Appendix F

Guidelines for high accuracy thermal modelling. Experiences and results from ESA study: Improvement of thermal analysis accuracy

Ulrich Rauscher
(EADS Astrium, Germany)


Guidelines for High Accuracy Thermal Modelling, Experiences and Results from the ESA Study:
Improvement of Thermal Analysis Accuracy
Ulrich Rauscher, Astrium GmbH
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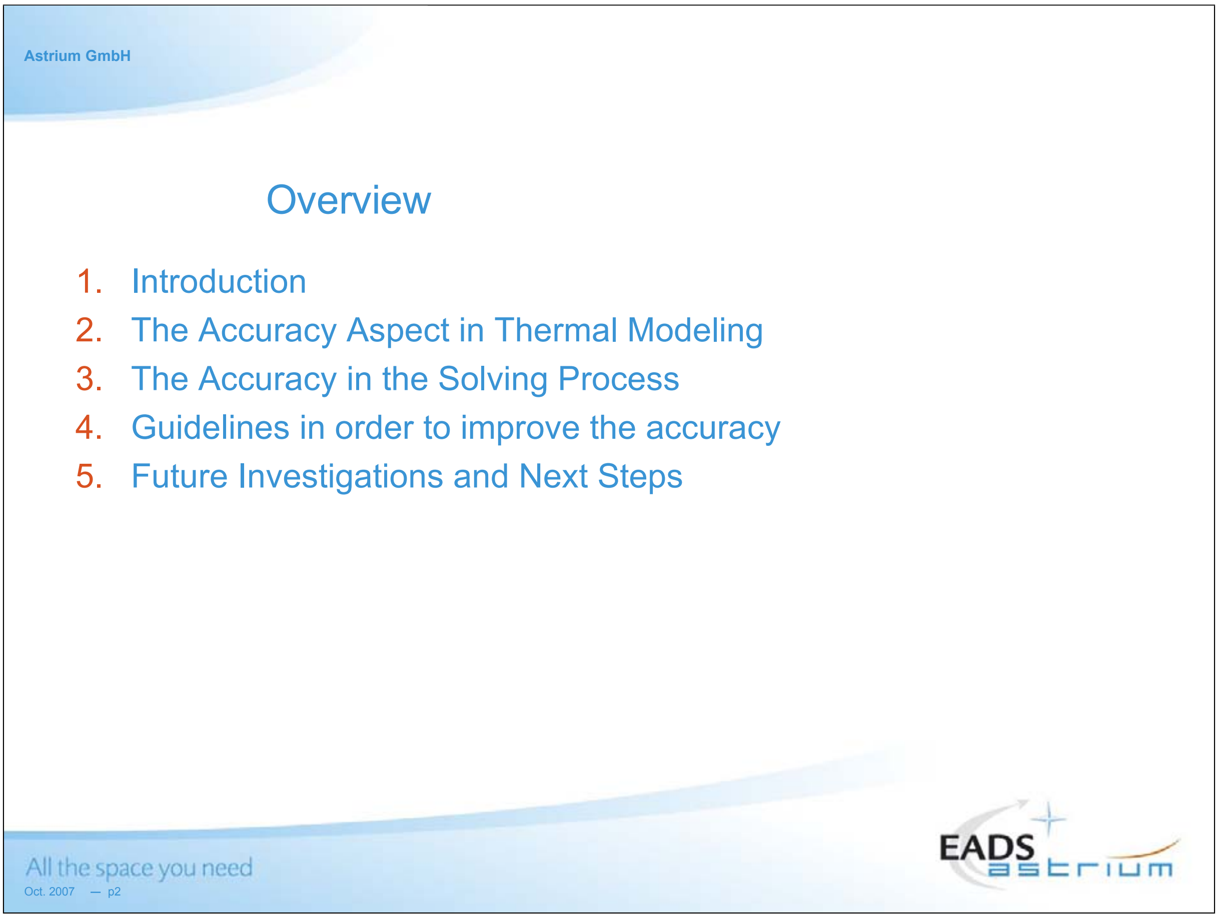
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Introduction

- Current and planned scientific Space Missions go constantly to higher accuracy of the instrument payload.
- This higher accuracy of the instruments causes high stability requirements for the instrument structures and instrument I/Fs.
- The stability of the instruments during in orbit operation is disturbed mainly by temperature changes caused by changing external and internal heat loads. These temperature changes induce thermo-elastic deformations of the structure, which influence the alignment of such an instrument structure and leads therefore to a degraded performance of the instrument.
- In order to minimize these effects, the sensible structures are de-coupled from the sources of disturbance by mechanical and thermal means whenever possible. Moreover thermo-stable structures are used to minimize the mechanical deformations.
- However, instruments have reached now a level of stability requirement, where de-coupling and mechanical design means come to border. The remaining influences are in the order of mK down to microK of variation in the structures, which leads to performance influencing deformations of the structures.

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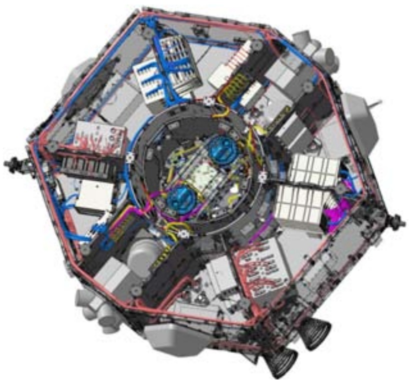
Introduction

Currently investigated missions, in which such phenomena play a role are the LISA pathfinder Mission and Gaia.

In Lisa pathfinder, (launch planned 2009) the sensitive component is a free flying mass in the center of the instrument, which is used for measuring gravitational wave effects. Disturbances are unwanted acceleration of this mass.



This basic requirement on acceleration is broken down to the different types of disturbance sources such as

- gravitational,
- (electro-)magnetic, etc.,
- Thermo-elastic induced accelerations
- and further subsystem and / or discipline specific requirements have been derived.

According to the acceleration requirement, which is expressed in the form of [quantity] / √ Hz the thermal requirement is formulated in the form [K / √ Hz]

The investigated ΔT at the sensors is in the range of 10^{-5} K

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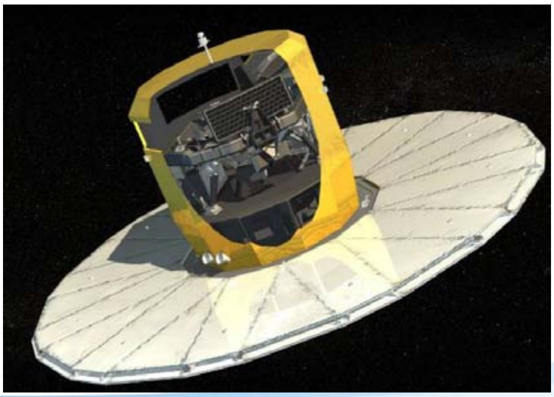
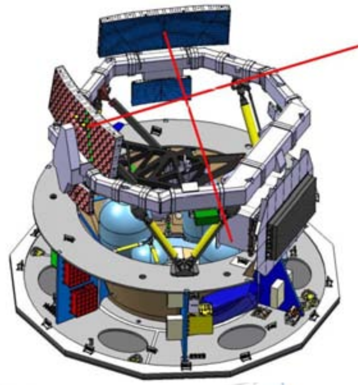
Introduction

- **Gaia** is an optical Telescope positioned at L2 with launch date begin of 2012, currently at end of Project Phase B. Gaia will provide positional, radial velocity and photometric measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars throughout our galaxy. The survey aims for completeness down to magnitude 20, with accuracies of 10 micro arcs second at magnitude 15
- The satellite consists of the SVM, a large deployable sun-shield (diameter 10 m), the telescope with its focal plane assembly mounted on a circular structure made from SiC and a protecting cover, the so-called thermal tent.
- The satellite is pointing with it's –X side to the sun with a solar aspect angle of 45° and performs a rotation about the x-axis in 6h in order to scan the starfield.





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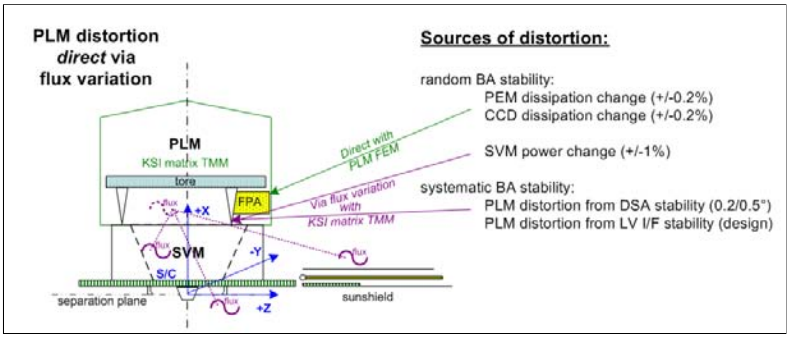
Introduction

The PLM structure is highly de-coupled from the SVM by insulating bipods to the SVM and high performance MLI at the structure itself and at the interface to the PLM enclosure.

The temperature fluctuations which are induced and which have to be analyzed are in the range of several micro K.

The resulting deformation leads to a variation of the basic angle between the 2 line of sights of the telescope in the order of several picorad.



The figure shows an example for the sources of distortion which act on the PLM. The sources can be differentiated in

- direct thermal variations in the telescope structure itself and
- temperature variations in the SVM structure, which cause a deformation of the mechanical interfaces of the PLM.

The distortion sources can moreover be separated in

- systematic distortions, which are coming e.g. from the geometrical configuration in conjunction with the rotation and the sun aspect angle of the satellite, and
- random effects like dissipation variation in components

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Introduction

From the temperature ranges it can be seen that major problem for such instruments is

the Analysis and the Verification of the Performance

in the spacecraft design process.

- Distortion sources and the transfer of these distortions can be verified only by scaling the distortions to higher levels.
- For a big structure like for example at Gaia this verification has to be done for each subsystem separately. With this testing only a characterization of the components can be achieved.
- The final end to end verification of the performance can then only be done with a final thermal and mechanical model.

In order to perform this design and verification process, the analysis tools must be able to reproduce the accuracy in temperature resolution as it will be during operation in Space, in order to validate the performance of the instrument and spacecraft.

For the current projects this means: Reproduction of temperature variations with the analysis tools in the order of 10^{-7} K at the Payload modules. On the other side of the heat transfer chain at the source of distortion the investigated temperature variations are in the range from several K up to 10K.

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The Accuracy Aspect in Thermal Modelling

Accuracy of a Thermal Model can be divided in 2 major field

3. Model Representation

Inaccurate modelling of the system is caused by:

- Discretization errors
- Material data inaccuracy
- Boundary conditions, dissipation assumptions
- For the linear coupling part the modelling uncertainty is still mainly caused by errors and inaccuracies in the, more or less, hand calculations and engineering judgement in the model.
- Simplified radiative modelling.

4. Solving Process

Inaccuracy in the solving process

- Heat imbalance errors
- Truncation and rounding errors in the calculation process, conversion between different number formats
- Influence of different solvers on the iteration process

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The Accuracy Aspect in Thermal Modelling

- Inaccurate modelling errors are user induced errors.
  - Errors from lack of information on configuration or degree of detail and operational boundary conditions in an early project phase.
  - Simplifications in order to keep model at controllable level of nodes and to limit computation time
  - Simplifications in modelling of material data
  - Coupling values which depend highly on configuration and workmanship (MLI)
  - Errors from worst case assumptions
  - The “human” factor: Undetected coupling calculation errors
  - These errors are not necessarily wrong calculations but are also normal steps in the evolution of a design
- Errors in numerical computation cannot be avoided to a certain degree and the user must be aware of them and must know the parameters and rules in the solvers to minimise them.

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The Accuracy in the Solving Process

In the ESA study : Improvement of Thermal Analysis Accuracy mainly the solver related accuracy aspects have been investigated, as in present projects the question arose whether the ESA tools ESARAD and ESATAN are able to resolve these small temperature variations with sufficient accuracy.

The investigations concentrated on:

- Mesh sizing
- ESATAN parameters:
  - Data handling in ESATAN
  - Solver performance steady state and transient solvers
- ESARAD parameters:
  - Number of Rays, Random seed
  - Calculation of External loads and the implementation in ESATAN
- Comparison to the Astrium solver THERMISOL (SYSTEMA)
- A first comparison to the heat transfer approach in the frequency domain

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The Accuracy in the Solving Process

Mesh Sizing

- Mesh sizing has been investigated at the elements of the heat transfer path between distortion source and the interface of the instrument.
- Mesh refinement is useful at locations next to interfaces or changing boundary conditions and at locations where changing temperatures for radiative exchange play an important role in the heat transfer path.
- The results in the study showed, that higher mesh refinement resulted in a damping of the temperature variation at the sensitive location (coming from a coarse model to finer meshing)
- Attention has to be paid to the geometrical representation of sensitive parts: The geometrical model must not be driven by the capabilities of the geometrical representation in the analysis Tool (ESARAD/THERMICA) but on the expected heat flow.
- In order to have useful mesh refinement a pre-analysis with a coarser model should be done, which is used to analyze the heat flow paths from distortion source to sensitive item. The mesh refinement can then concentrate on this path.
- Is a sufficient low heat imbalance and temperature relaxation reached in the model a sufficient mesh refinement can only be checked by variation of the mesh refinement at sensitive locations and comparison of the temperature variation or derived performance parameters of the instrument.

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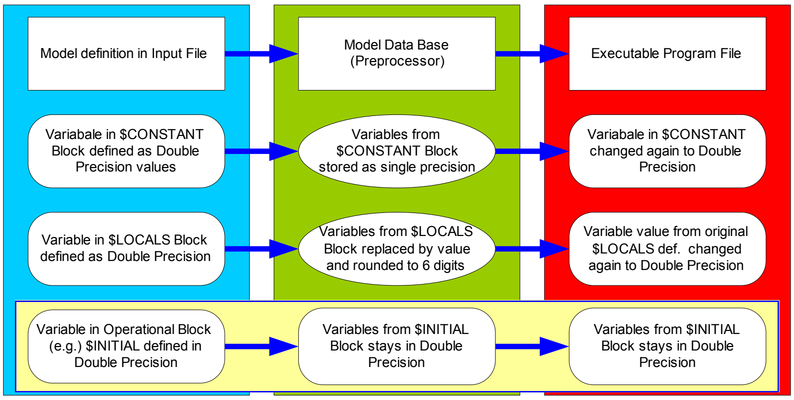
ESATAN related Investigations

- Data Handling in ESATAN: Defined Variable Format is changed in ESATAN from input file to executable file



- Values of LOCAL variables are rounded to 6 significant digits
- Value of LOCAL variable defined in D format appears in FORTRAN code in E format
- The only correct output is got for variables defined in operational blocks (e.g. $INITIAL)

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■ ESATAN Data Handling

Item	defined in	Input Value	Output (in Source Code or via $OUTPUTS)
user variable	$LOCALS	1.123456789	.112346E+01
user variable	$LOCALS	1.123456789D0	.112346E+01
user variable	$LOCALS	1.12345D0	.112345E+01
T	$NODES	123.56	.123559997559E+03
C	$NODES	521.2D0	.521200012207E+03
C	$NODES	751.23	.751229980469E+03
QI	$NODES	5.123D0	.512300014496E+01
QI	$NODES	1.123	.112300002575E+01
GL	$CONDUCTORS	3.1234	.312339997292E+01
GL	$CONDUCTORS	0.01234D0	.123399998993E-01
GR	$CONDUCTORS	0.1051	.105099998415E+00
GR	$CONDUCTORS	0.1051D0	.105099998415E+00
STEFAN	$CONSTANTS	5.6686D-8	.566860016704E-07
user variable	$CONSTANTS	1.23456E-08	.123456000978E-07
user variable	$CONSTANTS	1.23456D-08	.123456000978E-07
user variable	$INITIAL	1.23456E-08	.123456000978E-07
user variable	$INITIAL	1.23456D-08	.123456000000E-07
user variable	$INITIAL	1.23456	.123456001282E+01
array(1)	$ARRAYS	1.123456	.112345600128E+01
array(2)	$ARRAYS	2.123456D0	.212345600128E+01

- This means: If high accuracy is needed for a variable value the definition has to be done in an operational block. This includes also all data, which is normally defined in $NODES, $CONDUCTORS, $CONSTANTS and $ARRAY blocks, like the area, capacitance values, boundary temperatures, Dissipation.

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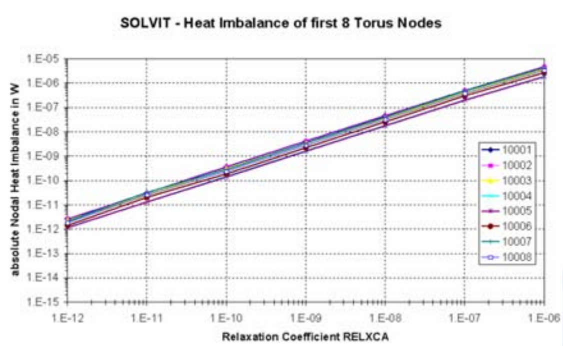
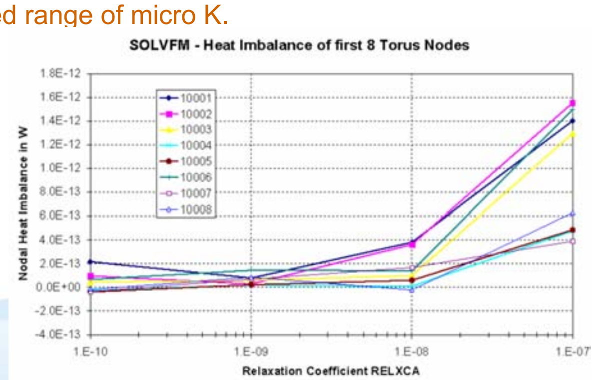
■ ESATAN Steady State Solvers SOLVIT and SOLVFM

Investigations in the present study showed:

- The matrix invert solver SOLVFM is faster and delivers lower heat imbalance at comparable relaxation coefficient as the successive point iteration solver SOLVIT.
- However: SOLVFM convergence is much more critical than SOLVIT.
- Therefore: If very low heat imbalance and relaxation coefficient is needed SOLVIT is more practical. Proposed way is: set relaxation coefficient to sufficient low value and check then heat imbalance values.
- The temperature level depends highly on reached heat imbalance and relaxation coefficient even in a relaxation range, which is much lower than the investigated temperature accuracy: Example GAIA: investigation in micro K range. RELXCA was varied between 10E-8 and 10E-12. All these calculations lead to different results in the considered range of micro K.





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The Accuracy in the Solving Process

- ### ESATAN Transient Solvers SLFWBK and SLCRNC
  - Both solvers are in principle identical solvers using the Crank Nicholson forward backward differencing method and a Newton Raphson iteration scheme for solving the equation system.
  - SLCRNC using always the actual temperatures during the iteration process for updating all temperature dependent variable values. SLFWBK uses for the whole iteration the temperature at the begin of the time step. > Advantage for SLCRNC if such couplings (e.g. MLI couplings, temp dependent material values) are used in the coupling definition
  - Main control parameters for the transient calculation is the relaxation coefficient RELXCA and the time step size DTIME. In order to guarantee convergence, the general rule exists to keep the time step at 95% of the time constant CSGMIN of the system. These parameters have been investigated in the present study.
  - Investigation concentrated hereby on the analysis of temperature fluctuations caused by a periodical variation at the boundary of the model (caused by external loads or dissipation variations

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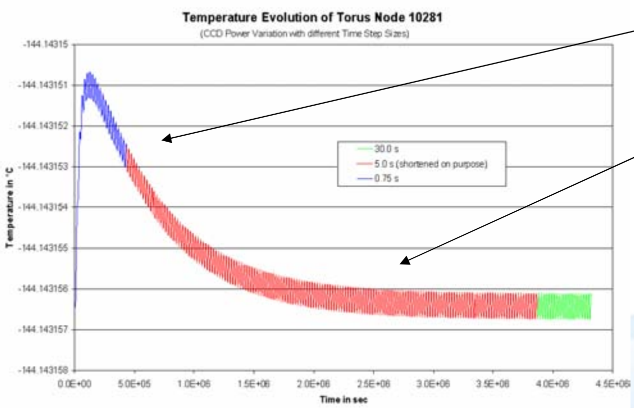
The Accuracy in the Solving Process

- ### ESATAN Transient Solvers SLFWBK and SLCRNC Results:
  - As expected both solvers are suitable for the high accuracy investigation
  - The results showed that not necessarily such a small time step has to be used as 95% of CSGMIN would mean.
  - Example GAIA: 95% of CSGMIN for the GAIA model means 0.75 sec at a period of 21600 sec. All results for other time steps up to 30 sec came to exactly the same results.
  - A steady state pre-calculation with very low heat in-balance is very important for an effective transient analysis in order to avoid drifting of overall temperature level

Each period in the graph is 6 h



Problem of Drift in the Transient Calculation leads to long simulation time !

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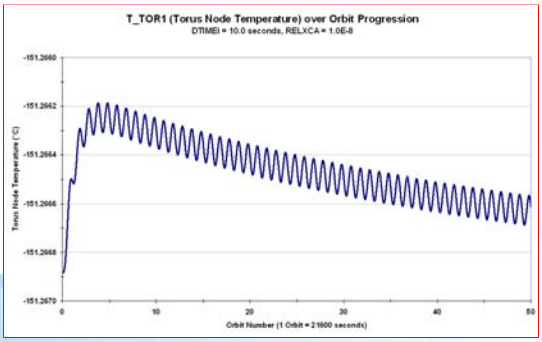
ESATAN Transient Solvers SLFWBK and SLCRNC Results DRIFTING Problem:

- For the drifting of the overall temperature level at sensitive locations 2 different effects could be seen in the analyses
  1. Drift in transient calculation which can be deleted by sufficient low relaxation coefficient
     - Main reason is here the difference between heat imbalance in steady state and final balance in transient.
  2. Drift which could not be removed
     - For the cases where variation was induced by external heat flux variation the drifting could not be removed.
- However: The transient calculation showed very stable behavior in the temperature answer at sensitive locations. The drift was superimposed to this variation at considered period. -> Therefore a De-Trending of the results has been performed in a region of the result, where constant drifting could be seen.



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ESATAN Transient Solvers SLFWBK and SLCRNC Results Implementation of External Loads

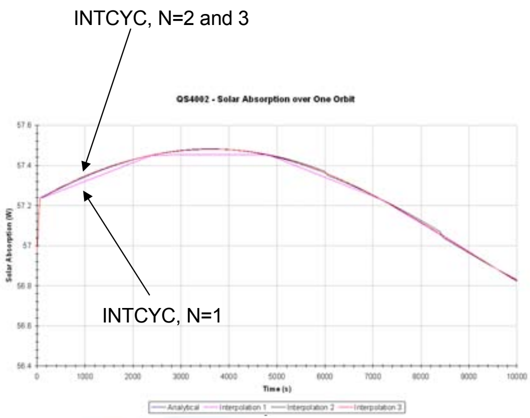
- With Respect to previous Problem the implementation of the External Loads, received by ESARAD have been investigated.
- Result here is that interpolation routines in ESATAN delivers sufficient possibilities to adapt the external loads interpolation, depending on
  - Sudden changes in illumination
  - Multi-reflections

By adapting:
- Angle gap and Eclipse offset parameter in ESARAD
- Number of independent variable pairs in the cyclic interpolation routine INTCYC

Shadowing of special parts can not be automatically detected but may not be neglected.

Such effects have to be overcome by analytical investigations of such points in time or a sufficient small number for the angle gap.

In the example of GAIA, where sun comes only from the –X side of the satellite and the variation is induced by the rotation of the satellite no difference could be seen in the results between the interpolation degree between 1 to 3 and an angle gap of 40°
(no eclipse)



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The Accuracy in the Solving Process

- ### ESARAD Aspects
  - For the ESARAD modeling mainly the points are important, which have been discussed for the meshing of the item an the loads implementation above:
    - Nodal breakdown shall be oriented on heat flow path
    - Calculation points have to be critically assessed in order to calculate really at extreme points of irradiation and changes of irradiation
  - Number of Rays for REF calculation / Random Seed for REF calculation
    - Investigation in number of rays and the check on consistency with different numbers for the random seed showed, that only very high number of rays of > 50000 leads to such a confidence in the REF, that also different random seed values lead to the same temperature results at the sensitive locations of high accuracy models.
    - In the GAIA example different random seed values at 20000 rays lead to a difference in temperature of up to 0.15 K at the sensitive parts. For 50000 rays this value goes down to 0.015K One can see here again that absolute temperatures cannot be investigated with high accuracy.
    - It is clear that higher number of rays means a strong increase in computation time.

Gaia example

Number of rays	Angle gap (°)	CPU time (mins)
5,000	10	34
15,000	10	67
15,000	15	67
15,000	20	59
20,000	5	174
20,000	10	114
20,000	15	85
20,000	20	75
20,000	30	64
20,000	40	58
50,000	10	259
100,000	10	500
200,000	20	698

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The Accuracy in the Solving Process

- ### Comparison to THERMISOL
  - The comparison to the Astrium Solver THERMISOL V4.0.34 was done with 2 load cases for different distortion sources. The solver is in principle able to read ESATAN input files with small changes in variable definition and solver routines.
  - THERMISOL has not the problem with the variable data format conversion as the solver is able to handle double precision data at every stage from input file to executable program.
  - The Steady State solver performance of THERMISOL reaches lower heat imbalance at same relaxation coefficient compared to ESATAN. Therefore the drifting in transient disappeared at higher relaxation coefficient than in ESATAN. For the case, where in ESATAN the drifting could not be removed, THERMISOL showed the same behavior.
  - Therefore THERMISOL is an alternative solver, which is useful for high accuracy problems. Any redefinition of variables or constants on operational blocks is not necessary.

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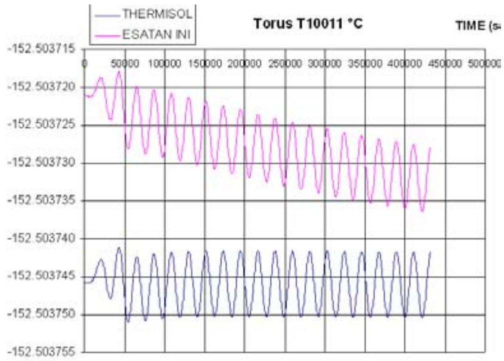
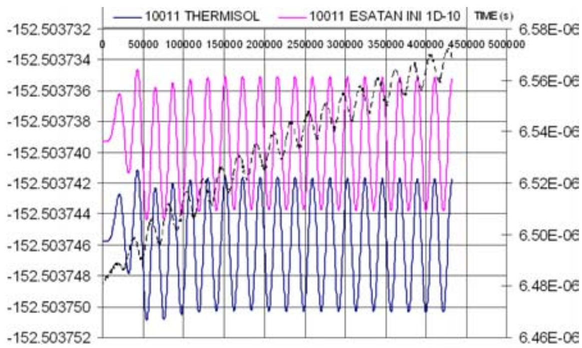
The Accuracy in the Solving Process

- Comparison to THERMISOL

ESATAN vs THERMISOL at RELXCA = 1.0E-8



ESATAN vs THERMISOL at RELXCA = 1.0E-10



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Guidelines in order to Improve the Accuracy

- MESH Size: Perform coarse model analysis for identification of heat flow paths in the investigated item then perform mesh refinement along heat flow path. Check result with heat imbalance /Relaxation of model and change of performance.
- ESATAN data handling: Define all sensitive values in Double Precision in $INITIAL in order to guarantee same value in Input and Executable program file, adapt output format to a format where relevant changes can sufficiently be resolved.
- ESATAN Solvers Steady State
  - SOLVIT and SOLVFM can both be used for high accuracy analysis
  - SOLVFM is faster and achieves small heat imbalances at larger RELXCA values than SOLVIT, but requires a DAMPT value less than 1.0 (e.g. 0.5)
  - For an investigated temperature resolution of 10 µK it is necessary to achieve very small heat imbalances (i.e. to work with RELXCA values as low as possible) in order to avoid small temperature drifting of the transient solution to a final temperature level.

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Guidelines in order to Improve the Accuracy

- ESATAN Solvers Transient
  - The solvers showed very stable results for temperature variations in the range of 10^{-6}K.
  - SLCRNC is the recommended solver because of the update of temperature dependent variables during the iteration process
  - Time step size must not necessarily be 0.95 x CSGMIN. With respect to calculation time it has been found that the optimum is at a value, which is about 10 times larger. In order to optimize this the loop count in the *.MON file can be checked.
  - The drifting of the transient solution can be diminished by minimizing the heat flux balance in the steady state pre-calculation. If this is not possible a de-trending of the results have to be used in a time period, where a constant drift of the results can be clearly identified.

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Guidelines in order to Improve the Accuracy

- ESARAD Parameters
  - Modeling and Mesh density shall be oriented at heat flow in the model. Minimum one loop has to be expected for optimization of the mesh.
  - In order to achieve stable REF calculation results the number of rays has to be so big, that different random seed values lead not to a significant temperature change in the considered range of analyzed temperature. Ray number > 50000 is proposed.
  - Angle gap and additional calculation points shall consider all expected extremes and sudden changes in illumination of an investigated item.

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Future Investigations and Next Steps

- Comparison to other Approach: Investigation in the Frequency Domain with a Heat Transfer Function
  - For the Study a comparison has also be performed between ESATAN results to a linearised version of the ESATAN model. This model could then be treated in MATLAB with an Ordinary Differential Equation Solver (ODE) From this model a heat transfer function could be evaluated, which was used for analysis in the frequency domain, based on a steady state temperature distribution calculated with ESATAN.
  - With the heat transfer function it is possible to get information in the form of

    GAIN = Output / Input

    The Input is the amplitude of variation for a parameter or a set of parameters of the model. The output is the amplitude of the variation of temperatures at a set of nodes. The gain is the amplification /damping between Input and Output
  - First comparison runs with the Gaia model (with about 1900 nodes) showed good compliance between the ODE solver results in the time domain and the HTF in the frequency domain but big differences to the ESATAN results. (ESATAN temperature variation was about factor 4 to 10 larger)
  - It is planned to continue the investigation in this area and to identify the differences between ESATAN results and HTF results. For this validity of the linearization of the model, especially at locations with bigger temperature changes, has to be checked

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