Appendix J

Innovative Ray Tracing Algorithms for Space Thermal Analysis

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Abstract

The objective of the presentation is to give a short overview of the Ph.D. thesis entitled Innovative Ray Tracing Algorithms for Space Thermal Analysis, performed at the University of Liège in Belgium, with the support of ESA and the Belgian National Fund for Scientific Research (FNRS). In this presentation, we will mention the requirements that the final algorithm must fulfil; we will briefly present some key elements of the developed method, such as the hemisphere method, the combination of geometrical primitives with finite element meshes, statistical accuracy control and report. The validation aspects are then covered with comparison with analytical cases and industrial-ESARAD type models.

Innovative Ray Tracing Algorithms for Space Thermal Analysis

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Objectives

- Design a new ray tracing algorithm
  - that combines the advantages of *Esarad*–type tools and finite element formalism
  - that is still compatible with common software for space thermal engineering
- Obtain a faster ray tracing for comparable accuracy, mesh, …
- Develop an efficient and intuitive statistical accuracy control

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References to measure results

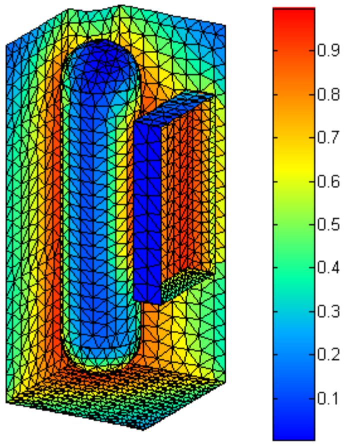
- *Esarad*
- *Samcef Bacon / Mecano Thermal*
- Simple test cases with analytical solution

Characteristics of *Esarad*

- Geometry based on primitive surfaces
  - triangle, quad, disc, sphere, cylinder, …
- Robust ray tracing
  - used for almost 20 years in industry
- Statistical accuracy control
  - although not fully implemented
- Thermal equations written in terms of REFs (GRs for solution with *Esatan*)

Characteristics of *Samcef* (1/2)

- Finite element model and formulation
- No geometrical primitives, but geometry approximated by triangular and/or quadrilateral facets
  - $\Rightarrow$ Fast ray tracing on simple elements
- Gradient of the VFs on the FE mesh
- Possibility to treat multiple (more than two) wavelength bands



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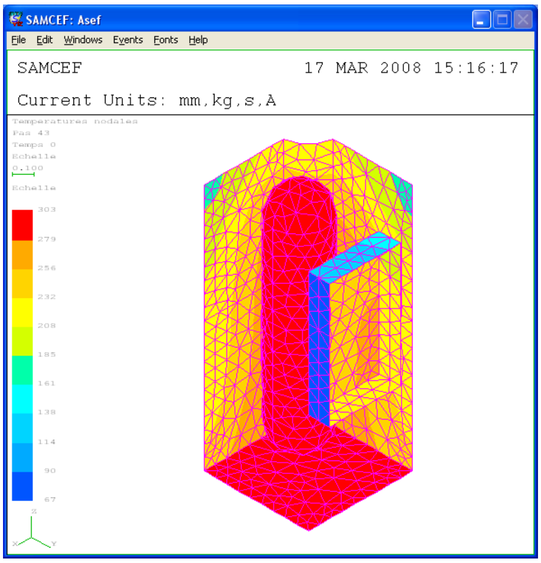
Characteristics of *Samcef* (2/2)

- Thermal equations written in terms of either VFs or REFs
  - Radiosity equations (VFs)
  - Gebhart equations (REFs)
- Smooth integration with heat conduction (directly on the FE mesh)
- Linear or quadratic temperature profile



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Common aspects

- VFs / REFs computed with purely random ray tracing
  - Random emission points on the faces
  - Random directions
- Uniform VF or REF per elementary surface patch
  - *Esarad* active face
  - *Samcef* finite element

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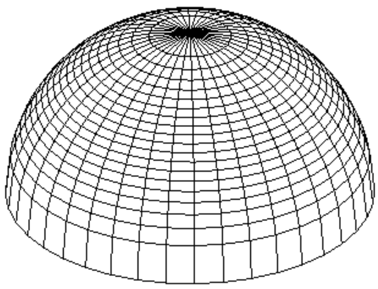
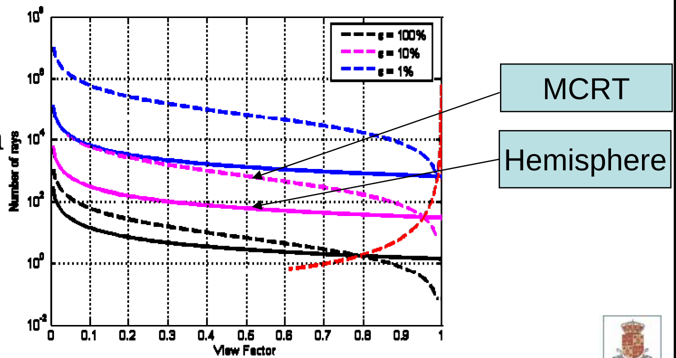
Solutions (1/4)

- Optimized generation of rays: *Hemisphere*
  - Better convergence
    - error α $1/N^{3/4}$
    - error α $1/N^{1/2}$ for MCRT
  - Adapted statistical accuracy control
  - Better than MCRT at handling large surface area differences





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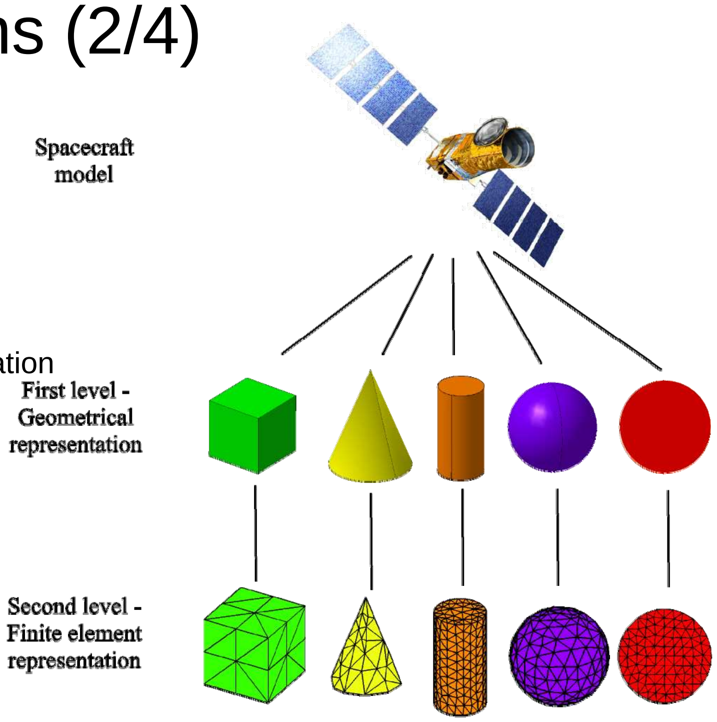
Solutions (2/4)

- Geometrical method
  - Geometrical model
  - Finite element mesh
  - ⇒ Combination
  - ⇒ Two level RT-acceleration method
- Geometrical model
  - ⇒ Radiation
- Finite element mesh
  - ⇒ Conduction



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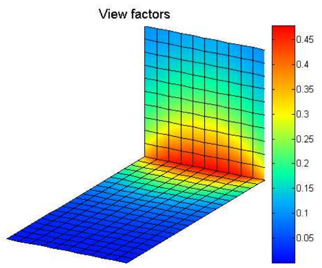
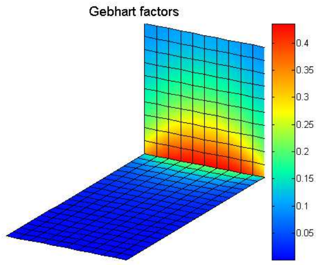
Solutions (3/4)

- Computation of VFs
  - And Extended VFs (EVFs) in case of specular reflection or transmission
- Use of the Gebhart's matrix method for REF's
  - Also in case of non-diffuse surfaces
  - Also in case of non-isothermal surfaces
  - Adaptive mesh for non-uniform mutual irradiation
- Complete ray tracing for absorbed heat fluxes





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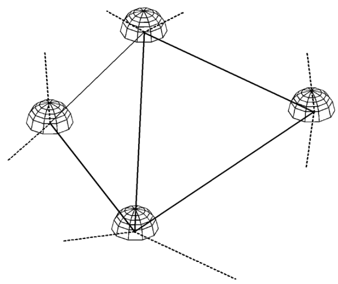
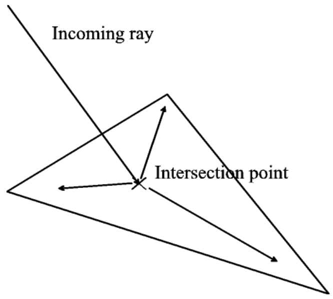
Solutions (4/4)

- Finite Element based VFs
  - Linear (or quadratic) VF field
  - Emission of the rays from the FE nodes
    - using the hemisphere method
  - Interpolation with the shape function
    - at the impact of each ray
  - Access to a detailed gradient of VF over each FE
  - Computation of temperatures on the FE nodes
    - Computation of extreme temperatures on auto generated mesh possible (e.g. identification of "hot spots")





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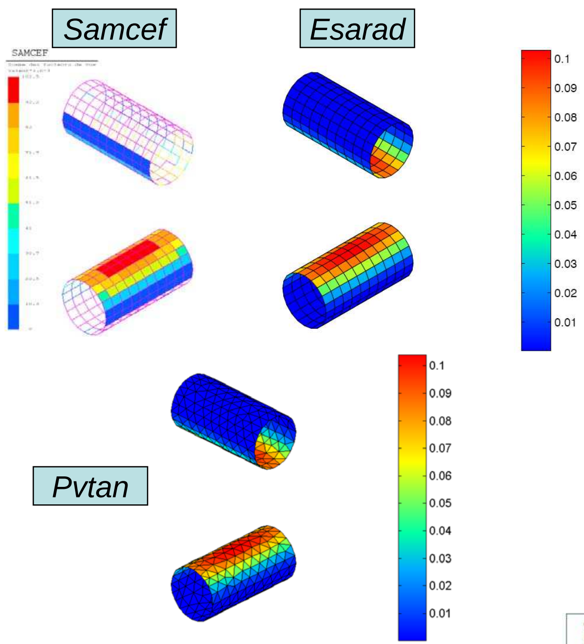
Validation (1/8)

- Small test cases
  - with analytical solutions
  - Convergence of the error with the number of rays
  - New method is well-behaved



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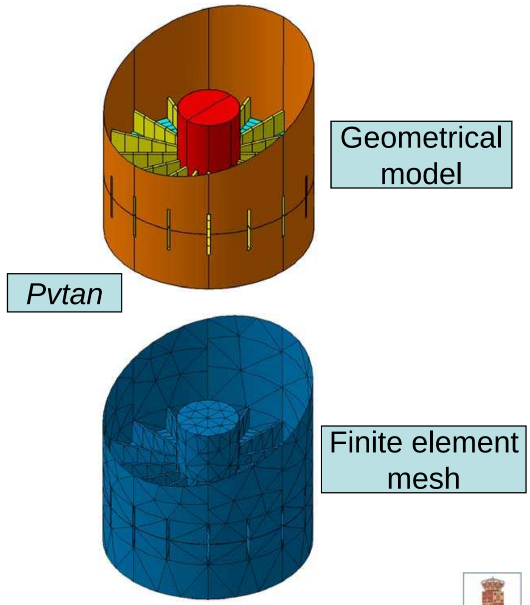
Validation (2/8)

- XEUS model
  - 1156 surfaces
  - Different primitives
  - Obstacles
  - Contains large and small surfaces
  - Large and small VF to deep space



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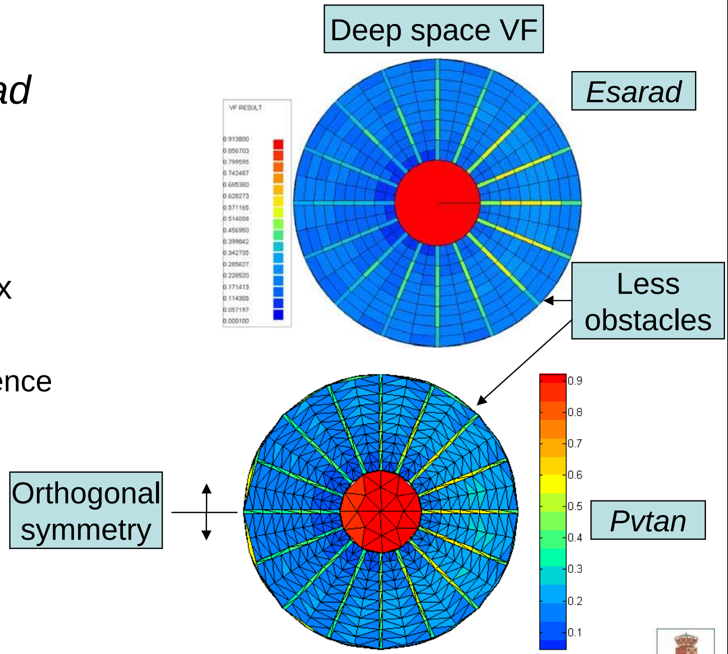
Validation (3/8)

- Comparison with *Esarad* and *Samcef*
  - Deep space VF & REF
  - Global VF & REF
  - Absorbed solar heat flux
  - Temperature field
    - First computed in absence of conduction, i.e. only radiative heat transfer taken into account



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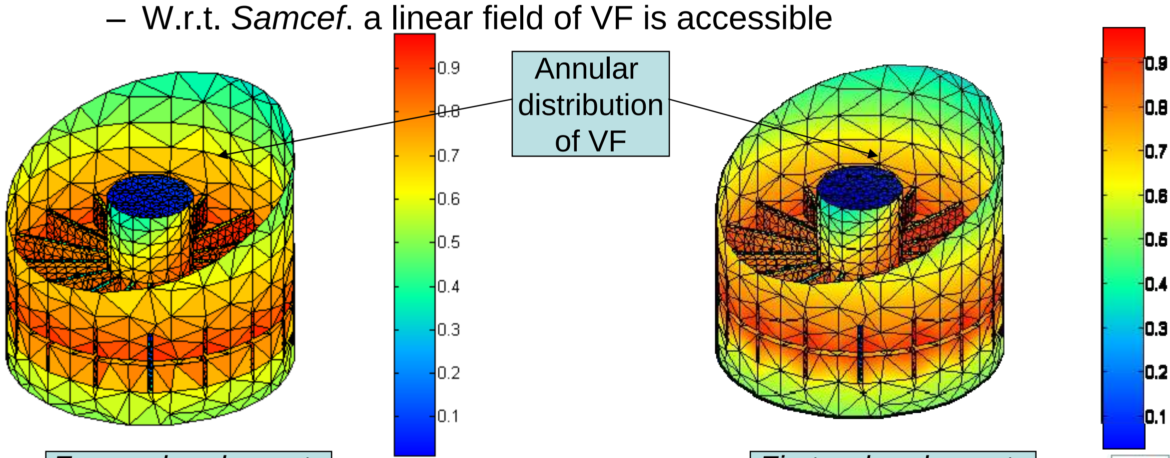
Validation (4/8)

- Finite element view factors
  - W.r.t. *Esarad*, a gradient is computed
  - W.r.t. *Samcef*. a linear field of VF is accessible



Zero order elements *First order elements*

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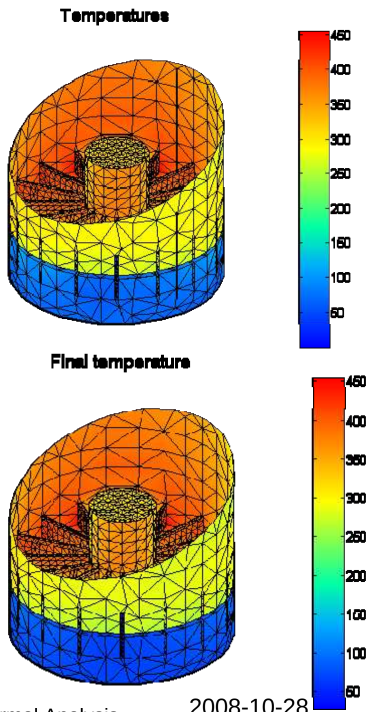
Validation (5/8)

- Second step: inclusion of conductive heat transfer in the shells
  - iterative scheme initiated with a first solution based on radiation only
- Temperature smoothing due to conduction



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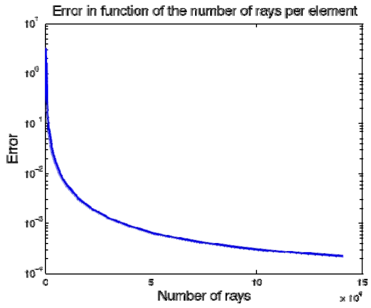
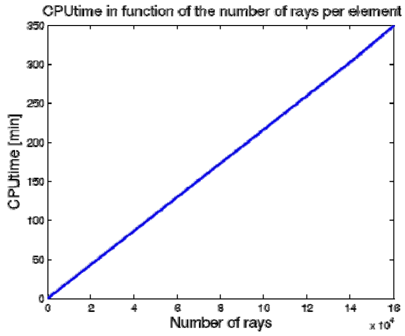
Validation (6/8)

- Mathematical behaviour

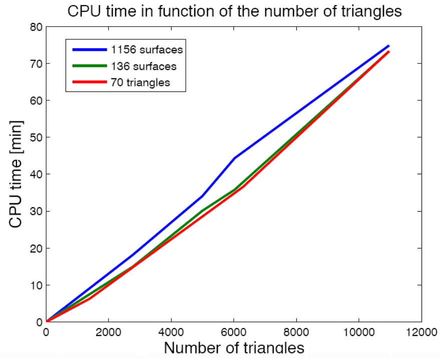


- CPU time
  - Linear with number of rays

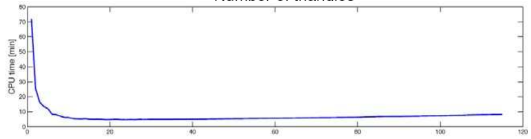


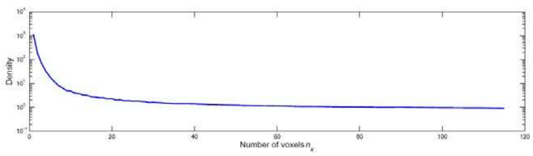
Validation (7/8)

- CPU time in function
  - Of the number of surfaces
  - Of the number of elements



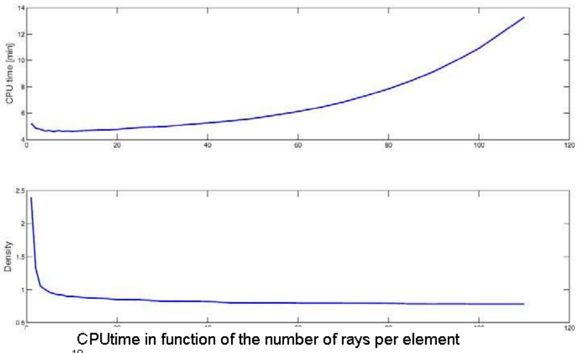
- Acceleration of the ray tracing (voxels)



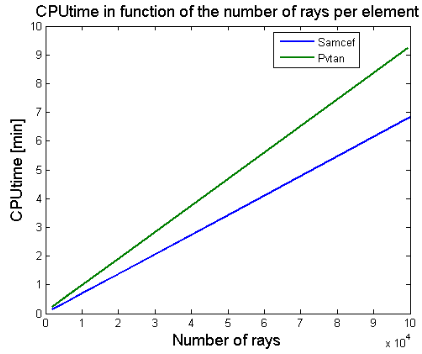


Validation (8/8)

- Acceleration of the ray tracing (geometrical method)



- Comparison CPU time *Samcef* and new algorithm
  - Currently *Pvtan* is about 1.25 times slower
  - But no performance tuning / profiling yet



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Perspectives (1/3)

- Optimal combination of the new algorithm's modules shows very promising potential for reduction of CPU time and memory usage for full orbit analysis
- (E)VFs could be used in place of REFs to avoid many multiple-reflection MCRT steps
  - In particular also for multiple wavelength bands
- Hemisphere Method can be extended to efficiently compute planet IR and albedo fluxes
  - Limit ray casting within solid angle from spacecraft to planet
  - Support for planet albedo and temperature (lat, long) maps

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Perspectives (2/3)

- Optimal combination of the new algorithm's modules enables CPU time and storage reduction
- for orbital simulations
  – Multi-reflection for each of the M spectral bands (cryogenics applications)
  ⇒M ray tracings
  – Heat flux for each of the N orbit positions
  ⇒ 3*N ray tracings
- We could reduce the number of RT
  ⇒1 ray tracing for the couplings
  – Heat flux for each of the N orbit positions
  ⇒ 2*N ray tracings for the heat fluxes

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Perspectives (2/3)

- N orbit positions
- M wavelength bands
- No moving geometry
- HM = Hemisphere Method

	Current *Esarad* & *Thermica*-like tools	New algorithm
VFs / REFs	• M * MCRT to compute REFs	• 1 * HM to compute (diffuse) VFs • M * ray-tracing for specular and/or transmission EVFs or 1 RT with M simultaneous updates
Planet fluxes	• 2N * MCRT to compute absorbed albedo and planet IR	• N * HM to compute planet VF • N * step to compute incident albedo and planet IR
Solar fluxes	• N * MCRT to compute absorbed solar	• N * ray-tracing to compute incident solar
Temperatures	• Solve REF (GR) based thermal equations (*Esatan*)	• Solve VF based thermal equations (radiosity, flux and temperature) • Solve REF based thermal equations

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Perspectives (3/3)

- New approach can support full accuracy control in all steps (VFs and fluxes)
- Integrates well with auto-generated FE meshes
- Supports radiative and conductive gradients over FE elements
- Has similar order of magnitude ray-tracing performance (per ray) as existing methods but needs significantly less rays for overall analysis case (e.g. one whole orbit)
- Thesis published in 2009