Appendix U

Calculation of Optimal Solar Array Steering Laws for Temperature Critical Missions

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Abstract

For the Solar Orbiter and Bepi Colombo missions it is required to steer the solar arrays of the Spacecrafts in such a way that sensitive parts (like solar cells) do not exceed a maximum temperature, while keeping the electric power output as high as possible. This is usually done by adapting the sun aspect angle of the array in dependency of the actual heat input from the sun and if present from the planet.
In this presentation a fast and accurate method is discussed in which the optimized solar array rotation angles at each orbit position are calculated by a modified iteration-scheme with a detailed solar array thermal model.
With the developed iteration scheme it became possible to limit the total number of time consuming calculations of the time dependent radiation exchange factors to a minimum without losing the stability of the scheme. A further decrease of computational time was achieved by splitting the radiation calculation into sub-processes. Those have been distributed among the available computers, leading to an efficient parallelization of the radiation calculations.

Calculation of Optimal Solar Array Steering Laws for Temperature Critical Missions

Solar Array Design
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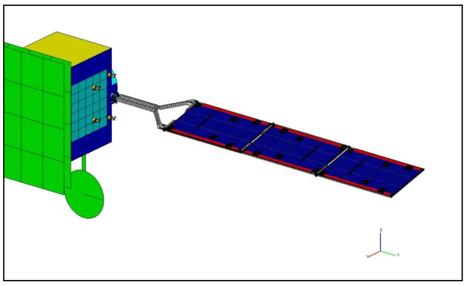
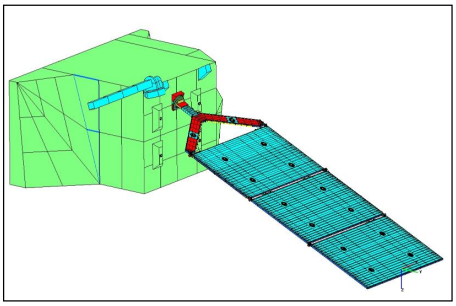
High temperature solar arrays

- Solar Orbiter



- Mercury Planetary Orbiter of the Bepi Colombo Mission



- Thermal / Geometrical Models
  - Modelled with ESATAN-TMS
  - Detailed (~5000 Nodes)
  - Time dependent radiation exchange factors → High computation time

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Challenges

- Both solar arrays are exposed to high solar radiant flux
  - Bepi Colombo (MPO): S=14.5kW/m²
  - Solar Orbiter: S=17.5kW/m²
- Bepi Colombo MPO Orbiter
  - Additional Planetary IR & Albedo loads from Mercury
- Components of the solar array must not exceed certain temperature limits
  - Adhesives, Carbon Fibre Structure, wires/harness
  - Solar cells
- Temperature control
  - Only passive thermal control
  - Coatings / mirrors (OSR) / SSM foils / shields
  - Sun aspect angle by rotation of the solar array

Consequence:
At each orbit position the solar array rotation angle has to be steered to keep the temperature below a certain limit (BILD)
→Steering law
→Inverse problem

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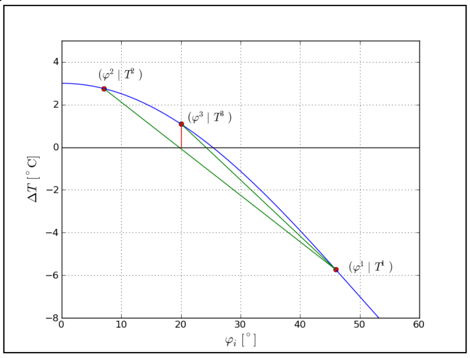
Classical solution method

Let $\{\phi_i\}$ the vector of the solar array rotation angles around an orbit
After GMM/TMM calculation that leads to a vector $\{T_i\}$
Goal: $T_i = T_{Target}$ for (almost) all orbit positions

→For each orbit position „i“ the roots of $T_i(\phi_i) - T_{Target} = 0$ must be found
→Performed by „regula-falsi“ or false-position method
→Better (faster): Anderson-Björk scheme



Procedure:

- First initial condition: edge on solar array → coldest possible temperature
- Second initial condition: face on solar array→ hottest possible temperature
- For each orbit position:
- Find approximate solar array rotation angle for which target temperature is reached
- Recalculate GMM/TMM with new set of sun aspect angles
- Repeat this iteration until maximum temperature of e.g. solar cells are within T_{Target} +/- 1.0°C

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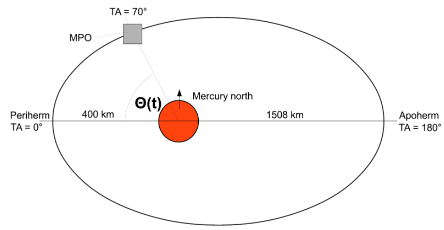
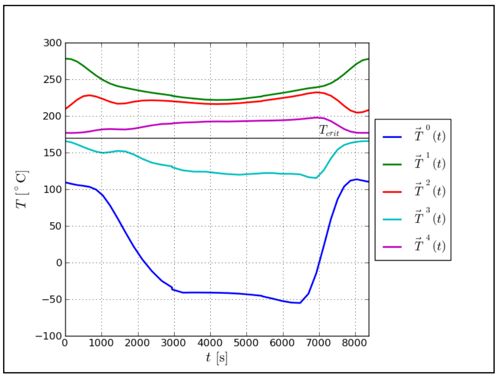
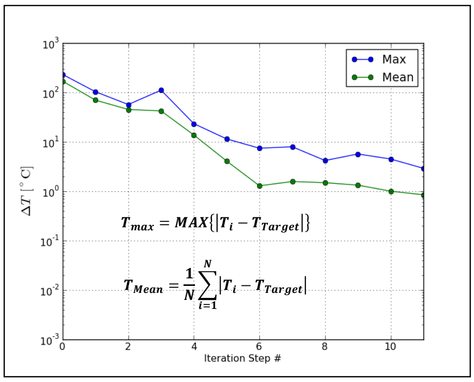
Example:

Mercury Planetary Orbiter







+ The iteration is stable
+ It converges, but there are cases where not
+ Easy to implement

- Slow (many iterations needed)
- Each iteration means one GMM/TMM calculation
- No complete convergence

→ Improvements necessary

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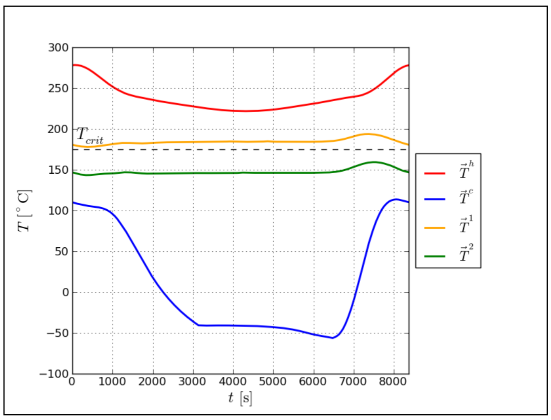
First Improvement

- Initial conditions

Start with initial conditions closer to the solution in order to lower the number of iterations needed

Usage of an „analytical“ model

- Thin plate approximation
- Neglecting reflections from the spacecraft



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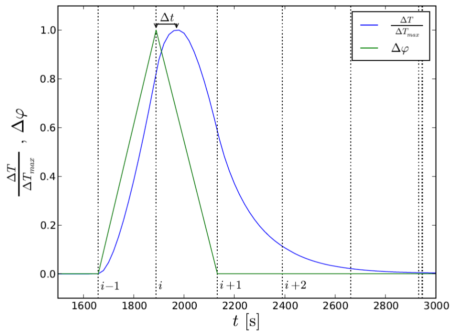
Second improvement I

- Acceleration of convergence & increase stability

If the thermal timescale τ of the solar array > t_{i+1}–t_i of the GMM time discretization

→classical method can break down or converges slowly

→Change of solar array rotation angle at position „i“ has an influence on the temperature at position „i-1, i, i+1, i+2,…“



Responese function can be calculated by simulation or by analytical solution of the transient „linearized“ heat equation

→False-position method doesn‘t work anymore

→Multi-dimensional root-finding method required

→Newton-scheme: $\vec{\varphi}^{(k+1)} = \vec{\varphi}^{(k)} - J^{-1} \cdot \vec{T}(\vec{\varphi}^{(k)})$

→With the yet unknown Jacobi-matrix **J**

$$J_{ij} = \frac{\partial T_i}{\partial \varphi_j}$$

Physical meaning: change of temperature of position „i“ due to the change of angle at position „j“

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Second improvement II

- The calculation of the full Jacobi-matrix J can not be achieved in suitable time
- Approximation & assumptions has to be made
  - Key assumption: The shape of the temperature response at position „i“ due to the change of angle at position „j“ is independent from the position. It only depends on the relative distance „i-j“
  - Information available from unit response
  - Approximation of the Jacobian by:

$$J_{ij} = \frac{\partial T_i}{\partial \varphi_j} \sim c_{j-i} \frac{\Delta T_i}{\Delta \varphi_j}$$

$$\boldsymbol{J} = diag(\Delta\vec{T})\boldsymbol{C_T} diag(\Delta\vec{\varphi})$$

<u>Benefits:</u>
→Transient effects are covered
→At each orbit position more informations (from other positions) are used to calculate the roots→ faster
→Higher stability of the scheme

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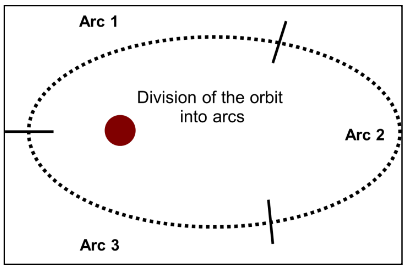
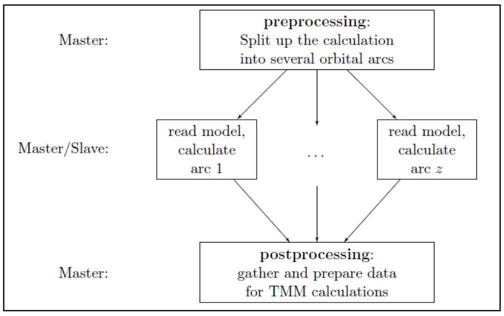
Third improvement

- The most effective measure to accelerate the calculation is achieved by the **parallelization** of the calculation of the view factors / heat loads (GMM)





- Method:
- Seperate the orbit into „N“ sub-arcs
- Distribute the calculation of the sub-arcs among the available computers
- Automated by the help of Python-scripts
- For the GMM $t_{calc} \sim 1/(N_{computers} * N_{cores})$
  - At the moment: 4 Computers with 4 cores each→ acceleration by a factor of 16
  - But: 16 ESATAN licenses needed

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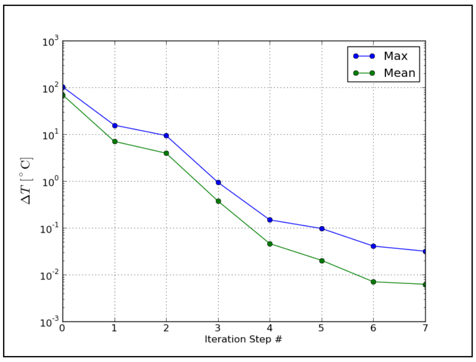
Putting all together / Summary



After using all the improvements

→ After 4 iterations an accuarcy of +/-0.2K is achieved (Old: after 10 iterations: +/- 3K)

→ Iteration is stable

→ Calculation time

- → Now: 7h for complete generation of a steering law
- → Without improvements: 5-7 days

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