A methodology to estimate near source gamma shine outside of Gaussian or semi-infinite assumptions applied to GIROSCOPE WP3 case studies.

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CONTEXT OF THE STUDY

PIANOFORTE PLATFORM

GIROSCOPE (GUIDANCE FOR INNOVATIVE REACTOR OFF-SITE CONSEQUENCES, PLANNED AND EMERGENCY)

Goal: to provide a robust scientific platform and framework for novel nuclear reactors (NNRs).

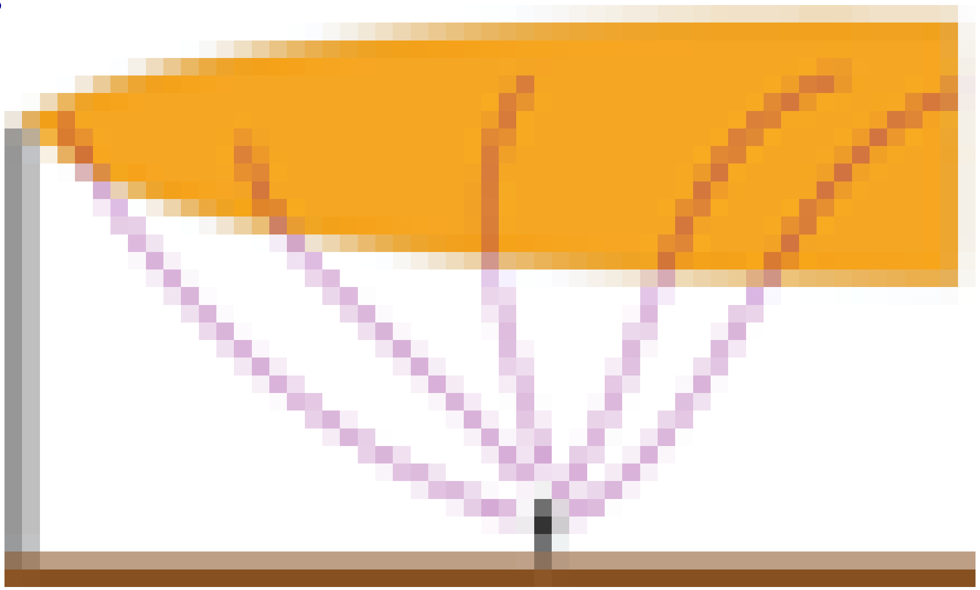
- **Emergency preparedness and response (EP&R)**
- **Environmental Impact Assessment (EIA)**

WORK PACKAGE 3

- **Focus on the modelling of dispersion and irradiation around NNRs**

NNR CHARACTERISTICS

- **Lower emissions compared to standard nuclear power plants**
- **Potential production of heat for industrial processes or residential**
- **Potentially located closer to inhabited areas**



- **Local scale irradiation (first few km)**
  - Small amount of neutron providers in release inventory
  - Dose proportional to local activity true for alpha and beta particles (with respectively lifespan in air ~cm and ~m)
  - Gamma photons may travel in air at relatively high distance (few km >> plume width close to release)
- **Operational model with simulation time scale around the minute.**

LINEAR ATTENUATION BASED CLASS OF MODELS

LINEAR ATTENUATION MODELS

- **Shine follows straight lines**
- **Particle physical interactions with matter modeled**

For a pair of punctual source and receptor and for a monoenergetic photon of energy γ

$$\dot{D}^{\gamma}_{rec,src} = \alpha^{\gamma} \frac{\exp^{-\mu^{\gamma} r_{rec,src}} B^{\gamma}\left(\mu^{\gamma} r_{rec,src}\right)}{4\pi r^2_{rec,src}} \mathrm{I}^{\gamma} A$$

$\dot{D}^{\gamma}_{rec,src}$: Dose rate (Sv. s^{-1})
α^{γ} : fluence to dose conversion factor (Sv. m²)
μ^{γ}: attenuation length (1/mean free path) (m^{-1})
$r_{rec,src}$: receptor-source distance (m)
I^{γ}: Intensity, number of photons emitted per radioactive trans.
A: activity, number of radioactive trans. per second in Bq (s^{-1})

$\exp^{-\mu^{\gamma} r_{rec,src}}$: photon interaction with media (air)
$B^{\gamma}\left(\mu^{\gamma} r_{rec,src}\right)$: buildup factor model scattered dose caused to scattered photons that still reach receptor
$4\pi r^2_{rec,src}$: Surface expansion with the solid angle (m^{-2})

SEMI INFINITE PLUME ASSUMPTION

- **Hypothesis: Concentration somewhat uniform on distances large compared to shine distance (~km)**
  - Valid for plume width > few km

For a given receptor and a monoenergetic photon of energy E^{γ}

$$\dot{D}^{\gamma} = \mathrm{I}^{\gamma} \mathrm{C} \underbrace{\iiint_0^{\infty} \alpha^{\gamma} \frac{\exp^{-\mu^{\gamma} \mathrm{r}} B^{\gamma}(\mu^{\gamma} \mathrm{r})}{4\pi\, r^2} \mathrm{dV}}_{\mathrm{cst}}$$

GAUSSIAN BASED LOOK-UP TABLE

- **Hypothesis: plume may be considered Gaussian**
- Valid after a few hundred meters

For a given receptor and a puff of monoenergetic photons of energy γ

$$\dot{D}^{\gamma}_{puff} = \mathrm{I}^{\gamma} A\, \widetilde{\mathrm{f}^{\mathrm{Gaus}}_{\mathrm{fit/intep}}} \left(\delta_z, r_h, \sigma_h, \sigma_z\right)$$

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FULL 3D DISCRETIZATION

- **No hypothesis on plume shape or dimension**
- **2D/3D plumes discretized as a sum of point sources**
- **Numerically more consuming**

MODELLING PATHWAYS

$$\dot{D}_{rec} = \sum_{RN}\left(\sum_{\gamma_i}\left(\alpha^{\gamma_i}\sum_{src}\frac{\exp^{-\mu^{\gamma_i} r_{rec,src}} B^{\gamma_i}\left(\mu^{\gamma_i} r_{rec,src}\right)}{4\pi r_{rec,src}^2} \mathrm{I}^{\gamma_i,RN} A_{src}^{RN}\right)\right)$$

By Energy class $\widehat{\gamma}_i$

With analytical form of linear attenuation model

$\dot{D}_{rec} = \sum_{src}\sum_{\widehat{\gamma}_i} f^{\widehat{\gamma}_i}\left(r_{rec,src}\right)\ A_{src}^{\widehat{\gamma}_i}$

By radionuclide (RN)

Use surrogate model or interpolator from precomputed results by RN

$$\dot{D}_{rec} = \sum_{src}\sum_{RN} \widetilde{f^{RN}}\left(r_{rec,src}\right)\ A_{src}^{RN}$$

If all RN have the same shape, fit a specific function for current RN

$$\dot{D}_{rec} = \sum_{\mathrm{src}} \widetilde{\widetilde{f^{Tot}}}\left(r_{rec,src}\right)\ A_{src}^{\mathrm{Tot}}$$

MODELLING SHINE BY ENERGY CLASS

1. SELECTION OF THE ENERGY CLASS

Set energy class range and center value

2. GET ACTIVITY BY CLASS

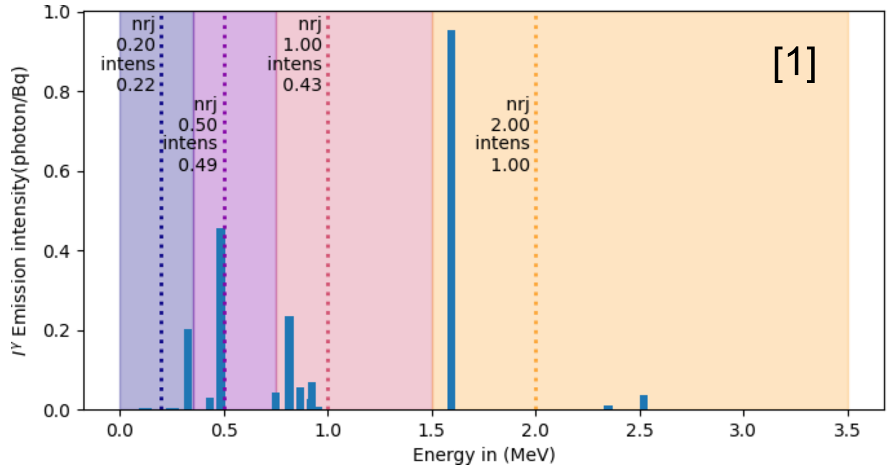
$$A_{src}^{\widehat{\gamma_i}} = \sum_{RN} A_{src}^{RN} I^{\gamma_i \in \widehat{\gamma_i}, RN}$$

3. COMPUTE DOSE RATE PER ACTIVITY, ENERGY CLASS AND DISTANCE

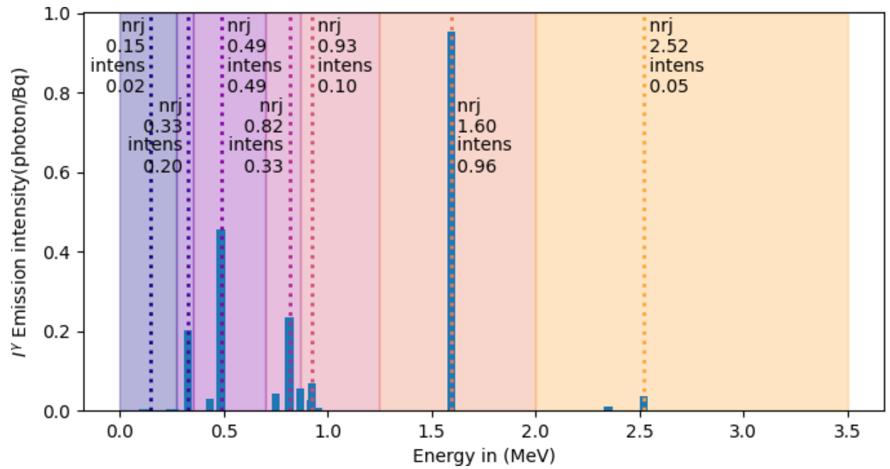
$$f^{\widehat{\gamma_i}}(r) = \alpha^{\widehat{\gamma_i}} \sum_{src} \frac{\exp^{-\mu^{\gamma_i} r} B^{\widehat{\gamma_i}}(\mu^{\widehat{\gamma_i}}, r)}{4\pi r^2}$$

4. SUM ON ALL SOURCE AND ENERGY CLASS

$$\dot{D}_{rec} = \sum_{src} \sum_{\widehat{\gamma_i}} f^{\gamma_i}(r_{rec,src}) \; A_{src}^{\gamma_i}$$



- **Computation time ∝ to the number of classes**
- **What error is introduced by this choice**



[1] Thykier-Nielsen, S., Deme, S., Lang, E., & Risoe National Lab., Roskilde (Denmark). Meteorology and Wind Energy. (1995). Calculation method for gamma dose rates from Gaussian puffs.

MODELLING SHINE BY RADIONUCLIDES

1. PRECOMPUTE DOSE RATE PER ACTIVITY, RN AND SAMPLED DISTANCES

$$f^{RN}(r_i) = \sum_{\gamma^{RN}} \frac{k}{\rho} \alpha^{\gamma^{RN}} \frac{\exp^{-\mu^{\gamma^{RN}} r_i} B^{\gamma^{RN}}(\mu^{\gamma^{RN}}, r_i)}{4\pi r_i^2} I^{\gamma^{RN}}$$

2. FIT SURROGATE OR INTERPOLATOR TO APPROACH IT

$$\widetilde{f^{RN}}(r) \cong f^{RN}(r_i)$$

- Error is caused at this step
- Choice of interpolator/surrogate

3. A. SUM ON ALL SOURCES AND RN

$$\dot{D}_{rec} = \sum_{src} \sum_{RN} \widetilde{f^{RN}}(r_{rec,src}) A_{src}^{RN}$$

3. B. FIT AGGLOMERATED SURROGATE

If all RN have the same shape

$$A_{src}^{RN} = w^{RN} A^{Tot}:$$

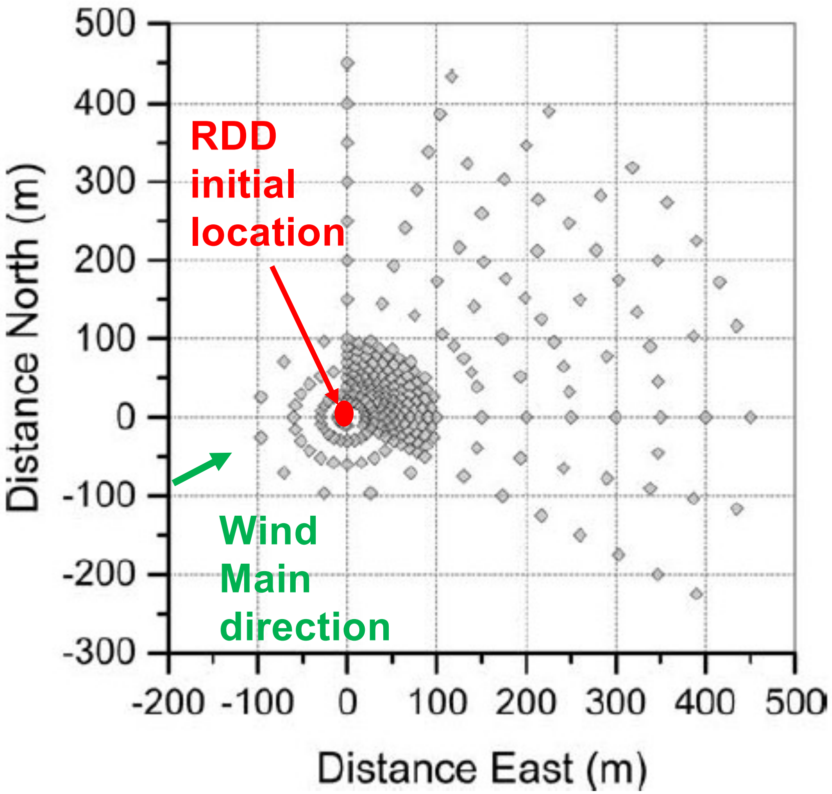
Can fit a single function for the computation

$$\widetilde{\widetilde{f^{Tot}}}(r) \cong \sum_{RN} \widetilde{f^{RN}}(r) w^{RN}$$

Sum on all sources

$$\dot{D}_{rec} = \sum_{src} \widetilde{\widetilde{f^{Tot}}}(r_{rec,src}) A_{src}^{Tot}$$

SUFFIELD IN SITU MEASUREMENT CAMPAIGNS



Positions of the Thermo RadEye PRD detectors during the FSRDD Field Trials. From [1]

3 TRIALS USING RADIOLOGICAL DISPERSAL DEVICES CONTAINING $^{140}\mathrm{La}$ (RDD) [1-4]

- **Before detonation measurements:**
  - Dose rate issue from the point source
- **After detonation measurements:**
  - Deposited concentration
  - Dose rate from deposited radionuclides
  - Integrated dose received during whole plume path

[1] Korpach, Ed; Berg, Rodney; Erhardt, Lorne; Lebel, Luke; Liu, Chuanlei. Real Time in Situ Gamma Radiation Measurements of the Plume Evolution from the Full-Scale Radiological Dispersal Device Field Trials. Health Physics 110(5):p 427-435, May 2016. |

[2] Erhardt, Lorne; Lebel, Luke; Korpach, Ed; Berg, Rodney; Inrig, Elizabeth; Watson, Ian; Liu, Chuanlei; Gilhuly, Colleen; Quayle, Debora. Deposition Measurements From the Full-Scale Radiological Dispersal Device Field Trials. Health Physics 110(5):p 442-457, May 2016.

[3]Green AR, Erhardt L, Lebel L, Duke MJ, Jones T, White D, Quayle D. Overview of the Full-scale Radiological Dispersal Device Field Trials. Health Phys. 2016 May;110(5):403-17.

[4]Lebel L, Bourgouin P, Chouhan S, Ek N, Korolevych V, Malo A, Bensimon D, Erhardt L. Radiation Modeling and Finite Cloud Effects for Atmospheric Dispersion Calculations in Near-field Applications: Modeling of the Full Scale RDD Experiments with Operational Models in Canada, Part II. Health Phys. 2016 May;110(5):518-25.

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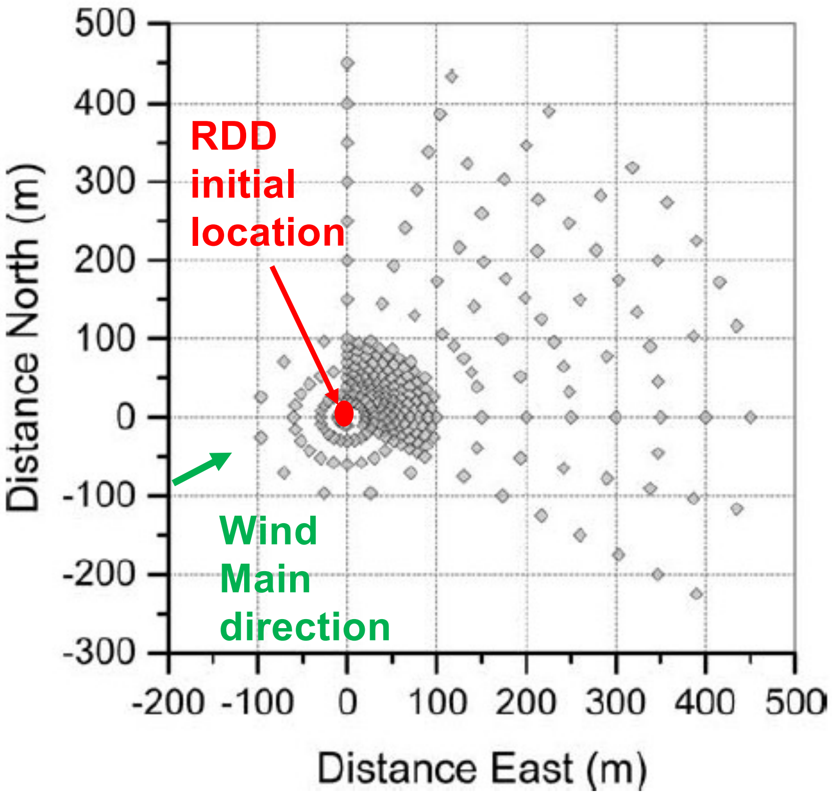

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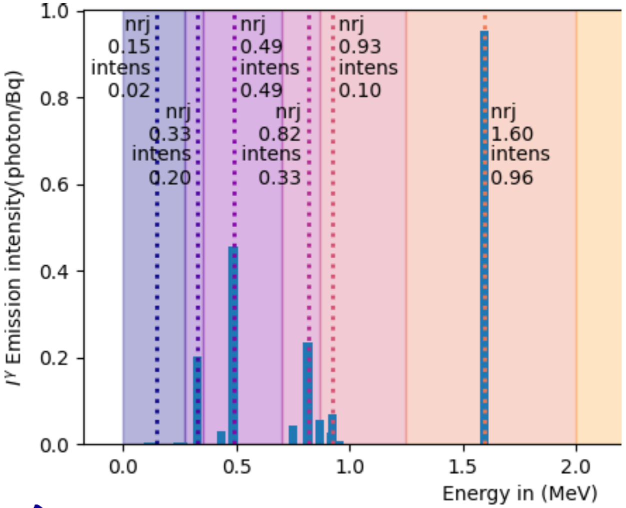
SUFFIELD CAMPAIGN: POINT SOURCE CASE BEFORE DETONATION

IMPACTS OF THE GROUND EFFECTS

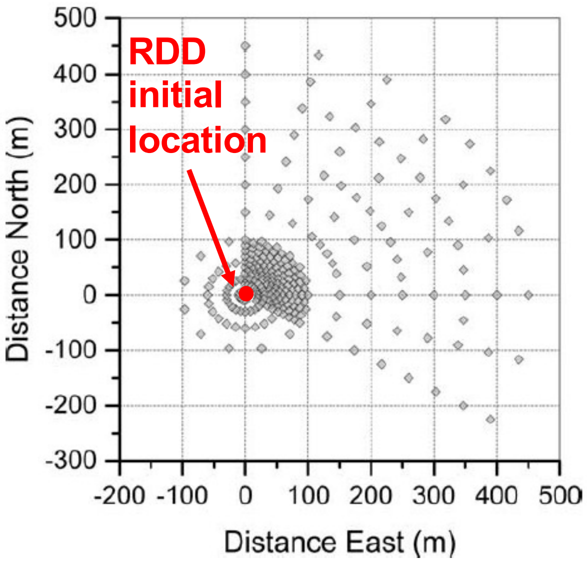
- **Full line: No modification of the buildup**
  - Fully reflective ground
  - Slightly overestimates the dose
- **Dashed line: Half of the buildup**
  - Tends underestimate dose rate
- **Dotted line: Half of the scatter part**
  $$B(\mu r) = 1 + 0,5\, f(\mu r)$$
  - Fully absorbing ground
  - Seems to fit better the center of distribution

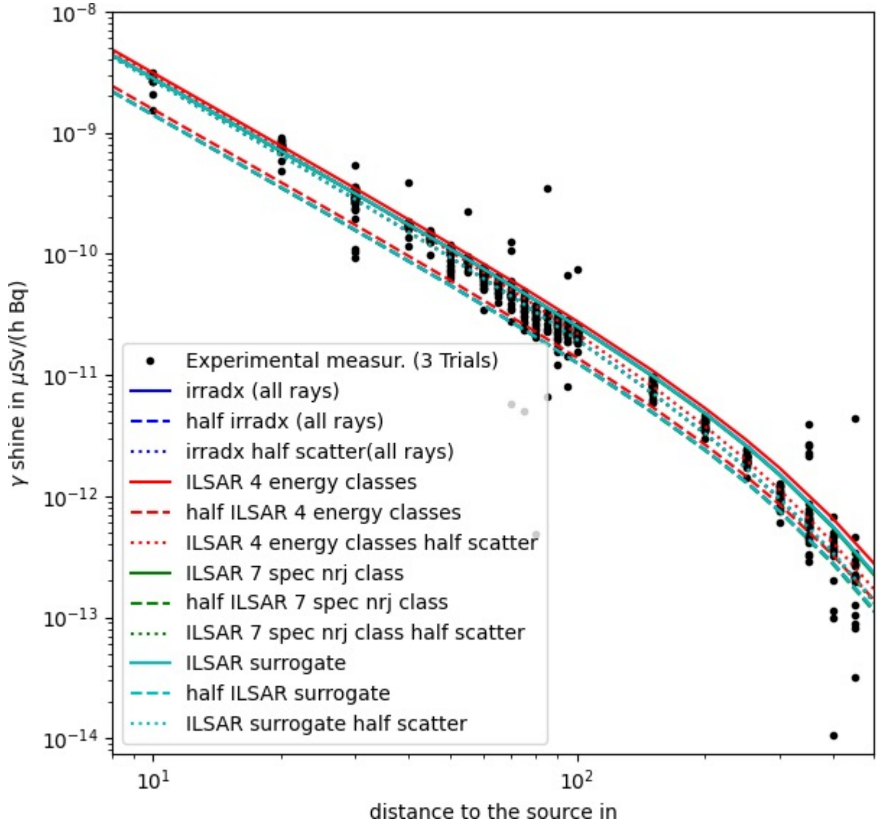


IMPACTS OF ENERGY DISTRIBUTION

- **(Blue) All ^{140}La emissions ~(39 energies)**
- **(Red) 4 "standard" energy classes [1]**
- **(Green) ^{140}La specific classes (7)**
- **(Cyan) Surrogate model for ^{140}La**

Impacts of limited energy class noticeable (10-20% at these distances up to 50% at one km)





Measured and simulated dose rate before detonation

[1] Thykier-Nielsen, S., Deme, S., Lang, E., & Risoe National Lab., Roskilde (Denmark). Meteorology and Wind Energy. (1995). Calculation method for gamma dose rates from Gaussian puffs.

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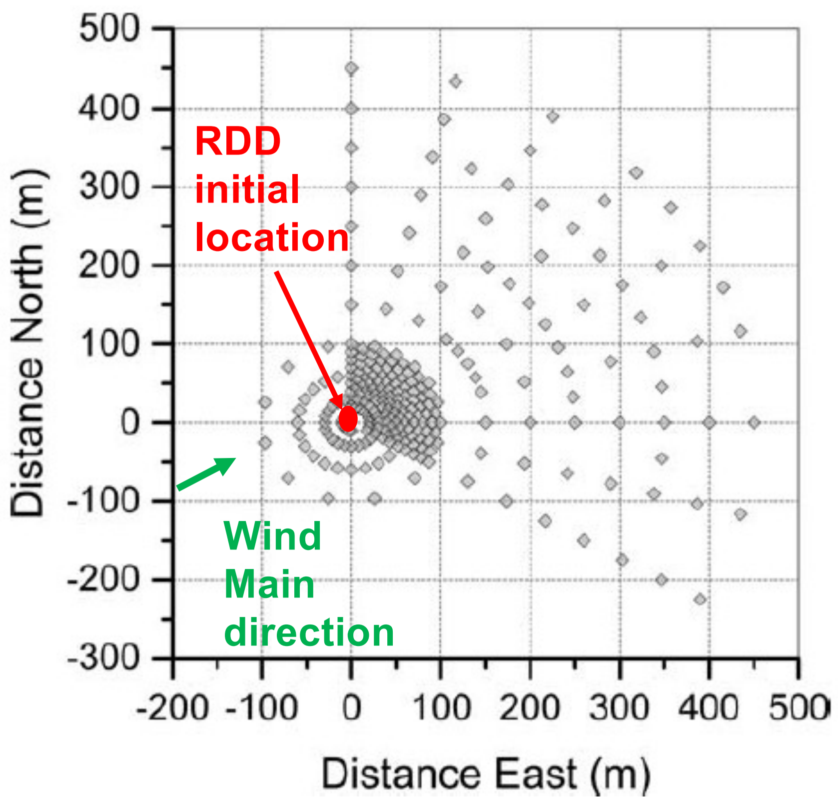

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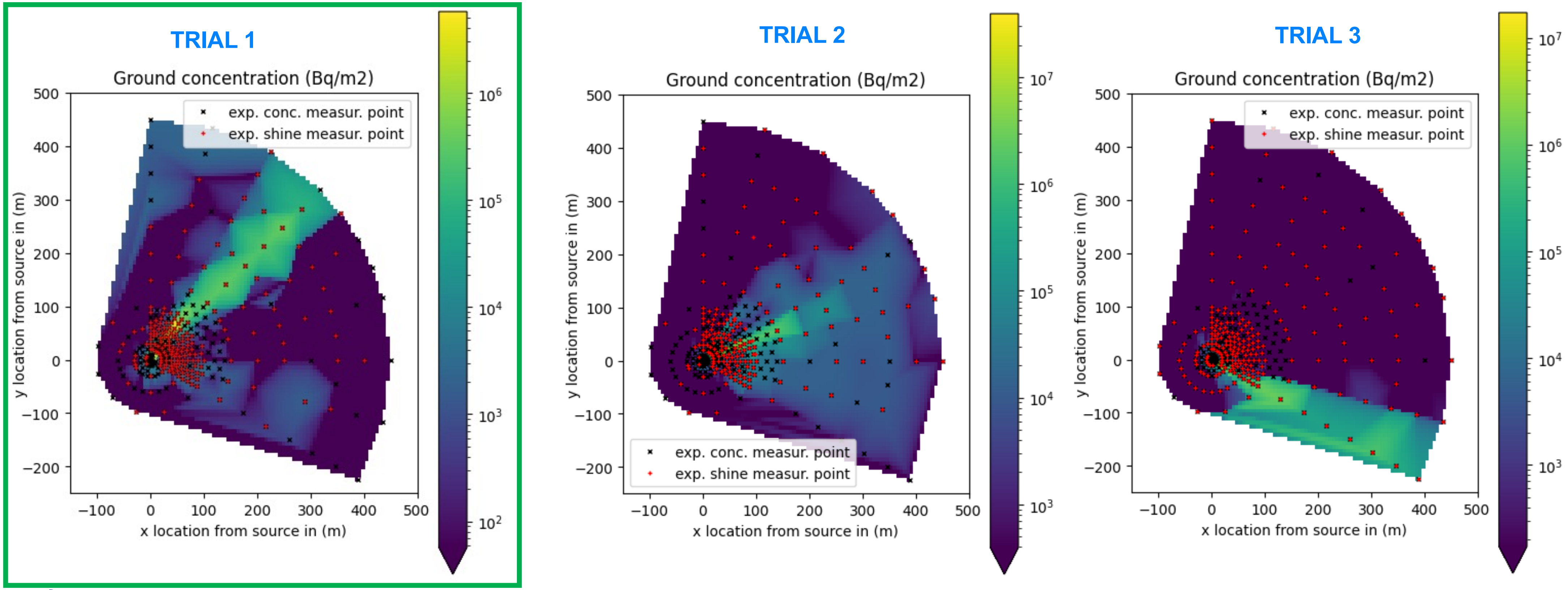
SUFFIELD CAMPAIGN: GROUND CONCENTRATION AFTER PLUME PATH

RESULTS AFTER DETONATION OF THREE RADIOLOGICAL DISPERSION DEVICES (RDDS)

Ground deposition linearly interpolated from campaign measurements (100*100 cells)



SUFFIELD CAMPAIGN: GROUND SHINE TRIAL 1

	3D worst*	3D Best**	IPA*** worst*	IPA*** Best**
FAC_2	0,56	0,86	0,26	0,28
FAC_5	0,99	0,997	0,42	0,38
Fract Error	0,62	0,36	1,32	1,36
Fract Bias	0,55	0,20	-1,10	-0,015

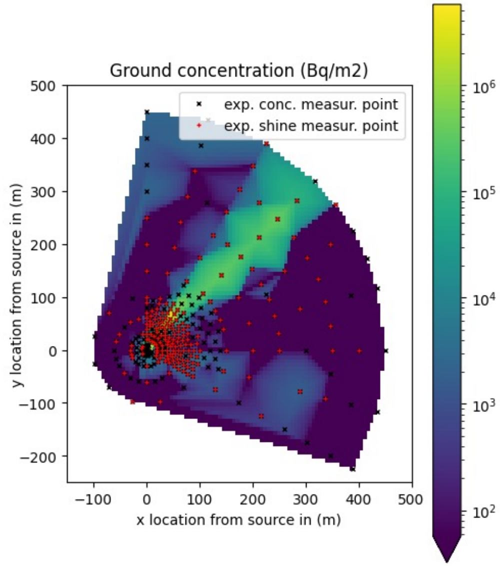
Statistics on 2D interpolated fields

Worst* 4 energy class reflective ground
Best** surrogate model absorbing ground
IPA*** Infinite Plume Assumption

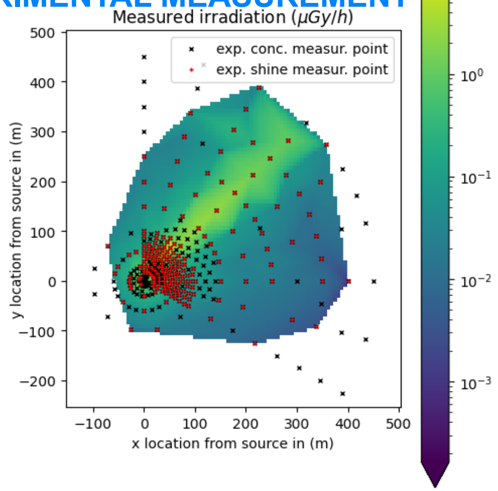
$$Fract\ Error = \frac{1}{N_{meas}} \sum_{N_{meas}} \frac{|Simu - Meas|}{0,5(Simu + Meas)}$$

$$Fract\ Bias = \frac{1}{N_{meas}} \sum_{N_{meas}} \frac{Simu - Meas}{0,5(Simu + Meas)}$$

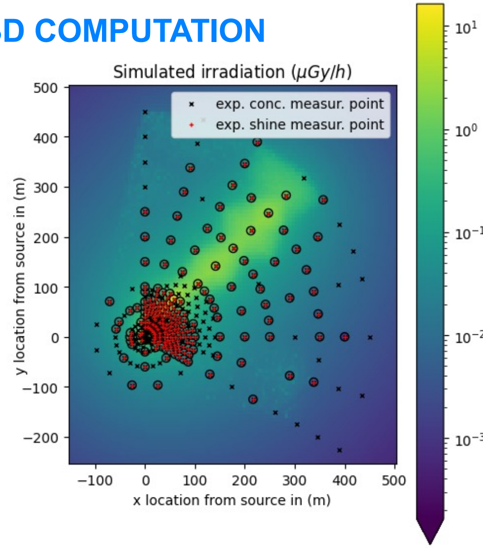
$$FAC_i = \frac{N_{val}\ (Simu > i\ Meas\ \&\ Simu > Meas\ /\ i\ )}{N_{Meas}}$$



LINEAR INTERPOLATION FROM EXPERIMENTAL MEASUREMENT

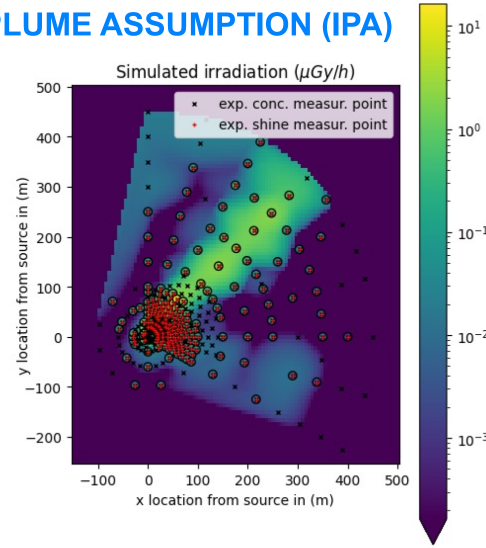


3D COMPUTATION



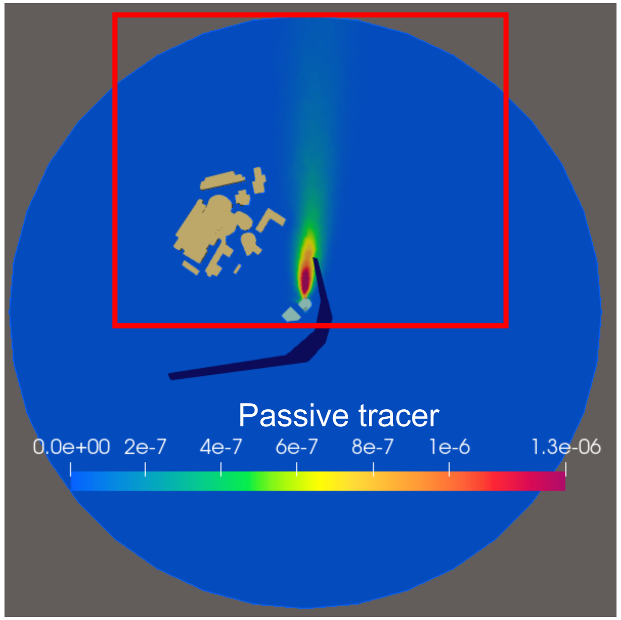
Dose rate computation time 62s

INFINITE PLUME ASSUMPTION (IPA)



DIFLU CAMPAIGN[1]

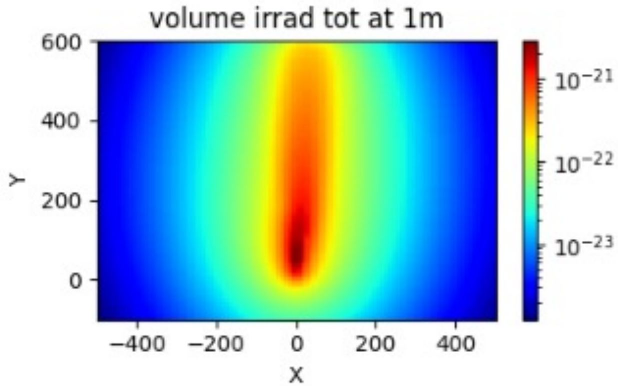
This gamma estimation model can also be coupled with CFD simulation :



Concentration fields of a passive tracer obtained using a hybrid moment/PDF approach (Fluent/SLAM)

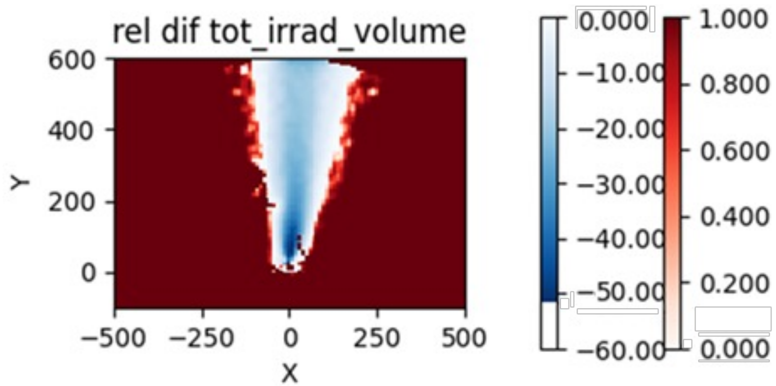
[1] Laguionie, P.; Connan, O.; Tien, T.L.; Vecchiola, S.; Chardeur, J.; Cazimajou, O.; Solier, L.; Charvolin-Volta, P.; Chen, L.; Korsakissok, I.; et al. Investigation of a Gaussian Plume in the Vicinity of an Urban Cyclotron Using Helium as a Tracer Gas. *Atmosphere* **2022**, *13*, 1223.

Total dose from airborne shine associated to 1Bq of $^{140}\mathrm{La}$ treated as a noble gas (preliminary results)



Dose computation time 173s

Total integrated dose at one meter



Corresponding relative bias between discretized and infinite plume assumption

$$\left(\frac{\mathrm{SIMU}^{3D} - \mathrm{SIMU}^{IPA}}{\mathrm{SIMU}^{3D}}\right)$$

CONCLUSIONS AND PERSPECTIVE

CONCLUSIONS

A method that does not assume any condition on the plume shape has been developed to account for gamma irradiation at the local scale

- **Permit a fast estimation of the dose (~minutes) at the local scale**
- **Permit an access by energy class and by radionuclides using surrogate models**
- **In the first few kilometers, methods finer than (semi-)infinite plume assumption are necessary**
- **For ground shine, ground induced absorption of scattered photons provide better results**

PERSPECTIVE

- **Build look up table for Gaussian puffs and fit a surrogate model by radionuclide**
- **Study with more complex plume shapes (more built environments) should be considered to highlight interest against Gaussian models**
- **Examine the impacts on the ground in more detail**
- **Study shadowing effects**
- **Work with a larger set of radionuclides to examine the impact on computation time and the precision of using an energy class compared to a surrogate by radionuclide.**
- **Add alpha and beta induced dose rate**

THANK YOU FOR YOUR ATTENTION

ANY QUESTION ?

DISCRETIZATION OF THE PLUME

$$\dot{D}_{rec} = \sum_{RN} \int_{10\text{keV}}^{\infty} \left(\alpha^{\gamma} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\exp^{-\mu^{\gamma} r_{rec,src}} B^{\gamma}\left(\mu^{\gamma} r_{rec,src}\right)}{4\pi r_{rec,src}^{2}} \mathrm{I}^{\gamma,RN} A_{src}^{RN} \, dx \, dy \, dz \right) d\gamma$$

$$\downarrow$$

$$\dot{D}_{rec} = \sum_{RN} \left(\sum_{\gamma_i} \left(\alpha^{\gamma_i} \sum_{src} \frac{\exp^{-\mu^{\gamma_i} r_{rec,src}} B^{\gamma_i}\left(\mu^{\gamma_i} r_{rec,src}\right)}{4\pi r_{rec,src}^{2}} \mathrm{I}^{\gamma_i,RN} A_{src}^{RN} \right) \right)$$

CHOICE FOR THE PLUME DISCRETIZATION

- **Deterministic**
  - one source is placed in each cell point
  - with weight proportional to local activity
- **Stochastic,**
  - source randomly located
    - probability and weight ∝ to local activity or potential to shine)

TREATMENT OF NEAR SOURCE SHINE (~M)

Use (pseudo-)analytical integral under uniform plume assumption

$$\boldsymbol{DCF^{R}} = \int_{\mathbf{0}}^{\boldsymbol{R}} \boldsymbol{k} \, \nu_{\boldsymbol{en}} E_i \alpha \frac{\boldsymbol{e}^{-\mu r} B(\mu r)}{4\pi r^{2}} \, \boldsymbol{d\Omega}$$

PLACEMENT OF THE SOURCES

Condition on radionuclide presence

Condition on the distance to the ground

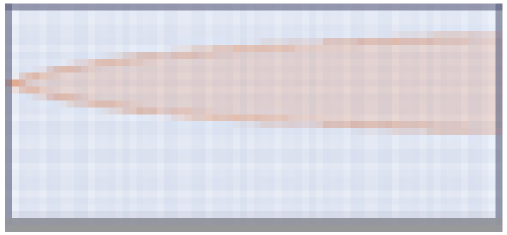
Condition on source-receptor distances

SOURCES DISCRETIZATION

DETERMINISTIC

STOCHASTIC

FULL DISCRETIZATION OF THE DOMAIN:



SET A THRESHOLD ON CONCENTRATION/ACTVITY:

SET A CONDITION ON THE GROUND DISTANCE:

STORE SOURCES INTO BOXES TO SET CONDITION

ON SOURCE TO RECEPTOR BOXES

MODELLING CHOICE INFLUENCE OF THE BUILDUP TERM

BUILDUP FACTOR

Modelling of the photons scattered between emitter and receptor still reaching receptor point obtained from Monte Carlo simulations

- **Linear Berger formulation**

$$B(\mu r) = 1 + a\mu r e^{-b\mu r} + c\mu r$$

- **Berger formulation**

$$B(\mu r) = 1 + a\mu r e^{-b\mu r}$$

- **Taylor**

$$B(\mu r) = a e^{-b\mu r} + (1-a) e^{-c\mu r}$$

- **Geometrical Progression (GP)**

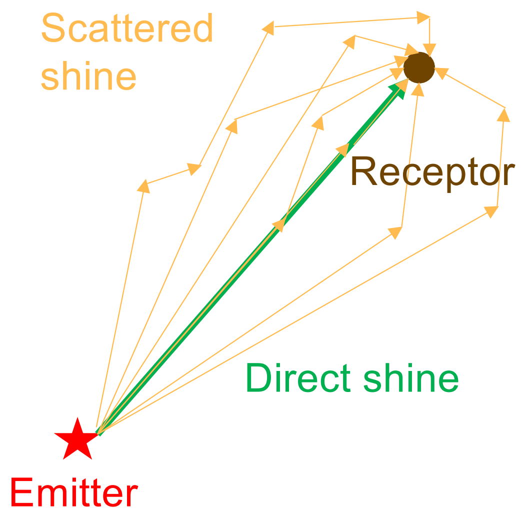
$$K = c(\mu r)^a + d\frac{\left(th\left(\frac{\mu_r}{x_k} - 2\right) - th(-2)\right)}{1 - th(-2)}$$

$$B(\mu r) = 1 + (b-1)\frac{K^{\mu r} - 1}{K - 1} \; si \; K \neq 1$$

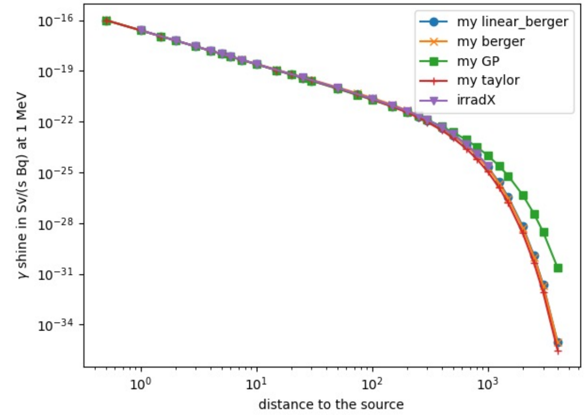
$$B(\mu r) = 1 + (b-1)\mu r \; si \; K = 1$$

- **Tabulated values**

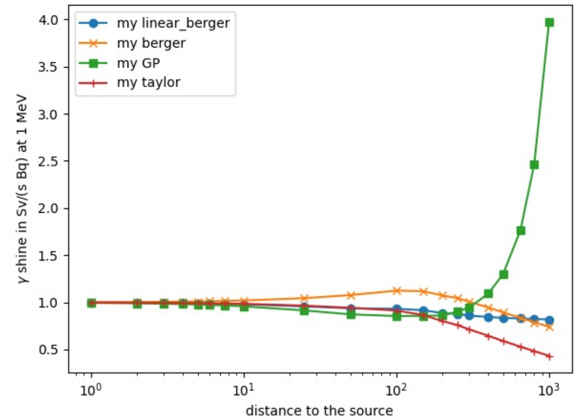
$$B(\mu r) = \overbrace{1}^{\text{Direct Shine}} + \overbrace{f(\mu r)}^{\text{Scattered shine}}$$



Dose rate per Bq for a point source emitting 1Mev γ photons with different models for buildup factor



Idem normalized by results with in-house tabulated values



SUFFIELD CAMPAIGN: GROUND SHINE TRIAL 1

Stat at exp Measurement points

	B = B_ref (no ground impact)	B = 0,5 B_ref (ground absorbs half shine)	B = 1 + 0,5 (B_ref-1) (gr. absord half scattered shine)
FAC_2	0,66	0,88	0,76
FAC_5	0,99	0,99	0,99
$Fract\ Error$	0,58	0,35	0,44
$Fract$ Bias	0,49	-0,16	0,34

Stat on plan Based on linear Interpolation

	B = B_ref (no ground impact)	B = 0,5 B_ref (ground absorbs half shine)	B = 1 + 0,5 (B_ref-1) (gr. absord half scattered shine)
FAC_2	0,66	0,84	0,86
FAC_5	0,998	0,98	0,997
$Fract\ Error$	0,52	0,35	0,36
$Fract$ Bias	0,42	-0,23	0,20

SUFFIELD CAMPAIGN: GROUND SHINE TRIAL 2

	3D worst*	3D Best**	IPA*** worst*	IPA*** Best**
FAC_2	0,13	0,20	0,17	0,20
FAC_5	0,62	0,84	0,37	0,36
$Fract\ Error$	1,15	0,99	1,40	1,43
$Fract\ Bias$	1,06	0,86	-1,02	-1,17

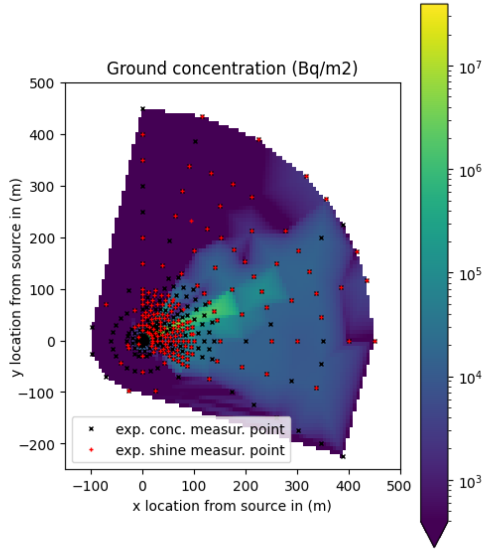
Statistics at measurements points

Worst* 4 energy class reflective ground
Best** surrogate model absorbing ground
IPA*** Infinite Plume Assumption

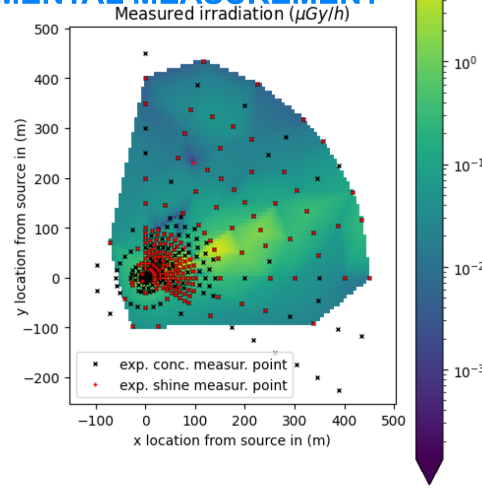
$$Fract\ Error = \frac{1}{N_{meas}} \sum_{N_{meas}} \frac{|\mathrm{Simu} - \mathrm{Meas}|}{0{,}5(\mathrm{Simu} + \mathrm{Meas})}$$

$$Fract\ Bias = \frac{1}{N_{meas}} \sum_{N_{meas}} \frac{\mathrm{Simu} - \mathrm{Meas}}{0{,}5(\mathrm{Simu} + \mathrm{Meas})}$$

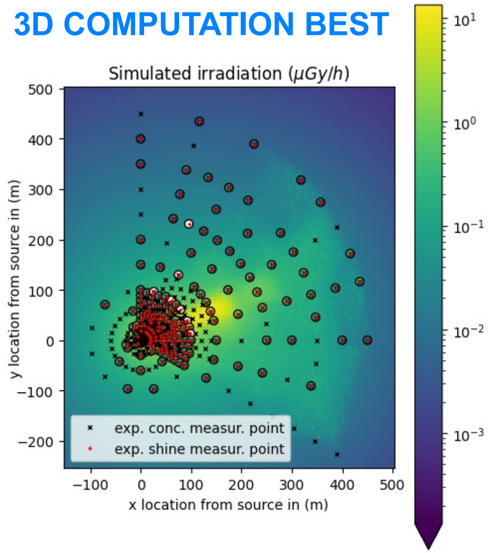
$$FAC_i = \frac{N_{val}\ (\mathrm{Simu} > \mathrm{i\ Meas}\ \&\ \mathrm{Simu} > \mathrm{Meas\ /\ i})}{N_{Meas}}$$



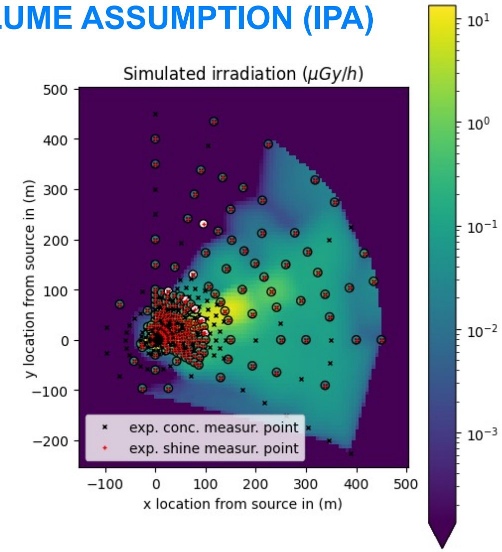
LINEAR INTERPOLATION FROM EXPERIMENTAL MEASUREMENT



3D COMPUTATION BEST



INFINITE PLUME ASSUMPTION (IPA)



SUFFIELD CAMPAIGN: GROUND SHINE TRIAL 2

Stat at exp

Measurement

points

	B = B_ref (no ground impact)	B = 0,5 B_ref (ground absorbs half shine)	B = 1 + 0,5 (B_ref-1) (gr. absord half scattered shine)
FAC_2	0,16	0,42	0,20
FAC_5	0,72	0,96	0,84
$Fract\ Error$	1,08	0,69	0,99
$Fract\ \mathrm{Bias}$	0,98	0,45	0,86

Stat on plan

Based on linear

Interpolation

	B = B_ref (no ground impact)	B = 0,5 B_ref (ground absorbs half shine)	B = 1 + 0,5 (B_ref-1) (gr. absord half scattered shine)
FAC_2	0,42	0,62	0,50
FAC_5	0,93	0,93	0,95
$Fract\ Error$	0,76	0,59	0,69
$Fract\ \mathrm{Bias}$	0,49	-0,097	0,28

SUFFIELD CAMPAIGN: GROUND SHINE TRIAL 3

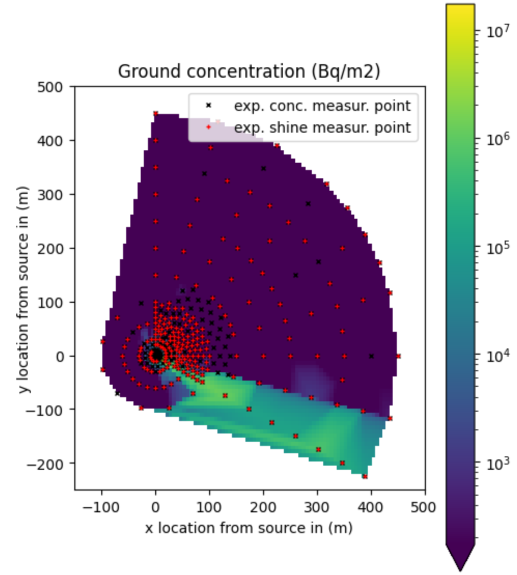
	3D worst*	3D Best**	IPA*** worst*	IPA*** Best**
FAC_2	0,6	0,87	0,04	0,035
FAC_5	0,98	0,996	0,071	0,067
$Fract\ Error$	0,59	0,36	1,85	1,86
$Fract\ Bias$	0,50	0,18	-1,79	-1,81

Worst* 4 energy class reflective ground
Best** surrogate model absorbing ground
IPA*** Infinite Plume Assumption

$$Fract\ Error = \frac{1}{N^{meas}} \sum_{N^{meas}} \frac{|Simu - Meas|}{0{,}5(Simu + Meas)}$$

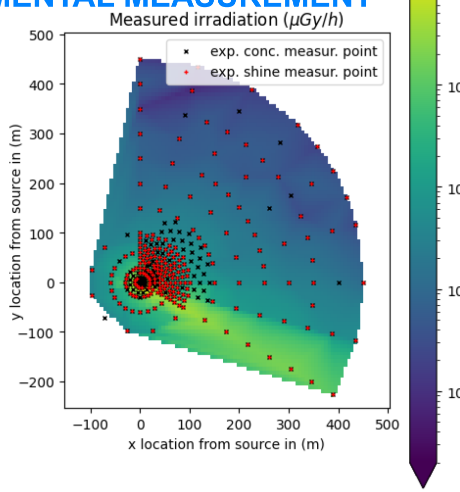
$$Fract\ Bias = \frac{1}{N^{meas}} \sum_{N^{meas}} \frac{Simu - Meas}{0{,}5(Simu + Meas)}$$

$$FAC_i = \frac{N_{val}\ (Simu > i\ Meas\ \&\ Simu > Meas\ /\ i\ )}{N_{Meas}}$$

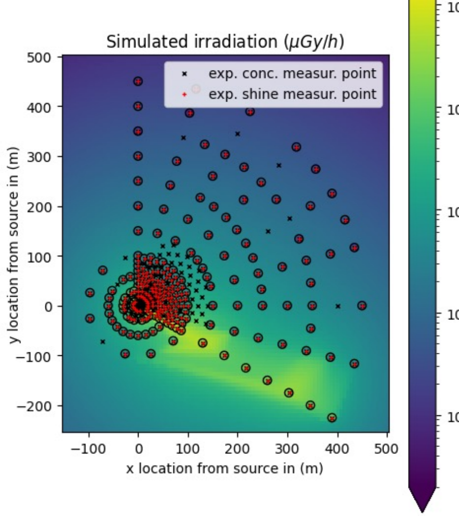


Statistics at measurements points

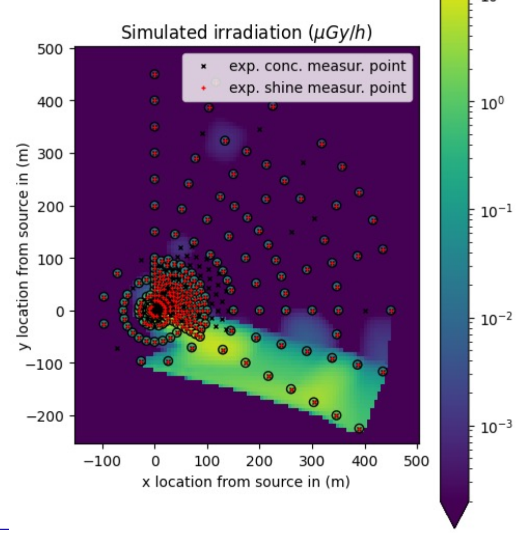
LINEAR INTERPOLATION FROM EXPERIMENTAL MEASUREMENT



3D COMPUTATION BEST



INFINITE PLUME ASSUMPTION (IPA)



SUFFIELD CAMPAIGN: GROUND SHINE TRIAL 3

Stat at exp

Measurement

points

	B = B_ref (no ground impact)	B = 0,5 B_ref (ground absorbs half shine)	B = 1 + 0,5 (B_ref-1) (gr. absord half scattered shine)
FAC_2	0,69	0,90	0,87
FAC_5	0,99	0,998	0,996
$Fract\ Error$	0,52	0,30	0,36
$Fract\ \mathrm{Bias}$	0,43	-0,13	0,22

Stat on plan

Based on linear

Interpolation

	B = B_ref (no ground impact)	B = 0,5 B_ref (ground absorbs half shine)	B = 1 + 0,5 (B_ref-1) (gr. absord half scattered shine)
FAC_2	0,61	0,84	0,85
FAC_5	0,995	0,98	0,998
$Fract\ Error$	0,58	0,35	0,36
$Fract\ \mathrm{Bias}$	0,53	-0,23	0,21