J-2: Investigation on the limits of the Ray-Tracing method applied on dose analysis for Radiation Hardness Assurance

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Outline

- Reminders on the existing dose calculation method in the Radiation Hardness Assurance (RHA) process
- Axis 1: Studying the key parameters impact on the Ray-Tracing accuracy
- Axis 2: Investigating the limits of the Ray-Tracing
- Recommendations and conclusion

Motivation

- Radiation effects simulation → *Key step of the Radiation Hardness Assurance process*

- Number of satellite launchings is increasing and accelerating → *Increasing demand of radiation analysis*

- Increasing use of COTS instead of Rad-Hard parts → *Reduction of the design dose*

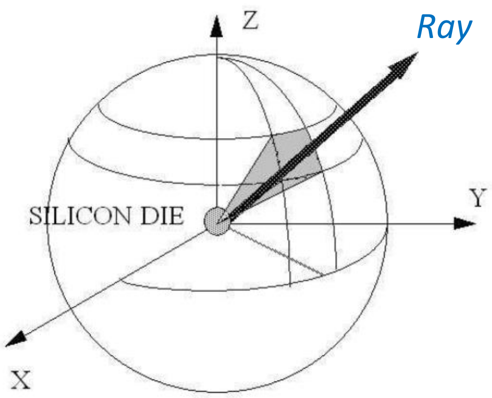
Motivation

- Radiation effects simulation → *Key step of the Radiation Hardness Assurance process*
- Number of satellite launchings is increasing and accelerating → *Increasing demand of radiation analysis*
- Increasing use of COTS instead of Rad-Hard parts → *Reduction of the design dose*
- The Ray-Tracing (used a lot) is very fast, but relies on strong hypotheses contrary to the Reverse Monte Carlo (reference in the space industry)
- The space market is evolving, but the Ray-Tracing tool did not really evolve for 40 years
- Need to increase the accuracy and keep a low computation time

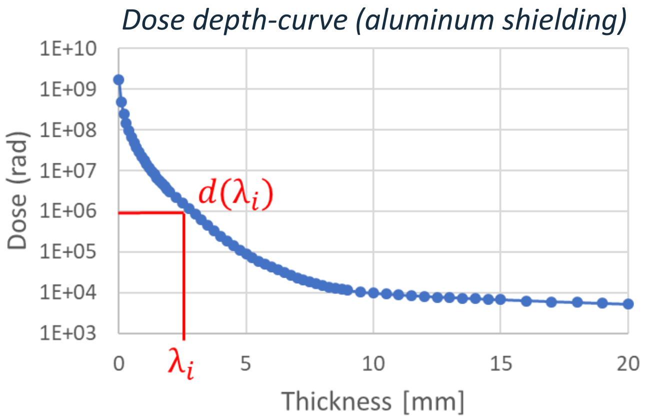
Main motivation: Survey of the key parameters and assumptions made in the Ray-Tracing

Context: some reminders

- Two methods are used in the space industry to compute the dose inside a spacecraft:
  - **1) Ray-Tracing (RT) = Sector analysis**
  - 2) Reverse Monte Carlo (RMC) = Particle-matter interactions



Dividing the space into sectors



Density ratio

$$\lambda_i = \frac{t_i}{\cos(\theta)} \frac{\rho_{Mi}}{\rho_{Alu}}$$

Equivalent aluminum thickness

$$D = \sum_{i=1}^{N} \frac{d(\lambda_i)\Omega_i}{4\pi}$$

Total dose computation

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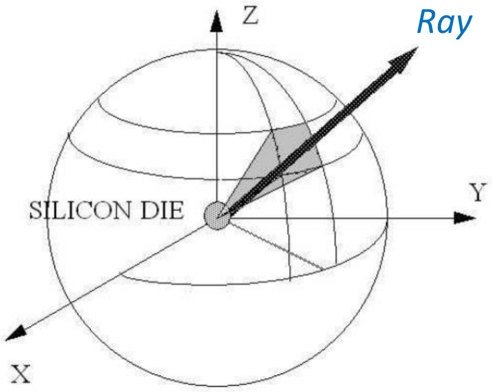

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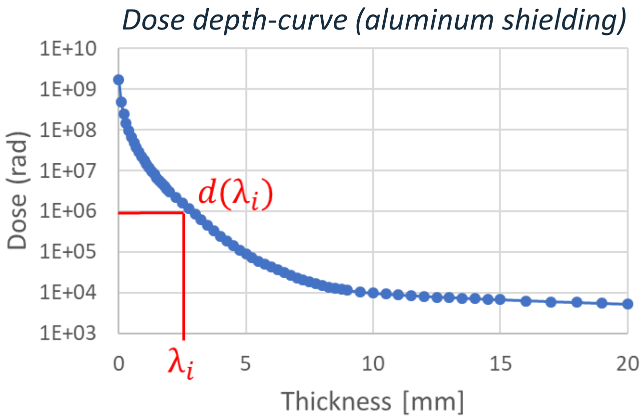

+ Fast computation time (<1s for 1 detector)
• Generally overestimates the dose
- Straight line propagation of particles
- Equivalent aluminum thickness: material density ratio

Density ratio

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Equivalent aluminum thickness

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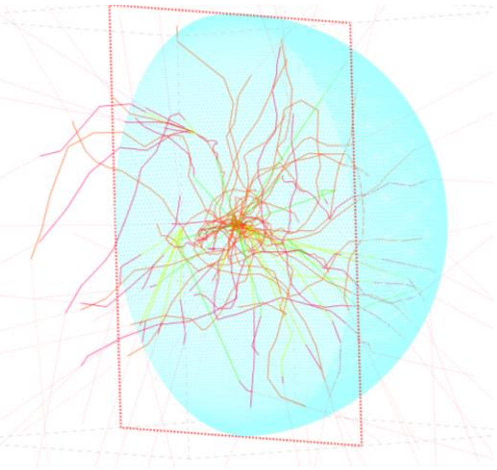
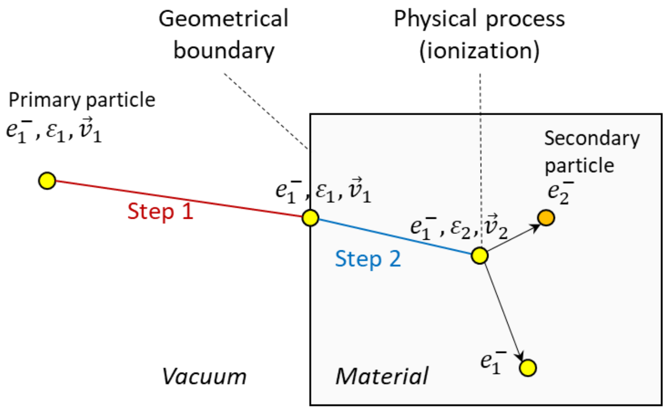


Electrons scattering in a sphere



Particle-matter interactions at each step

$$TID = \frac{E}{m}$$

Total dose computation

\+ Energy loss calculated all along the real particle path

\+ Creation and tracking of secondary particles

\+ Considers realistically the materials

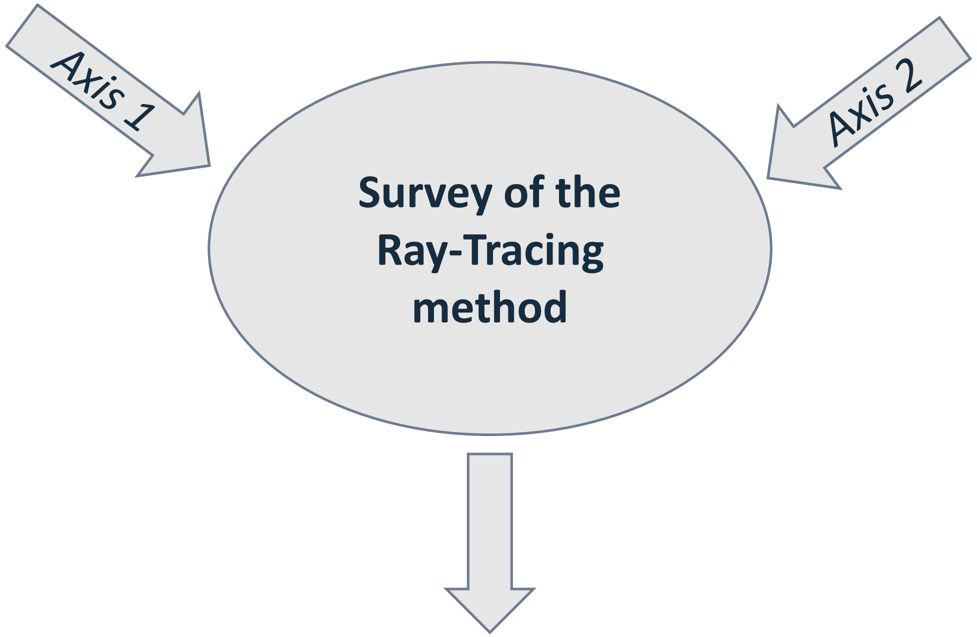
\+ Better accuracy on the deposited dose level

\- Slower than Ray-Tracing

Objectives

- Studying the key parameters of RT
  - Sectoring resolution
  - Model orientation

- Investigate the Ray-Tracing limits
  - Aluminum equivalent thickness
  - Material distribution
  - Geometric effects

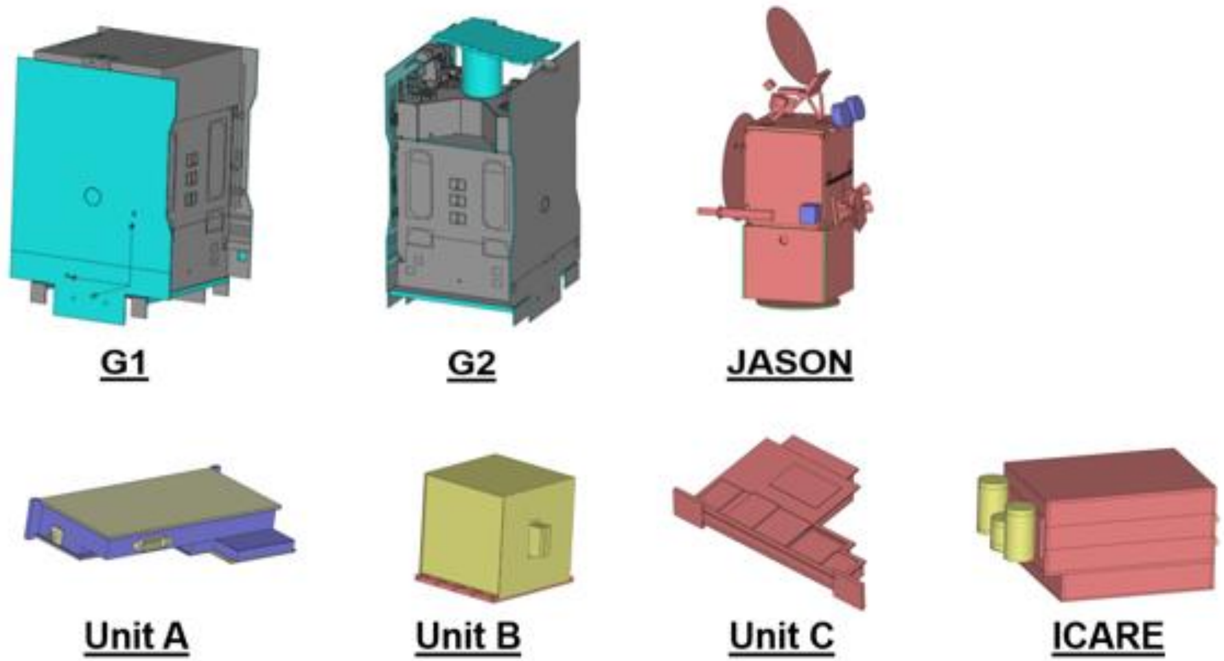


- Suggesting recommendations
- Proposing ways of improvement for future works

Axis 1: Study of the key parameters of RT

Mission: GEO, 35784km, 15 years
= Worst-case for Ray-Tracing

Input data



Geometric models: satellite platforms (G1, G2, JASON) and different units

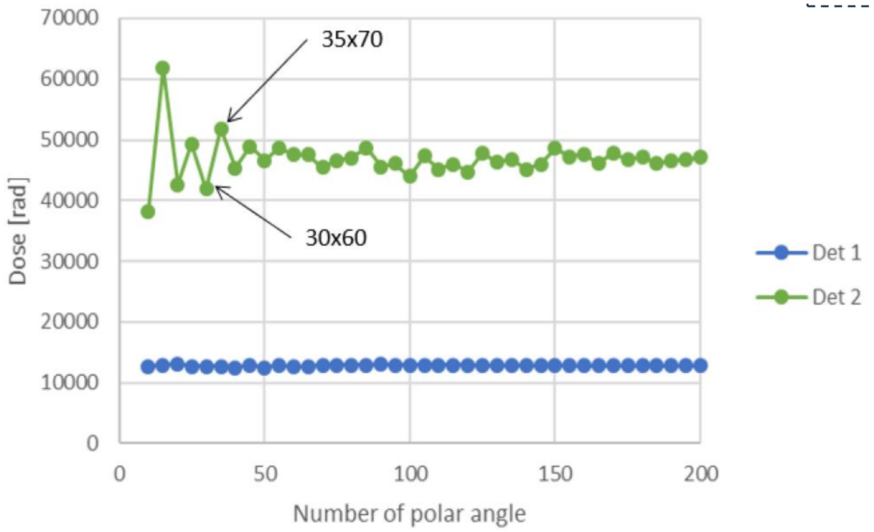
- Detectors randomly placed in each unit
- Combinations of units and satellite platforms
- Total: **5800 detectors**

Need for a statistical analysis

From R. Benacquista *et al.*, “Comparison of Ray-Tracing and Reverse Monte-Carlo Methods: Application to GEO orbit,” in *2019 19th European Conference on Radiation and Its Effects on Components and Systems (RADECS)*, Montpellier, France: IEEE, Sep. 2019, pp. 1–5.

Axis 1: Study of the key parameters of RT

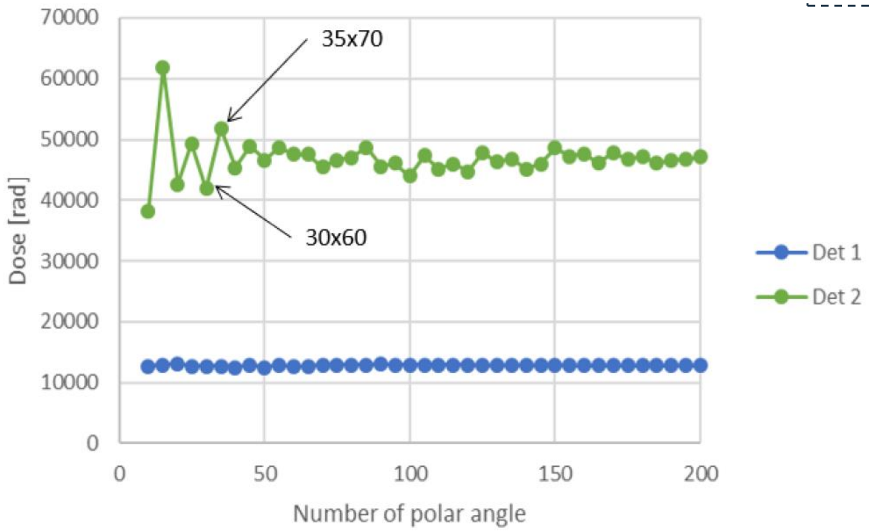
Statistical analysis



- Variation of the dose with the **sectoring resolution = Key parameter**
- Reference dose: RT computation with 100 x 200 sectors
- Minimum: 30 x 60 sectors, as recommended by ECSS (European standards)

Axis 1: Study of the key parameters of RT

Statistical analysis



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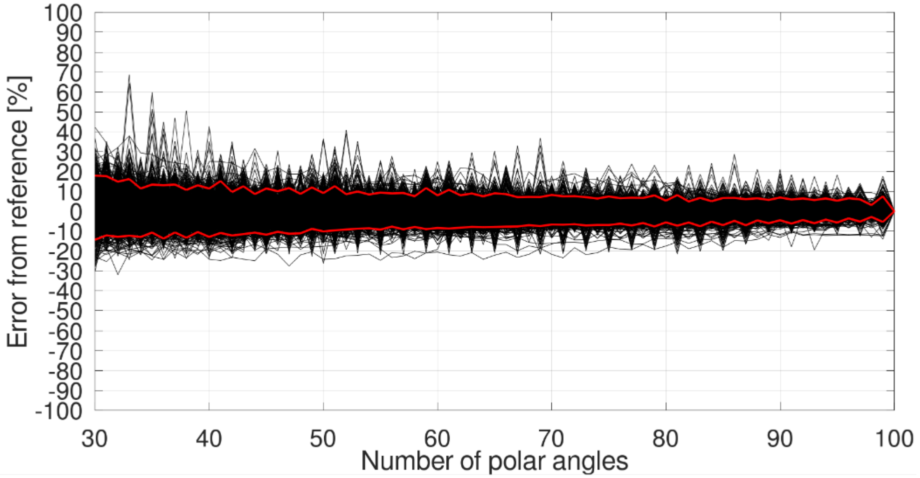
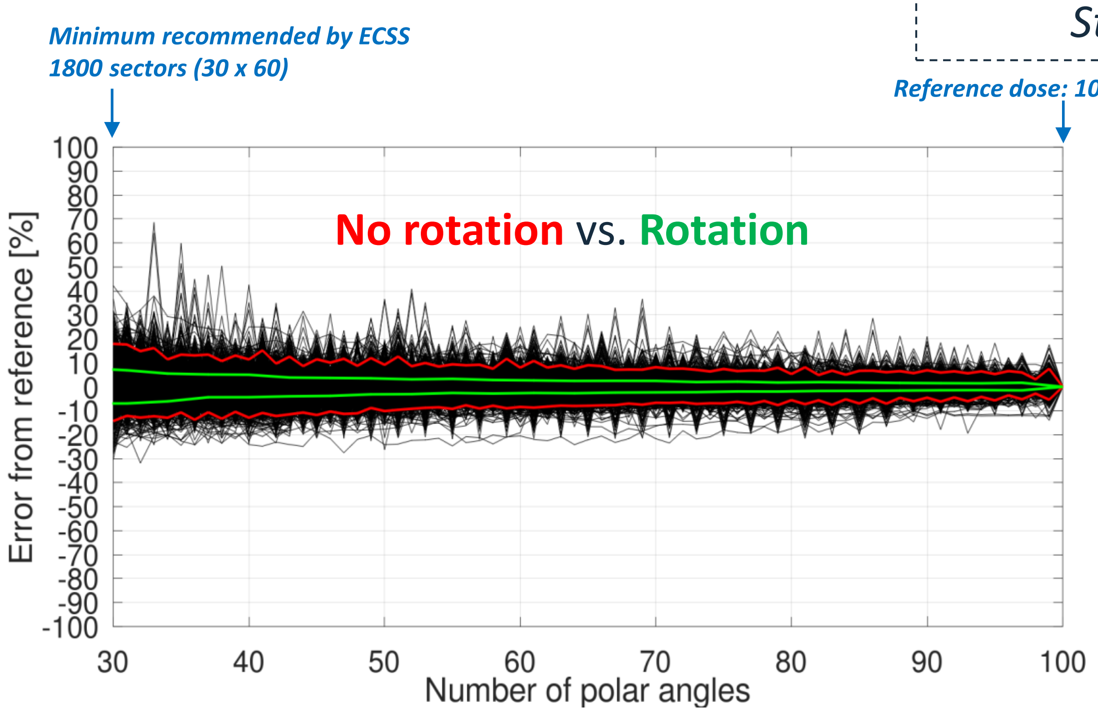
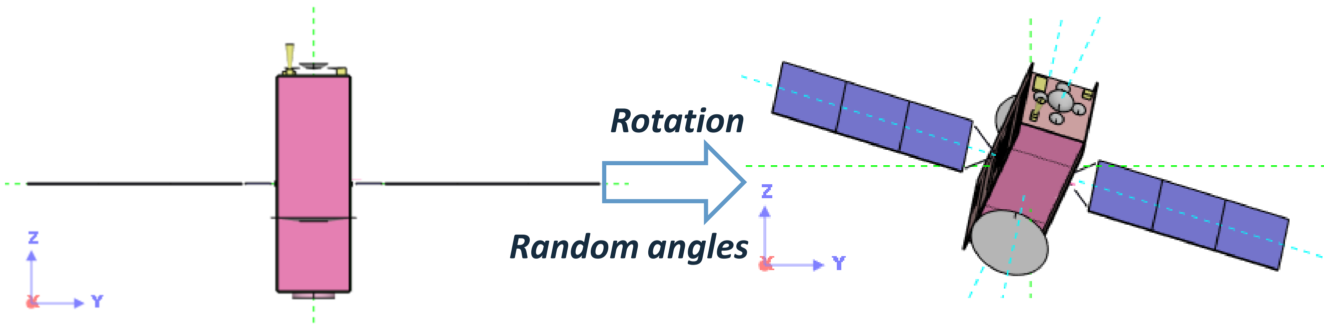


- Error : relative difference between the reference dose and the calculated one
- 1 black curve = 1 detector
- 5800 detectors on the same graph
- Pair of **colored curves**: 1st and 99th percentiles **= Dose error interval**
- Two configurations: without and with rotation of the geometric model

Axis 1: Study of the key parameters of RT

Statistical analysis





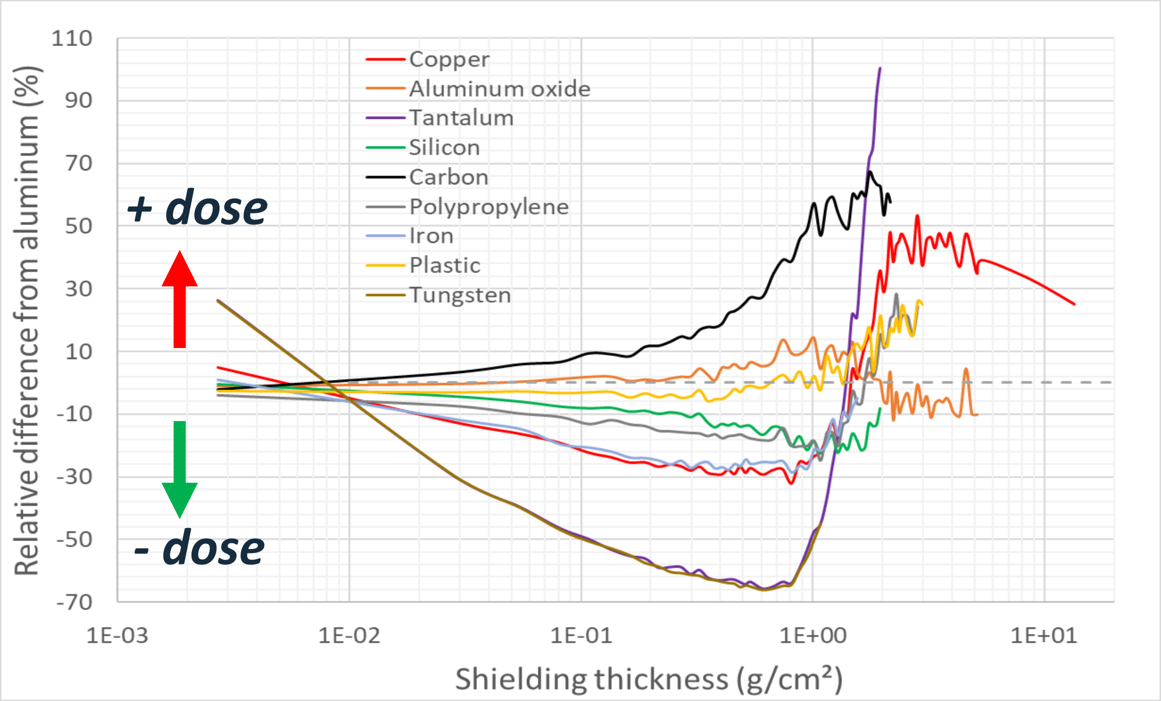
Observations & Results

- ↗ number of sectors ≠ ↗ RT accuracy significantly
- 30x60 sectors recommended by ECSS → Sufficient
- Rotation increases the accuracy by **lowering the dose error by a factor ≈ 2**
- **Significant impact of the rotation, contrary to the sectoring resolution**

Axis 2: Investigate the Ray-Tracing limits

- Improving the consideration of the material:
  - Estimation of the error induced by the density ratio:

Mission: GEO, 35784km, 15 years



Variation of the dose according to the shielding thickness.
Reference material: aluminum

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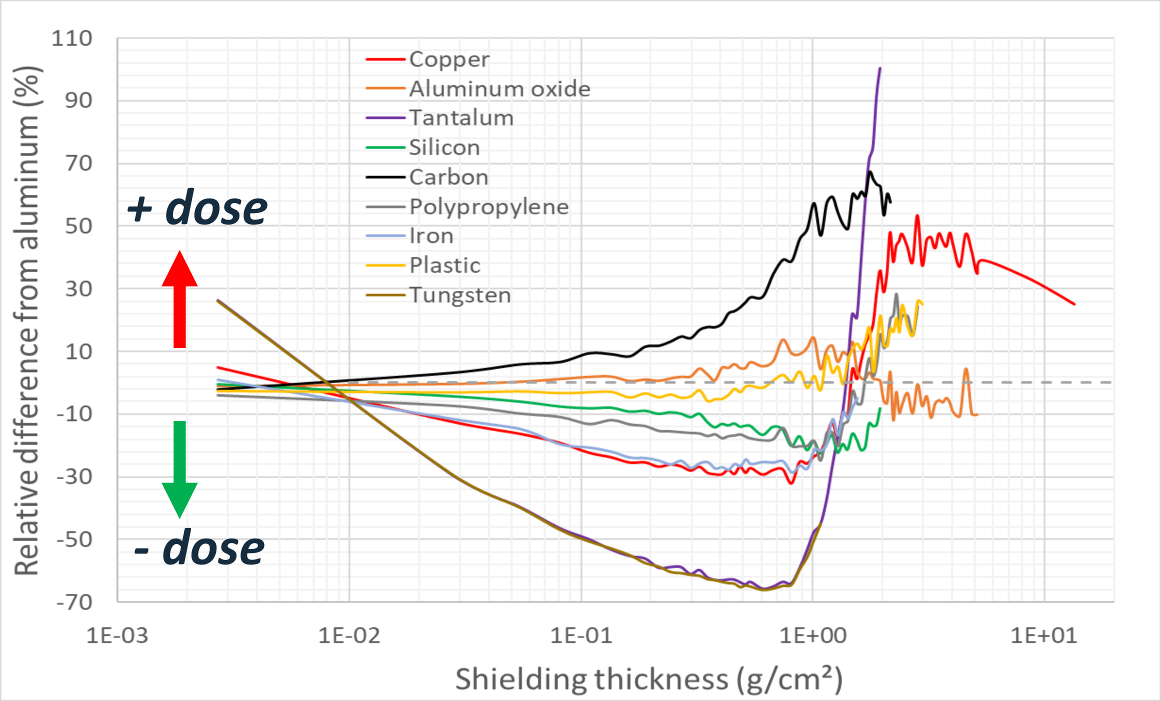
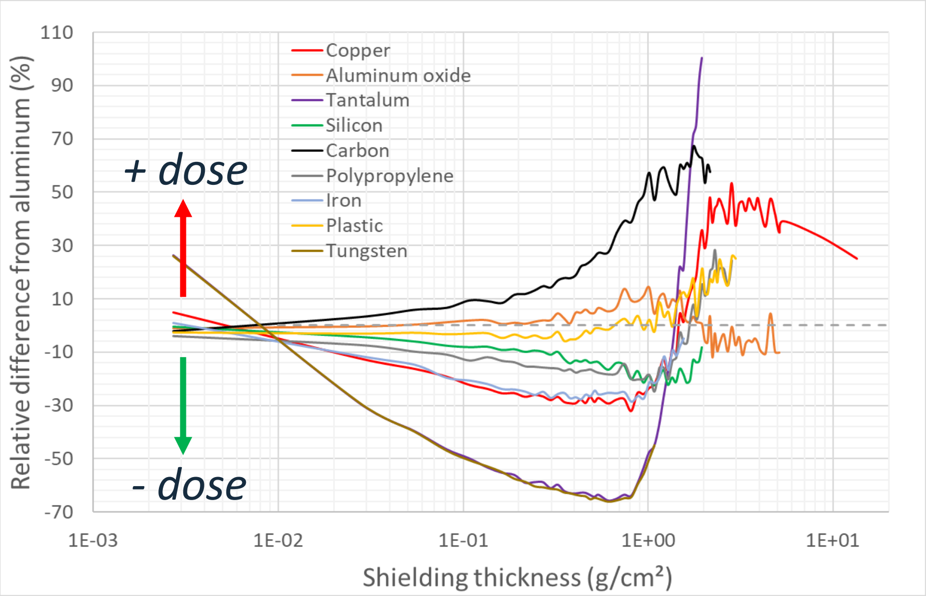


Variation of the dose according to the shielding thickness.
Reference material: aluminum

- Error = relative difference between dose computed for aluminum shielding and another shielding material
- Dose variation: [-70% ; +100%] → **Non negligible bias**
- Provides an idea of the **error induced by the aluminum equivalent thickness → Bias in the RT calculation**

Axis 2: Investigate the Ray-Tracing limits

- Improving the consideration of the material
  - New approach: use of multiple dose-depth curves (instead of only aluminum)
  - Proposed test: equivalent aluminum thickness that brings the same dose behind the true material thickness shielding



Variation of the dose according to the shielding thickness.
Reference material: aluminum

Mission: GEO, 35784km, 15 years

- Works well on simple geometries (concentric spheres, electrical component package) but less on more realistic ones (unit, satellite platform)

- The material approximation induces some bias but other ones seem to be not negligible: **geometric effects**

Axis 2: Investigate the Ray-Tracing limits

- Geometric effects:
  - Distribution of the materials along the path of the particles
  - Spacing between shielding elements

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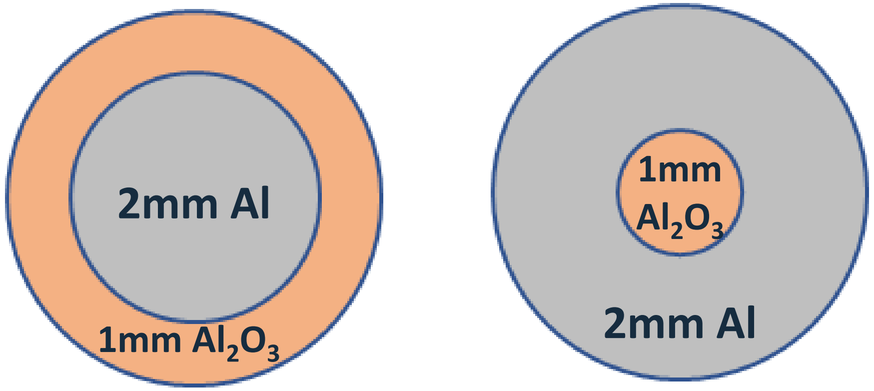
Case study

Concentric spheres (GEO)

→ Same total thickness



Case 1 *Case 2*

Axis 2: Investigate the Ray-Tracing limits

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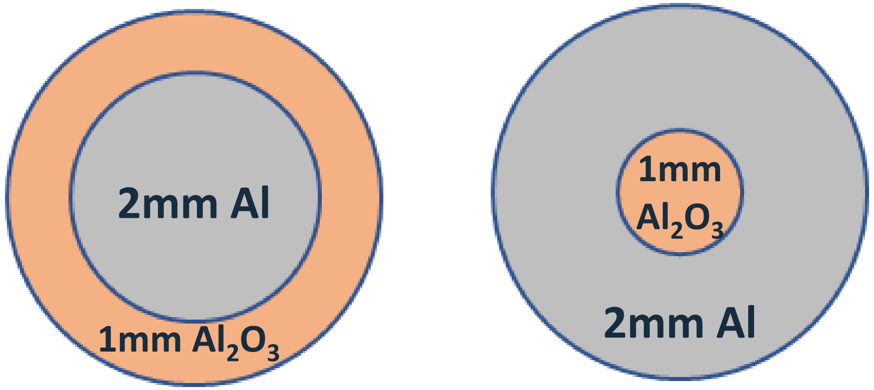


Case 1 *Case 2*

Results

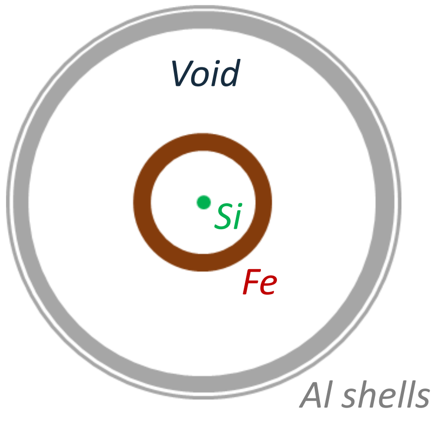
Method	Case 1	Case2
Ray-Tracing	325krad	
Reverse Monte Carlo	336krad (+3,5%)	383krad (**+18%**)

- The Ray-Tracing is not able to take into account the material sequence
- Non negligible bias even for a very simple case

Axis 2: Investigate the Ray-Tracing limits

- Geometric effects:
  - Distribution of the materials along the path of the particles
  - **Spacing between shielding elements**

- Sequence of shielding materials:
  - Silicon, iron and aluminum shells
  - Separated with void spacing



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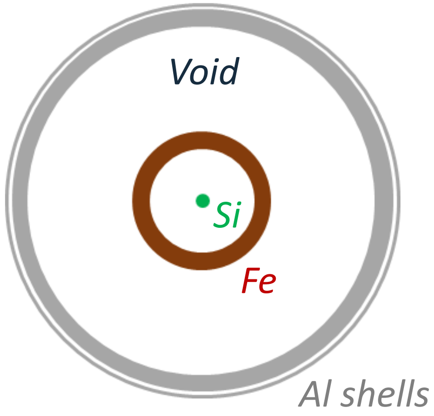


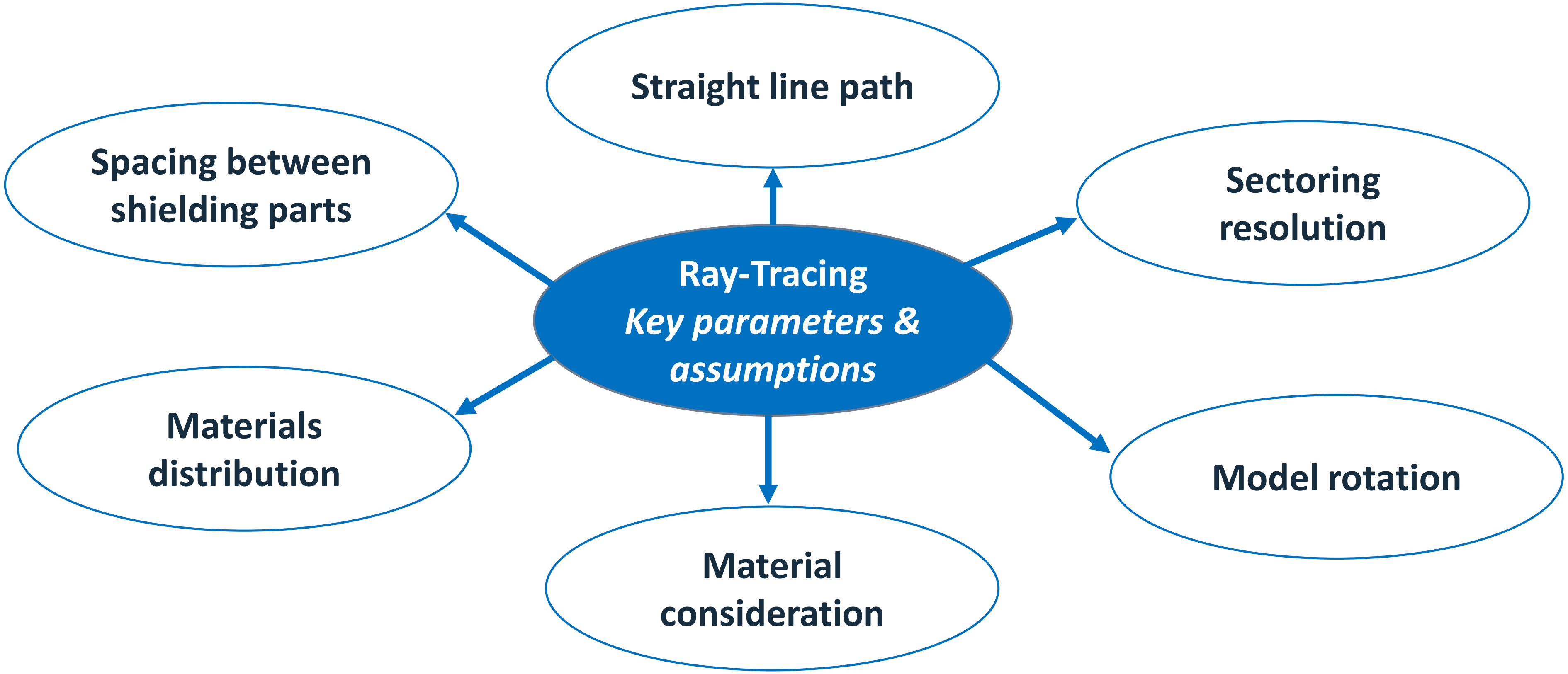
Results

	Dose (krad)	RT error (%)
RT	1378	-
RMC	698	-49

- Factor 2 between the RT and RMC
- **Non negligible bias induced by the spacing**
  - Scattering of the particles

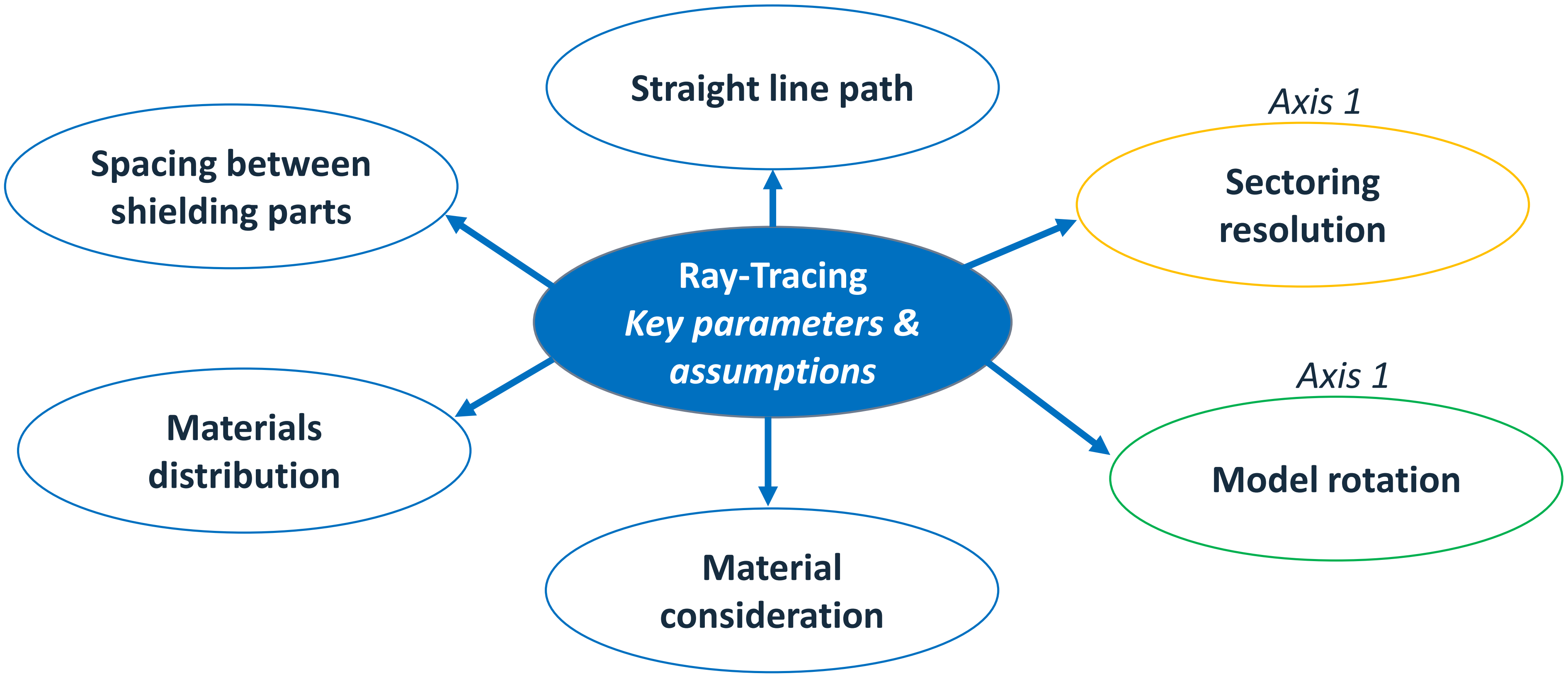
Discussion and Conclusion

- Competition between different factors in the Ray-Tracing calculation
  - ➢ Quantifying each of them independently is a harsh task → Act at the same time



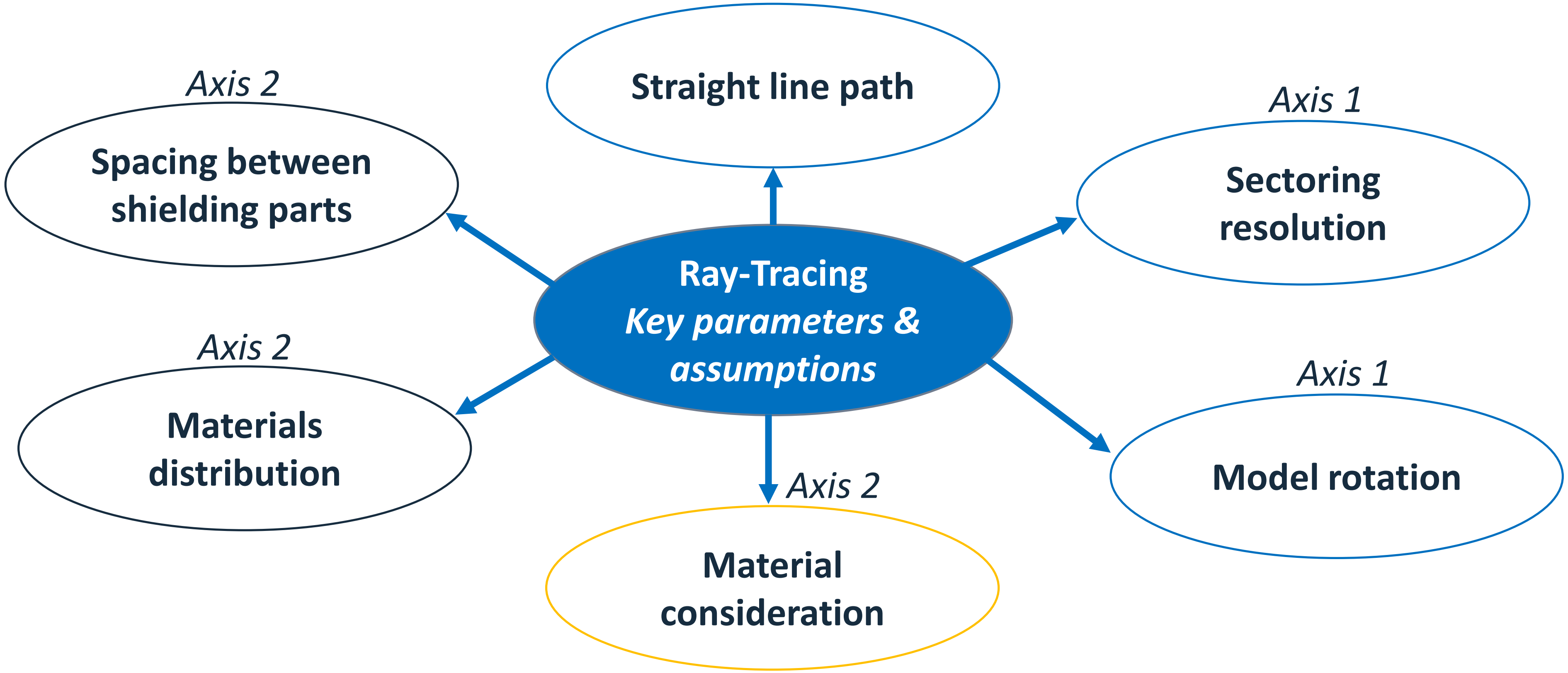
Discussion and Conclusion

- <u>Axis 1: Studying the key parameters impact on the Ray-Tracing accuracy</u>
  - ➢ Increase the number of sectors is not very efficient to reduce dose variations
  - ➢ Confirm the minimum number of sectors recommended by ECSS
  - ➢ Apply a random rotation seems to increase the Ray-Tracing accuracy



Discussion and Conclusion

- Axis 2: Investigate the Ray-Tracing limits
  - ➢ Highlight the limits of the ratio density for the material consideration
  - ➢ Strong impact of the geometric effects on a electron-dominated orbits due to scattering effects



Recommendations and Future Prospective

- Recommendations or suggestions
  - Avoid Ray-Tracing on electron-dominated orbits as much as possible → Confirms ECSS suggestion
  - Use RMC as a validation tool on most critical cases → Complementary simulations

- Future prospective
  - Investigate solutions to consider both **material** and **geometric effects** at the same time

Acknowledgements & Contact details

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- TRAD software development team (OMERE and FASTRAD)

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Thank you for your attention !