Appendix J

THERMICA-THERMISOL 4.3.4

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Abstract

THERMICA Performances

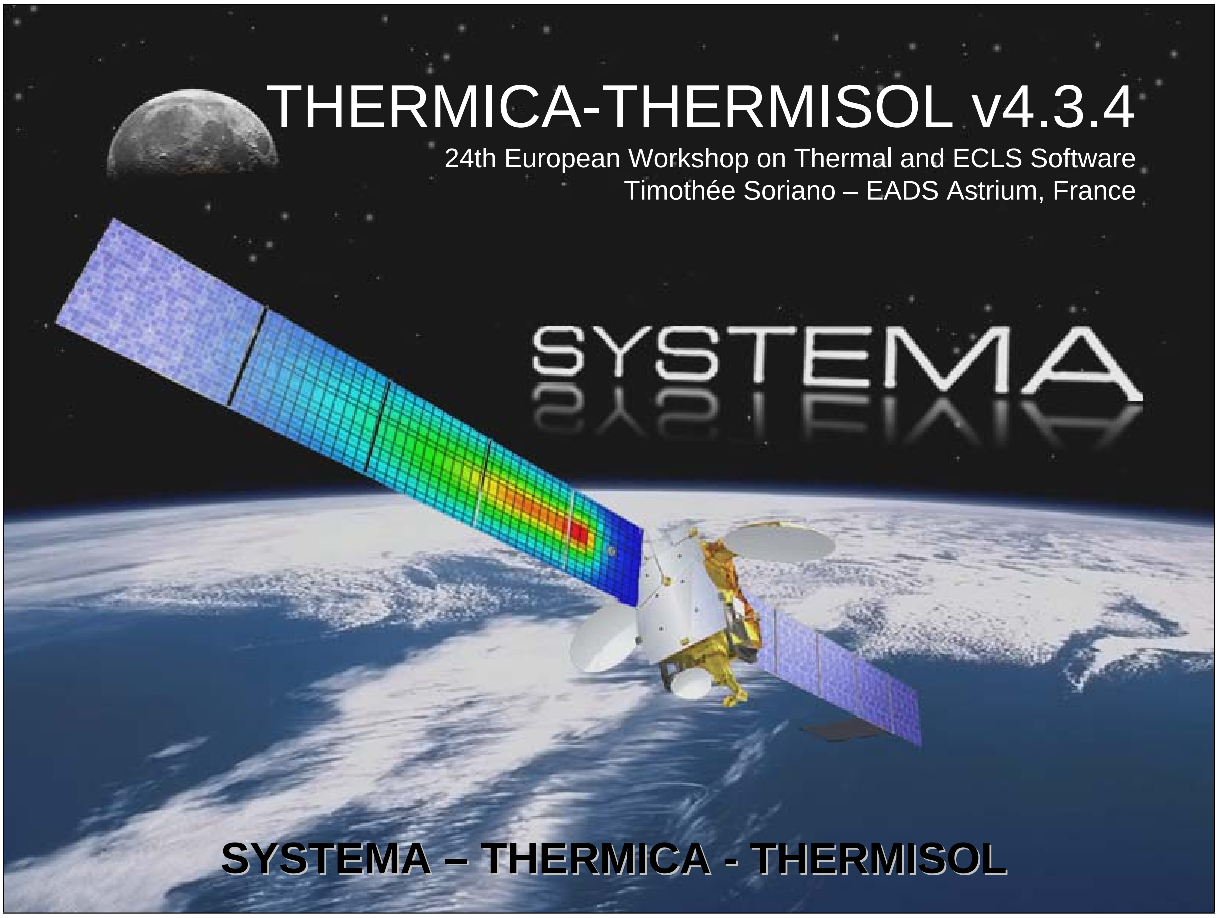
For its latest version 4.3.4, one major concern was the computation performance. The ray-tracing algorithm has been reviewed in order to speed-up its execution. Besides, THERMICA is now multi-threaded which allows to take benefit of the computer performance. Results and CPU time will be compared on significant cases, demonstrating that not only the accuracy of the v4 has been improved but the execution time has also become one of the strengths of THERMICA.

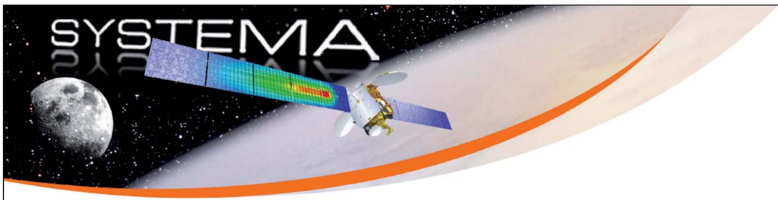
Ray-tracing visualization

Another major feature of the 4.3.4 version is the ray-tracing display in 3D view. In order to understand THERMICA results, ray paths can be displayed around the spacecraft visualization in the realistic mission render. User is free to navigate around rays and geometry, to filter by bouncing or emitting meshes, and to display in a same view results as shape color or textual value.

THERMISOL Evolutions

Performance issues have also been raised for complex models such as satellite systems including biphasic fluid loops. This kind of models requires small time-steps in order to converge. Therefore we decided to investigate on the multi time-steps algorithm already studied a few years ago. The principle of this algorithm is to adjust the main time-step so a certain percentage of the nodes (usually about 95%) have a good accuracy. For the other nodes, an adequate sub-step is used in order to get a full convergence of the system.





Content

- THERMICA   Ray-Tracing Performances
- THERMICA   Ray-Tracing Visualization
- THERMICA   Conductive aspects
- THERMISOL Multi Time-Steps

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Content

THERMICA

Ray-Tracing Performances

THERMICA
Ray-Tracing Performances

- THERMICA 4.3.4
  - **Double Precision Multi-threaded software**
  - Uses a wide voxels discretization **optimized** for better performances
  - Accuracy problems are avoided thanks to **error controls** in the ray-tracing process
  - Performs computation **directly** on thermal nodes, then symmetries the results
  - Write **compressed** hdf5 files (rad.h5 and optional box.h5)
  - Uses dynamic memory allowing more **complex models**

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Ray-Tracing Performances

Execution Time Comparison

- Machine used:
  - Red Hat Linux 64bits with 2 quad core processors
- Model description:
  - Telecommunication External model composed of 3500 meshes
  - Geo-stationary orbit with 16 orbital positions and kinematics body
- Execution Time Summary:

Versions	3.2.32	4.3.4		
Number of threads	1	1	4	8
Radiation	83 min	28 min	11 min	10 min
Solar Flux	5 min	2 min	1 min	1 min
Total Time	88 min	30 min	12 min	11 min
Ratio vs 3.2.32		**2.93**	**7.33**	**8**

Ray-Tracing Improvements **+ Multi-threading**

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Ray-Tracing Performances

Ray-Tracing Performances: Conclusion

THERMICA v4.3.4 is a high-performance ray-tracing algorithm

- The performances mainly depend on the number of rays.
- The complexity of the model has a limited impact on the CPU time but increases the amount of necessary RAM

This improvements allow to:

- Decrease the execution time (by about 7 on a quad core machine)
- Increase the model complexity
- Use directly CAD geometries on a thermal model

The v4 has now a performance level never reached in thermal analysis software

It is optimized for accuracy, fast execution and lower hard-drive memory usage

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Ray-Tracing Visualization

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Ray-Tracing Visualization

Ray-Tracing Visualization

- It is now possible to store all the computed rays in a hdf5 file
- The rays can then be easily viewed in SYSTEMA with filtering options
  - By emission node
  - By impacted node
  - Between nodes

  with multi-selection is available
- SYSTEMA can handle an incredible amount of rays without a lost of 3D performances

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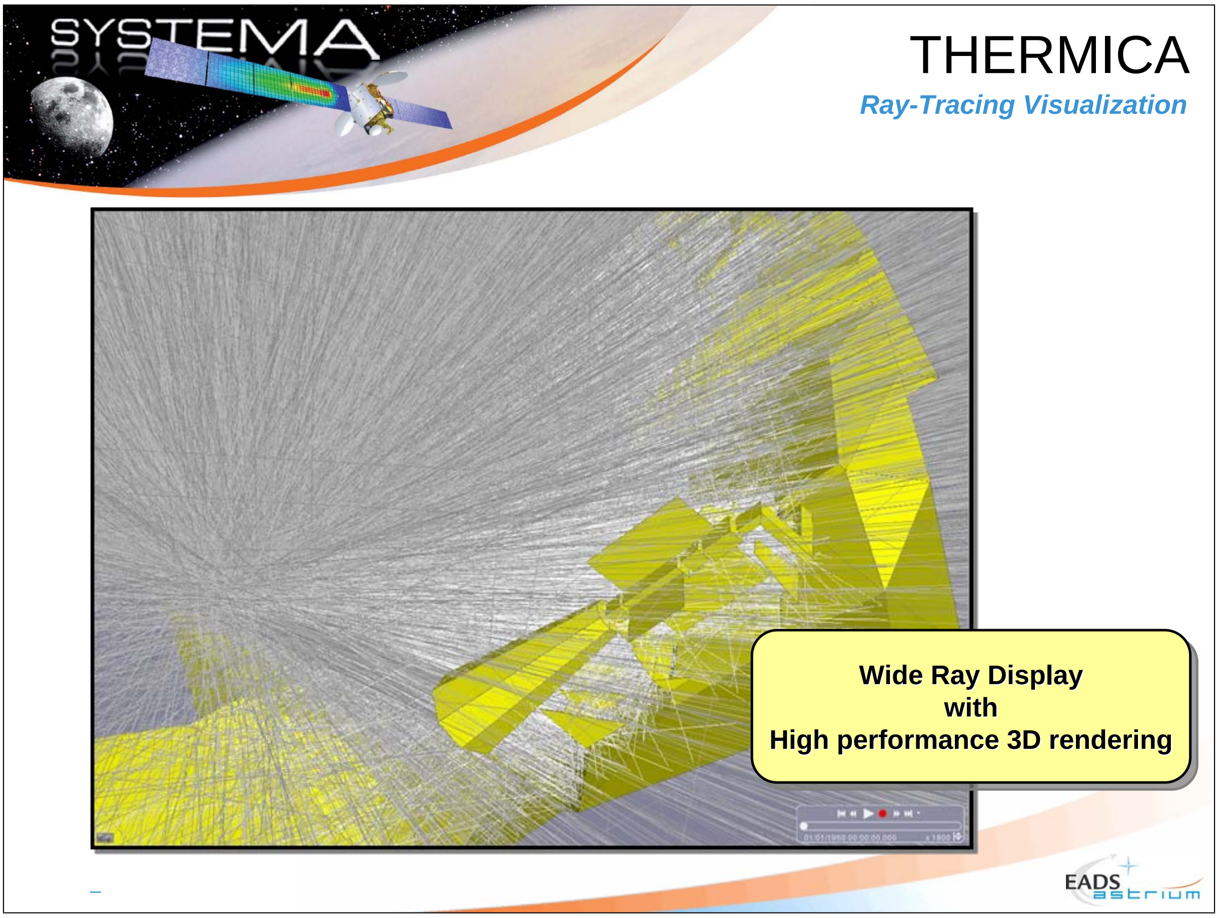
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Ray-Tracing Visualization
Wide Ray Display
with
High performance 3D rendering
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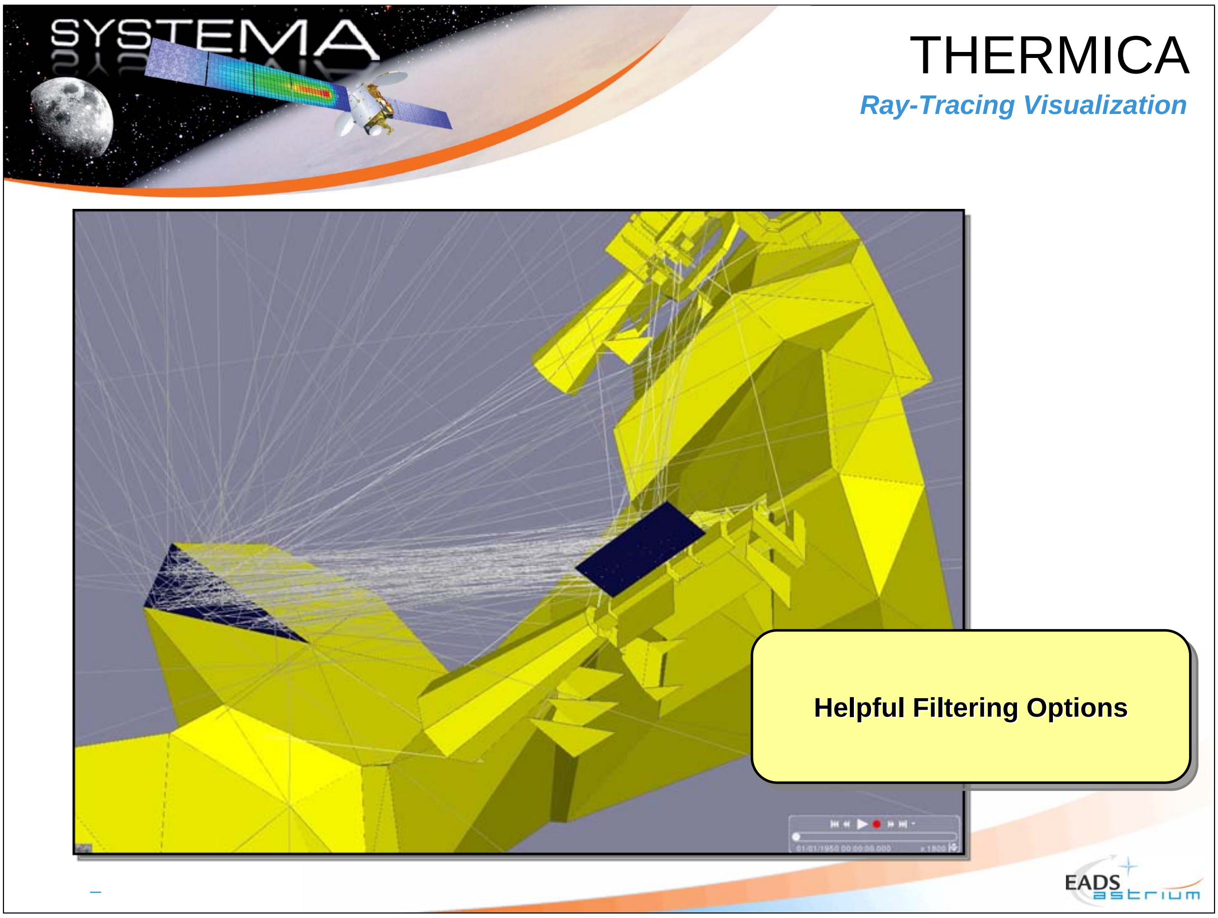
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THERMICA
Ray-Tracing Visualization
Helpful Filtering Options
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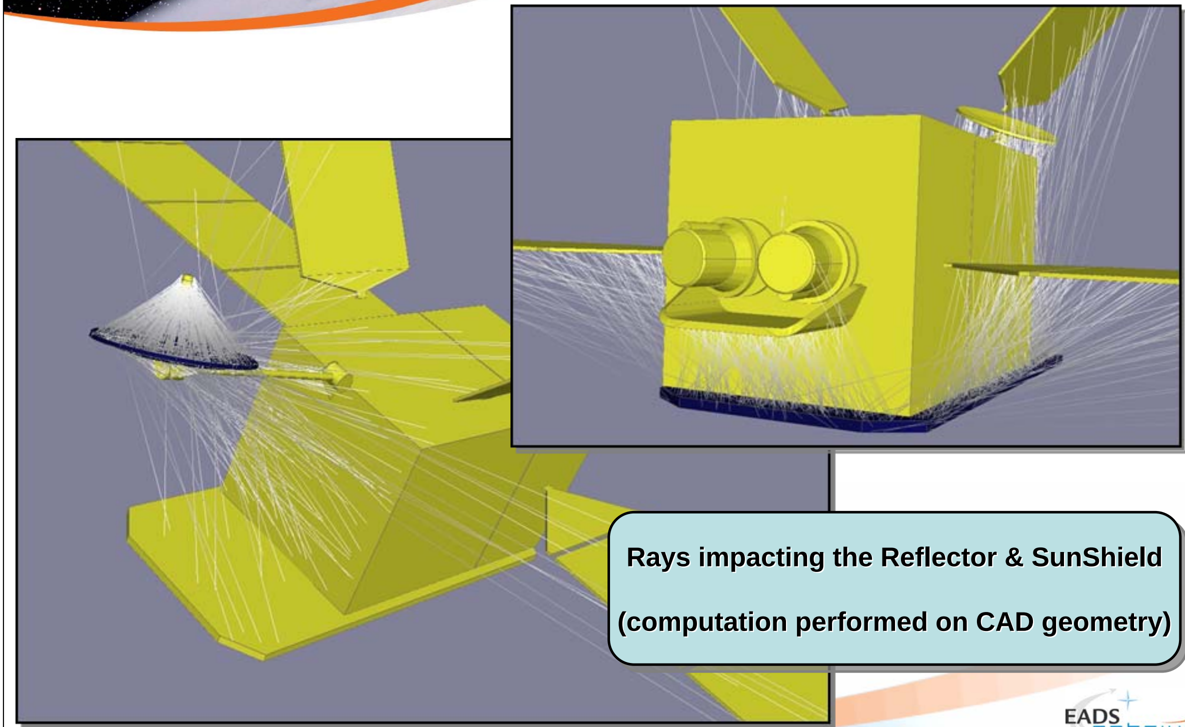
Ray-Tracing Visualization



Rays impacting the Reflector & SunShield

(computation performed on CAD geometry)

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Conductive Aspects

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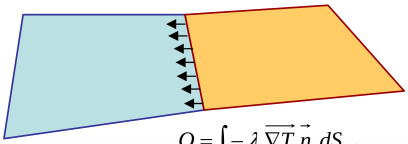
Conductive Couplings

Conduction Principle

- Generality
  - The conduction is driven by the Fourier's law $Q = \int_V -div(\lambda.\overrightarrow{gradT})\ dV = \int_C -\lambda.\overrightarrow{\nabla T}.\vec{n}\ dC$
  - The power exchanged by conduction between 2 shapes depends on the temperature gradient at their common frontier



$$Q = \int_{Edge} -\lambda.\overrightarrow{\nabla T}.\vec{n}\ dS_{Edge}$$

  - The temperature gradient between 2 shapes cannot be determined only with the knowledge of their average temperatures

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Conductive Couplings

Conductive Couplings topologies

- Shape-to-Shape couplings (without edge nodes)
  - This topology usually requires the following hypothesis:

    - The average temperature of a shape is located at its center

      ➔ *implies linearity of the temperature profile inside each shape*

    - The temperature gradient at the frontier is more or less $\Delta T\ /\ length$

      ➔ *implies linearity of the temperature profile across the 2 shapes*

  - Limitations:

    - A linear temperature profile is equivalent to have only conductive fluxes

      ➔ *the mesh size shall be decreased to minimize the surface fluxes*

    - There is no mathematical evidence of the couplings solving equations

      ➔ *it is not possible to quantify the error made*

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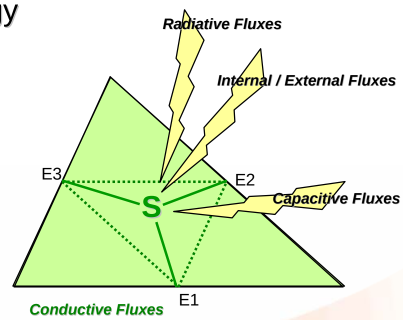
Conductive Couplings

Conductive Couplings topologies

- Necessity of the Edge Nodes
  - They are used to compute the temperature gradients on their dimension
  - This information is required to compute accurately the conductive flux
- Possible couplings using a “edge node” topology
  - It can be demonstrated that it exists an infinite set of couplings on a shape which are linearly exact
  - Among all those possibilities, it is also possible to demonstrate that it exists one and only one solution consistent with the radiative mesh
  - This solution lays on only one hypothesis:

    The surface flux shall be uniform on the surface



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Conductive Couplings

The Reduced Conductive Network method is now mathematically demonstrated

- Key points of the demonstration
  - Definition of all linear solutions in a triangle (6 parameters to be defined)

    A set of 5 equations can be written to define them

    A 6th coefficient can be of any value $(\forall a \in \Re^+)$
  - Introduction of a tiny power on the triangle surface $\tilde{Q}_S = \varepsilon_S$

    Then the 6th equation becomes $\exists a \;/\; \tilde{T}_S = T_S + a.\varepsilon_S + o(\varepsilon_S^2)$

    Meaning that not all solutions of the linear case are solutions of this problem

    But it exists at least one solution among them (which we don't know…)

    The error made on the temperature is proportional to the power ε_S

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Conductive Couplings

- Key points of the demonstration

  - The Detailed Conductive Network: Study of a shape with significant surface powers

    If we discretize the shape into small triangles, the surface power (supposed uniform) is distributed to the submesh. Each submesh triangle is then conform to the previous case.
    We write a detailed conductive network on the submesh.
    This detailed conductive network is written with unknown values of the a coefficients.

  - Reduction of the detailed network: creation of the reduced network

    It can also be demonstrated that there is an exact reduction of the detailed network under the only hypothesis of a uniform surface flux.

    This reduction do not sum the error made on each triangle but average those errors !!!!

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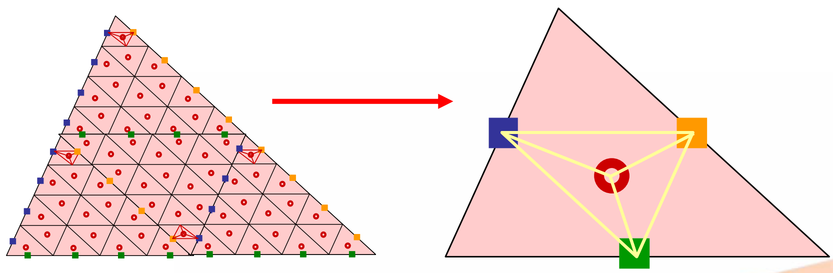
Conductive Couplings

Demonstration conclusion

Even if the analytical description of the couplings is not known, and even if the detailed network is written using only a linear solution (and not the solution of the real problem),
The reduction of such network tends to the exact solution of the problem as the submesh size decreases.



Detailed Conductive Network *Reduced Conductive Network*

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Conductive Couplings

The RCN method

- Disadvantages
  - Creates an edge nodes structure
  - The conductive flux is given by a few couplings contributions
- Advantages
  - The conductive fluxes are accurately computed
  - It lays on the same hypothesis than the radiative couplings and external fluxes
  - The mesh size is dimensioned according to the radiative constraints
    - ⇨ reducing the mesh for conductive aspects is not necessary and even meaningless
    - ⇨ the nodal network can be composed with less surface nodes

The RCN is the only 2nd order known method which is Mathematically consistent with our thermal analysis

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Multi Time-Steps

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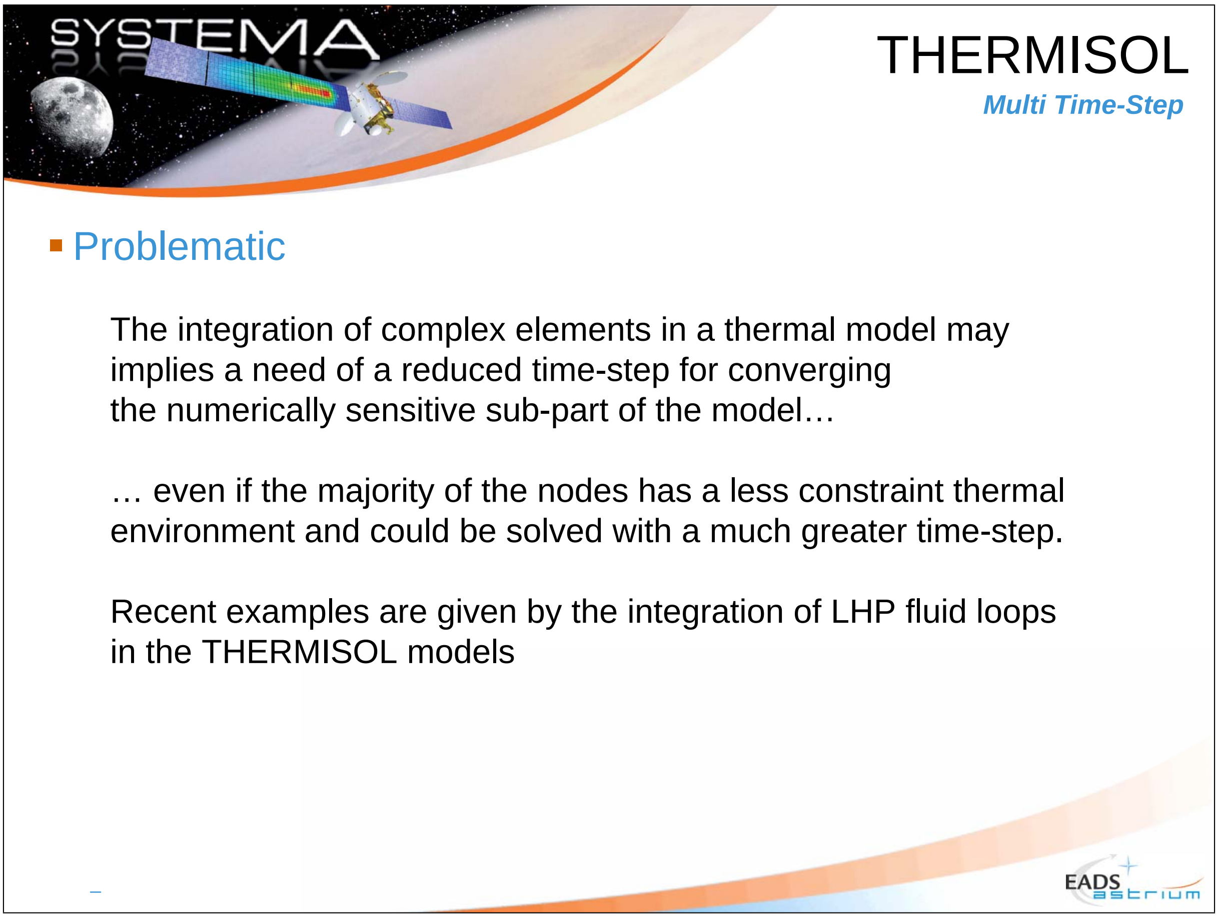
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Multi Time-Step
Problematic
The integration of complex elements in a thermal model may implies a need of a reduced time-step for converging the numerically sensitive sub-part of the model…
… even if the majority of the nodes has a less constraint thermal environment and could be solved with a much greater time-step.
Recent examples are given by the integration of LHP fluid loops in the THERMISOL models
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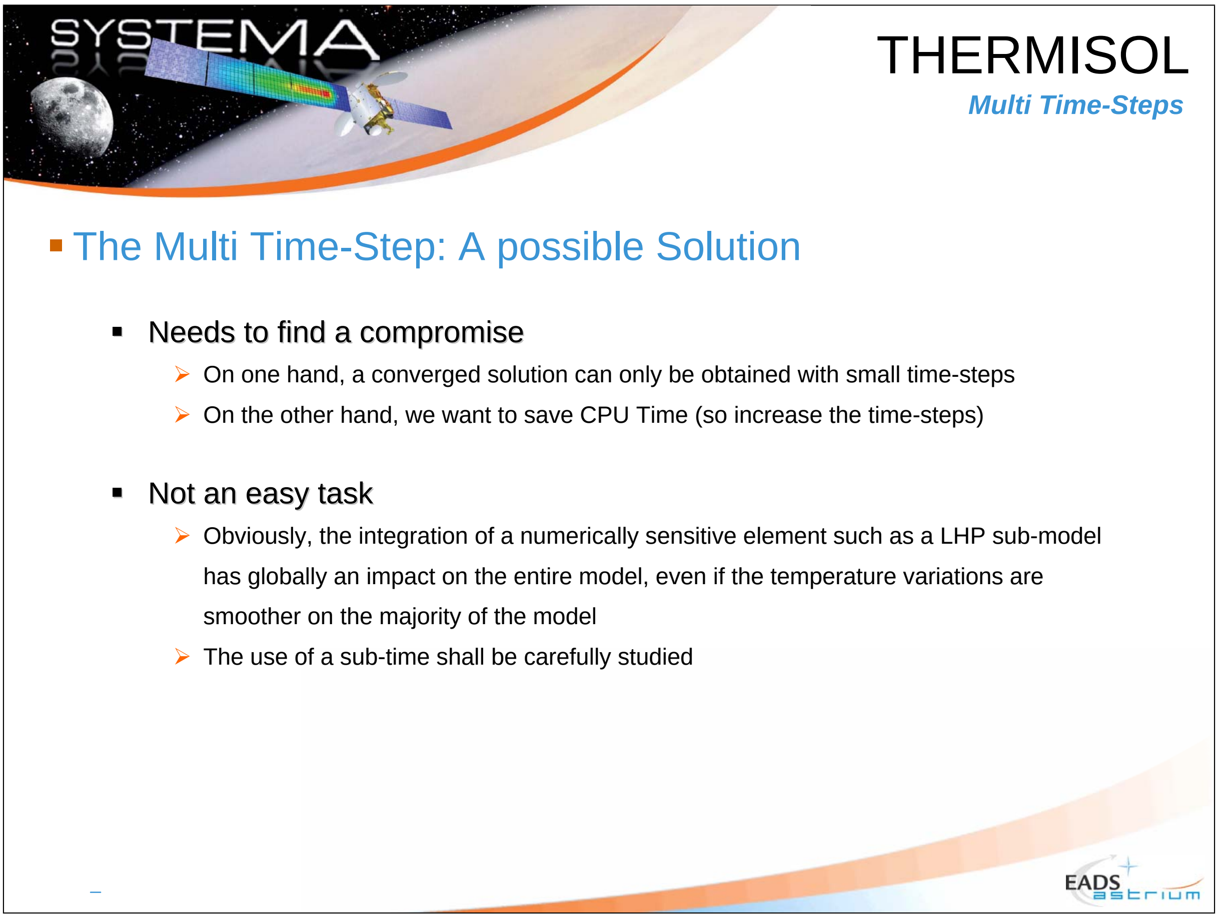
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Multi Time-Steps
The Multi Time-Step: A possible Solution
Needs to find a compromise
On one hand, a converged solution can only be obtained with small time-steps
On the other hand, we want to save CPU Time (so increase the time-steps)
Not an easy task
Obviously, the integration of a numerically sensitive element such as a LHP sub-model has globally an impact on the entire model, even if the temperature variations are smoother on the majority of the model
The use of a sub-time shall be carefully studied
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Multi Time-Steps

Principles

- THERMISOL computes a 2nd order solution and a good error estimation at the 3rd order
- Nodes are divided into 2 categories: with an acceptable error / with too much error
- A sub time-step may be used for the rejected nodes group
- The other nodes are interpolated according to their quadratic temperature profiles
- All node's temperatures are recomputed at the rendez-vous. The solutions are compared and the entire time-step (prime+subs) is validated or rejected

No mathematical evidence of the convergence

- The errors are only estimations and the interdependences of the nodes do not allow a mathematical justification of the re-computation of a sub-group only.
- The complex interactions in a thermal model makes it difficult to pre-define groups of sensitive nodes
- Precautions shall be taken: the multi time-steps algorithm needs to verify that the subdivision of the thermal model in 2 groups is valid

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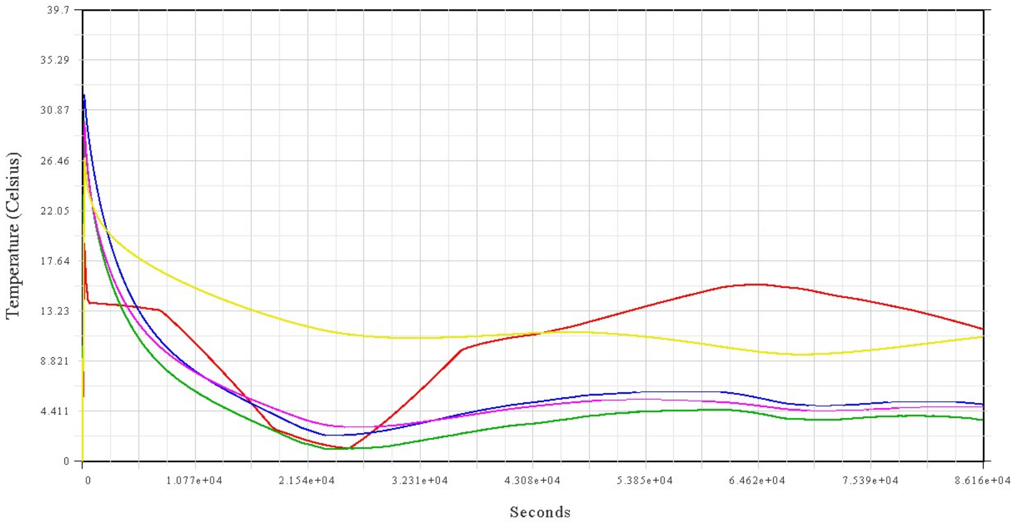
Multi Time-Steps

Example: a telecommunication satellite including 12 LHP

- Fixed Time-Step of 1s :

Convergence: Excellent / Execution Time: 160 minutes



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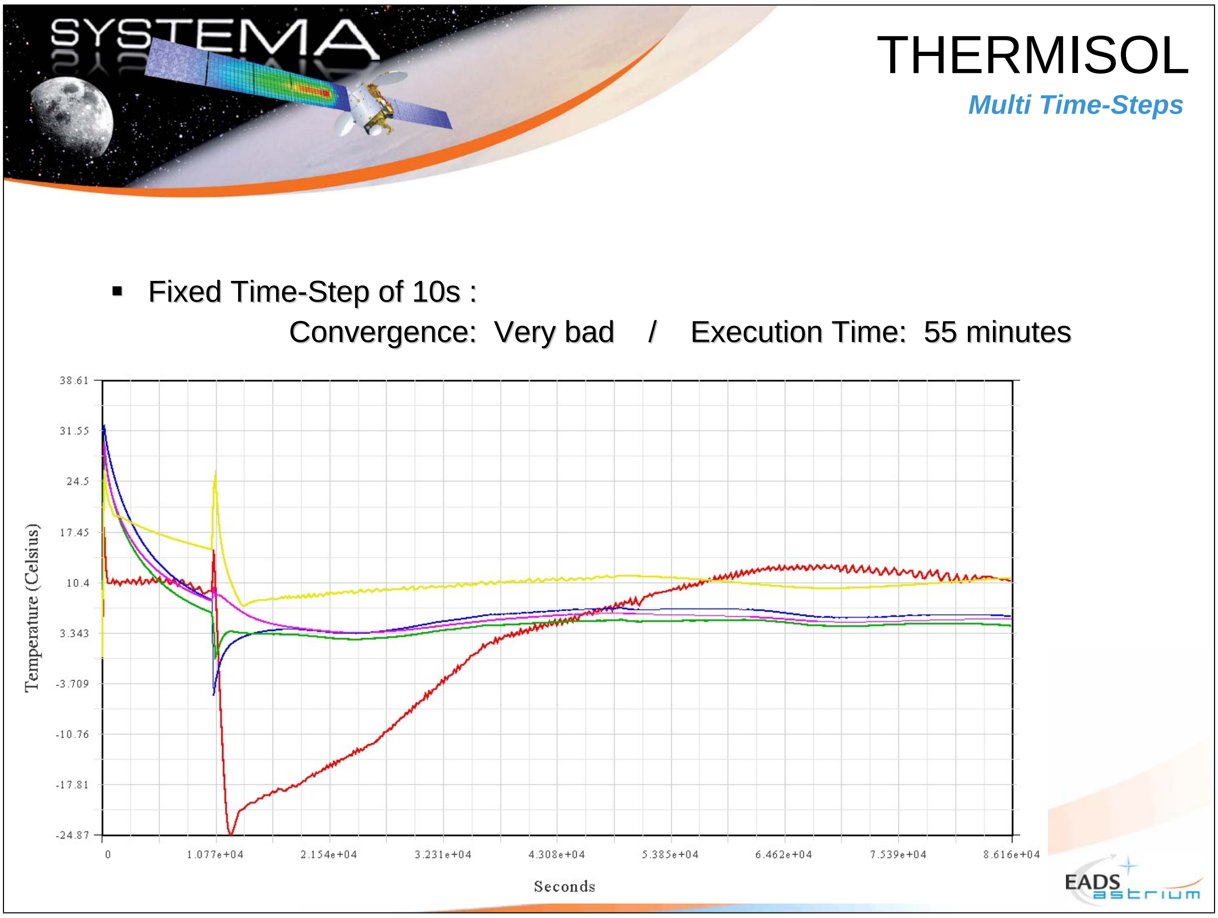
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Multi Time-Steps
▪ Fixed Time-Step of 10s :
Convergence: Very bad / Execution Time: 55 minutes
38.61
31.55
24.5
17.45
10.4
3.343
-3.709
-10.76
-17.81
-24.87
Temperature (Celsius)
0
1.077e+04
2.154e+04
3.231e+04
4.308e+04
5.385e+04
6.462e+04
7.539e+04
8.616e+04
Seconds
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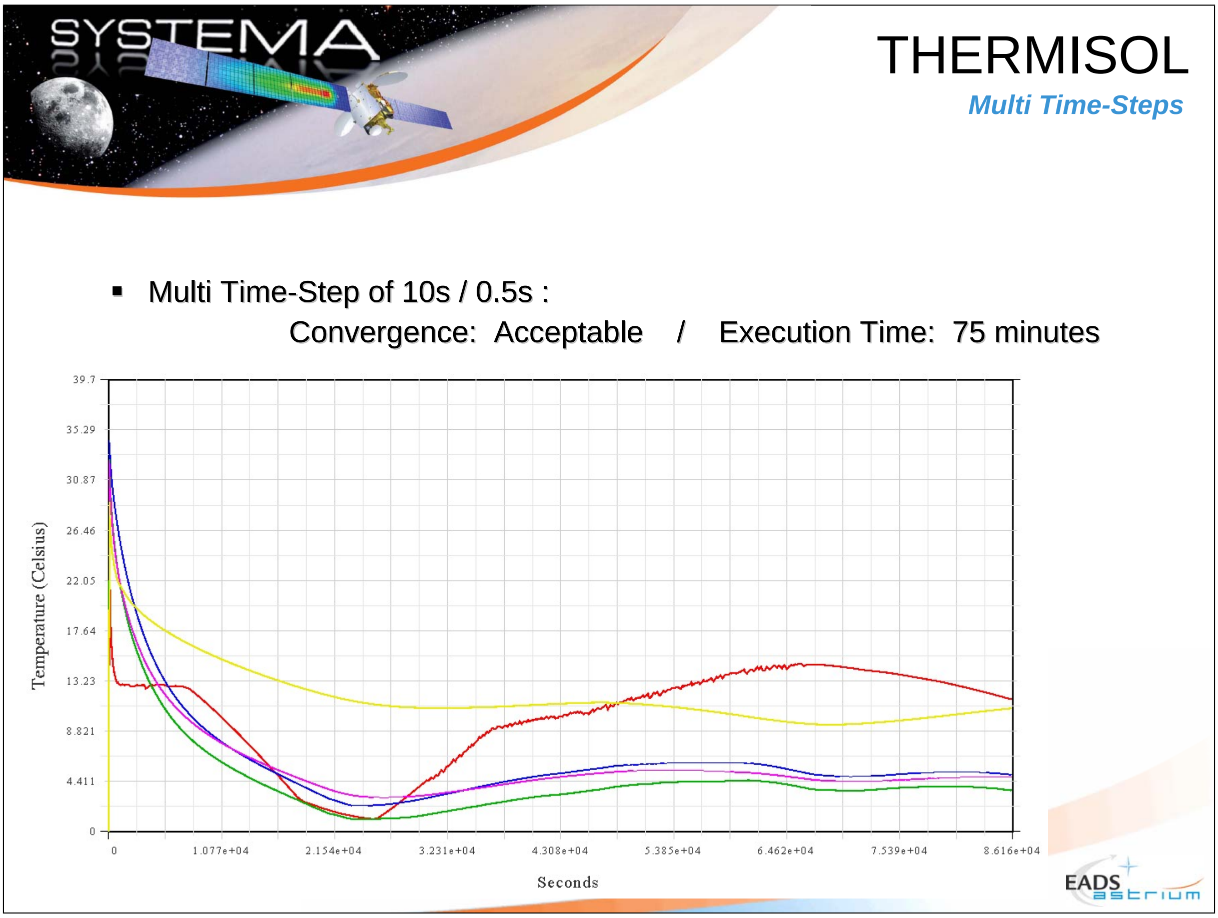
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Multi Time-Steps
▪ Multi Time-Step of 10s / 0.5s :
Convergence: Acceptable / Execution Time: 75 minutes
39.7
35.29
30.87
26.46
22.05
17.64
13.23
8.821
4.411
0
Temperature (Celsius)
0
1.077e+04
2.154e+04
3.231e+04
4.308e+04
5.385e+04
6.462e+04
7.539e+04
8.616e+04
Seconds
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Multi Time-Steps

Multi Time-Steps conclusions

- This algorithm has a completely automatic behavior
  - The prime time-step may be fixed or automatically adjusted
  - The sub-division of nodes is automatically computed
  - The sub-step is automatically computed
- The accuracy is well managed
  - Errors are systematically double-checked before and after any sub-step establishment
  - Users constraints (time-steps limitations) are taken into account
- Convergence / CPU Time : a good compromise
  - See the previous slides

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Multi Time-Steps

Next step: consolidation of the algorithm

- Minimize rejected computations
  - Automatic prime-step leads to a lot of rejected computations (which increases CPU time)
- Minimize the number of nodes to re-compute
  - All arithmetic nodes are systematically recomputed – need to find an alternative
- Validation of the convergence vs time compromise
  - More cases shall be studied to identify rules and possible improvements of the algorithm

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THERMISOL - Applications
THERMISOL has been used, validated and optimized on many projects. Thanks to 5 years of intense use in Astrium, convergence optimizations were finely tunes. Here are examples of the THERMISOL special features.
Automatic time-step adjustment
SCRANKAUTO provides an automatic time-step based on minimum and maximum error specifications.
control variables have been added in the paragraph $CONTROLS :
ERRMIN = 0.01; ERRMAX = 0.01;
The new solution is plotted in the following graph :
Automatic time-step adjustment