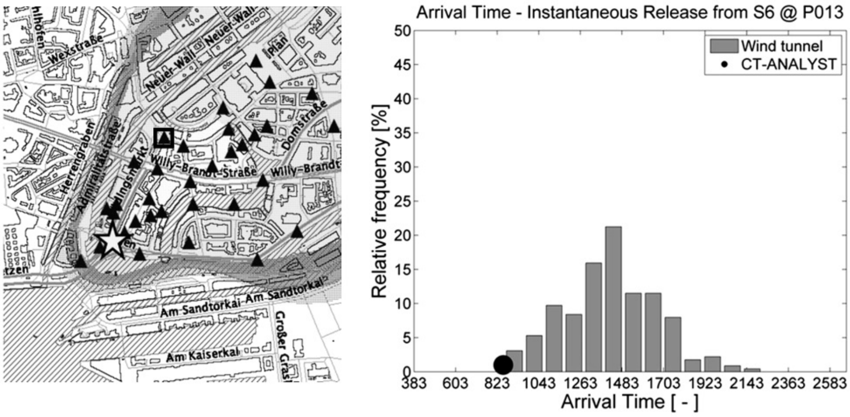


Figure 5: Puff travel time validation: the bars represent the frequency distribution of measured cloud arrival times for the measurement location marked by the square, the circle indicates the arrival time as predicted by CT-Analyst.

In a similar way, concentration levels were validated. Here again continuous releases were simulated because they can be assumed as worst case of a release, including all possible concentration fluctuations a transient puff signal may contain. From sufficiently long concentration time series, the frequency distribution of measured or possible instantaneous concentration values was calculated and subsequently compared with the corresponding CT-Analyst predictions. As can be seen in Figure 6, the concentration value predicted by CT-Analyst closely resembles the mean and/or most frequent concentration value derived from the frequency distribution of measured concentrations.

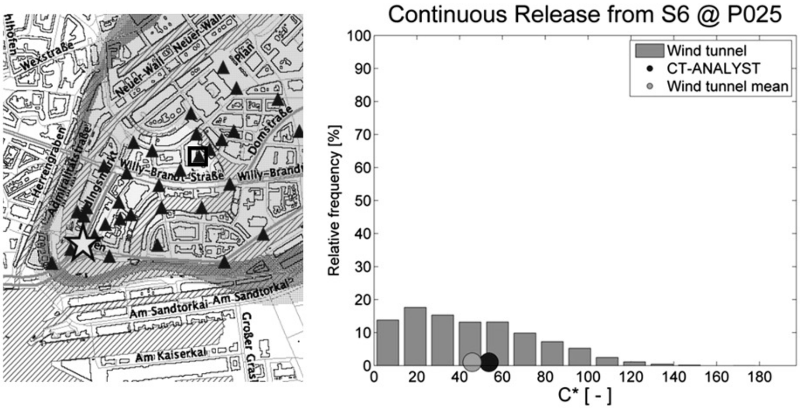


Figure 6: Validation of predicted concentrations: at the location marked by the square, the frequency distribution of concentration values measured in the wind tunnel are indicated by the bars while the two circles show the corresponding mean predicted and measured values.

Many different release scenarios with usually several tens of measurement locations were used to carefully validate the model predictions of CT-Analyst. Considering the level of model simplification implemented in CT-Analyst the agreement for predicted values with corresponding reference values was again found to be remarkably good. As intended, the tool clearly replicates the effect of local obstacles in dispersion plumes or puffs even for the complex and heterogeneous geometry of a European city.

3. Conclusions

An innovative concept for the use of sophisticated flow modelling in the context of local-scale emergency response has been presented. Based on dispersion Nomografs derived from pre-calculated flow field data, the easy-to-use first responder's tool CT-Analyst can predict instantly for a given release the affected area, pollutant travel time, and exposure levels as they are needed for emergency response management. The tool has been validated successfully for application in the city of Hamburg and is being used by Hamburg Fire Brigade services at operational level.

Acknowledgments

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