CONSTRUCTION OF OBSERVATIONAL OPERATOR FOR CLOUDSHINE DOSE FROM RADIOACTIVE CLOUD DRIFTING OVER THE TERRAIN

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INTRODUCTION

We are presenting a specific method for real-time calculation of cloudshine dose used for purposes of online assimilation of model predictions with observations from terrain. Model predictions of cloudshine dose are calculated in an array of measurement sensors located on terrain around a nuclear facility. The method enables to construct an observation operator for data assimilation systems where gamma dose rate measurements must be compared with dispersion model evaluating activity concentration in air.

The dynamics of radioactive cloud propagation over the terrain is simulated by two approaches. In the near distances from the source of pollution (several hundreds meters covering the teledosimetric circle of sensors (TDS) on the fence of a nuclear facility) we are presenting a certain modification of classical straight-line Gaussian solution of the near-field dispersion problem. Further movement driven by changing meteorological conditions is described according to segmented Gaussian scheme. In both cases the n/μ method introduced for photon transport in the ambient air ensures fast generation of predicted external irradiation doses/dose rates entering the assimilation procedures. Early stage of an accidental release of radioactivity into the living environment is examined with definitive intentions to utilize this effective software in the further process of Bayesian tracking during the cloud passage over the terrain.

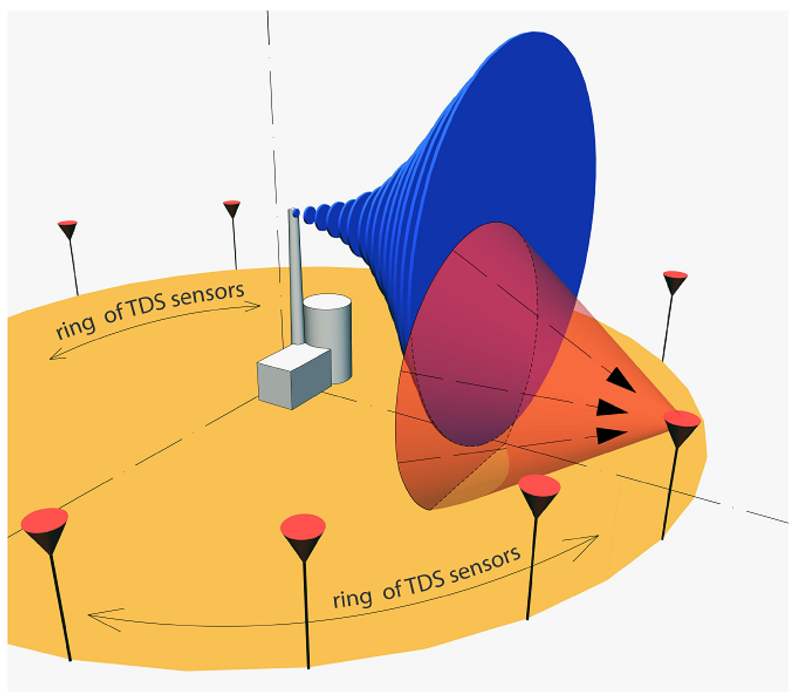

Figure 1: Schematic illustration of ring of TDS sensors around NPP.

DISPERSION MODELING

We shall adopt a classical solution of diffusion equation for description of the initial phase of radioactive discharges drifting (near-field model). 3-D distribution of specific radioactivity concentration C^n of nuclide n in air $[Bq.m^{-3}]$ is expressed by the straight-line Gaussian solution. The approach has long tradition of its use for dispersion predictions.

Proved semi-empirical formulas are available for approximation of important effects like interaction of the plume with near-standing buildings, momentum and buoyant plume rise during release, power-law formula for estimation of wind speed changes with height, depletion of the plume activity due to removal processes of dry and wet deposition and decay, dependency on physical-chemical forms of admixtures and land use characteristics, simplified account of inversion meteorological situations and plume penetration of inversion, plume lofting above inversion layer, account for small changes in surface elevation, terrain roughness etc.

Straight-line solution is limited for its use to short distances from the source (up to several kilometers corresponding to the first hour (half an hour) of the short term meteorological forecast). In the further phases of the plume drifting the meteorological conditions have to be considered more realistically. For this purposes a segmented Gaussian plume model (SGPM) is introduced (Hofman,R. and P. Pecha, 2011) which takes into account the hourly (half-hourly) changes of meteorological conditions given by short term forecast (48 hours forward) provided by the meteorological service.

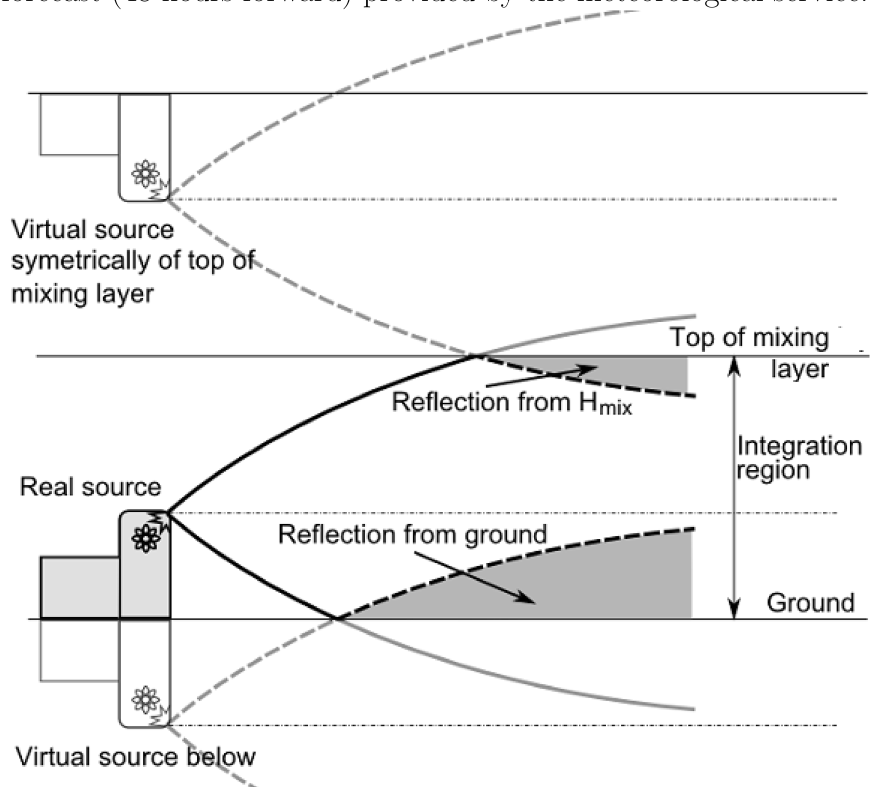

Figure 2: Chart of straight-line Gaussian solution with reflections.

NEW METHOD FOR CLOUDSHINE DOSE CALCULATION

Transport of photons with energy E_γ from the source of emission to receptors R will be described by the quantity of photon fluency rate $\Phi(E_\gamma, R)$ in units $m^{-2}s^{-1}$. Calculation of the fluency rate $\Phi(E_\gamma, R)$ from the whole plume based on the three-dimensional integration is given by the scheme:

$$\Phi_{\text{total}}(E_\gamma, R) = \iiint_V \frac{f\ C(r)\ B(E_\gamma, \mu\ |r|) \exp(-\mu\ |r|)}{4\pi\ |r|^2} dV. \quad (1)$$

$B(E_\gamma, \mu\ |r|)$ stands for build-up factor, μ is linear attenuation coefficient, $|r|$ is distance between receptor point R and element of the plume. f is branching ratio for E_γ.

Activity concentration given by analytic equation of a Gaussian plume is schematically illustrated in Figure 1. Continuous and constant release in direction of x-axis with average velocity $\bar{u}$ is segmented into equivalent number of elliptic discs according to Figure 3. Thickness of discs is selected as $\Delta x = 10m$. Disc i reaches the position $x_i = (i - 0.5)\Delta x$ during $x_i/\bar{u}$ seconds. Lumped parameter technique is introduced when model parameters are averaged within interval Δx on the disc i.

The $5/\mu$ method (generally n/μ method) imposes integration limit up to d_{max} and considers such significant only those sources of irradiation lying up to distance $5/\mu$ from the receptor R. Integration boundary (see also integration circle in Figure 4) is formed by intersection of the cone (receptor R in the cone vertex) and the plane of the newest disk I. Only those points located inside contributes to the fluency rate at R. Substantial benefit has occurred with regard to the computational speed and capability to run the successive assimilation procedures in the real time mode. Traditional methods based on full 3-D integration techniques are computationally expensive (Raza, S.S., R. Avilla and J. Cervantes, 2001).

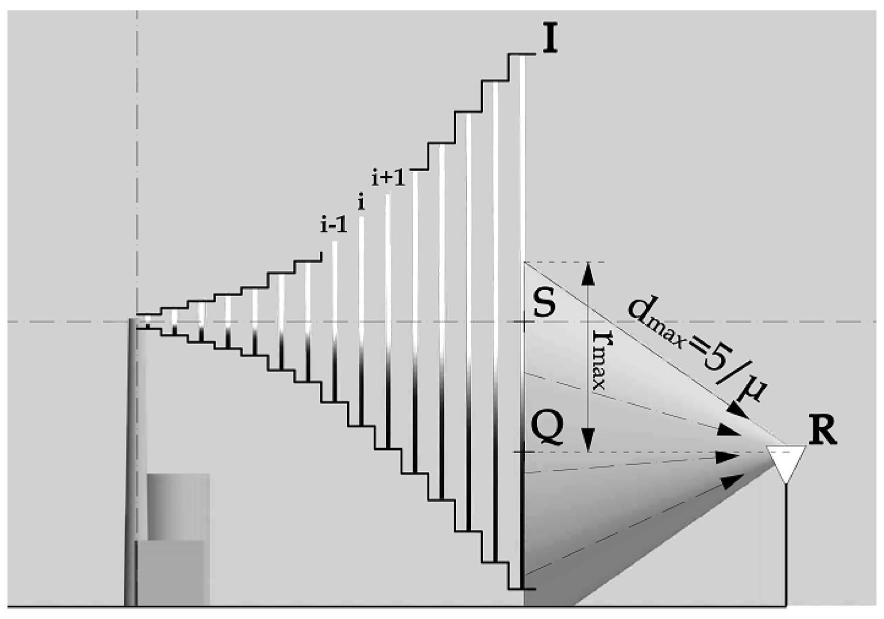

Figure 3: Segmentation of continuous release into equivalent disc sequence.

STEPWISE 2-D COMPUTATIONAL SCHEME

In Figure 3 is demonstrated lateral view on the segmented plume propagation. The same situation is outlined in the front view in Figure 4. The boundary of integration region lying in the plane of disk I is based on $5/\mu$ approximation (bold dashed line composed of the part of circle above ground with radius $r_{\max}$ and centre in the point Q). For $r_{\max}$ holds true the relationship $r_{\max}^2 = (5/\mu)^2 - [x(R) - x(Q)]^2$. Contribution of the disc I to the photon fluency rate at receptor R is given by

$$\Phi(E_\gamma, R, I) = \frac{\Delta X}{4\pi} \int_{r=0}^{r_{max}} \int_{\phi=0}^{2\pi} \frac{C^I(x_I; r, \phi) B \exp(-\mu\ d)}{d^2} r\ d\phi\ dr. \quad (2)$$

Referring to Figure 4, d is distance between R and M, $x(S) = x_I = (I - 0.5)\Delta x$ is a distance of centre of the disc I from the release point; $y(M) = r\sin(\phi)$; $z(M) = z(R) + r\cos(\phi)$. The equivalent mean activity concentration $C^I(x_I, y, z)$ in disc I is expressed using dispersion model equation. Valid values of coordinate z should be positive, dispersion coefficients and depletion factors are calculated for position x_I in dependence on physical-chemical form of nuclide.

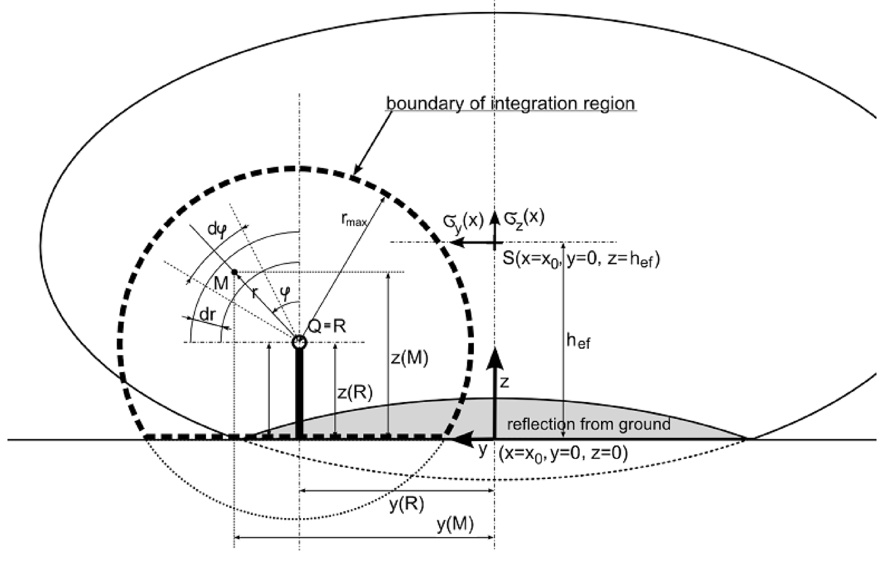

Figure 4: Frontal view from receptor point R to elliptical disk I and circular integration region.

Continuous release of admixtures still lasts: the plume has reached position of the disc I. Propagation to the $I+1$ disk is in progress. Contribution of each elemental disk i to the $\Phi(E_\gamma, R, i)$ at receptor R were calculated in the previous steps. The new contribution $\Phi(E_\gamma, R, I+1)$ from disk $I+1$ is calculated using (2). Recurrent formula for overall Φ at R is:

$$\Phi(E_\gamma, R, i = 1 \div I+1) = \Phi(E_\gamma, R, i = 1 \div I) + \Phi(E_\gamma, R, I+1)$$

$$\text{where } \Phi(E_\gamma, R, i = 1, \ldots, I) = \sum_{i=1}^{I} \Phi(E_\gamma, R, i).$$

Entire photon fluency Ψ at receptor R from the same beginning of release is given by:

$$\Psi(E_\gamma, R, i = 1, \ldots, I+j+1) = \sum_{i=1}^{I} [(I+1-i)\Delta t_i \Phi(E_\gamma, R, i)] + \Delta t_i \Phi(E_\gamma, R, I+1).$$

Release terminated, propagation continues: Let the plume has reached position of the disc I just at moment when the release has terminated. Propagation continues to the disks positions $I+1, I+2, ..., I+j$. Fluency rate $\Phi(E_\gamma, R, I+j+1)$ for position $I+j+1$ is calculated from the previous position $I+j$ according to:

$$\Phi(E_\gamma, R, i = 1, \ldots, I+1+j+1) = \Phi(E_\gamma, R, i = 1, \ldots, I+j) + \Phi(I+j+1) - \Phi(j+1).$$

Hence, contribution from the leftmost disk of a parcel is skipped, the new rightmost one is calculated. Similar considerations lead to expressions for the total fluency Ψ:

$$\Psi(E_\gamma, R, i = 1, \ldots, I+1+j+1) = \Psi(E_\gamma, R, i = 1, \ldots, I+j) + \sum_{i=j+1}^{I+j+1} \Delta t_i \Phi(E_\gamma, R, i).$$

NUMERICAL RESULTS

Responses on 40 sensors surrounding NPP (a ring of 24 TDS sensors on fence of NPP with distances roughly about 450 meters from a hypothetical source, the rest of sensors is situated in larger distances inside emergency planning zone). Our approach is demonstrated on a continuous hourly release of 9.0E+14 Bq of nuclide ^{131}I.

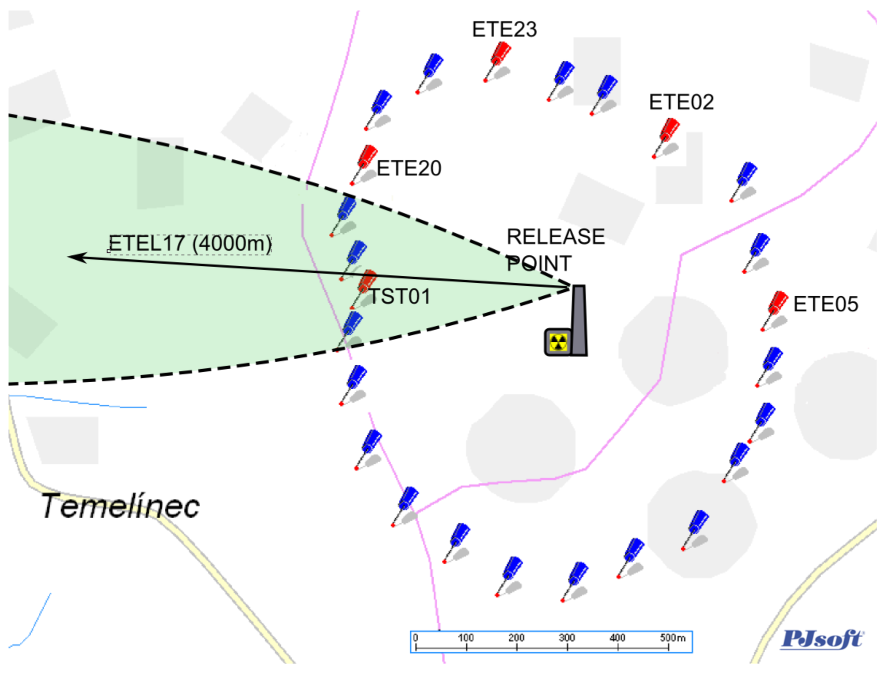

Figure 5: Tele-dosimetry ring on fence of NPP Temelin (24 detectors)

Time evolution of fluencies/fluency rates and cloudshine doses/dose rates from one hour release 9.0E+14 Bq of ^{131}I activity are simulated on all 40 sensors at once. Even for multiple nuclide group the calculations are very fast and capability for real-time assimilation techniques has been proved.

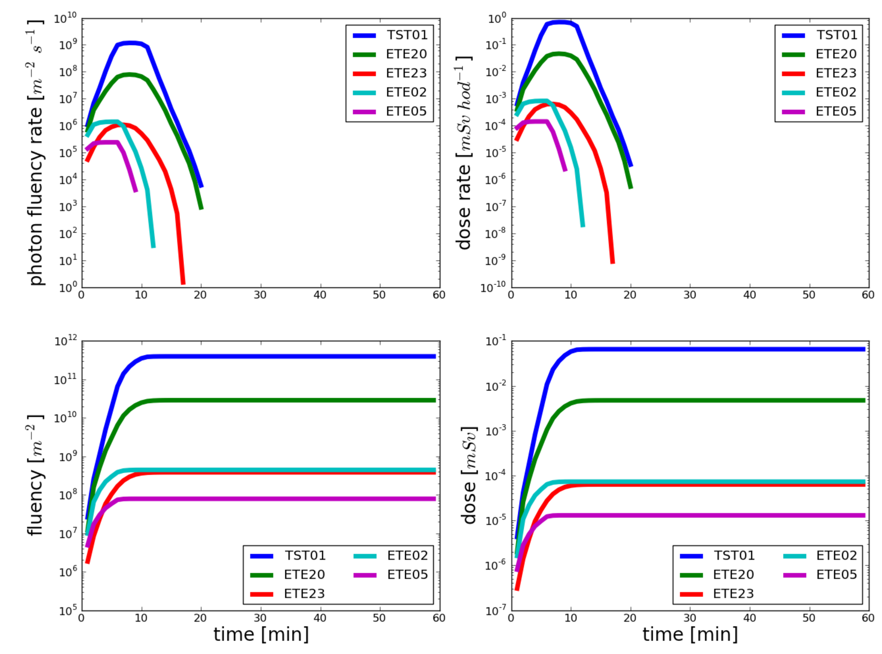

Figure 6: Time evolution of sensor response during spreading of smaller plume of 6 min duration of continuous ^{131}I release.

APPENDIX - TEST OF INTEGRATION PROCEDURE

The photon fluency given by expression (1) is integrated numerically using Gauss-Legendre integration formula which is the most commonly used form of Gaussian quadratures. We have tested the precision of integration procedure for using a comparison with analytically evaluated integrals as illustrated in Figure 7. Emitting disk with optional radius R is located in the plane (x, z) with centre in the origin of coordinate system. We assume that without loss of generality we can simplify the expression (1) in three manners:

1. Uniform radioactivity concentration deposited on the disc surface is assumed - $C(x; r, \phi) = 1Bq\ m^{-2}$
2. Photon absorption in medium between disc and receptor point R is not taken into account ($\mu = 0$)
3. Photons are emitted from the disk elements isotropically and without any secondary collision during its path from the source up to the receptor point (built-up factor is 1)

Photon fluency rate ($m^{-2}\ s^{-1}$) is now expressed by simplified equation (1):

$$\Phi(E_\gamma, R) = \frac{1}{4\pi} \int_{r=0}^{r_{\max}} \int_{\phi=0}^{2\pi} \frac{1}{d^2} r\ d\phi\ dr \quad (T1)$$

The equation (T1) can be integrated analytically and number of photons crossing 1 m2 per second at position of the sensor R is expressed as:

$$\Phi = \frac{1}{4} \ln \left(\frac{r_{\max}^2 + b^2 - a^2 + \sqrt{r_{\max}^4 + 2r_{\max}^2(b^2 - a^2) + (a^2 + b^2)^2}}{2b^2} \right) \quad (T2)$$

30 points of Gauss-Legendre integration formula is used to integrate numerically the equation (T1) for various ranges of constants a and b. Partial comparison of numerical and analytical values are presented in Table 1. Additional tests revealed a certain numerical instability for case when the sensor S lies in plane of the disc ($b = 0$) and constant a is approaching to zero. In this instance we are using the lowest value of constant b slightly above zero ($b \cong 0.2$m).

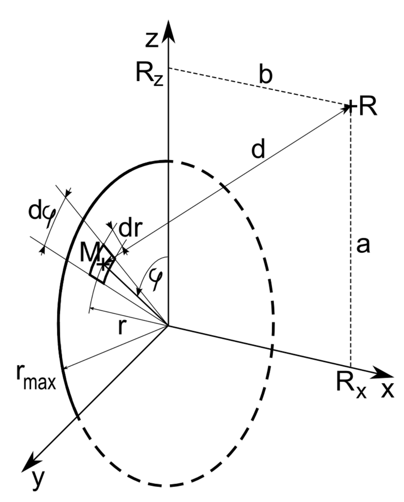

Figure 7: Disc in plane (z, y) irradiating the receptor R.

a=b	Φ numerically	Φ analytically
144	1.446555 E-02	1.446555 E-02
100	2.994087 E-02	2.994087 E-02
60	8.189546 E-02	8.189548 E-02
40	1.733492 E-01	1.733493 E-01
20	4.547102 E-01	4.547104 E-01
10	7.950500 E-01	7.950501 E-01
4	1.252774 E+00	1.252774 E+00
1.0	1.945767 E+00	1.945910 E+00
0.5	2.290156 E+00	2.292484 E+00
0.2	2.744151 E+00	2.750629 E+00
0.1	3.064821 E+00	3.097203 E+00

Table 1: Comparison of numerical and analytical values of photon fluency rates for various values a, b of the sensor R positions. Radius of radiating disc is $r_{\max}$=49 m.

CONCLUSION

Fast algorithm is presented for generation of the model responses from cloudshine irradiation on a net of sensors surrounding NPP including both from fixed stations and from potential mobile vehicles. The main branches of its utilization are summarized:

- The algorithm is designed for purposes of application of computationally expensive assimilation methods based on particle filtering techniques.
- Another significant field of application can be an of environmental monitoring network configuration for early emergency assessment and for verification of detection abilities of the networks.
- The advantage of the extremely fast model allows include a real discharged radionuclide mixture. For each nuclide all levels of emitted photons and its branching ratios could be considered and finally summed up. A separation into 6 energy subgroups was realized when successive calculations and summations are based on effective energy determined by weighting photons from cascades.
- Presented method is designed for the near field model. For distances beyond the TDS ring within zone of emergency planning (up to 15 km) or longer the SGPM dispersion model was developed which can include short term forecast of meteorological conditions. The cloudshine doses from an arbitrary shape of the radioactive cloud are again estimated numerically using the $5/\mu$ idea and the trilinear interpolation in larger ranges.
- The proposed technique accounts for depletion due to dry and wet deposition. In means that a simplified assessment of contamination of measured cloudshine dose rates caused by the activity deposited on the ground can be done.
- Finally, the originated plume segmentation method based on lumped parameter approach according to Figure 3 can be proposed as a basic scheme for formulation of a certain dispersion scheme alternative to the puff model with methodical extension to the medium range distances.

REFERENCES: see extended abstract

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