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18th European Workshop on

Thermal and ECLS Software

ESTEC, Noordwijk, The Netherlands

5-6 October 2004

(Cover image courtesy of Alstom)

ABSTRACT

This document contains the minutes of the 18th European Thermal and ECLS Software Workshop held at ESTEC, Noordwijk, The Netherlands on the 5th and 6th October 20034 It is intended to reflect all of the additional comments and questions of the participants. In this way, progress (past and future) can be monitored and the views of the user community represented. The final schedule for the Workshop can be found after the table of contents. The list of participants appears as the final appendix. The other appendices consist of copies of the viewgraphs used in each presentation and related documents.

Table 1: Printing History

Release	Date of issue	Reason
1.0	2004-12-01	Document creation
1.1	2005-01-24	Draft for internal comment
1.2	2005-02-11	Initial release to participants

The organisers would like to dedicate this workshop and the proceedings to Charles Stroom, who retired in 2004 from his role as head of the Thermal Analysis and Verification Section after thirty one years with the European Space Agency. Charles was the founder of the Workshop, organised many of the first seventeen, and was responsible for establishing the Workshop as the premier meeting place for the European space thermal analysis community.

Appendices

Final Programme

18th European Thermal and ECLS Software Workshop
ESTEC, Noordwijk, The Netherlands
5th-6th October 2004

Tuesday 5th October 2004

09:00	Registration
10:00	Welcome And Introduction Harrie Rooijackers, ESA/ESTEC, Netherlands Opening Olivier Pin, ESA/ESTEC, Netherlands
10:20	Finite Element Based Analysis Tool for Re-entry Vehicle TPS Ablators Tom van Eekelen, SAMTEC HQ, Belgium
10:45	EcosimPro Current Status and Future Improvements Ramón Pérez Vara, Empresarios Agrupados, Spain
11:10	Capabilities of the Therm-OSS Tool Matthias Haupt, Technical University Braunschweig, Germany
11:35	Coffee break
11:50	ESATAN, FHTS, ThermXL and ESARAD - Product Status Chris Kirtley, ALSTOM, UK
12:15	Feasibility of using a Stochastic Approach for Space Thermal Analysis Matteo Gorlani, Blue Group, Italy
13:00	Lunch
14:00	Automates Thermal Model Reduction for Telecom Spacecraft Walls Frédéric Jouffroy, EADS ASTRIUM, France
14:25	Advances in the Thermal Analysis in the frequency domain Algorithms development, integrated software tools and post processing Marco Molina, Carlo Gavazzi Space, Italy
14:50	LHP Transient Modelling using EcosimPro Carmen Gregori, Empresarios Agrupados, Space
15:15	Designing for mK/µK revisited Valter Perotto, Alenia Spazio, Italy
15:30	Coffee break
16:00	GAETAN Usage at Alcatel Space Karine Caire, Alcatel Space, France
16:25	Thermal Analysis of the Mechanical Structure of the Solar Telescope GREGOR Thomas Bornkessel, Technical University Darmstadt, Germany
16:50	Modelling of Cryocoolers Martin Linder, ESA/ESTEC, Netherlands
17:30	Social Gathering
20:00	Dinner

Wednesday 6th October 2004

09:00	Optimization of a Direct Condensing LHP Radiator with the Improved ALGOCAP Reinhard Schlitt, OHB System AG, Germany
09:25	Innovations in Thermica Marc Jacquiau, Astrium, France
09:50	Thermal and Radiative Modelling Julian Thomas, ALSTOM, UK
10:15	A Thermal Network Viewer Henri Brouquet, ALSTOM, UK
10:40	Coffee break
10:55	Modelling the Martian Surface Thermal Environment with ESATAN and ESARAD Bryan Shaughnessy, Rutherford Appleton Laboratory, UK
11:20	Data Exchange between CFD and ESATAN in the case of Natural Convection Christian Wendt, EADS Space Transportation, Germany
11:45	Development of an Interface Software for Patran/Thermal and ESARAD Cosmas Heller, Astrium Friedrichshafen, Germany
12:10	New version of BAGHERA STEP viewer based on open standard technologies Eric Lebegue, CSTB/GRAITEC, France
12:35	Interface between STEP-TAS format and Alcatel Space's CIGAL2 application (which works together with the CORATHERM solver) Christian Caillet, Open Cascade, France
13:00	Lunch
14:00	STEP-TAS and TASverter from the user's point of view David Alsina Orra, ESA/ESTEC, Netherlands
14:25	STEP-TAS and TASverter from the software developer's point of view Hans Peter de Koning, ESA/ESTEC, Netherlands
15:00	Workshop Close

1. Tuesday 5th October - Morning Session

1.1. Welcome and Introduction

H. Rooijackers (ESA) welcomed everyone to the workshop. He explained that the workshop was an opportunity for all three areas of the European space thermal community, namely ESA, the tool developers and the tool users, to exchange information and feedback. (See Appendix A)

O. Pin (ESA) introduced himself as the new head of the Thermal Analysis and Verification section at ESA, replacing Charles Stroom, who had retired earlier in the year, and who could be regarded as the father of some major European tools. It was he who had pushed for independent tools in Europe, had initiated many activities during his 31 years at ESA, and who had also founded the Thermal and ECLS workshop. For this reason, the staff of the Thermal Analysis and Verification section wanted to dedicate this workshop to him.

O. Pin emphasised that there would be no discussion of harmonisation during the workshop because ESA would be establishing the policy with the Harmonisation Steering Board in a meeting immediately after the workshop. All discussions on harmonisation policy would take place there.

1.2. Finite Element Based Analysis Tool for Re-entry Vehicle TPS Ablators

T. van Eekelen (Samtech) explained the basics of heat protection systems based on ablation processes, and described the development of a software tool to model these processes. (See Appendix B)

H.P. de Koning (ESA) asked about the validation of the results, and how many parameters needed to be changed between runs. Did they start with measured properties, or did they need correlation with test results? T. van Eekelen said that EADS did the actual work, and not Samtech, so it was difficult to know exactly. One group would do tests, the other analysis. It could take months to qualify the material properties and select the appropriate values.

1.3. EcosimPro Current Status and Future Improvements

R. Pérez (Empresarios Agrupados) presented recent developments of EcosimPro, including the replacement of the Smartsketch proprietary tool with their own code. (See Appendix C)

H. Rooijackers (ESA) understood that the new version would be available on Windows, Linux and Unix platforms, and asked whether it would be possible to exchange data between Windows and Linux versions. R. Pérez said that they were using ASCII for the data files, and the diagrams were encoded in ASCII XML, so there should be no problem in exchanging data across platforms.

1.4. Capabilities of the Therm-OSS Tool

M. Haupt (TU-Braunschweig) described the current status of Therm-OSS, a tool to demonstrate the use of open source software components to handle the full thermal analysis chain from mission specification, radiative analysis of simple geometrical models, the solution of the thermal mathematical model and even visualisation and post-processing of results. (See Appendix D)

M. Molina (Carlo Gavazzi Space) said that the end user interest in open source software was driven by the learning time. He asked for an estimate of the learning time required before an ordinary thermal user would be able to work with Therm-OSS. M. Haupt said that ESATAN was a relatively simple solver and that Therm-OSS was a more complex system, but with an architecture which allowed more flexibility and functionality than ESATAN and ESARAD. He felt that it would be necessary to divide the target users into developers and end-users and ask what the end-users expect. Therm-OSS had been designed for someone in between the full software developer and the thermal end-user. If Therm-OSS allowed the end-user to build the geometry and then push a button to get the results, it was not difficult to hide the details.

M. Molina asked how often new versions of the open source components were released, and whether these versions were related to debugging or development. M. Haupt said that some releases were intended to eliminate errors, but others were for development purposes. For example, a recent release of the k3d software had some changes to the architecture.

C. Heller (EADS) asked about the verification of the tool. M. Haupt said that the calculation with the lumped parameter solver had been checked against NASTRAN. The linear and non-linear solver and the OHB example had been checked against ESATAN. C. Heller asked about the radiative calculations. M. Haupt said that Therm-OSS had used TOPIC, which had a lot of restrictions, but an investigation was in progress into the use of RenderPak which would handle irradiance, etc.

H.P. de Koning (ESA) emphasised that Therm-OSS had been intended as a study and exploration. The main interest had been to discover what components were available to the software engineer developing a tool rather than the thermal engineer, and to provide techniques and a possible architecture for future development. M. Haupt said that after gaining experience during the year’s development he would like to rewrite everything. The architecture was fine, but some details of the implementation could be better.

1.5. ESATAN, FHTS, ThermXL and ESARAD - Product Status

C. Kirtley (ALSTOM) described recent developments across the range of ALSTOM tools and the expected release schedule. (See Appendix E)

H. Rooijackers (ESA) had noted that the oct-tree handling introduced into ESARAD had resulted in a factor of three speed improvements for some models, and asked whether there were any guidelines on expected speed improvements for particular types of models. C. Kirtley said that the speed improvement depended on the actual bounding box and the geometry. If the geometry included a large projection, such as an antenna, then the oct-tree handling allowed a coarser mesh to be used where there were no shells, leading to better performance. The speed improvement varied depending on the model, but so far had been between 2 and 3 times as fast on average, possibly even 4.

1.6. Feasibility of using a Stochastic Approach for Space Thermal Analysis

M. Gorlani (Blue Group) presented details of a study into the use of stochastic techniques for space thermal analysis. (See Appendix F)

M. Molina (Carlo Gavazzi Space) said that the optimization of the algorithms to use stochastic methods looked promising. He had noted the remark on the Phase-A study described, and wondered why the standard approach had failed. M. Gorlani said that the database used had not been tailored for EUSO and many configuration problems had not been considered, such as the exact configuration of the ISS. The stochastic method had taken these configuration options into account.

M. Molina said that he was suspicious of the effect of the roll angle. He asked how the thermal engineer should approach the conflict between the -15 and +15 degrees of roll angle. V. Perotto (Alenia) said that Alenia had made the initial database, but it had not been tailored for EUSO. The database had been created by running thousands of test cases involving the ISS with cubes attached in various locations to estimate the fluxes. There had been no cube which corresponded with EUSO, so the database was inadequate for EUSO. Even so thanks to the stochastic methods, they had still been able to find the worst cases for EUSO. However, he noted that it would not always be possible to have such a detailed database available for Phase-A studies.

M. Molina noted that in Phase-A studies it might be necessary to scan all combinations of beta angles, etc. How did the engineer know which optimization tool to select? M. Gorlani said that this functionality was already embedded in ST-ORM[1], which had been one reason why ST-ORM had been selected. The user could run a series of Monte Carlo simulations to calculate the response of the system over a range of values, but then needed to set up the physical runs.

O. Pin (ESA) said that this [study of Stochastic Methods] activity fitted with the ESA strategy to develop methodologies and algorithms to improve thermal analysis rather than develop software. He felt that this was a better use of funding for the overall benefit of all thermal engineers in the ESA states in general. He emphasised the fact that all thermal engineers in the ESA states had a right to benefit from ESA funded studies and he invited people to download the report once it was made available.

C. Kirtley (ALSTOM) noted that there had been 60 runs with 15 shots. What did this mean? Did it mean 15 parallel processes? M. Gorlani said that they were able to run 4 analysis runs in parallel, and this was independent of the number of shots. The example had shown different Monte Carlo simulations, each one with 15 shots, but it could have been run using only 5 shots.

C. Kirtley said that ALSTOM would be interested in supporting stochastic methods for the benefit of users if that is what users wanted. The question was: what licence scheme was needed

1. ST-ORM is the **St**ochastic **O**ptimization and **R**obustness **M**anagement tool from EASi in Germany

by ST-ORM to support it? M. Gorlani said that it depended only on the CPU. ST-ORM didn't delay the CPU, so 15 licences allows 15 simultaneous runs. HB asked how many licences would be required for 100 analyses. M. Gorlani said that they had used 4 or 5 CPUs at a time, so they had only required 4 or 5 licences.

P. Sahlin (EASi Engineering) said that they were interested in working with the space community and had been following the evaluation with interest. They had started cooperation with the software developers and had a joint proposition for ALSTOM and Astrium on the rapid introduction of stochastic methods into their tools. The first step, during the autumn and winter would allow the evaluation of ST-ORM and to overcome any initial problems. They would provide access and ST-ORM licences for ESARAD, ESATAN and Thermica and would run workshops on how to work with ST-ORM, the theory behind it, etc. The first result will be a joint workshop with ALSTOM in Leicester at the end of October. A similar workshop would be held with Astrium, but no date had been arranged. The second step would be to agree on a joint pricing and licensing scheme with each software developer.

2. Tuesday 5th October - Afternoon Session

2.1. Automated Thermal Model Reduction for Telecom S/C Walls

F. Jouffroy (EADS) described the algorithms and use of a tool, developed over ten years, for providing fast computation of results using a reduced thermal model generated from the highly detailed thermal model of a spacecraft required for other types of analysis. (See Appendix G)

S. Appel (ESA) said that the slide had shown a nice set of equations relating to the reduced system, but he didn't understand the load vector P(i). Did this depend on the temperature of the eliminated nodes? F. Jouffroy said that the condensed nodes were introduced into the matrix and the whole system was solved, but then only a subset of the couplings were extracted. S. Appel said that the reduced model power vector included the radiative fluxes from the eliminated nodes and therefore it was dependent on the temperature of the nodes which had been taken out. F. Jouffroy admitted that there was a trick in the method which allowed it to be independent of the eliminated condensed nodes. S. Appel felt that not only the condensed nodes, but also the detailed nodes needed to be taken into account, but it would be better to discuss this separately later.

2.2. Advances in Thermal Analysis in the Frequency Domain

M.Molina (Carlo Gavazzi Space) described one approach being taken to estimate the thermal stability of highly sensitive spacecraft instruments which require not only that the temperature be restricted to a narrow range, but also that the rate of change of temperature is constrained. (See Appendix H)

H. Rooijackers (ESA) asked whether the algorithm shown had involved a Laplace transformation. M. Molina said that the Laplace transformation had been used to convert from the time to the frequency domain. H. Rooijackers asked why he had not used a Fourier transform. M. Molina said that he had not been working with periodic variation so he had not needed a Fourier transform. The step function could be handled using Laplace, and did not require a lot of terms to do so, but could not be handled as easily using a Fourier transform.

M. Gorlani (Blue Group) noted that the equilibrium conditions were used as a starting point, but wondered whether they were then discarded. M. Molina said that the linearisation holds around the equilibrium point, so the function depended on the equilibrium point. M. Gorlani said that the temperature was really temperature deviation. M. Molina said that the gain was a dimensionless term, so by multiplying by the temperature it was possible to get the temperature deviation. M. Gorlani wondered whether it would be possible to use the eigenvalues or eigenvectors directly. M. Molina said that the system was always stable by definition, but admitted that some improvement to the method would be possible.

2.3. LHP Transient Modelling using EcosimPro

C. Gregori (Empresarios Agrupados) presented the experiences of modelling a loop heat pipe component using EcosimPro. (See Appendix I)

V. Perotto (Alenia) noted that there were a number of elements to describe the loop, and asked whether there was an element to describe the capillary isolators. C. Gregori said that the model didn't have such an element because the model assumed homogeneous flow, so it was not necessary to separate the fractions. She still wanted to evaluate the advantages and disadvantages of the current model, but there were various ideas in development.

C. Kirtley (ALSTOM) said that there are various effects in capillary devices. He wondered how the start-up phase was detected, when the heat load was enough for the flow rate. C. Gregori said that it was possible to see the void fraction in the wick, and how much coupling there was with the liquid, and to calculate the capillary pressure. C. Kirtley asked whether it was possible to calculate the drying out of the wick, and C. Gregori confirmed that it was possible.

2.4. Designing for mK/μK revisited

V.Perotto (Alenia) revisited his presentation from the previous workshop and discussed how the results of test cases that had been run during the year discounted the initial findings from Alenia which had been reported at the previous workshop. (See Appendix J)

O. Pin (ESA) thanked V. Perotto for the clarification. He had now proven that the original test case presented no issues for ESATAN, but obviously it wasn't possible to say the same for all possible models. A study was required. The question now was whether we really understood what the problems actually were. M. Molina (Carlo Gavazzi Space)'s presentation had shown another way around the problem. It was important to collect the user requirements from GAIA, LISA, etc. to find out exactly what problems needed to be addressed. O. Pin said that ESA had started working on this area even though it was difficult to find the time.

H.P. de Koning (ESA) commented that it might not be the absolute temperature as such, but temperature gradients of milli- and micro-kelvin which might be the issue. For the solvers it would be important to have an accurate transfer of results from the radiative analysis to the thermal solver. Which parameters would be critical?

E. Werling (CNES) said that even if you obtained results, how could you verify them? O. Pin said that GAIA had asked this question, and this was exactly why this analysis was required. E. Werling said that there were some micro-kelvin projects, but these involved relative values. The difficulty was linked to the verification aspects rather than any specific requirements. The 3 milli-kelvin range gave difficulties.

M. Molina said that following his approach it was possible to work the other way round: first validate the model and then linearise. This is what he was trying to do with the LTP. M. Gorlani (Blue Group) said that there were still problems with absolute temperatures for frequency analysis, and that it was important not to discard information during the linearisation.

2.5. GAETAN usage at ALCATEL Space

K.Caire (Alcatel) described how the complete thermal analysis process at Alcatel was now based around GAETAN, and outlined the benefits of the approach. (See Appendix K)

O. Pin (ESA) had an observation, not on GAETAN itself, but related to post-processing. The ESATAP project had started at the beginning of the year. There had been a user survey of requirements, and the project was busy with the architectural design phase, with a PDR to be held the week after the workshop. The planned delivery date for ESATAP was currently September 2005.

2.6. Thermal Analysis of the Mechanical Structure of the GREGOR Solar Telescope

T. Bornkessel (TU- Darmstadt) presented the requirements for the GREGOR Solar Telescope and how the analysis had been performed using ANSYS. (See Appendix L)

C. Heller (EADS) asked whether it was possible to calculate specular reflection in ANSYS. T. Bornkessel said that ANSYS handled diffuse reflection only. They had no access to any other software - only ANSYS - but with some effort it had been possible to achieve the required results and demonstrate the design requirements.

2.7. Modelling of Cryocoolers

M. Linder (ESA) described one approach to modelling cryocooler elements in ESATAN models using physical fit functions in order to avoid polynomial fit functions based on experimental data. (See Appendix M)

E. Werling (CNES) asked whether the algorithm presented could be implemented as a module in ESATAN. M. Linder said that, in principle, it was not necessary to have a complete module because everything could be handled via a single equation. Therefore this equation could be expressed in the model directly.

E. Werling asked whether there were any plans for pulse tube equations. M. Linder answered that further work was required on the single stage pulse tube shown using results provided by Air Liquide. More work would be required to extend the method to handle multi-stage coolers.

G. Theurer (EADS) asked where the empirical values had come from which had been used in the equations. M. Linder said that they had been calculated using empirical measurement data, therefore they provided the characteristic for that particular cooler only. He had needed about 20 data points. There was a dependence on the sink temperature and the cold tip temperature therefore fewer data points were required than for a complete polynomial fit. G. Theurer asked whether there had been any comparison with the fit function results. M. Linder said that this had not yet been done. The fit function was only accurate to within 5%.

C. Kirtley (ALSTOM) said it would be possible to introduce the equation into a $ELEMENT in ESATAN. M. Linder agreed, because the equation could be parameterised to give a general element. O. Pin (ESA) said it would be easier to provide the equation as a subroutine if no nodes were required. G. Theurer said it would be easy to use the equation within $VARIABLES1.

3. Wednesday 6th October - Morning Session

3.1. Optimization of Direct Condensing LHP Radiator using ALGOCAP

R. Schlitt (OHB) described how the ALGOCAP tool had been used with ESATAN to model the AMS instrument payload on the ISS, and how the different requirements of the two tools had been addressed. (See Appendix N)

F. Jouffroy (EADS) asked how the synchronisation of the two models was handled. Were they run from the same ESATAN execution? R. Schlitt said that they switched off the ESATAN model while calculating the low level model using ALGOCAP, then use the temperature and switch the model back on. The temperatures of the low-level and high-level models compared quite well.

3.2. Innovations in Thermica

M.Jacquiau (Astrium) presented the latest developments in Thermica, including importing CAD geometry, the provision of an ESATAN-compatible solver in Systema, and the automated calculation of conductive links. (See Appendix O)

R. Schlitt (OHB) noted that M. Jacquiau had talked to the project managers concerning the import of CAD models, but had not talked to the structural engineers, and had not considered NASTRAN itself. Why not pre-process the NASTRAN model into a thermal model? Why introduce a new model? M. Jacquiau said that the classical approach had been retained because this is how they were working already. The thermal people at the system level wanted this in their software, the Thermica end-users wanted this capability, but different companies have different structural analysis tools. He admitted that R. Schlitt was right in that only one model was really needed, but the two model solution had been chosen. Sometimes two solutions were better than one.

S. Appel (ESA) remarked that the geometry required by the structural engineer was not usually the same model required by the thermal engineer. The thermal engineer wants only the outer surfaces, MLI, etc. The structural engineer wants the load carrying part of the geometry. These are not usually the same. Even if the thermal engineer used PATRAN, there would still be a difference in the required geometry. R. Schlitt argued that if they used the same model it would simplify work. One source model was a lot better than a series of modified models.

O. Pin (ESA) asked what happened when the CAD model was updated. How was it reprocessed? M. Jacquiau said that there was no easy way to reprocess automatically. If the CAD model changed, the user could import both the CAD and thermal models and see the changes in the visualisation. The thermal model still needed to be updated by hand.

M. Molina (Carlo Gavazzi Space) asked about the error in the calculation of the conductive links. Did this relate to the finite element method, or the finite volume method? M. Jacquiau said that both methods had similar levels of error. M. Molina said that he would have expected to see symmetry across the axis. M. Jacquiau said that he hadn’t investigated too closely because the actual error was so small. The conductive links had been calculated using double precision, but the geometry was defined using only single precision. H.P. de Koning (ESA) agreed that if this had been a test case then the results should have been absolutely symmetrical.

A. Torres (CASA) asked how the CAD definitions of individual units and equipment were handled rather than the full space craft model. M. Jacquiau said that all data came from the design office, and the tests had involved the entire CAD file. He didn’t know how the design office assembled individual units into the overall CAD model. A. Torres said that there had been some examples of complex shapes. Were these re-meshed? M. Jacquiau said that they were all re-meshed into the standard surfaces, and the user could re-mesh further if required.

O. Pin remarked on the statement about the price increase in the solvers. He said that the statement wasn’t true: ESATAN now used FlexLM to enforce licence use, so it was more strict than it had been before. The cost of the licence had not increased. M. Jacquiau replied that he had repeated what his purchase office had told him. O. Pin said that the cost of a licence had not changed in 4 years. J. Thomas (ALSTOM) said that there were some fluctuations in the Sterling/Euro exchange rate, but the Sterling price had remained unchanged. M. Jacquiau said that he would need to verify the figures. C. Kirtley (ALSTOM) said that the figure might relate to total number of network licences, rather than price per licence.

C. Kirtley asked about the new multi-timestep feature in the solver. How did the user choose which boundaries to use? M. Jacquiau said that the solver could auto-detect errors on small surfaces, etc. The user specified the accuracy required, globally, on all nodes. C. Kirtley asked whether all other nodes were treated as boundary nodes and whether they were decoupled. M. Jacquiau said that the solver decoupled the boundary nodes and interpolated from the last temperature value. C. Kirtley commented that ESATAN had multi-timestep handling on one of the fluid routines to handle the fluid and thermal interpolation.

3.3. Thermal and Radiative Modelling

J.Thomas (ALSTOM) described and demonstrated the use of the analysis case in ESARAD and how the template files could be modified to bring in additional non-geometric nodes, links, and other user-defined logic. (See Appendix P)

3.4. A Thermal Network Viewer

H. Brouquet (ALSTOM) demonstrated ThermNV, the new thermal network results viewer available with ESATAN. (See Appendix Q)

M. Molina (Carlo Gavazzi Space) recommended that the developers at ALSTOM should sit down with some SINAPS users to get feedback on the network viewer. ThermNV provided a graphical user interface, so why use numbers to represent flow? Why not use line thickness to show the flow. It wasn't possible to read numbers for anything other than a simple network model. M. Molina appreciated that ThermXL was integrated with Excel, but asked why ThermNV used tables which then required an interface to Excel. J. Thomas (ALSTOM) said that it was possible to cut and paste the tables directly into Excel, so a dedicated interface to Excel was not strictly necessary. ALSTOM would be looking at this and other issues as they already had a huge list of feature requests. ALSTOM were keen to give the alpha version to people in order to have comments. J. Thomas said that they had not been able to cross check the interface with that of SINAPS. A. Goizel (RAL) asked whether it was also possible to cut and paste the report layout, etc. H. Brouquet said that it was possible: the table and time row could be pasted directly into Excel.

3.5. Modelling the Martian Surface Thermal Environment with ESATAN and ESARAD

B. Shaughnessy (RAL) described some of the additional factors which needed to be taken into account when modelling the Martian surface environment, including diffuse solar radiation, dust storms and convection. (See Appendix R)

H.P. de Koning (ESA) asked how they had handled the transmission through the atmosphere. Had they used MODTRAN? B. Shaughnessy said that they had been calculated using ESATAN subroutines written in f77. A specific atmosphere module had been written especially for them in order to calculate the diffuse fluxes and the surface temperatures. H.P. de Koning asked how they had handled the different alpha values. B. Shaughnessy said that they had found it adequate to use the alpha values corresponding to the solar wavelengths. They had seen no evidence of how JPL had handled these issues for their landers.

3.6. Data Exchange using CFD and ESATAN in the case of Natural Convection

C. Wendt (EADS) described an approach for coupling the results of CFD and ESATAN analyses to handle convective effects in a cavity within the body of the Ariane5 ESC-A launcher. (See Appendix S)

J. Persson (ESA) asked whether test verification was available for this type of modelling. C. Wendt said that they compared against a correlated ESATAN model. Both gave the same wall temperatures and heat fluxes. There would be a ground test in the week following the workshop.

K. Duffy (MAYA) asked how they achieved convergence between the CFD and ESATAN models: buoyancy terms had been introduced which required iteration back and forth between the tools. C. Wendt agreed that this was the case. For the LOX tank membrane the same heat fluxes and conditions applied, so the models were the same. K. Duffy asked how the models were synchronised. Were all of the nodes treated as boundary nodes? C. Wendt said that they used steady state ground analysis models and other compound models. They assumed that the heat conduction related to linear flow as long as the temperatures didn’t vary too much. The flow needed to have the same shape.

M. Gorlani (Blue Group) assumed that the model didn’t use GFs. C. Wendt said that they used GRs, even for the case nodes. GFs were one way conductors, and as there was no gas flow in the tubes the heat flow could be in both directions. A. Rodriguez (ESA) said that the model should really use GFs and calculate the mass flow rate to ensure positive flow.

3.7. Development of Interface software between PATRAN/Thermal and ESARAD

C.Heller (EADS) described the development of software to allow the transfer of a geometrical model created by PATRAN into ESARAD so that radiative exchange factors and environmental fluxes could be calculated and then transferred back to PATRAN/Thermal for use in thermal analysis, temperature mapping and thermo-distortion analysis. (See Appendix T)

S. Appel (ESA) asked whether they were using PATRAN fields for the interpolation from the thermal to the structural mesh. He said that PATRAN allowed 3d fields, and these could be used to get the temperatures. C. Heller said that they hadn’t decided whether to use PATRAN fields or to use other methods for interpolation. They still had to talk to the structural people. He said that they only had temperatures on edge nodes, so this could lead to problems. S. Appel asked whether the same geometry was used for both models. C. Heller said that the automatic GL calculation was handled by P/Thermal so everything inside the model was calculated.

H.P. de Koning (ESA) said that he had been at TFAWS earlier in the year and so had MSC, the developers of PATRAN. They had discussed that PATRAN was going to support STEP-TAS. He felt that this would be a more efficient route for EADS to follow than a custom interface. He made a plea for everyone to use open standards and not to implement tool-to-tool data exchange.

It would be better to do it once and to get it right than to have dedicated effort per tool combination. In PATRAN 5 to be released in 2005 all of the “thermal” primitive shapes would be supported so PATRAN could also be used to build thermal models. C. Heller said that he was aware of the STEP-TAS interface in PATRAN, so generating the geometry in PATRAN was easy, but radiative exchange factors were not yet supported.

J. Thomas (ALSTOM) commented that the malformed sphere problem shown during the presentation related to the use of a second order quadrilateral mesh that didn’t map to the first order mesh used by ESARAD. If the quadrilateral mesh were converted to use triangles then the model exchange should work. C. Heller acknowledged that the curved quadrilateral elements gave “point not in plane” problems for ESARAD and agreed that splitting these quadrilaterals into two triangles would probably solve the problem. He argued that support for second order primitives in the radiative tools would also solve the problem.

3.8. New version of BAGHERA STEP viewer based on open standard technologies

E. Lebegue (Graitec) presented the latest developments in BAGHERA, and demonstrated its use to visualise STEP files. (See Appendix U)

3.9. Interface between STEP-TAS and Alcatel Space’s CIGAL2 application (which works with the CORATHERM solver)

C. Caillet (Open Cascade) described the development of a STEP-TAS interface for CIGAL2 and outlined some of the problems encountered and the solutions which had been used to address them. (See Appendix V)

S. Appel (ESA) commented that CIGAL2 used certain primitives for which support was not yet complete. C. Caillet admitted that the support for the CIGAL primitive conversion to and from STEP-TAS was not yet complete.

R. Schlitt (OHB) asked whether loop heat pipes would be included in the schema in the future. C. Caillet said that for ARTES-8 it would be necessary to handle all of the elements which existed in both Astrium and Alcatel tools.

4. Wednesday 6th October - Afternoon Session

4.1. STEP-TAS and TASverter from the user’s point of view

D. Alsina (ESA) presented the capabilities of the TASverter tool and the use of the different options for converting user models. (See Appendix W)

O. Pin (ESA) drew everyone’s attention to the fact that the CIGAL2 reader and writer were currently being developed by Alcatel with the help of Open Cascade. He wanted to generalise the scheme so that the other readers and writers were handled by the developers, so the Thermica reader and writer would go to Astrium and the Esarad reader and writers would go to ALSTOM. A prototype of an ESATAN to STEP-TAS converter had still to be discussed.

M. Jacquiau (Astrium) asked whether the community could expect that the deliveries for ESA space projects would now be in STEP-TAS format. O. Pin said that this would be a topic under discussion at the Harmonisation Steering Board meeting the following day.

R. Schlitt (OHB) expressed concerns about maintaining data exchange across future versions of the tools. H.P. de Koning (ESA) said that this would be addressed in the following presentation.

4.2. STEP-TAS and TASverter from the software developer’s point of view

H.P. de Koning (ESA) described the underlying principles and architecture of STEP-TAS and TASverter and what options were open to software developers in creating conversion tools. (See Appendix X)

A. Fagot (Dorea) said that additional libraries had been mentioned in the scope of the new integration of CIGAL and STEP-TAS, and wanted to know what was available in TASverter. H.P. de Koning said that additional libraries were now used to load a run-time protocol specific dictionary which could be used by all tools. ESA would provide an example of how to add new readers and writers and then it would be up to individual companies to publish their own readers and writers.

4.3. Workshop Close

H. Rooijackers (ESA) had heard various comments that holding the workshop “early in October” was too soon after the summer break, but there had still been enough presentations and questions to exceed the programme time. There had been some interesting discussions, even in the coffee and lunch breaks. There had been an exchange of information between developers and users, there had been some inspiring application demonstrations, and we had even seen some coupling between structural and thermal analysis. He expected these topics to return. He hoped that the next workshop would be as easy to organise. He thanked the presenters, because preparing presentations took a lot of work, and thanked the other participants for taking part. He hoped to see everyone again at the next workshop.

Appendix A: Welcome and Introduction

Welcome and Introduction

H. Rooijackers
ESA/ESTEC

esa

ESTEC
Thermal and Structures Division

Workshop objectives

- To promote the exchange of views and experiences amongst the users of European thermal/ECLS engineering analysis tools and related methodologies
- To provide a forum for contact between end users and software developers
- To present (new versions of) thermal/ECLS engineering analysis tools and to solicit feedback for development
- To present new methodologies, standardisation activities, etc.

ESTEC
Thermal and Structures Division

ESA Workshop Team

Harrie Rooijackers	Organiser
Duncan Gibson	Software Support & Workshop Secretary

with help from the ESA Conference Bureau

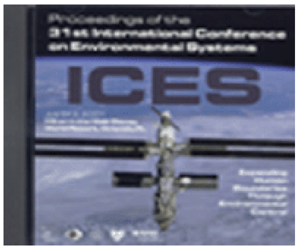
ESTEC
Thermal and Structures Division

Programme

- Two-day programme
- Presentations include 5 minutes for questions and discussions.
- Cocktails today after the workshop in Erasmus ISS Visitor Centre
- Dinner (optional) tonight in Noordwijk
- Conclusions tomorrow at end of Workshop

ESTEC
Thermal and Structures Division

ICES 2005



- The 35th International Conference on Environmental Systems will be held July 11-14, 2005, Hotel Villa Pamphili, Rome, Italy,
- Deadline for submitting abstracts: Friday 29 October, 2004
- abstracts may be submitted online at http://www.sae.org/ices (preferred)
- or sent to: Olivier Pin, email olivier.pin@esa.int
- Abstracts must include paper title, author(s) name(s), mailing and e-mail addresses, phone and fax numbers.

ESTEC
Thermal and Structures Division

Practical information

- Presenters: If not done already please leave your presentation (floppy or CD-ROM with PowerPoint and PDF file) with Duncan or Harrie before the end of Workshop. Please leave also a paper copy to avoid problems with embedded fonts/logo’s or Mac.
- No copyrights, please!
- Workshop Minutes will be supplied to participants afterwards, in hard copy and on the Web.

Practical information

- Lunch: 13:00 - 14:00. The “Foyer” tables are reserved for us
- Cocktail today at 17:30 in Erasmus ISS Visitor Centre
- Check your details on the list of participants and inform the Conference Bureau of any modifications. Leave your email address!

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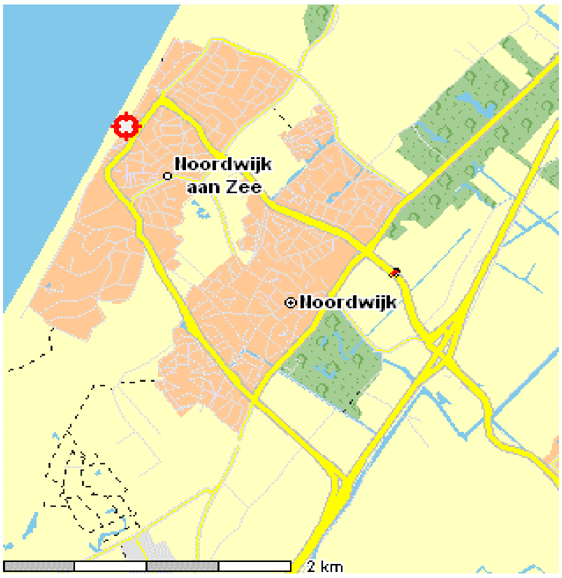
Thermal and Structures Division

Dinner (tbc)

- "Dutch" dinner == to be paid by yourself   :-(
- in “La Galleria", Kon. Wilhelmina Boulevard 18, Noordwijk a/Z, tel +31-71-361-7196
- fixed menu with choice of main course for 26 euro p.p., excl drinks *Suggestion: calculate drinks bill per table and share equally*
- Restaurant booked today for 20:00. Please arrange your own transport
- If you would like to join, then you would have to complete the last sheet of hand-out and return it to one of the organisers (Duncan or Harrie)
- ultimate time today: 14:00, to let the restaurant know.

Resto “La Galleria"



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Menu

(€ 26.00 p.p. excl. drinks.)

Crespelle Casanova
a thin pancake filled with mozarella, rucola, tomato and artichokes

~~~~~~~~~~~~~~

Salmone Al Vapore Con Salsa Di Basilico
poached salmon with a fresh basil sauce

or

Saltimbocca Alla Romana
veal medallions with Parma ham in a white wine sauce

or

Tris Di Pasta Della Casa Vegetariana
three different kinds of vegetarian home made pasta

~~~~~~~~~~~~~~

Cassata Royal
Sicilian ice-cream

Appendix B: Finite Element Based Analysis Tool For Re-entry Vehicle TPS Ablators

Finite Element Based
Analysis Tool
For
Re-entry Vehicle
TPS Ablators

T. van Eekelen
SAMTECH s.a.

Finite Element Based Analysis Tool For Re-entry Vehicle TPS Ablators

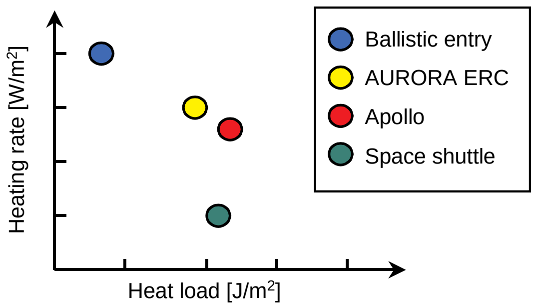
18th European Thermal & ECLS Software Workshop
ESA-Estec, Noordwijk, The Netherlands.
5-10-2004

Tom van Eekelen,
SAMTECH s.a.

Re-entry vehicle

- Hypersonic re-entry into the atmosphere.

  - Convection (v^3), Radiation
- TPS is needed to maintain low enough temperature
- Speed of re-entry (slow/fast)
  - Heating rate
  - Heating load



TPS concepts

- Active systems
  - Cooling fluid (externally supplied)
  - Transpiration/film cooling
- Semi passive systems
  - Cooling fluid (internally supplied)
    - Heat pipes
    - Ablators/pyrolysis
- Passive systems
  - Heat sink
  - Insulation
  - Re-radiation (hot structure)
- Trade off between:
  - high heat removal capacity
  - complexity (possible failure)

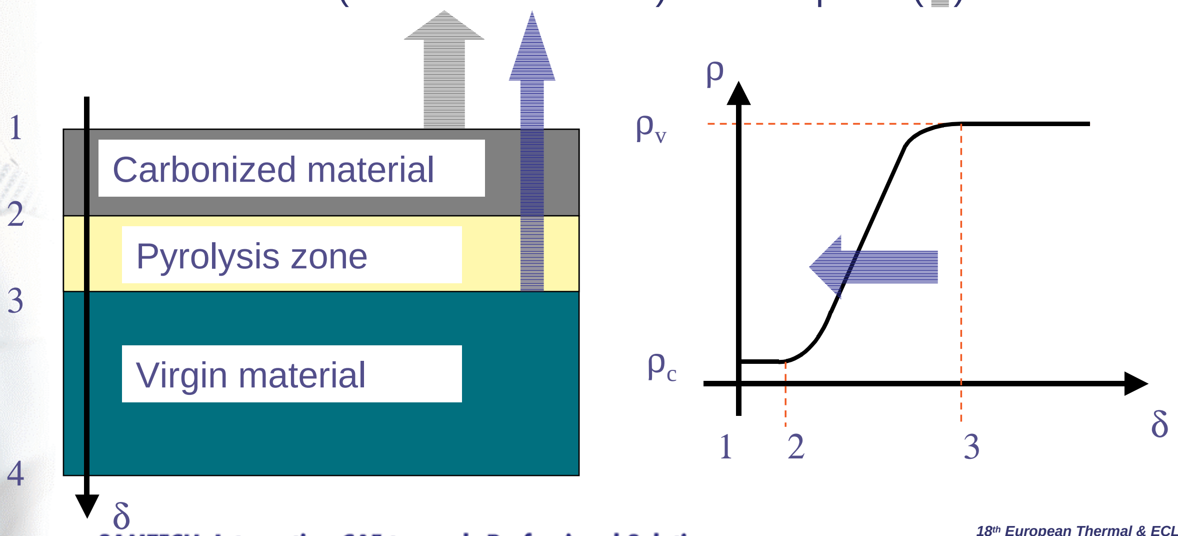
TPS phenomena

- Insulation of the structure
  - Maximum allowable structural temperature
  - Low density (maximum TPS mass)
- Re-radiation into the environment
  - High allowable wall temperature
  - High emissivity
  - Good insulation properties
- Pyrolysis
  - Endothermic chemical reactions (volume)
  - Blocking of boundary conditions
- Ablation
  - Sublimation (surface recession)
  - Blocking of boundary conditions
  - Low versus high density ablators:
    - insulation
    - recession rate

SAMTECH, Integrating CAE towards Professional Solutions

TPS ablators

- Material subjected to degradation ($\dot{\rho}$)
- Density ρ varies between ρ_v virgin and ρ_c carbonized state
- Degradation will cause Gas mass flow (m_i^g ⬆).
- Surface ablation (removal of material) will take place (⬆)



Mathematical model

- Heat balance equations:

$$-H_P\dot{\rho} + \rho\frac{dh}{dt} = \partial_i\left(\lambda_{ij}\partial_j T\right) - m_i^g \partial_i h^g + Q$$

- Darcy equation:

$$\partial_i\left(K_p \partial_j P\right) = \dot{\rho}$$

- Arrhénius equations:

$$\dot{\rho} = -A\rho_v^{1-N}\left(\rho - \rho_c\right)^N e^{-E/RT}$$

Material properties

- User defines properties in « virgin » and « charred » state (dependent on temperature and pressure).
- Program calculates material properties during the analysis (as a function of ρ):

$$\lambda = g(\lambda_v, \lambda_c, \rho) \qquad c = f(c_v, c_c, \rho)$$

$$\beta = h(\beta_v, \rho) \qquad K_p = \frac{M^g \beta P}{\mu^g RT}$$

- The constitutive equations define the heat and gas mass flux respectively:

$$q_i = -\lambda_{ij} \partial_j T \qquad m_i^g = -K_p \partial_j P$$

Ablation definition

- Three types of ablation can de defined:
  - Mechanical: (explicit definition of ablation speed)

$$\dot{s}_m = a(\tau + bP) e^{-T_E / T}$$

  - Chemical: (explicit definition of ablation speed)

$$\dot{s}_c = \dot{s}_c(T, P, m_i^g n_i)$$

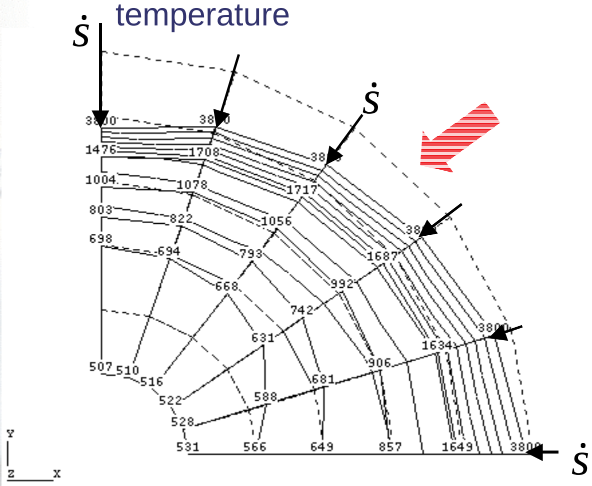
  - Phase change: (implicit definition of ablation speed)

$$\lfloor \rho L_{ph} + \eta_1 (H_a - H_w) \rfloor \dot{s}_{ph} = q_{reaction}$$

    - Ablation speed is found to satisfy the thermal equilibrium on the surface. $q_{reaction}$ is due to maximum phase change temperature (contact)

Variable mesh algorithm

- Due to ablation, the external surface moves.
  - Ablation speed perpendicular to external surface
  - Mesh moves along « master » lines
  - Internal mesh distribution can depend on penetration depth of the temperature



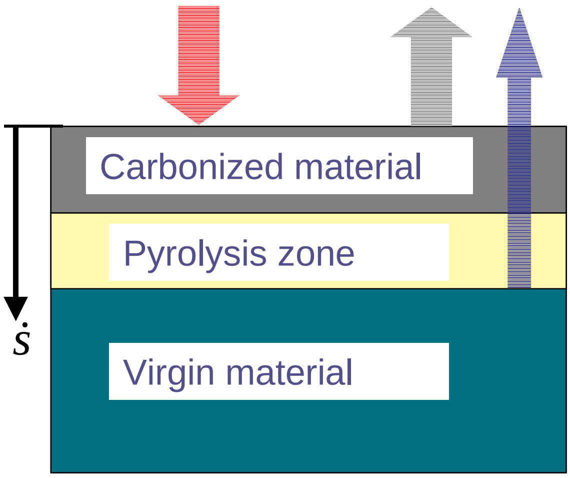
- Two solution strategies:
  - Convective term added:

$$\frac{DT}{Dt} = \frac{dT}{dt} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}$$

  - Nodal values re-calculated per time step

Boundary conditions

- Classical boundary conditions ( ); flux, convection,radiation, etc.
- Blocking terms due to injection of material into the surrounding:
  - Due to Gas flux ( )
  - Due to Ablation ( )



- Gas mass flux blocking term:

$$q \cong -g(T,P)m_i^g n_i$$

- Ablation blocking term:

$$q \cong -h(T,P)\dot{s}\rho$$

Boundary conditions

Additional terms

- Applied flux:
  - Added flux due to combustion of pyrolysis gas
  - Blocking terms due to ablation material

$$q + m_i^g n_i H_{comb} - \dot{s}_c \rho H_c - \dot{s}_{ph} \rho L_{ph}$$

- Convective flux (enthalpy formulation):

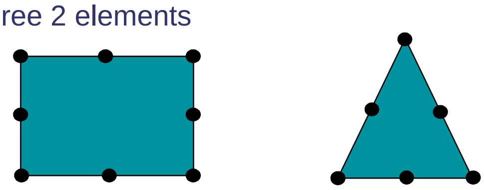
$$q_i n_i = \left(\alpha - \eta_2 m_i^g n_i - \eta_1 \rho \left(\dot{s}_c + \dot{s}_{ph}\right)\right)\left(H_a - H_w\right)$$

  - Blocking terms due to ablation material and pyrolysis gas
  - The enthalpy $H_w(T,P)$ per unit of fluid mass, is automatically calculated using a Mollier diagram

Finite Element solution

SAMCEF Amaryllis

- 2D/Axis-symmetric finite element mesh with three degrees of freedom per node:
  - Temperature (T),
  - Pressure (P) and
  - Density (ρ)
- Triangular and quadrangular elements
  - Degree 1 and degree 2 elements

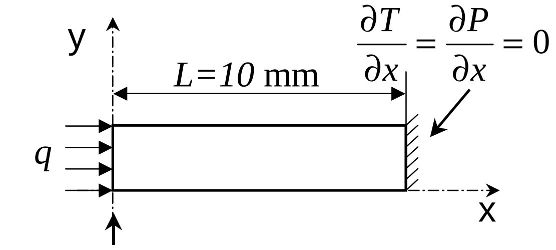


- Fully integrated into SAMCEF Thermal
  - Steady state & Transient analysis
  - Coupling with other elements (3D/Controller)

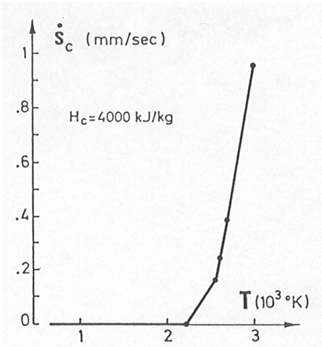
TPS Analysis

1D thickness calculation

- Test specimen subjected to:
  - External pressure
  - Convection (enthalpy form)
  - Radiation flux (outward)



- Undergoing:
  - Chemical ablation



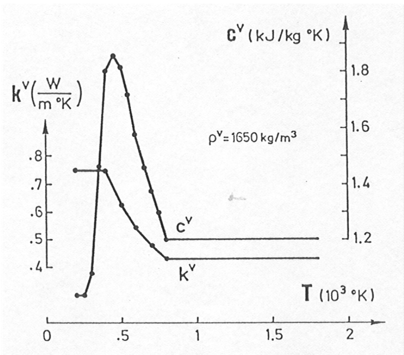
- Pyrolysis
  - N = 3
  - E = 99768
  - A = 10^7

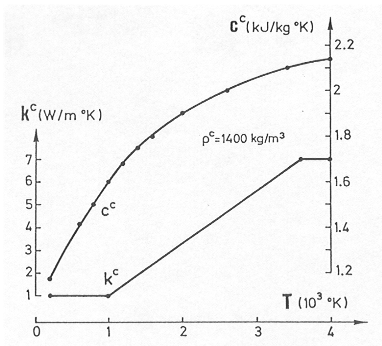
$$\dot{\rho} = -10^7 .1650^{-2} (\rho - 1400)^3 e^{-99768/RT}$$

TPS Analysis

1D thickness calculation

- Conductivity **K** and capacity **C** (“virgin” and “charred”)





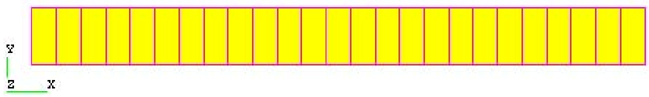
- Pressure conductivity $\mathbf{K_p}$
  - β_v = 7.3881 10^{-13}
  - μ = 1 10^{-4}
  - M^g = 2.8 10^{-2}

$$K_p = \frac{M^g \beta}{\mu R} \frac{P}{T}$$

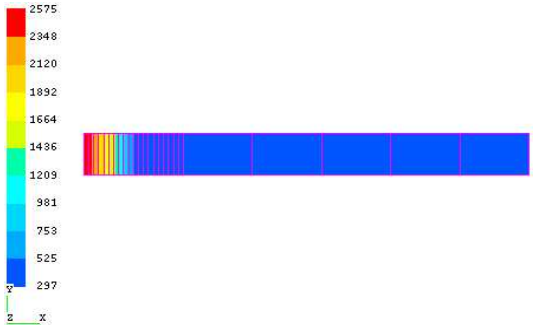
TPS Analysis

1D thickness calculation

- Element distribution:
  - 25 elements
  - 20 elements in a zone of 2.δ(t)
  - (δ=penetration depth)



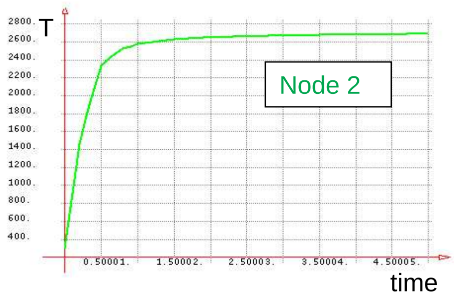
- Blocking terms taken into account:
  - η_1 : blocking due to ablation material
  - η_2 : blocking due to gas mass flow
- Transient calculation between 0 and 5 seconds.
  - Temperature distribution
  - at t = 1.0 s

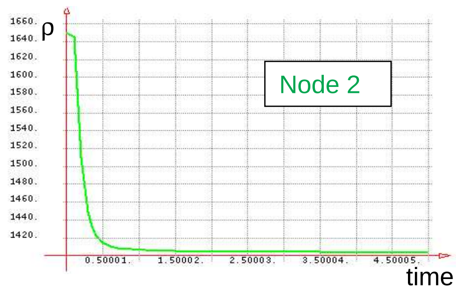


TPS Analysis

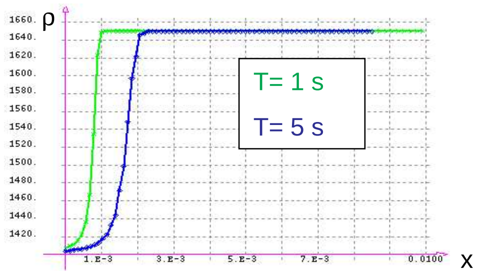
1D thickness calculation

- Temperature/density evolution at ablation front

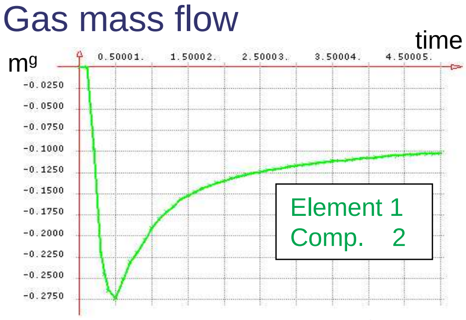




- Density distribution



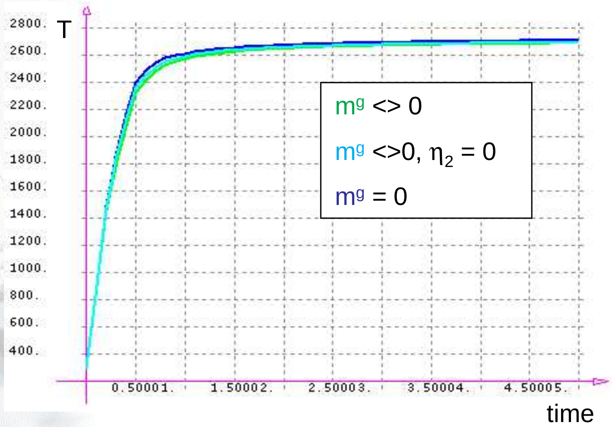
- Gas mass flow

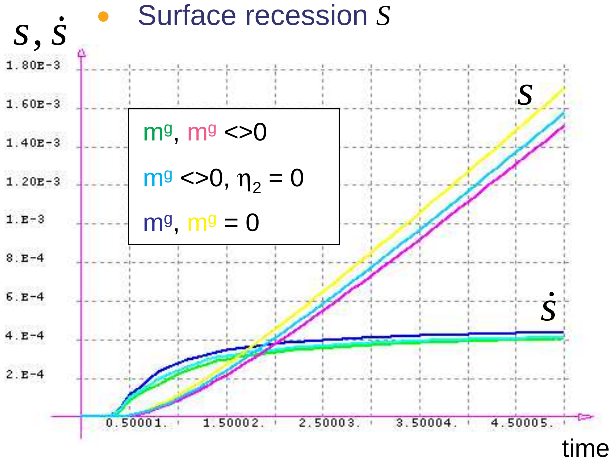


TPS Analysis

1D thickness calculation

- Influence of gas mass flow
  - Temperature evolution
  - Surface recession S



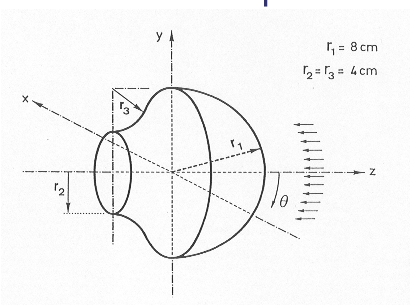


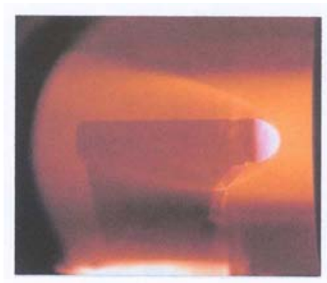
- Large influence on ablation depth (+12.8 %) via:
  - Gas flow through charred material.
  - Blocking of convection load.

TPS Analysis

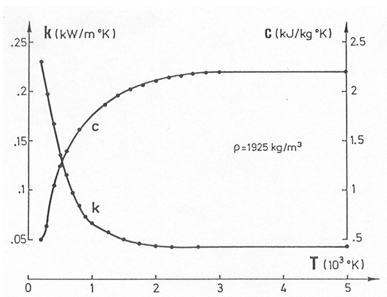
2D thickness distribution

- Ablation of a Carbon sphere





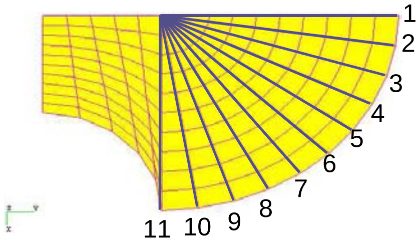
- Material properties for Carbon:
  - Conductivity
  - Capacity
  - No pyrolysis



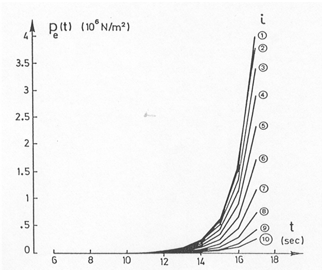
TPS Analysis

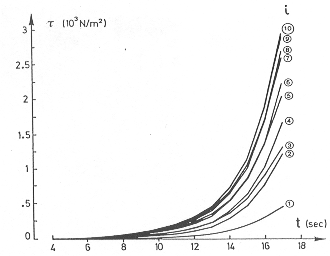
2D thickness distribution

- Axis-symmetric mesh
  - Re-meshing lines



- Mechanical ablation:
  - Position and time dependent pressure
  - A = 1 10^{-9}
  - B = 1.
  - T_E = 300.

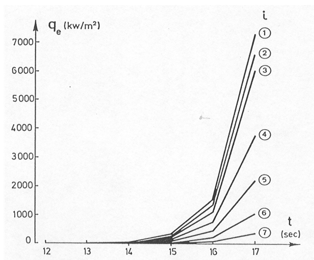




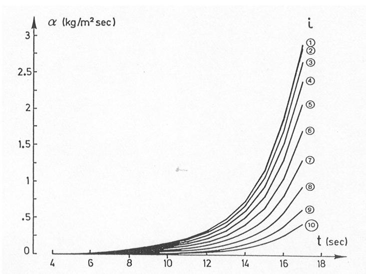
TPS Analysis

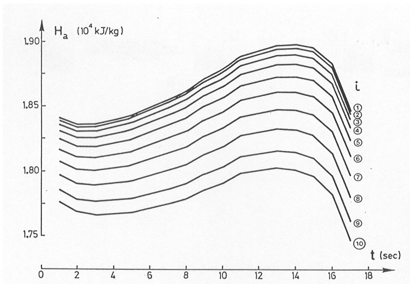
2D thickness distribution

- Radiation with the environment + radiation load
  - T_R = 300, $\sigma\varepsilon$ = 5.103 10^{-11}
  - Position dependent
  - Time dependent



- Convection load (enthalpy formulation)
  - Position dependent
  - Time dependent
  - Blocking term η_2

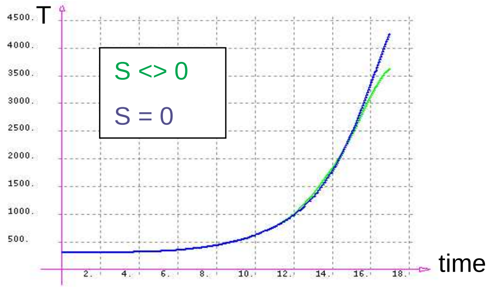




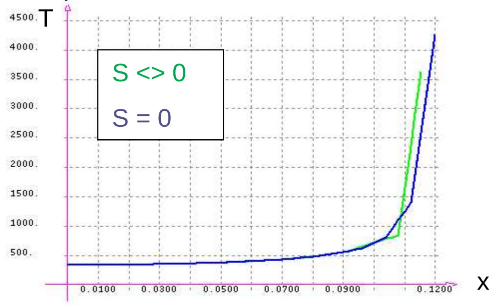
TPS Analysis

2D thickness distribution

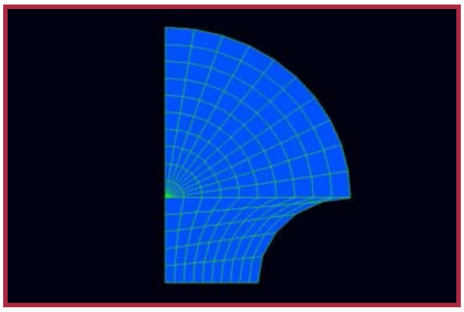
- Temperature at the outer surface



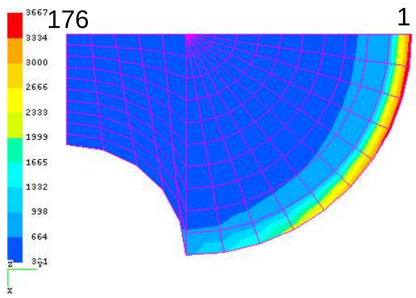
- Temperature in section N 176 -> 1



- Temperature distribution



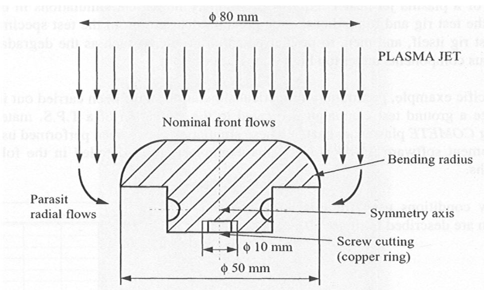
- Temperature distribution at t = 17 s

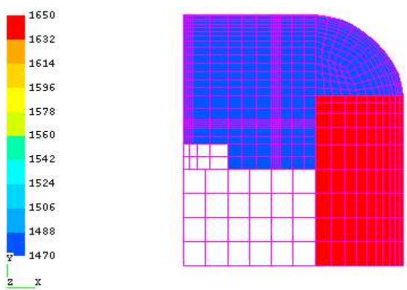


TPS Analysis

Axis-symmetric test specimen (EADS-ST)

- The test specimen subjected to:
  - Convection (enthalpy form)
  - Re-radiation
  - Chemical ablation
  - Combustion heat
  - Blocking terms (pyrolysis/ablation)
- Analysis to prepare for material test phase
- Density distribution of the virgin material
  - Test specimen (ablator)
  - Side protection (ablator)
  - Metal structure
- Moving Contact between different materials

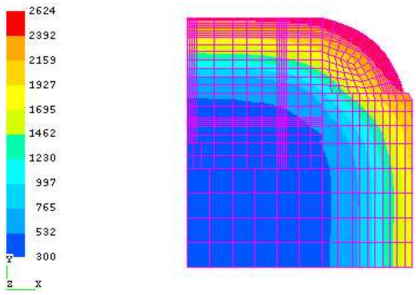




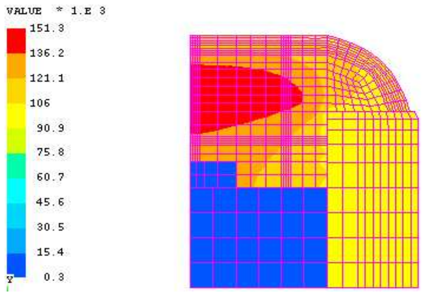
TPS Analysis

Axis-symmetric test specimen (EADS-ST)

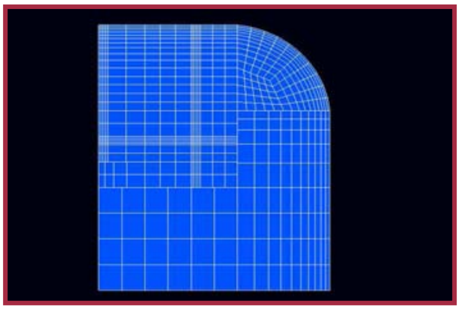
- Temperature at t = 80 s



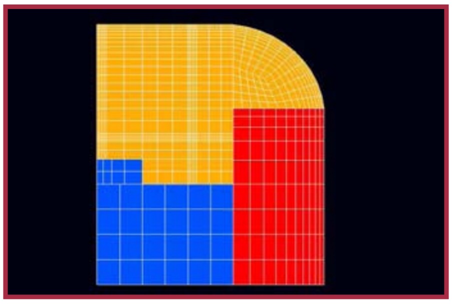
- Pressure at t = 80 s



- Temperature evolution



- Density evolution



Conclusion

- Ablation and pyrolysis are:
  - needed for material characterization
  - both necessary for Ablation distribution

- SAMCEF Amaryllis:
  - is capable of modelling 2D/Axis-symmetric structures of practical complexity
  - will be used in the AURORA program: *Delta Qualification testing of TPS ablators*

Appendix C: EcosimPro Current Status and Future Improvements

EcosimPro
Current Status
and
Future Improvements

R. Pérez Vara
Empresarios Agrupados

EcosimPro Current Status and Future Improvements

RAMON PEREZ VARA
EMPRESARIOS AGRUPADOS

CONTENTS

- Introduction
- EcosimPro History
- EcosimPro Latest Improvements
- Future Improvements
- Example of EcosimPro-Excel connection

INTRODUCTION

INTRODUCTION (1)

EcosimPro is the ESA software tool for the simulation of ECLS systems.

EcosimPro was designed as two parts:

> A Generic Simulation Kernel, which includes
- a **language** to define new modeling components
- a **graphical user interface**

> A Library of ECLSS components implemented using the language.

EMPRESARIOS AGRUPADOS

INTRODUCTION (2)

EcosimPro is not limited to ECLSS simulation and it is being applied to other simulation fields:

> Hydraulic and pneumatic circuits
> Simulation of Space Propulsion systems
> Simulation of Aircraft Gas Turbines
> Chemical process
> Electrical power plant cycles (Steam Cycle and Combined Gas Cycle)

EMPRESARIOS AGRUPADOS

ECOSIMPRO HISTORY

18TH European Thermal & ECLS Software Workshop *ESTEC, October 2004*

EMPRESARIOS AGRUPADOS

ECOSIMPRO HISTORY

Version 3.0 (December-1999) was the first commercial version for PC- windows.

There is a continuous development effort to produce upgraded versions:

Latest release:

> Version 3.3 (March-2004)

Future releases:

> Version 3.4 (December 2004)
> Version 4.0 (expected by 2005)

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ECOSIMPRO LATEST IMPROVEMENTS (version 3.3)

ECOSIMPRO LATEST IMPROVEMENTS (1)

The major differences between version 3.3 and previous version 3.2 are:

> a new graphical model builder, EcoDiagram

> new connection between EcosimPro and Excel, which is very easy to use

> upgraded ECLSS library with new components

> multiple language improvements

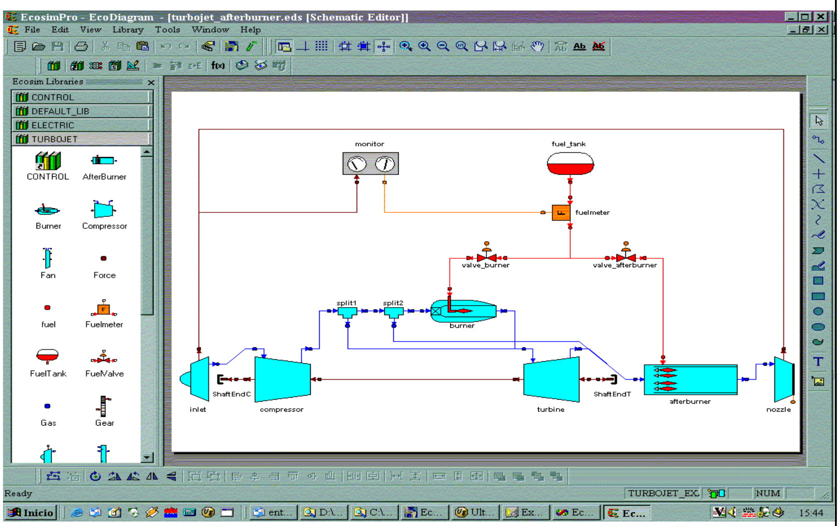
ECOSIMPRO LATEST IMPROVEMENTS (2)

New graphical model builder, **EcoDiagram**

> it eliminates the complexities of the previous graphical editor (a commercial tool named Smartsketch)

> Consistency between the text and graph is automatically kept

> Graphical models are saved using XML language (Ascii file)



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ECOSIMPRO LATEST IMPROVEMENTS (3)

New connection EcosimPro-Excel

> Connection between EcosimPro and Excel enables to deliver EcosimPro models that can be run by system engineers without any EcosimPro knowledge

> Previous connection between EcosimPro models needed Visual Basic programming to manage the EcosimPro model object

> An Excel Add-In has been designed that enables to link Excel cells to EcosimPro model variables only by selection in graphical menus.

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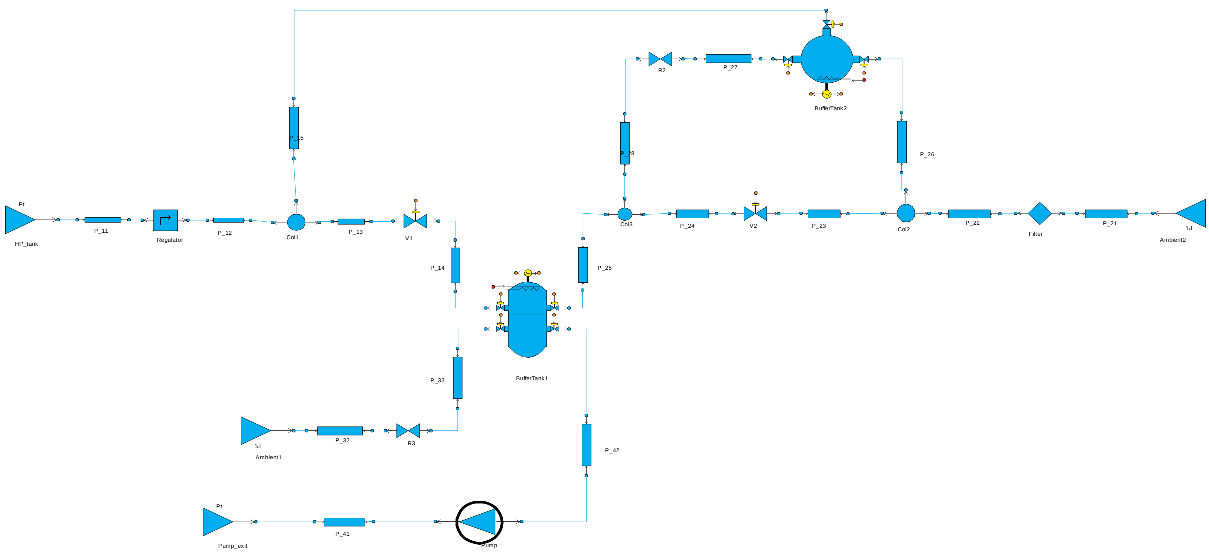
ECOSIMPRO LATEST IMPROVEMENTS (4)

EcosimPro Model of a pneumatic system connected to Excel for exploitation



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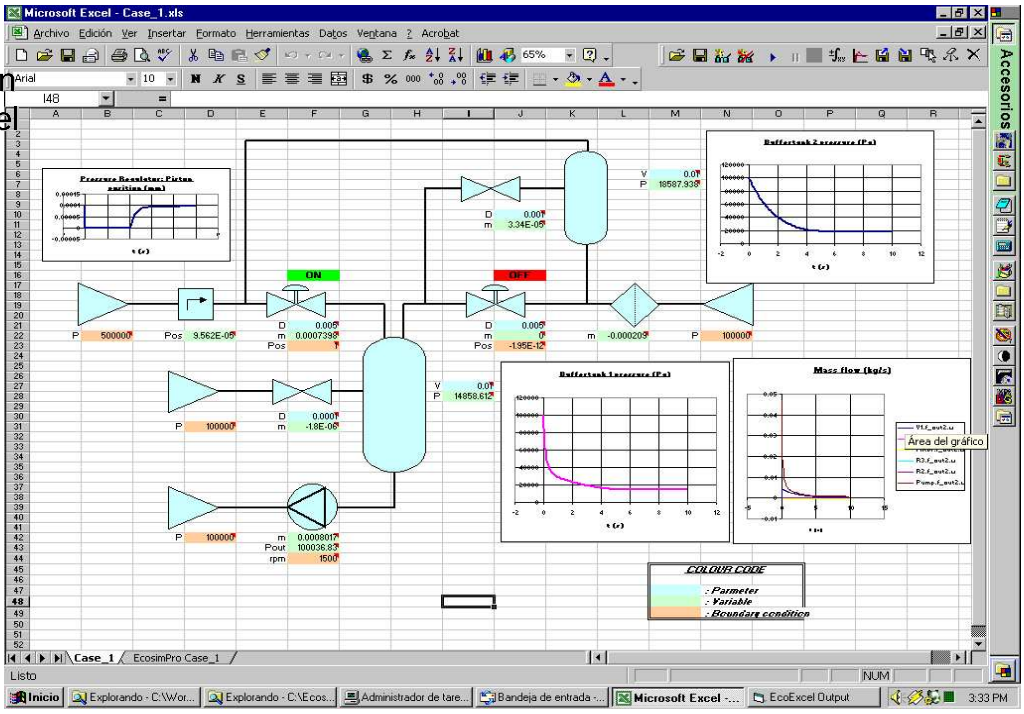
ECOSIMPRO LATEST IMPROVEMENTS (5)

Excel interface to run the EcosimPro model of the pneumatic system



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ECOSIMPRO LATEST IMPROVEMENTS (6)

Upgraded ECLSS Library:

> New components for molecular flow

- **Pipe** with compressible formulation, which is able to work in turbulent, viscous and molecular flow regimes
- **Orifice** with formulation including the compressible region, and the molecular flow region

> Very detailed crew model

> Pressure regulator valve model, and relief valve model

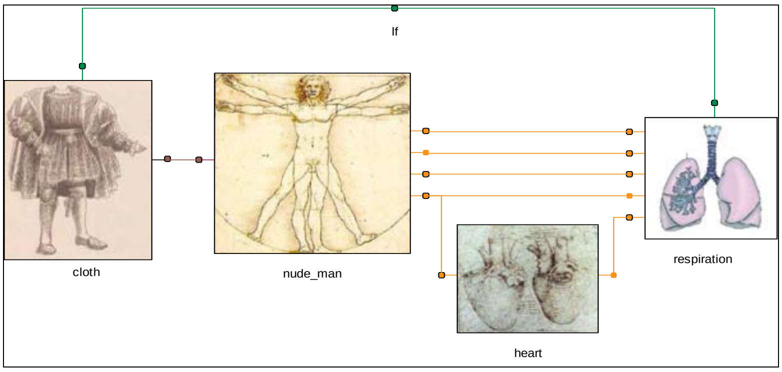
> Membrane Separator Model

ECOSIMPRO LATEST IMPROVEMENTS (7)

Upgraded ECLSS Library: Detailed Crew Model

The detailed crew model was designed as a compound component consisting of:

- Nude man thermal model with 25 nodes
- A cloth model
- A heart model
- A respiratory model



FUTURE IMPROVEMENTS

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EcosimPro Future Improvements

Ecosim Version 3.4 shall be released in December 2004. Major changes from an users view point:

> It shall have an optimization module callable from the experiments

> A pre-processor with “Include” and “Macro”, PDE’s easily modelled using the Macro

> Multiple functions to read tables in different formats

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EcosimPro Future Improvements

Ecosim Version 4 shall be released by the end of 2005

> Current EcosimPro version runs only in PC-windows, although it can generate model executables that run under Windows, Linux & Unix

- The graphical user interface was designed using Visual Basic and C++

> EcosimPro version 4.0 shall be multiplatform software running on Linux and Windows:

- EcosimPro Graphical User Interface is being redesigned using Qt

18TH European Thermal & ECLS Software Workshop *ESTEC, October 2004*

EXAMPLE OF CONNECTION BETWEEN ECOSIMPRO AND EXCEL

EXAMPLES (1)

An EcosimPro model of a cooling loop of an spacecraft has been built. The main features of the loop are:

> Mechanically pumped (COF pump)

> Single phase

> Working fluid is a design variable (the coolant can be selected between a set of predefined coolants)

> Thermal power to dissipate is 6000 W

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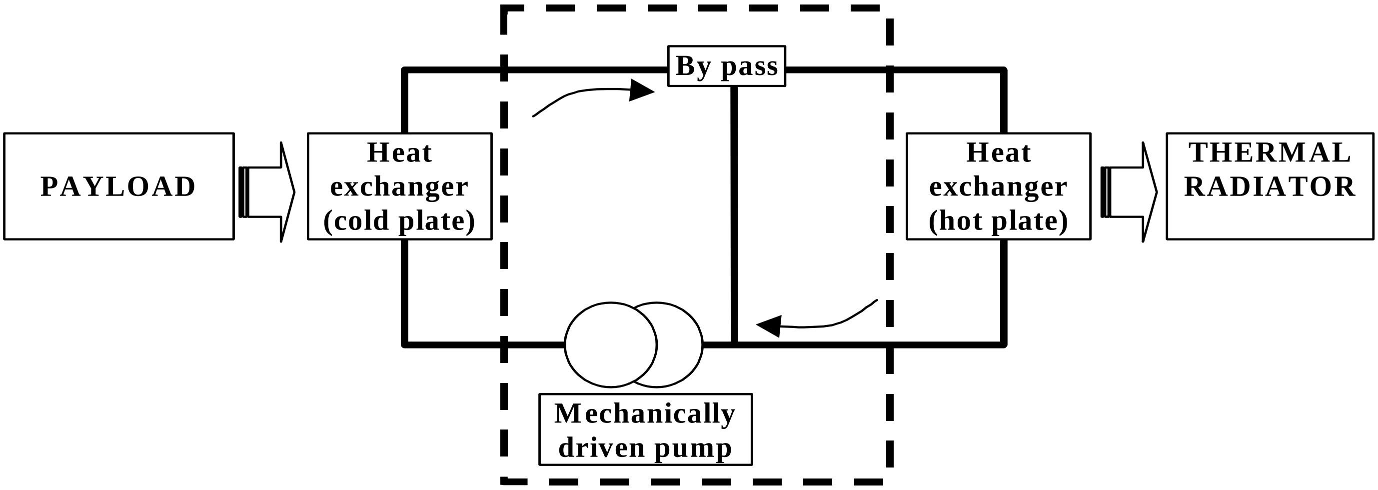
Example (2)
Schematics of the Cooling Loop to Simulate



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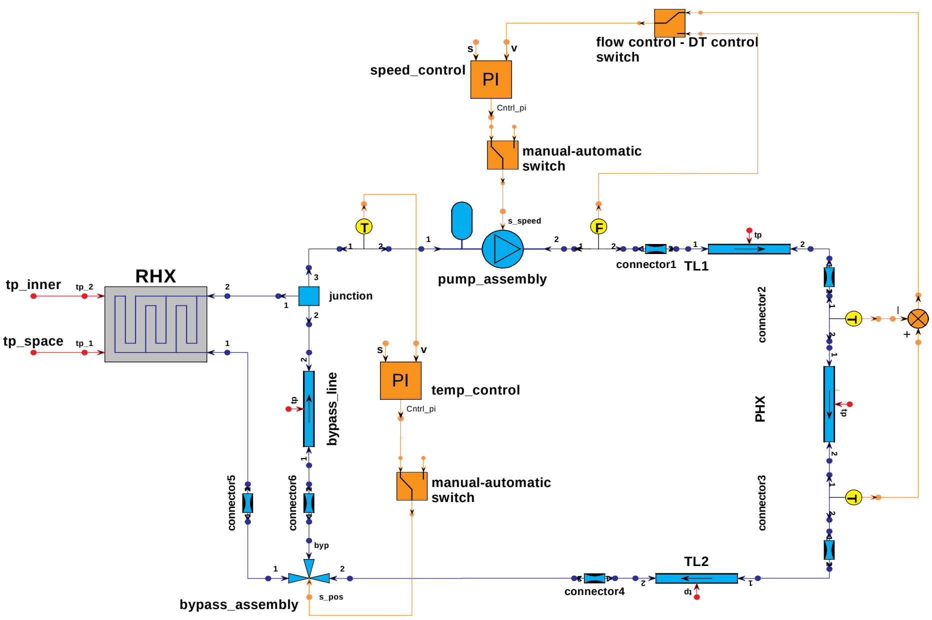
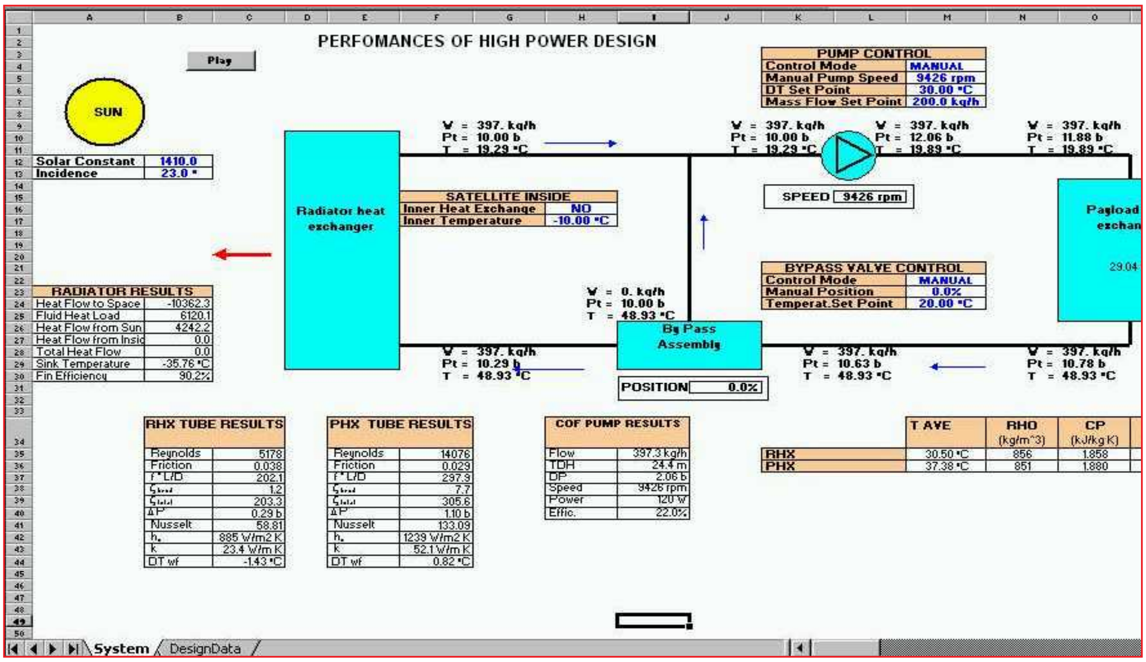
Example (3)
EcosimPro model of the cooling loop



Example (4)
Excel Interface to the Cooling Loop Model



Appendix D: Capabilities of the Therm-OSS Tool

**Capabilities
of the
Therm-OSS
Tool**

M. Haupt
TU-Braunschweig

Capabilities of the Therm-OSS Tool

18th European Thermal & ECLS Software Workshop
ESA/ESTEC, Noordwijk 5-6 October 2004

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Matthias C. Haupt
Reinhold Niesner

Reinhard Schlitt (OHB)
Frank Bodendieck (OHB)

Charles Stroom (ESA/ESTEC)

Objectives of the Therm-OSS Project

- To assess how OSS can be used to build applications
- To provide to developers a useful source of reference for their developments
- To assess whether the OSS approach could be useful as a distributed model for end-users

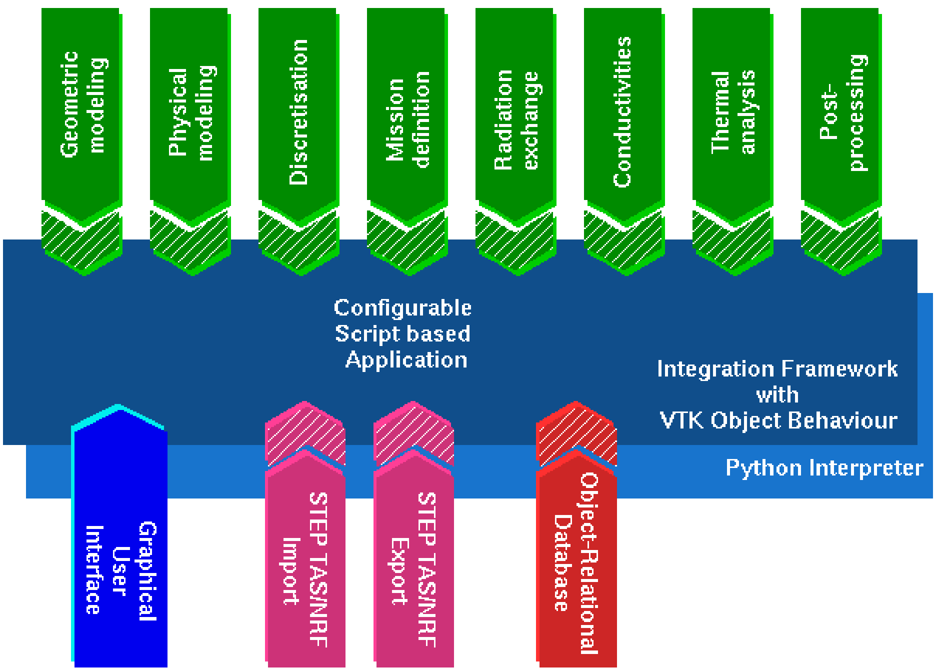
Introduction

Therm-OSS

- Statement of work
  - The system to be developed, will be able to perform the complete thermal analysis of a spacecraft, or part thereof. This includes:
  - the definition or modification of a model of
    - the spacecraft or component (Primitives)
    - the environment
    - the mission and scenario
  - the definition and execution of the analysis (lumped parameter approach)
  - the evaluation or assessment of the results
  - Use of Open Source Software (OSS) as far as possible
- Approach *in my role as a developer*
  - Survey of suitable OSS
  - Development of the general architecture
  - Implementation, test and ...

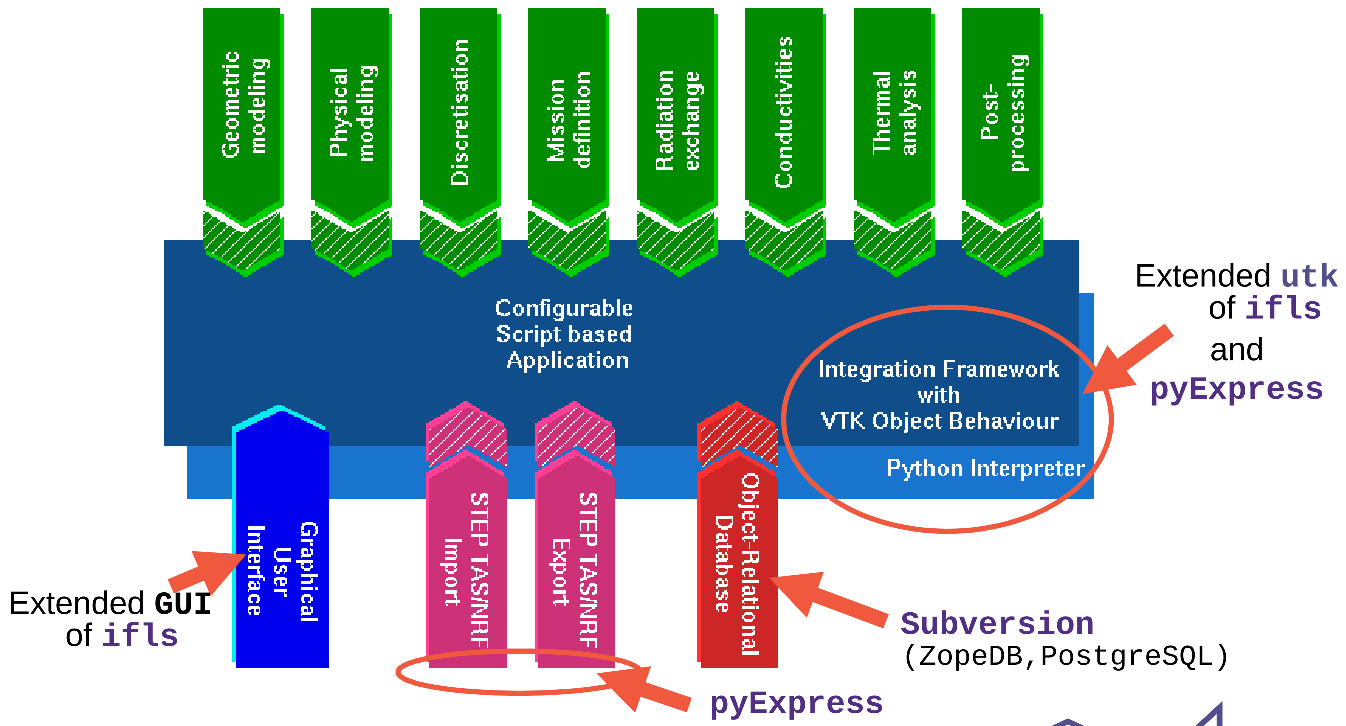
Architecture

Proposed Design



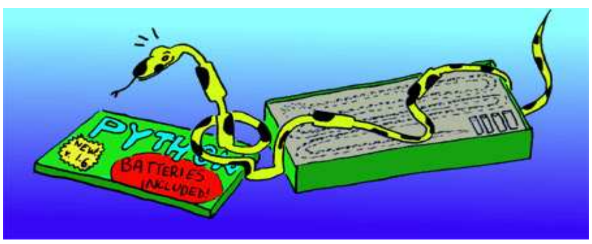
Architecture

- Engineering Infrastructure



Architectural Components

- **ifls** uses for Implementation and Scripting
  - **Python**
    Object-orientiented scripting language contains elements of traditional languages
    - Nice, simple syntax
    - Modular structure
    - Great number of books
    - Unix, Windows, ... very stable
    - Scientific computing
    - Increasing acceptance



```
class MyClass:
    "A simple example class"
    i = 123
    def f(x):
        if x > 0:
            return 1
        else:
            return 0
```

Standard packages of **Python**

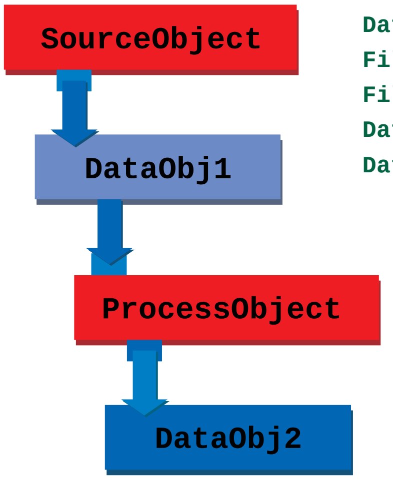
- **Tkinter**:
  Widgets from **Tk** for GUI's
- **Numerical/numpy**:
  Vector / matrix objects
- **Scientific Python**:
  Scientific tools, MPI, NetCDF, Optimization, ...

Interface generators

- **pyfort**: **Fortran**
- **swig**: **C, C++**

Architectural Components

- **ifls** extents the **vtk** pipeline
  - DataObjects
    represent information
  - ProcessObjects
    operates on input data to generate output data
  - Pipeline Execution
    causes processObjects to operate



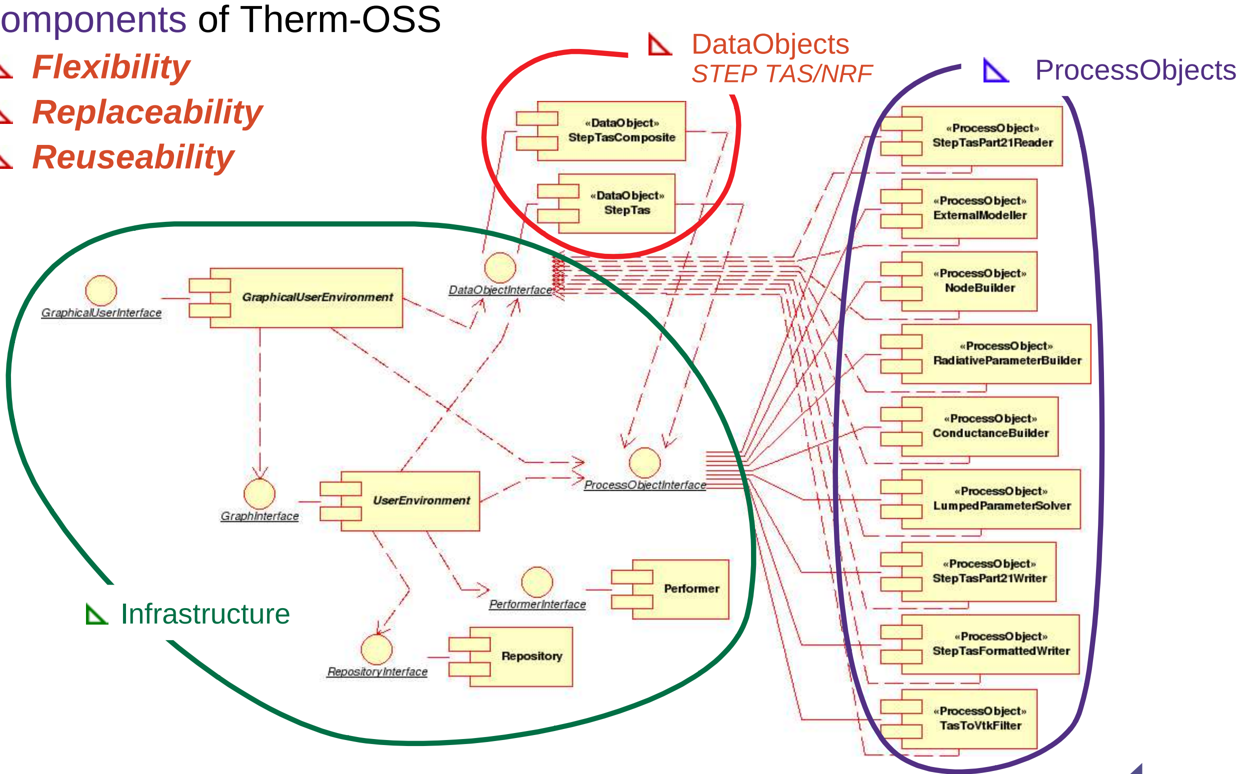

```
Reader = SourceObject()
DataObj1 = Reader.GetOutput()
Filter = ProcessObject()
Filter.SetInput( DataObj1 )
DataObj2 = Filter.GetOutput()
DataObj2.Update()
```

New approach of solving problems with software components

utk connects **vtk** and pure **Python** classes to maintain pipeline mechanisms

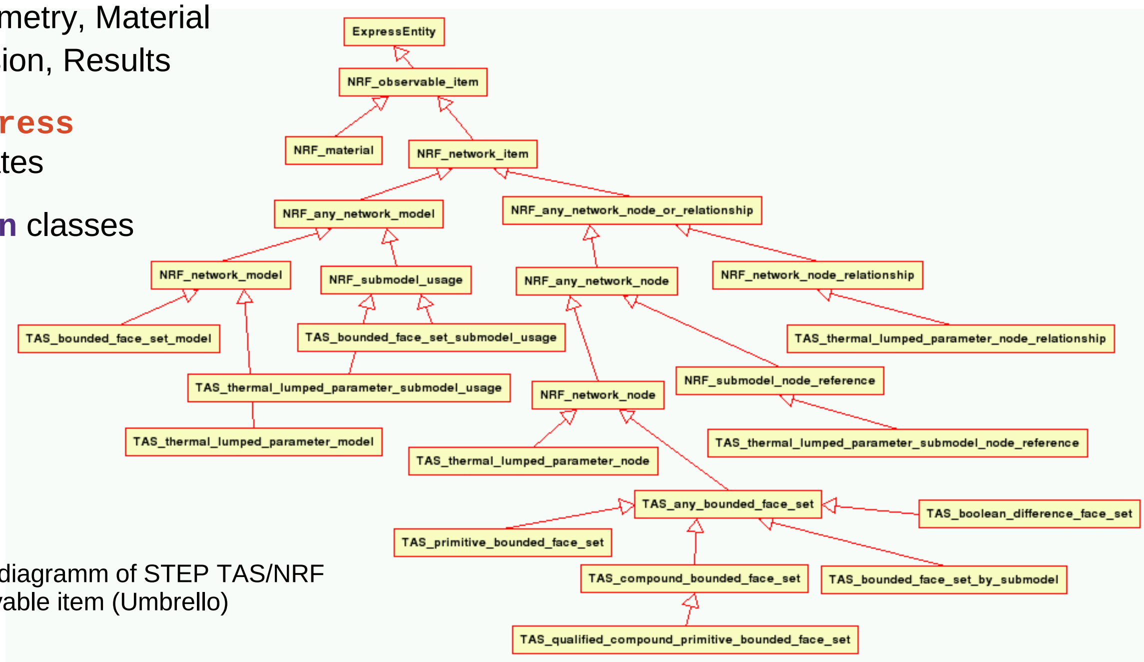
Architectural Components

- Components of Therm-OSS
  - ***Flexibility***
  - ***Replaceability***
  - ***Reuseability***



Architectural Components

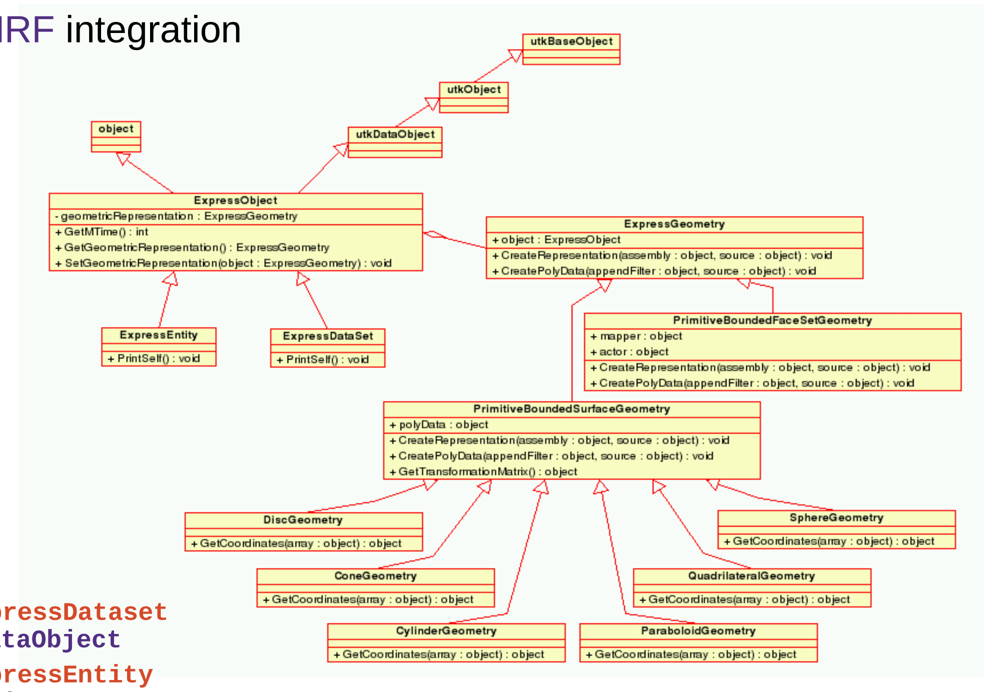
- STEP TAS/NRF integration
  - STEP TAS/NRF data model
    - Geometry, Material
    - Mission, Results
  - **PyExpress** generates **Python** classes



- Class diagramm of STEP TAS/NRF observable item (Umbrello)

Architectural Components

- STEP TAS/NRF integration

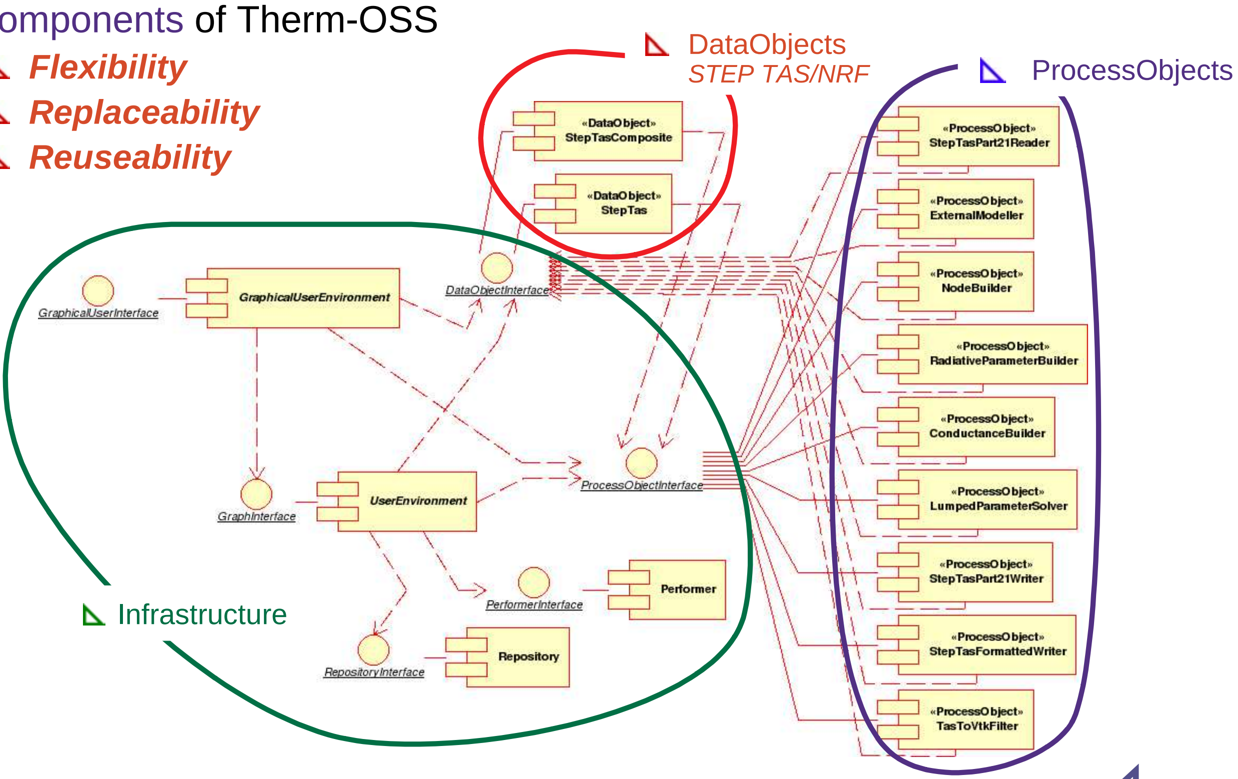


- Inheritance
  - Deriving **ExpressDataset** from **utkDataObject**
  - Deriving **ExpressEntity** from **utkObject**
- Adding attribute **model**
  - Representation / physics

- Class diagramm of STEP TAS/NRF UTK integration

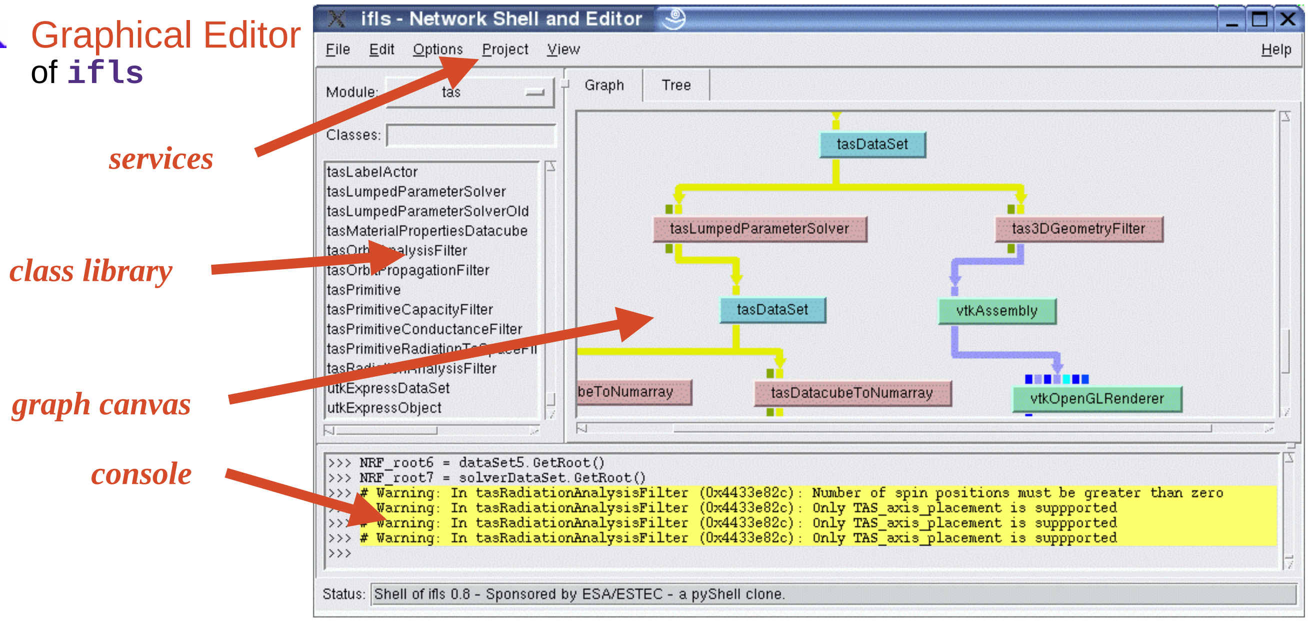
Architectural Components

- Components of Therm-OSS
  - ***Flexibility***
  - ***Replaceability***
  - ***Reuseability***



Architectural Components

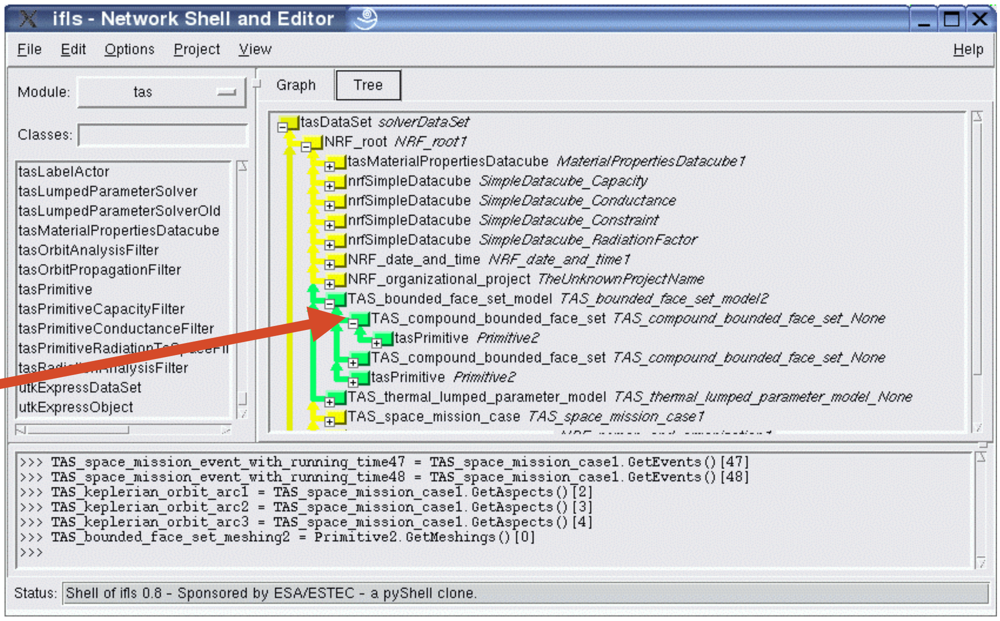
- Graphical Editor of **`ifls`**



- Interactive manipulation and visual programming of networks/dataflow
- Analyses and visualizes the programmed object interactions/networks (tree / **graph**)
- **`Python`** codes are executable without the graphical editor in batch mode

Architectural Components

- **Graphical Editor** of `ifls`

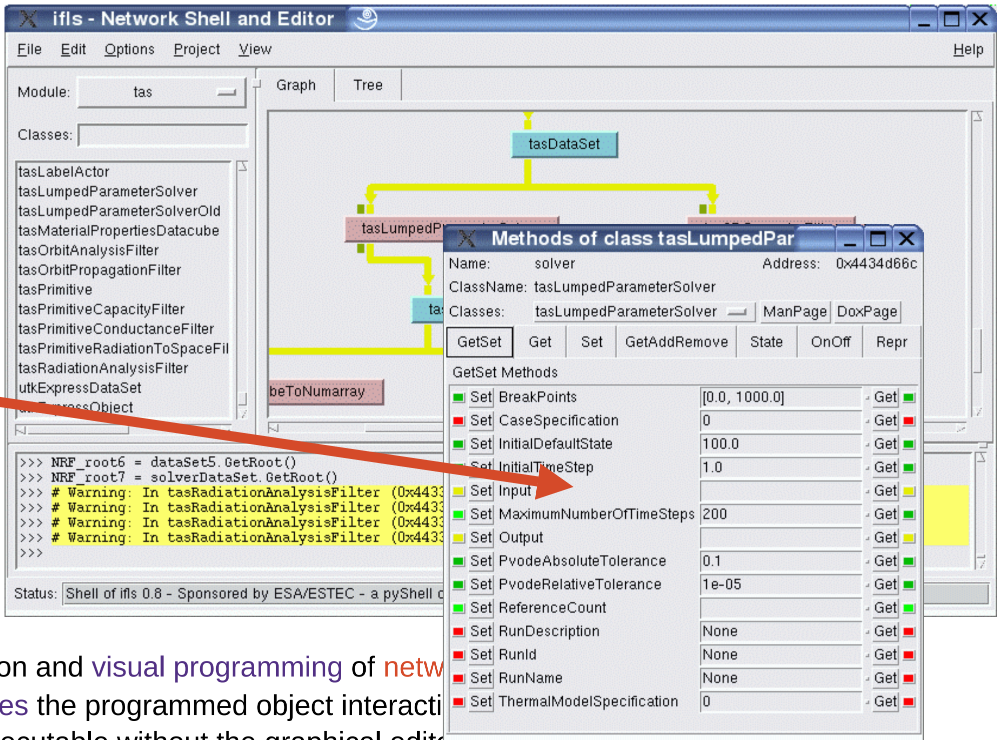


tree canvas

- Interactive manipulation and visual programming of networks/dataflow
- Analyses and visualizes the programmed object interactions/networks (**tree** / graph)
- `Python` codes are executable without the graphical editor in batch mode

Architectural Components

- **Graphical Editor** of `ifls`

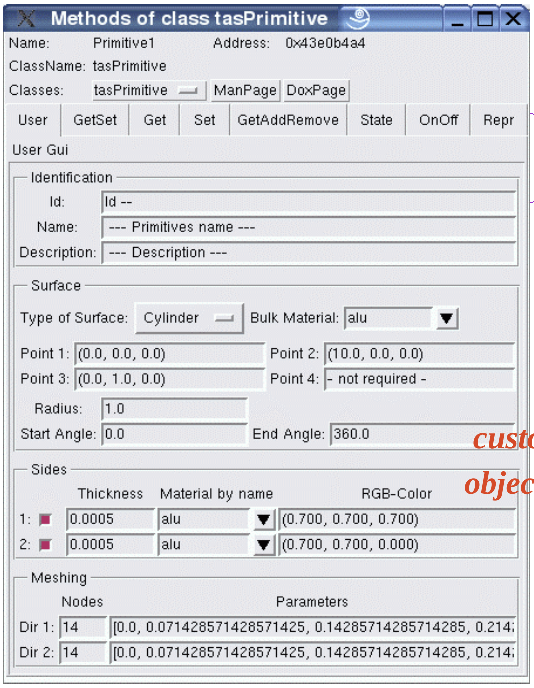


generic object editor

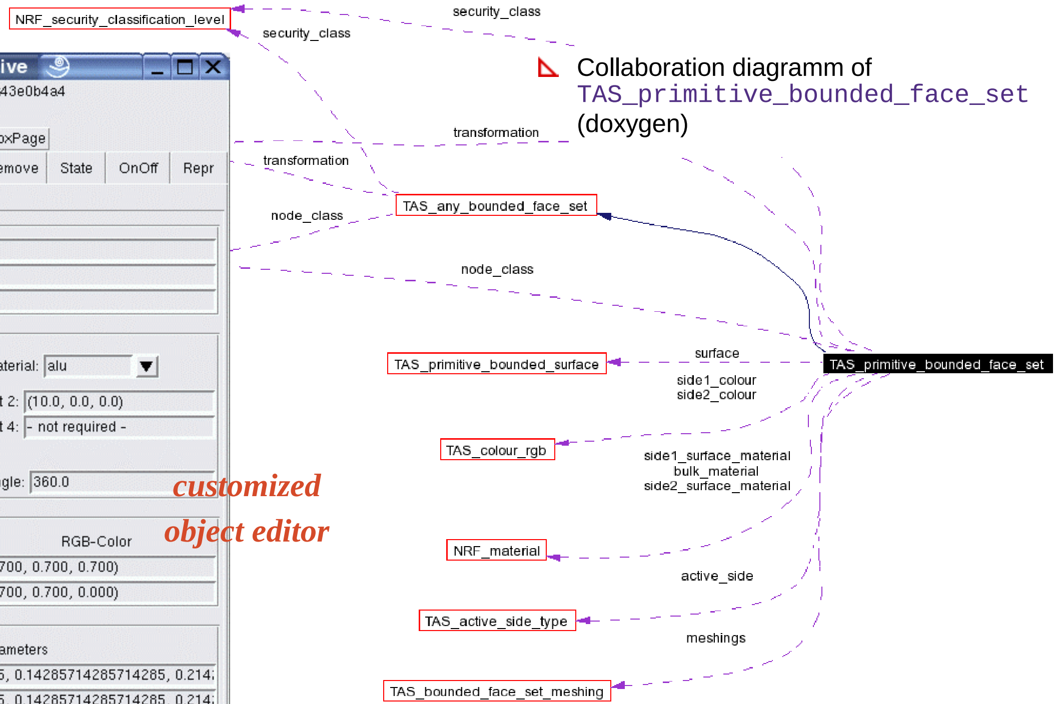
- Interactive manipulation and visual programming of netw…
- Analyses and visualizes the programmed object interacti…
- `Python` codes are executable without the graphical editor in batch mode

Architectural Components

- Composite Classes ... to hide the aggregation ... for easy use.



customized object editor



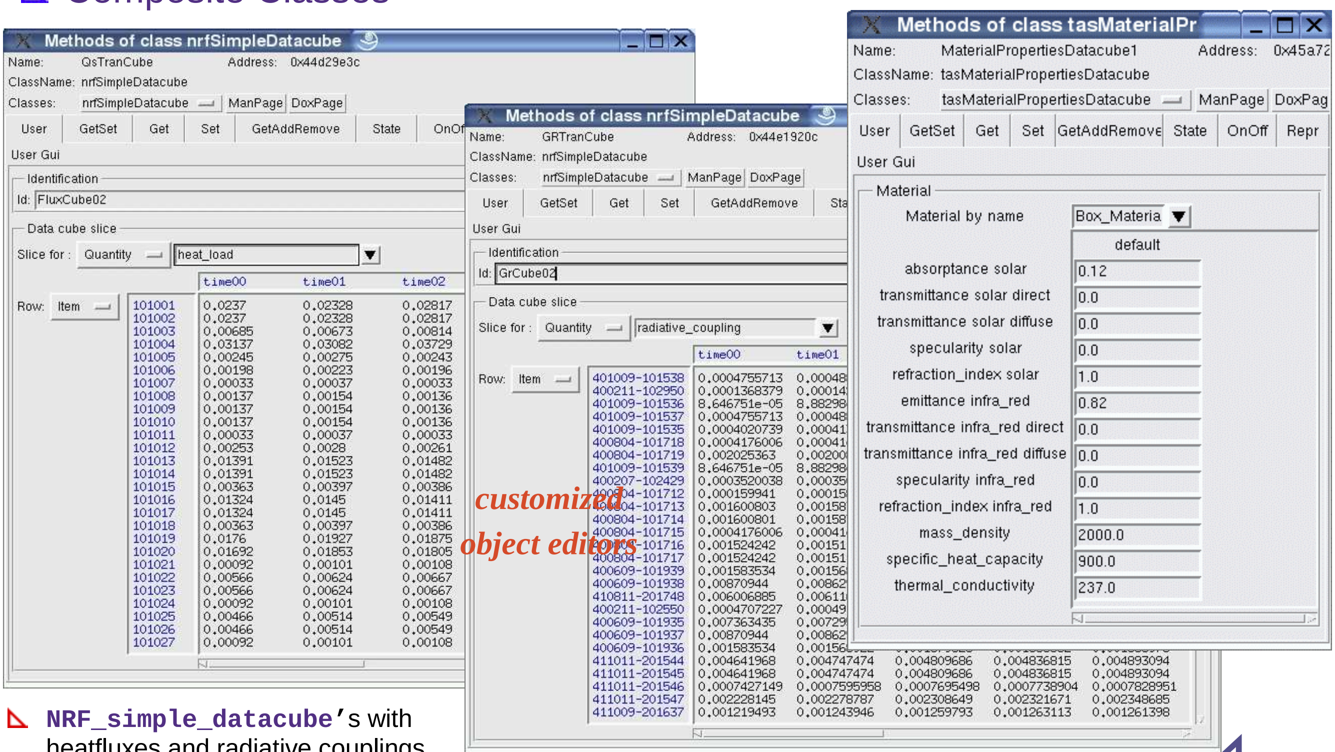
- Collaboration diagramm of `TAS_primitive_bounded_face_set` (doxygen)

IFL

Architectural Components

- Composite Classes

- `TAS_material_properties_datacube`



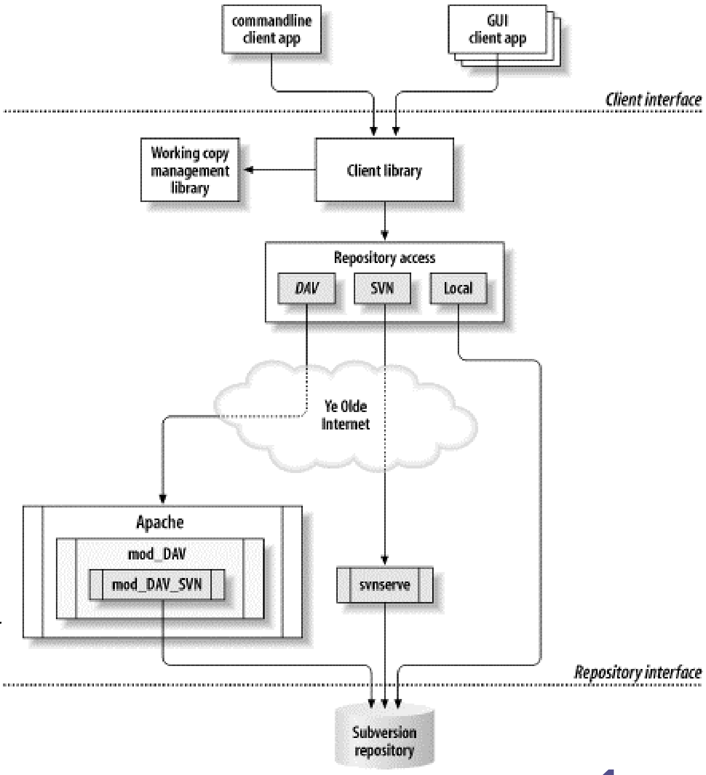
customized object editors

- `NRF_simple_datacube`'s with heatfluxes and radiative couplings

IFL

Architectural Components

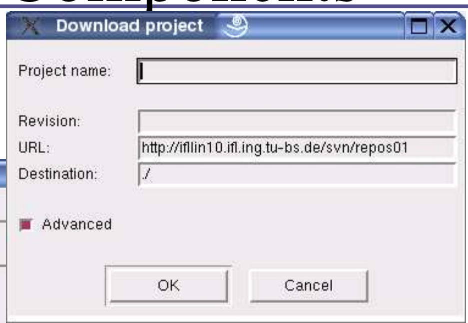
- Version Control
  - File oriented environment
    - Python scripts, STEP-TAS files, …
  - Subversion
    - Manages Files (incl. binary) … and Directories
    - Central repository … similar to CVS
    - Choice of network layer … (http/svn/ssh)
    - Collection of shared libraries … Python bindings
  - Extension of the environment with a *simple* client

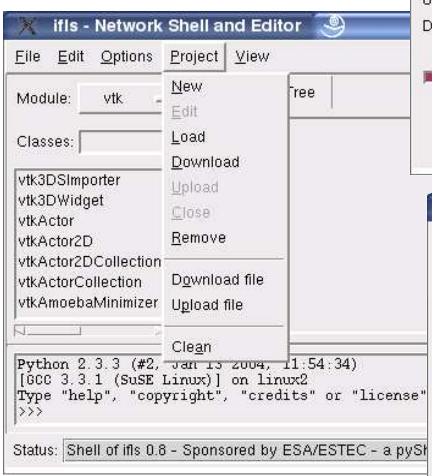


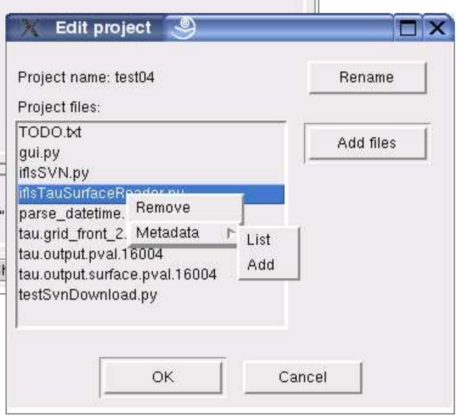
IFL

Architectural Components

- Version Control



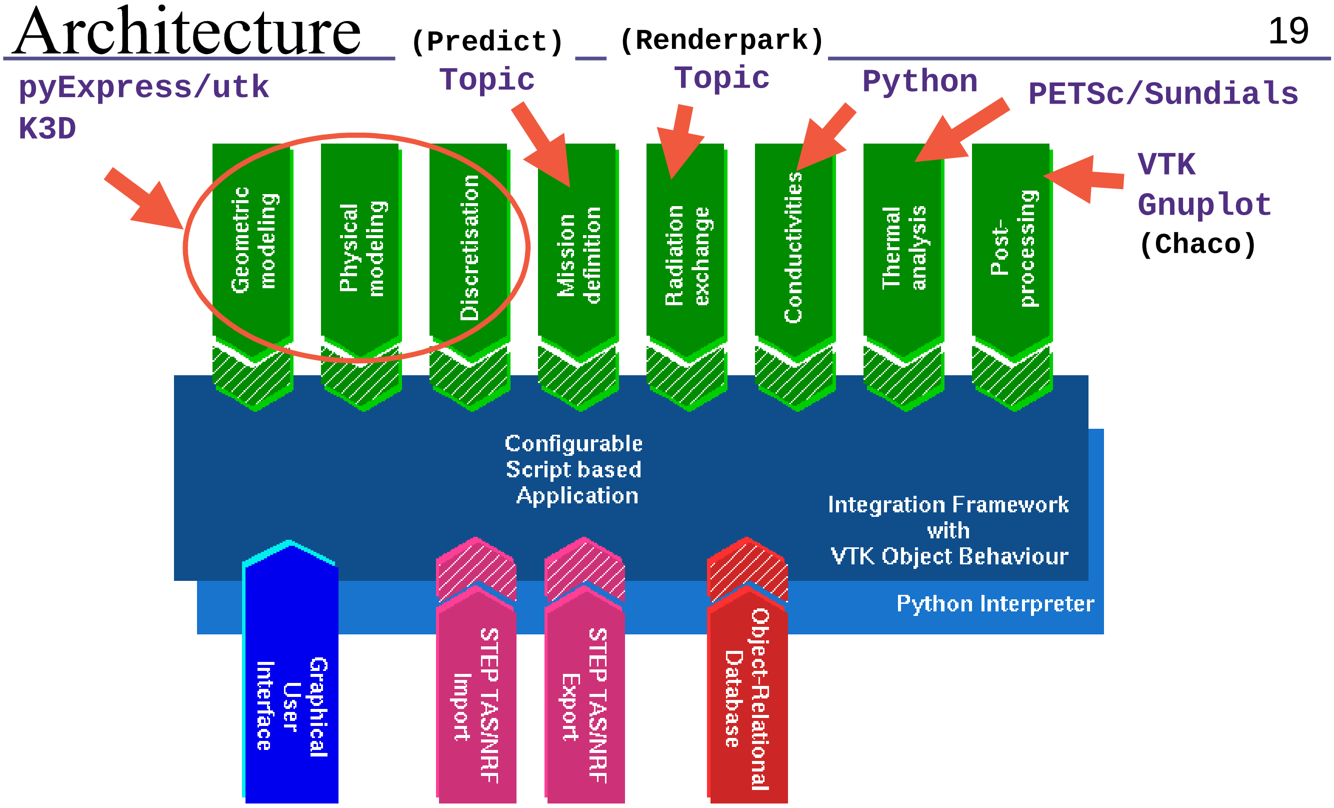




- Extension of the environment with a *simple* client

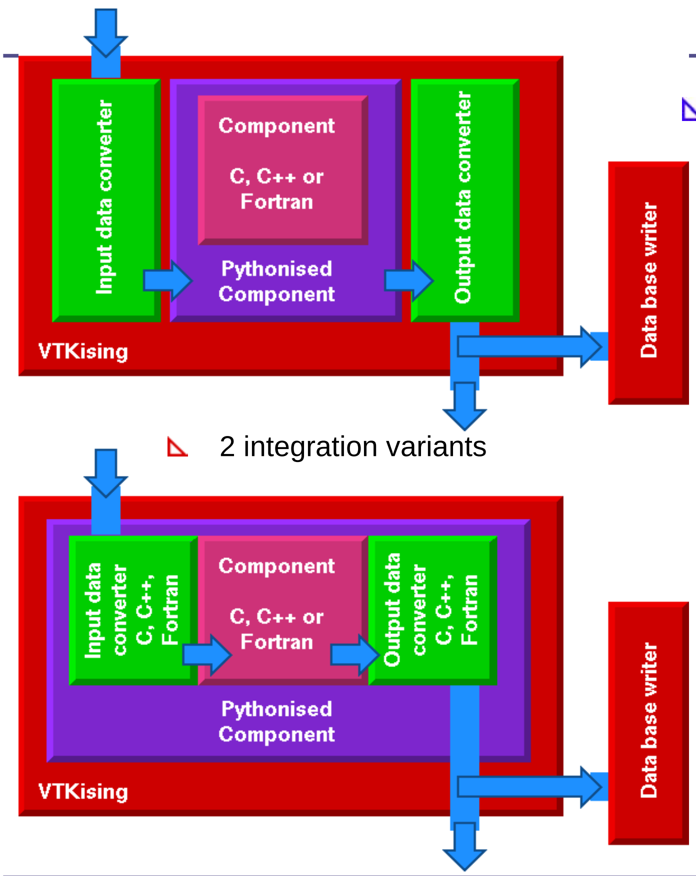
IFL

Architecture



- Functional modules

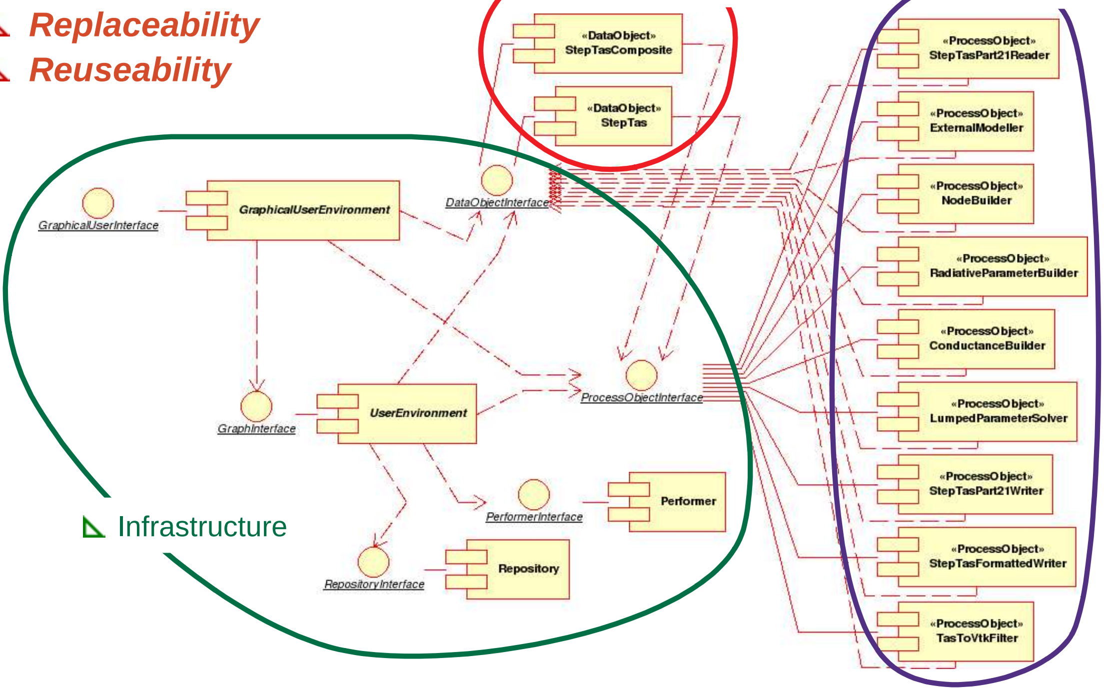
Integration



- Integration of modules / tools as ProcessObjects:
  - **VTK** ising makes tool behave like a ProcessObject.
  - Data Transforming converts the input format into the tools format and vice versa *if required.*
  - `Python`-ising tool must talk `Python`.

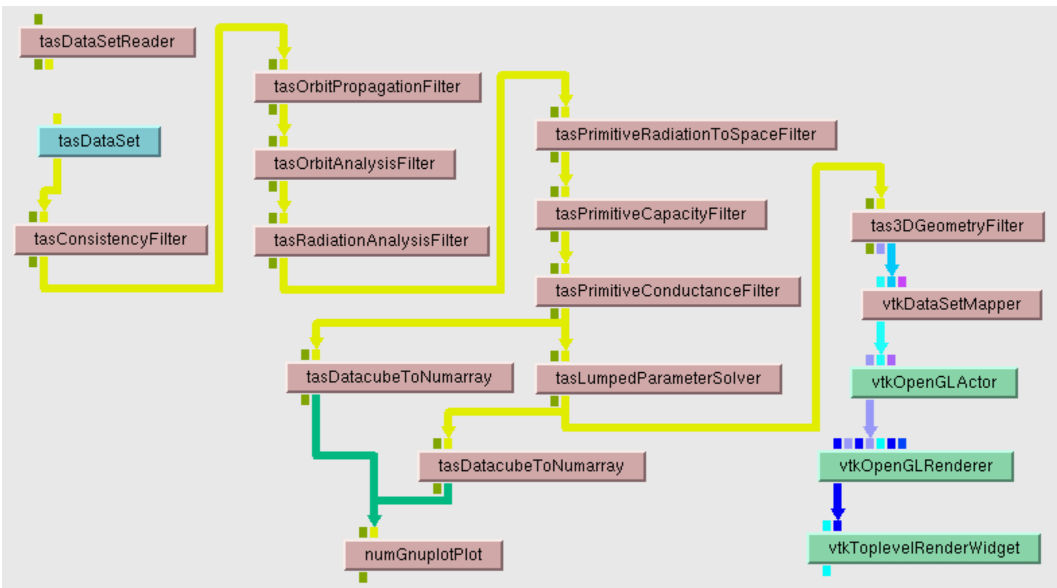
Architectural Components

- **Components** of Therm-OSS
  - ***Flexibility***
  - ***Replaceability***
  - ***Reuseability***
- DataObjects
  STEP TAS/NRF
- ProcessObjects
- Infrastructure



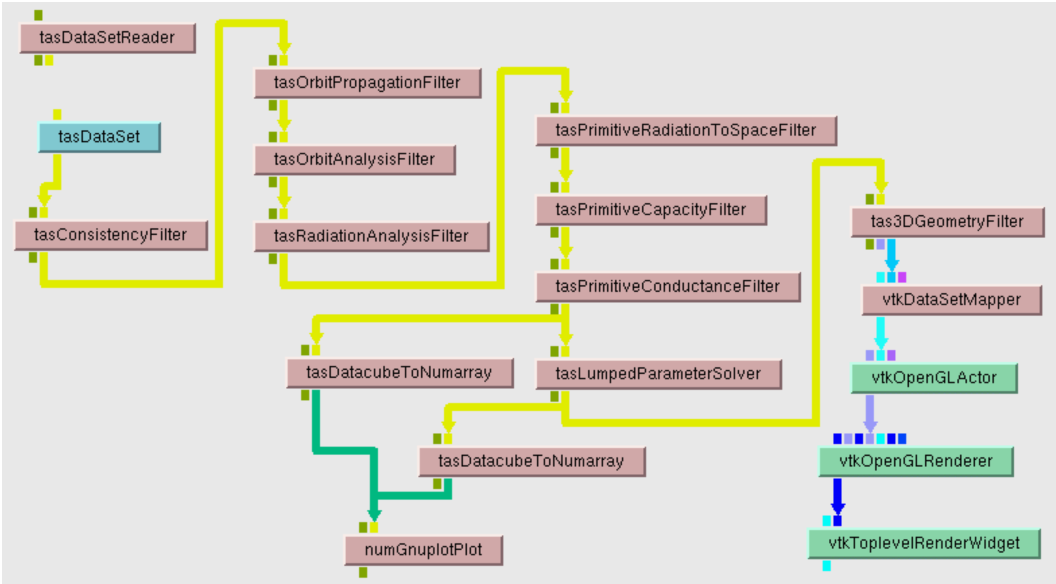
Application

- The Network ... from persistence storage, script or via GUI



Application

- The Network ... from persistence storage, script or via GUI

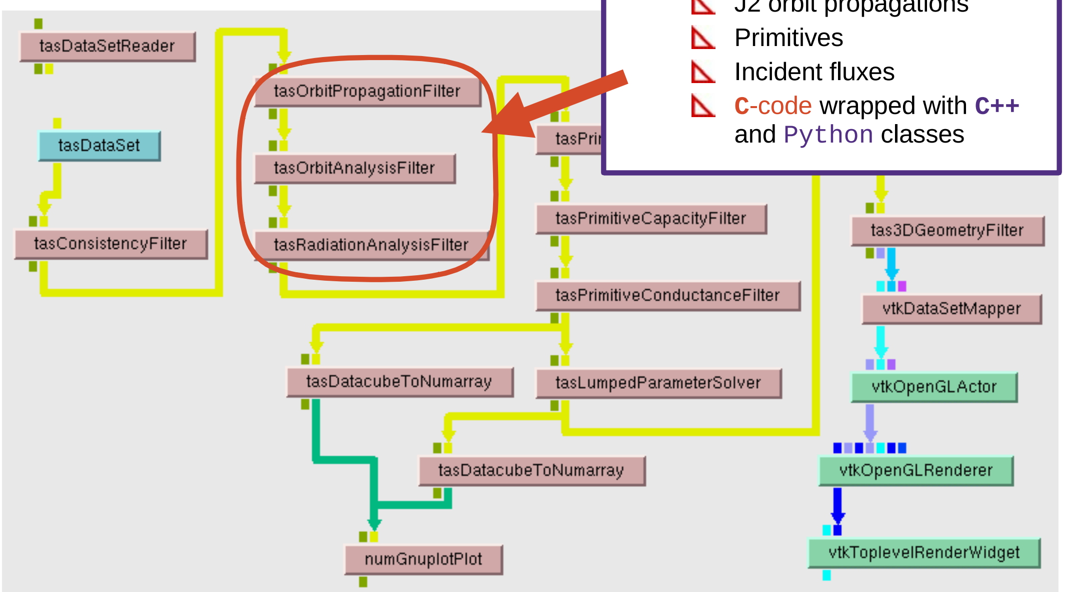


Build your own application
Include your own components

Application

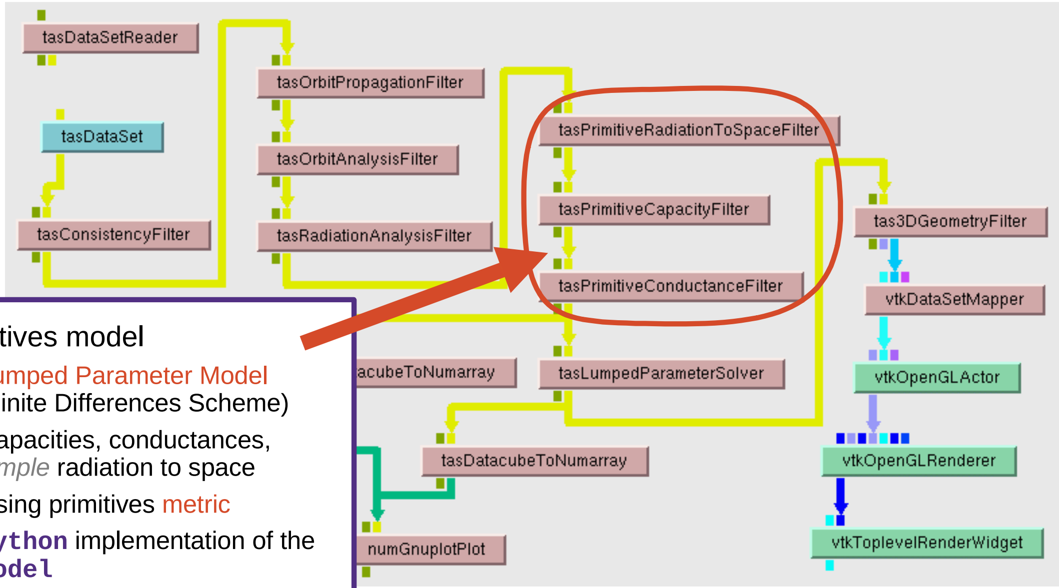
- The Network

- Topic (ESA/ESTEC):
  - Earth orbits
  - J2 orbit propagations
  - Primitives
  - Incident fluxes
  - C-code wrapped with **C++** and `Python` classes



Application

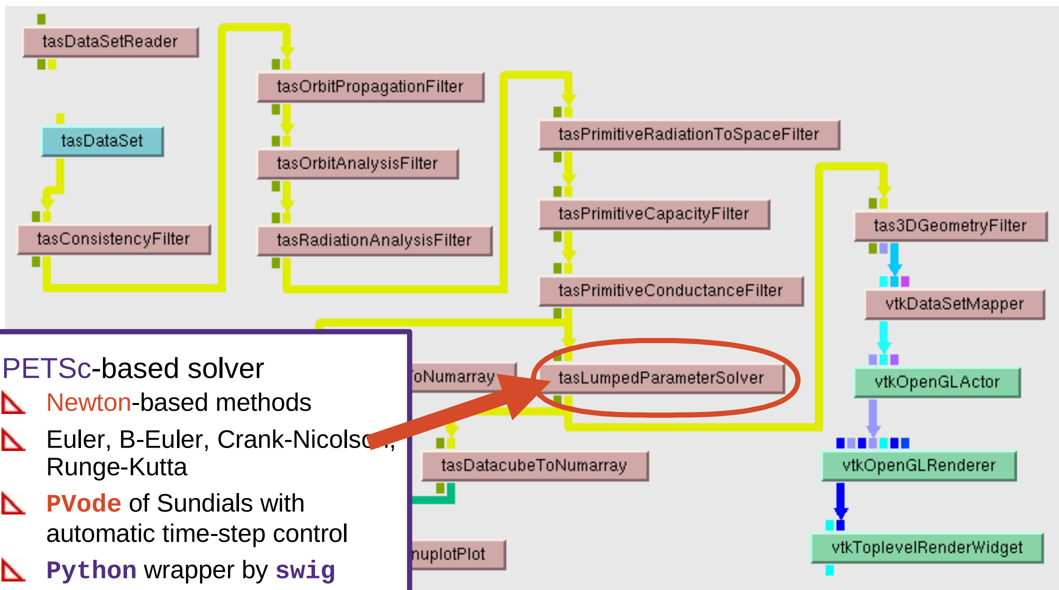
- The Network



- Primitives model
  - Lumped Parameter Model (Finite Differences Scheme)
  - Capacities, conductances, *simple* radiation to space
  - Using primitives metric
  - `Python` implementation of the `model`

Application

- The Network



- PETSc-based solver
  - Newton-based methods
  - Euler, B-Euler, Crank-Nicolson, Runge-Kutta
  - `PVode` of Sundials with automatic time-step control
  - `Python` wrapper by `swig`
  - General solver class
  - `Function` and `Jacobian`
  - Robust and fast

Applic

The Netw

OHB-Example

```
# Stdout: Nonlinear solver
# Stdout:                 Iteration   Residual
# Stdout: SNES-Convergence    0        1.38101e+02
# Stdout: SNES-Convergence    1        4.89064e-01
# Stdout: SNES-Convergence    2        4.98388e-04
# Stdout: SNES-Convergence    3        7.53985e-08
# Stdout: SNES ConvergedReason: SNES_CONVERGED_FNORM_RELATIVE (F < F_mintol*F_initial)
# Note: SNES Number of iterations: 3; CPU time: 3.653200
# Stdout: SNES Object:
# Stdout:    type: ls
# Stdout:      line search variant: SNESCubicLineSearch
# Stdout:      alpha=0.0001, maxstep=1e+08, steptol=1e-12
# Stdout:    maximum iterations=50, maximum function evaluations=10000
# Stdout:    tolerances: relative=1e-08, absolute=1e-50, solution=1e-08
# Stdout:    total number of linear solver iterations=18
# Stdout:    total number of function evaluations=4
# Stdout:    KSP Object:
# Stdout:      type: gmres
# Stdout:        GMRES: restart=30, using Classical (unmodified) Gram-Schmidt Orthogonalization with no it
# Stdout:        GMRES: happy breakdown tolerance 1e-30
# Stdout:      maximum iterations=10000, initial guess is zero
# Stdout:      tolerances:  relative=1e-05, absolute=1e-50, divergence=10000
# Stdout:      left preconditioning
# Stdout:    PC Object:
# Stdout:      type: ilu
# Stdout:        ILU: 10 levels of fill
# Stdout:        ILU: max fill ratio allocated 1
# Stdout:        ILU: tolerance for zero pivot 1e-12
# Stdout:             out-of-place factorization
# Stdout:             matrix ordering: nd
# Stdout:             Factored matrix follows
# Stdout:        Matrix Object:
# Stdout:          type=seqaij, rows=3138, cols=3138
# Stdout:          total: nonzeros=256010, allocated nonzeros=256010
# Stdout:            not using I-node routines
# Stdout:      linear system matrix = precond matrix:
# Stdout:      Matrix Object:
# Stdout:        type=seqaij, rows=3138, cols=3138
# Stdout:        total: nonzeros=21380, allocated nonzeros=56898
# Stdout:          not using I-node routines
```

PE

IFL

Applic

The Netw

OHB-Example

```
# Stdout: Transient Solver
# Stdout:         Timestep   Time
# Stdout: TS         0       0.00000e+00
# Stdout: TS         1       1.90181e-03
# Stdout: TS         2       1.90200e+01
  ....
# Stdout: TS       129       5.39841e+03
# Stdout: TS       130       5.45760e+03
# Note: TS Number of time steps: 130; final time: 5457.602388; CPU time: 34.318804
# Stdout: TS Object:
# Stdout:    type: pvode
# Stdout:    PVode integrater does not use SNES!
# Stdout:    PVode integrater type BDF: backward differentiation formula
# Stdout:    PVode abs tol 0.01 rel tol 1e-06
# Stdout:    PVode linear solver tolerance factor 0.05
# Stdout:    PVode GMRES max iterations (same as restart in PVODE) 5
# Stdout:    PVode using unmodified (classical) Gram-Schmidt for orthogonalization in GMRES
# Stdout:      PC Object:
# Stdout:        type: ilu
# Stdout:          ILU: 10 levels of fill
# Stdout:          ILU: max fill ratio allocated 1
# Stdout:          ILU: tolerance for zero pivot 1e-12
# Stdout:               out-of-place factorization
# Stdout:               matrix ordering: nd
# Stdout:               Factored matrix follows
# Stdout:          Matrix Object:
# Stdout:            type=seqaij, rows=3138, cols=3138
# Stdout:            total: nonzeros=256010, allocated nonzeros=256010
# Stdout:              not using I-node routines
# Stdout:        linear system matrix = precond matrix:
# Stdout:        Matrix Object:
# Stdout:          type=seqaij, rows=3138, cols=3138
# Stdout:          total: nonzeros=21380, allocated nonzeros=56898
# Stdout:            not using I-node routines
# Stdout:    maximum steps=1000
# Stdout:    maximum time=5400
# Stdout:    total number of nonlinear solver iterations=212
# Stdout:    total number of linear solver iterations=197
```

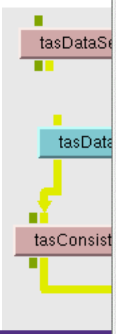
PE

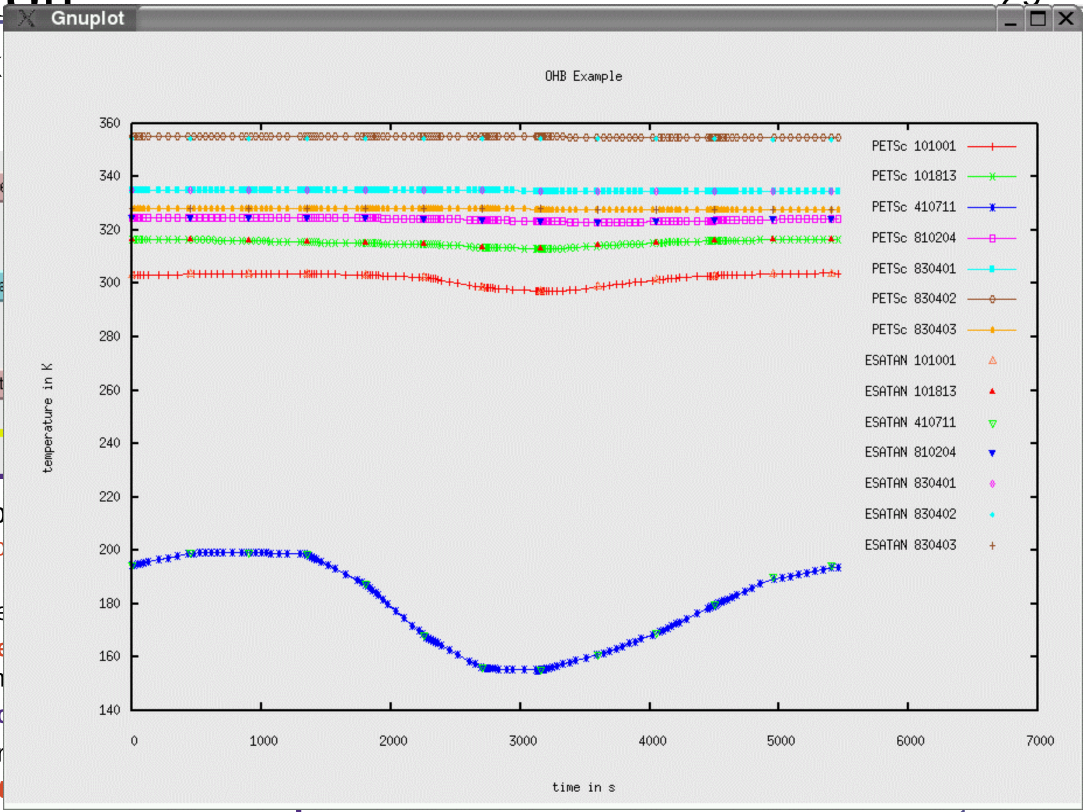
- Robust and fast

IFL

Application

- The Network





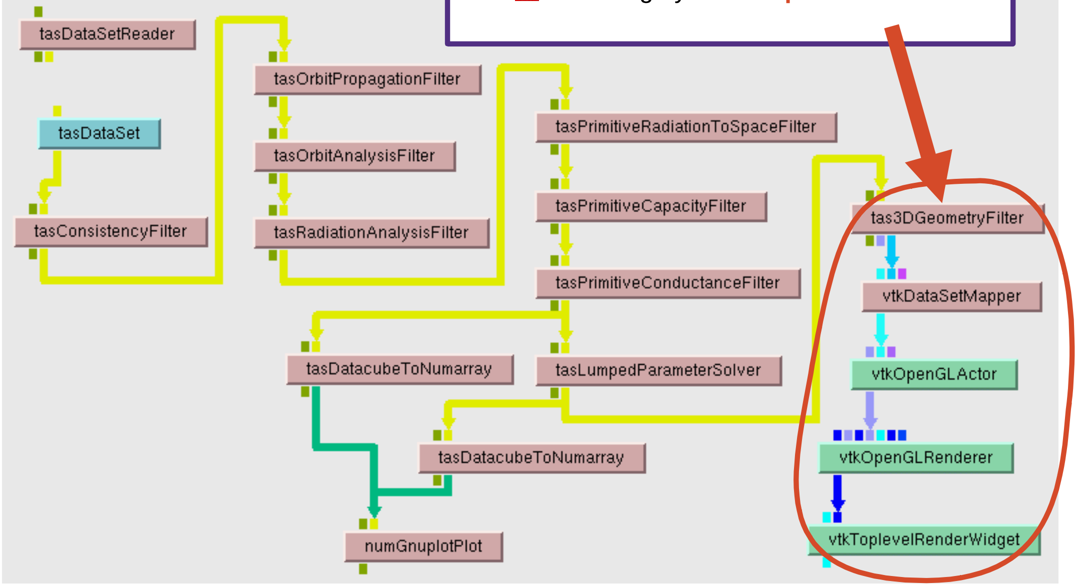
- PETSc-b
  - Newto
  - Euler, Runge
  - PVode autom
  - Pytho
  - Gener
  - Funct
  - Robust and fast

IFL

Application

- The Network

- **vtk**-based visualization
  - **STEP TAS** to **vtk** conversion
  - **vtk**-processing and rendering
  - 3D-geometry incl. Labels
  - Coloring by **nrfSimpleDatacube**

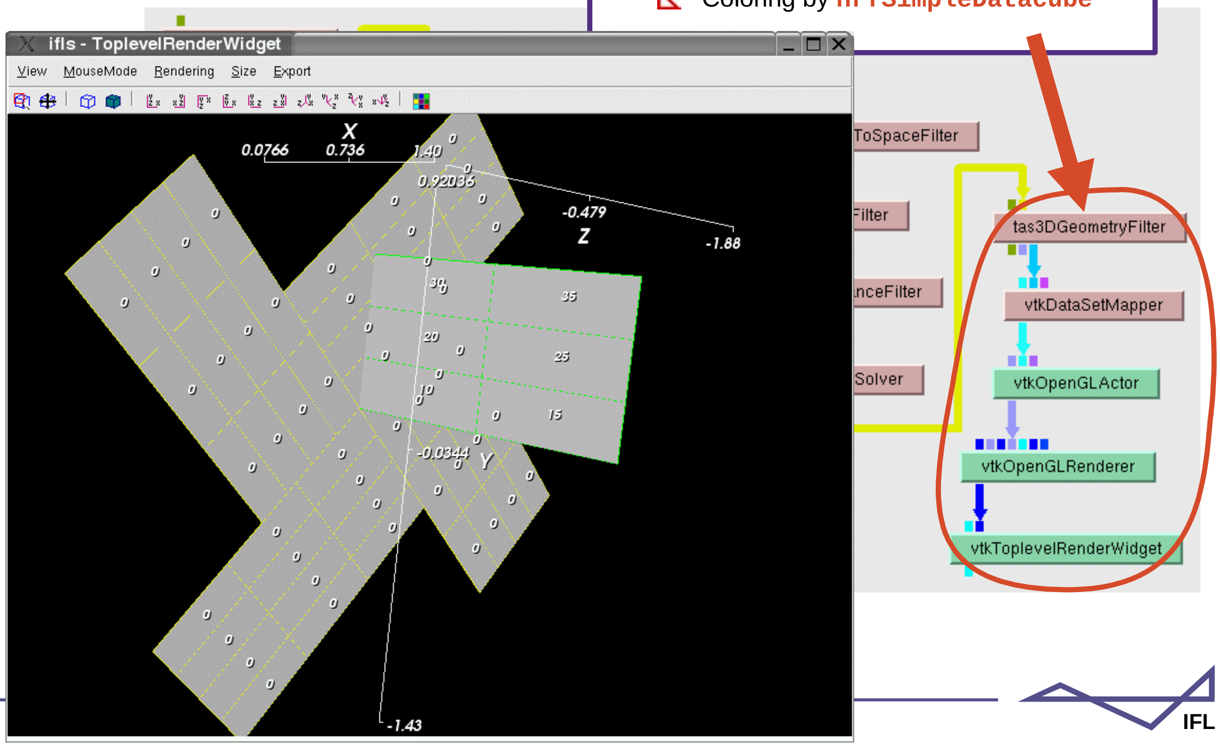


IFL

Application

- The Network

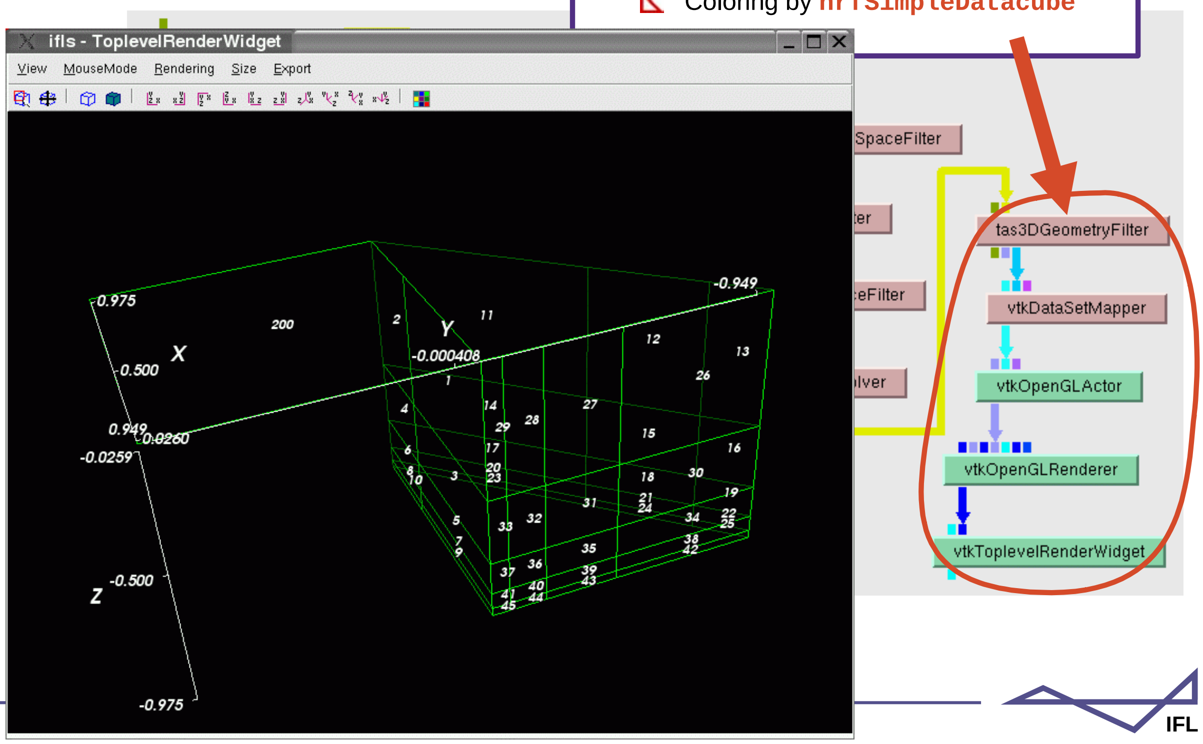
- **vtk**-based visualization
  - **STEP TAS** to **vtk** conversion
  - **vtk**-processing and rendering
  - 3D-geometry incl. Labels
  - Coloring by **nrfSimpleDatacube**



Application

- The Network

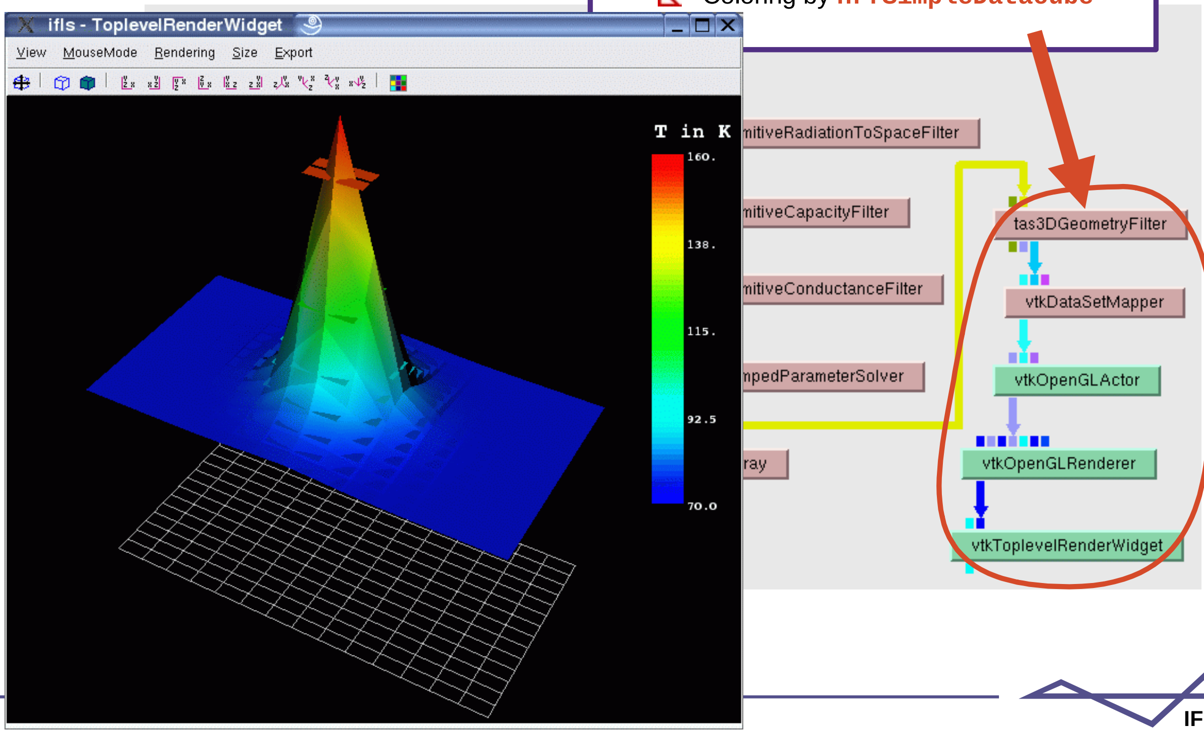
- **vtk**-based visualization
  - **STEP TAS** to **vtk** conversion
  - **vtk**-processing and rendering
  - 3D-geometry incl. Labels
  - Coloring by **nrfSimpleDatacube**



Application

- The Network

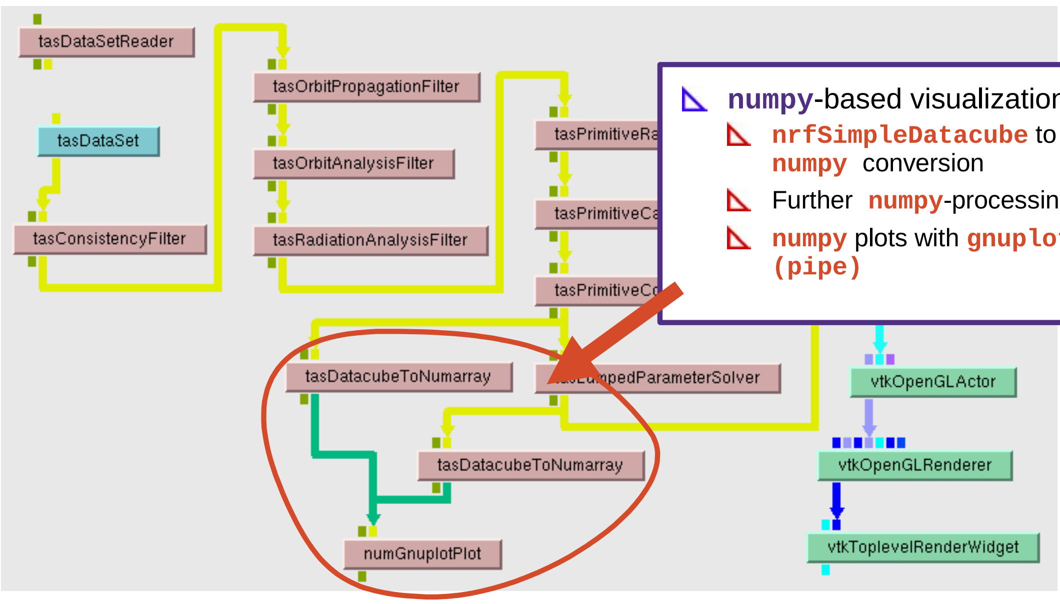
- **vtk**-based visualization
  - **STEP TAS** to **vtk** conversion
  - **vtk**-processing and rendering
  - 3D-geometry incl. Labels
  - Coloring by **nrfSimpleDatacube**



Application

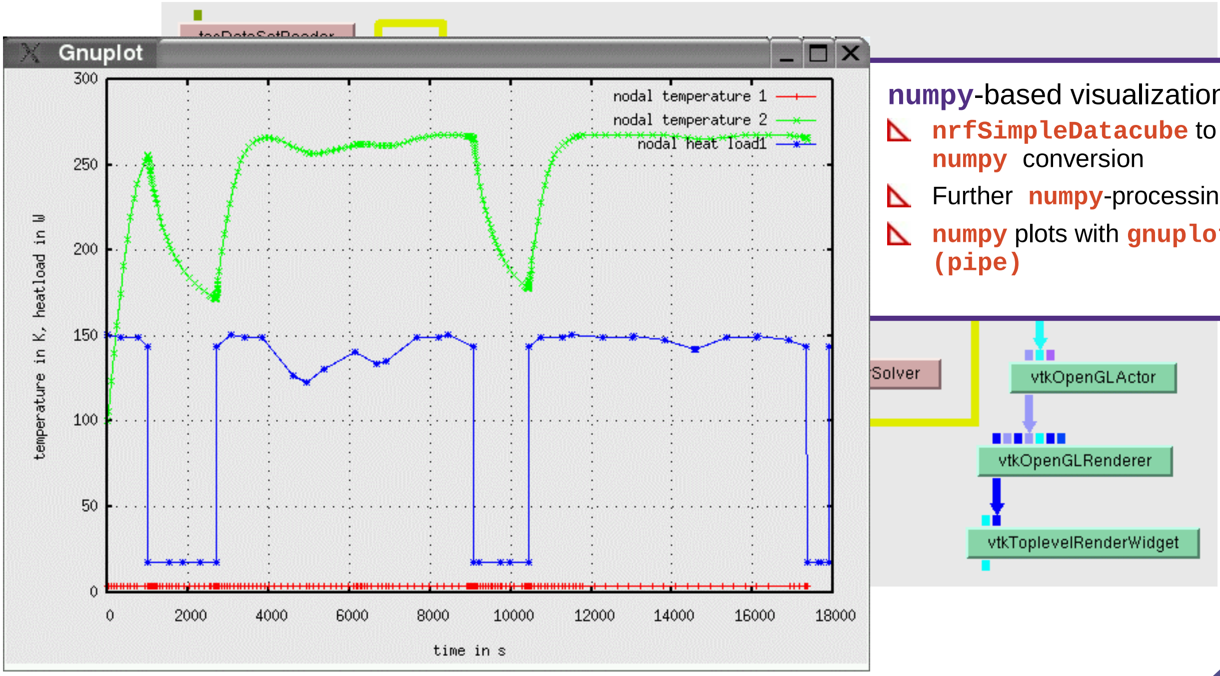
- The Network

- **numpy**-based visualization
  - **nrfSimpleDatacube** to **numpy** conversion
  - Further **numpy**-processing
  - **numpy** plots with **gnuplot (pipe)**



Application

- The Network



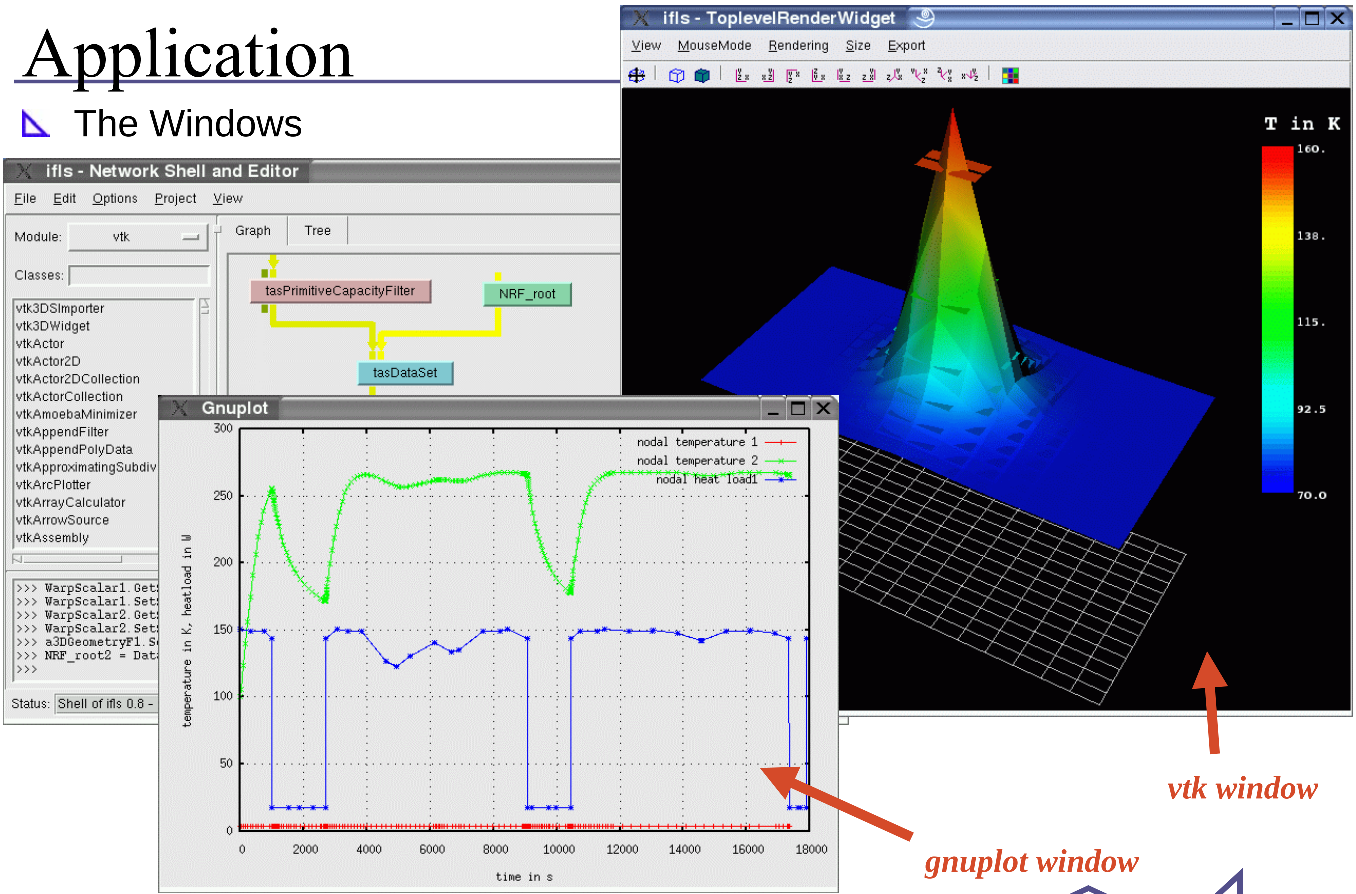
numpy-based visualization

- **nrfSimpleDatacube** to **numpy** conversion
- Further **numpy**-processing
- **numpy** plots with **gnuplot (pipe)**

IFL

Application

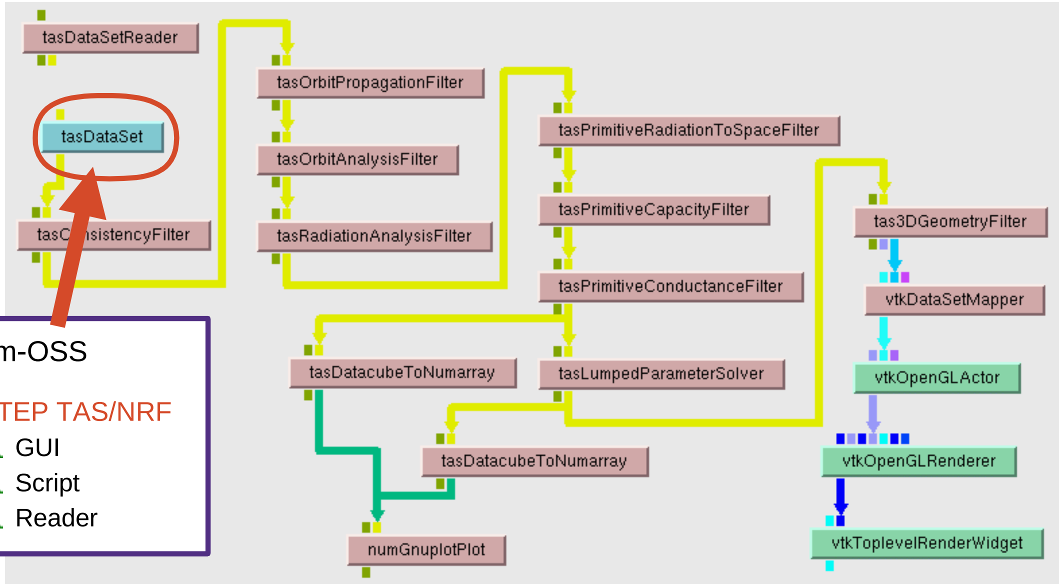
- The Windows



IFL

Application

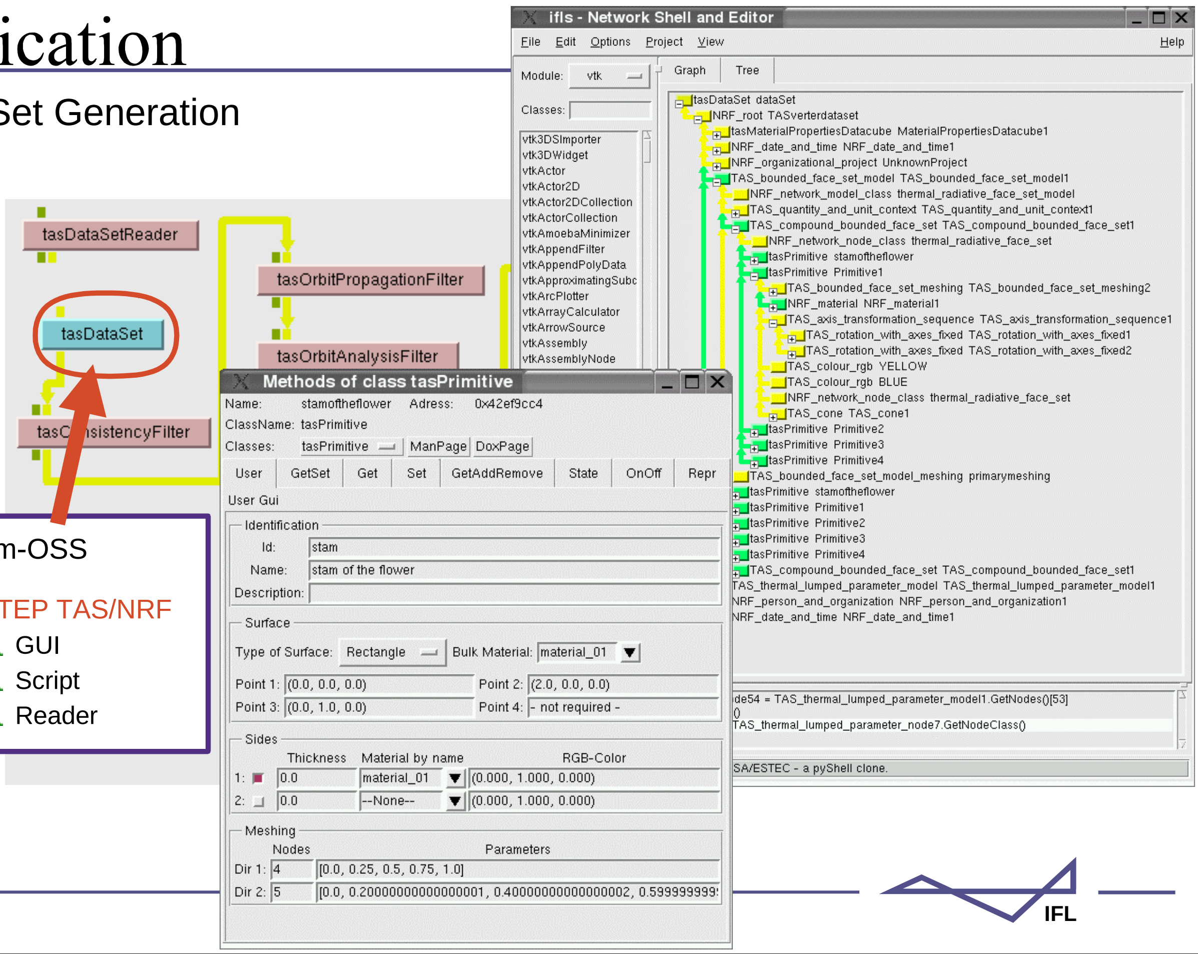
DataSet Generation



- Therm-OSS
  - STEP TAS/NRF
    - GUI
    - Script
    - Reader

Application

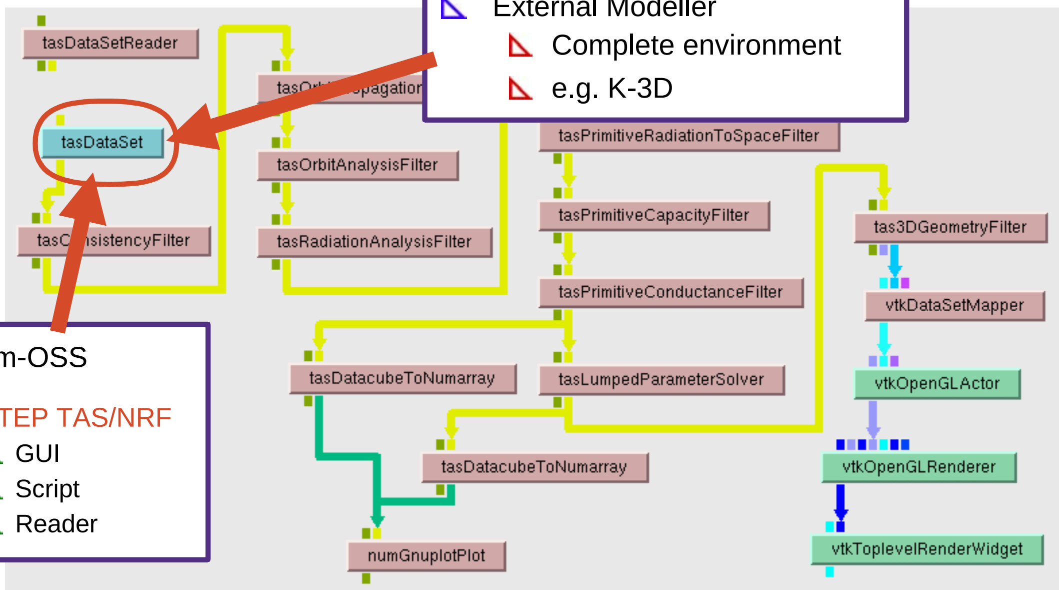
DataSet Generation



- Therm-OSS
  - STEP TAS/NRF
    - GUI
    - Script
    - Reader

Application

- DataSet Generation

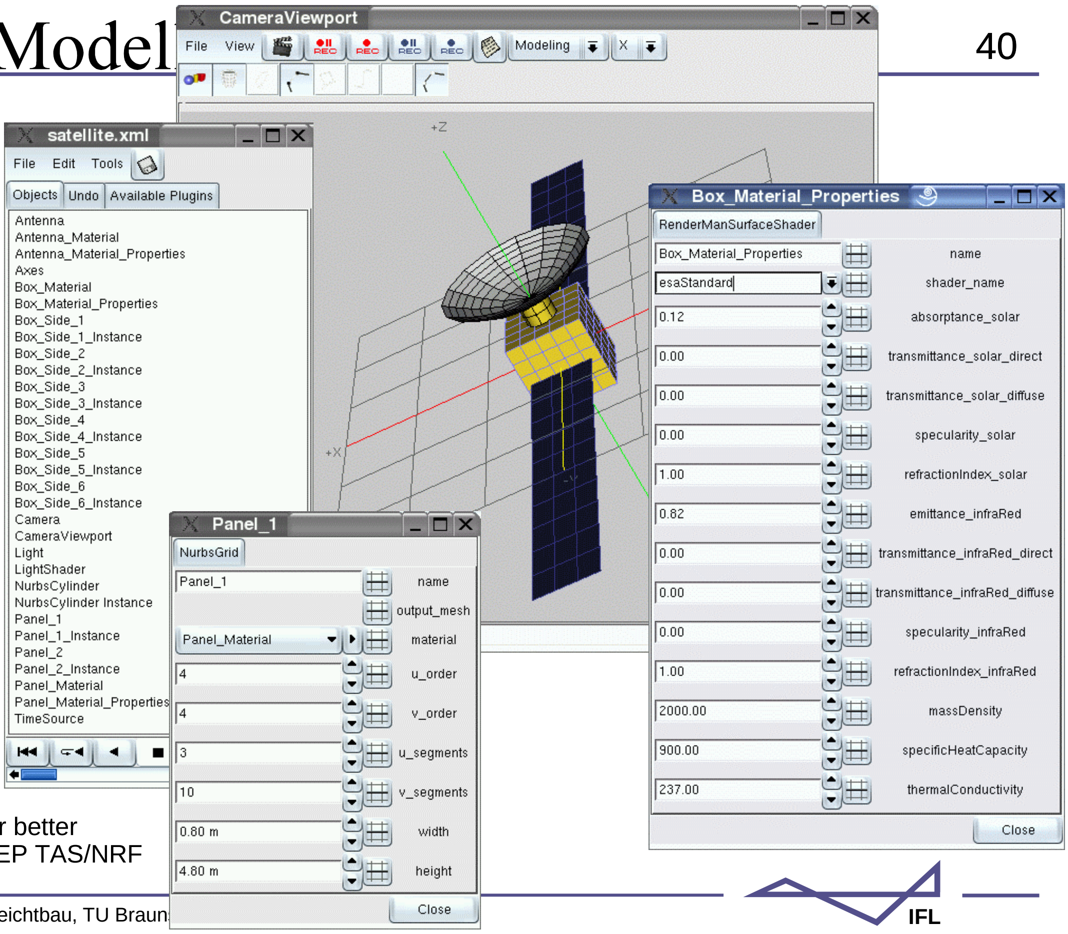


- External Modeller
  - Complete environment
  - e.g. K-3D

- Therm-OSS
  - STEP TAS/NRF
    - GUI
    - Script
    - Reader

External Model

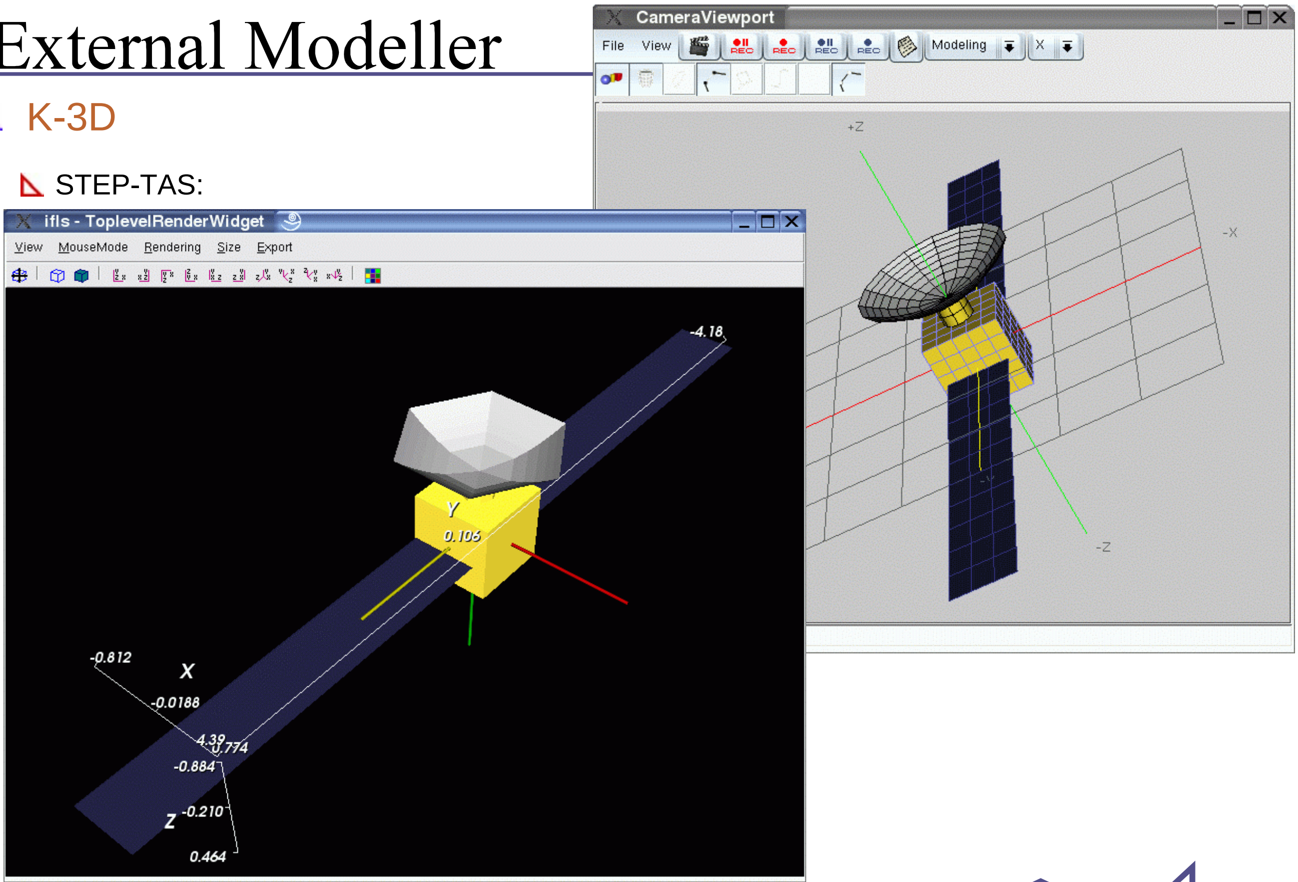
- K-3D
  - Primitives
    - RenderMan
    - NURBS
    - Meshes
  - Hierarchy
    - Graph
  - Material
    - Shader



- Therm-OSS
  - **Reader**
  - **Writer**
  - ***Filter***
  - ... ***Plug-Ins*** for better support of STEP TAS/NRF

External Modeller

- K-3D
  - STEP-TAS:



Conclusions Outlook

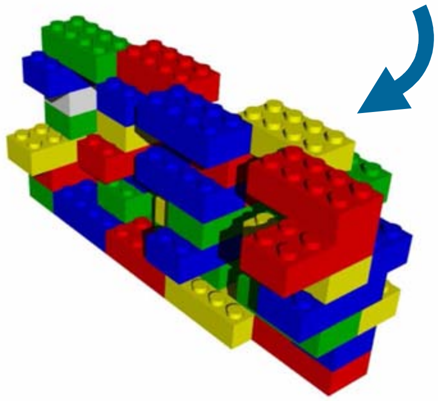
Lessons learned

- *Powerful tools for design, analysis and tool integration available as OSS*
- *Finding and evaluation of OSS is not easy*
- *License problem (free for research, not for commercial)*
- *Tools are 80-90 % satisfying*
- *Rapidly changing versions*
- *Don't think straight*

- *Open Source approach of a tool integration platform is successful*
- *Everything runs on Linux and Windows*
- *Installation from source*

www.Therm-OSS.org

Component based architecture



Therm-OSS development

- More comfortable for the simple user
- More sophisticated components
- *New components: Predict and RenderPark*

Objectives of the Therm-OSS Project

- To assess how OSS can be used to build applications
  - Architecture, components and processes of this prototype
- To provide to developers a useful source of reference for their developments
  - OSS-Survey, experiences and ideas
- To assess whether the OSS approach could be useful as a distributed model for end-users
  - Still open … interest for end-users ?

Appendix E: ESATAN, FHTS, ThermXL and ESARAD - Product Status

ESATAN, FHTS,
ThermXL
and
ESARAD
Product Status

C. Kirtley
ALSTOM

Oct 2004

ESATAN/FHTS, ThermXL & ESARAD Current Status

Chris Kirtley, Programme Manager

ALSTOM

Introduction

ALSTOM

- Many improvements made to the tools over 2004
- ESATAN v9.2 and ESARAD v5.6 being finalised
  - pre-release shortly available to Beta test sites
  - full releases planned early November 2004
- ThermXL version 3.0 released Jan 2004
- ThermXL version 4.0 under development
- Aim of presentation
  - outline the improvements & new functionality
  - highlight current development activities

- Introduction -

Contents: ESATAN

ALSTOM

ESATAN v9.2

- FHTS solver enhancements
- New elements
- Groups, Events & Phases
- Sink temperature
- Solution run-time monitor
- Thermal Network Viewer

FHTS Solver Enhancements

ALSTOM

FHTS Solver Development

Two-phase quasi-transient solver

- FGENFI extended to handle quasi-transient
  - hydraulic steady-state (pressure & flow rate)
  - selected as an option via QTRSOL (=YES || **NO**)
  - no need for a pressure boundary
  - assumes fixed fluid mass within loop
- useful when hydraulic response unimportant compared to the thermal response
- significant speed improvements seen
  - 5 fold speed increase seen for realistic user models

Contents: ESATAN

ALSTOM

ESATAN v9.2

- FHTS solver enhancements
- New elements
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- Sink temperature
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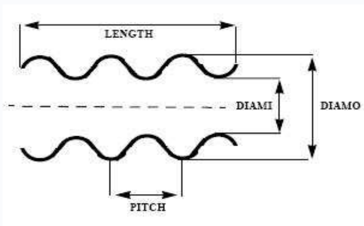
- Thermal Network Viewer

ESATAN Developments

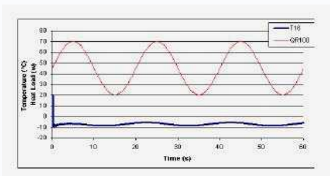
ALSTOM

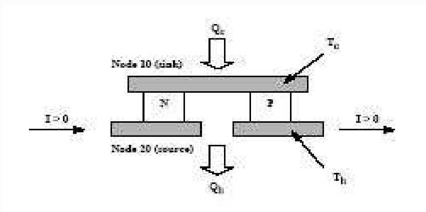
Provision of new elements



Flexible Hose Model
- user-defined geometry
- in-built or user defined loss

PID Controller
- 3 term controller
- positive control action





Peltier Element
- thermo-electric device
- heat pump

Contents: ESATAN

ALSTOM

ESATAN v9.2

- FHTS solver enhancements
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ESATAN Developments

ALSTOM

Modelling enhancements: Groups

- Ability to define & refer to a group of nodes

```
# Define groups
Group1 = '#1-3;sub1:1-10';
Group2 = '#1-Bar_mid'
```

- Library routines extended to support groups
- New library “Node Group Functions”
  - report average of specified nodal entity
  - minimum & maximum of specified nodal entity
  - report sum of specified nodal entity
- Heat flux between specified groups

ESATAN Developments

ALSTOM

Modelling enhancements: Events

- Language updated to support named events
  - time step and output events supported
  - time step event forces integration step to occur at event
  - output event forces $OUTPUT to be called at event
  - both event types can be periodic
  - reference to event by name

```
$EVENTS
$TIMESTEP
   My_event = 100.0;            # simple event at 100.0
   Another_event = 50.0, 100.0; # periodic event 50.0, 150.0, 250.0 ...
$OUTPUT
   Output_event = 125.0;        # output at 125.0
$VARIABLES1
      IF(AFTER(My_event, 0)) ...
```

- ESATAN Version 9.2 -

ESATAN Developments

ALSTOM

Modelling enhancements: Alias

- Ability to alias a node to a name
- Increase readability of model
- Decrease model dependence on nodal mesh

```
$NODES
   D10,10.0...;
   ...
$ALIAS
   Thermocouple1 = D10;
   ...
   $VARIABLES1
         IF(T:Thermocouple1 ...
            QI:Thermcouple1 = 50.0
```

- ESATAN Version 9.2 -

Contents: ESATAN

ESATAN v9.2

- FHTS solver enhancements
- New Elements
- Groups, Events & Phases
- Sink temperature
- Solution run-time monitor
- Thermal Network Viewer

ESATAN Developments

Sink temperature calculation

- T_{sink} between any thermal item & an environment
- Four sink calculations supported
  - black body radiation sink temperature $T_{S,bbr}$

$$\sigma\varepsilon_i A_i(T_i^4 - T_{S,bbr}^4) = \sum_{j \in E}[\sigma GR_{ij}(T_i^4 - T_j^4)] - (QS_i + QA_i + QE_i)$$

  - grey body radiation sink temperature $T_{S,gbr}$

$$\left(\sum_{j \in E}[\sigma GR_{ij}]\right)(T_i^4 - T_{S,gbr}^4) = \sum_{j \in E}[\sigma GR_{ij}(T_i^4 - T_j^4)] - (QS_i + QA_i + QE_i)$$

  - radiation sink temperature $T_{S,r}$

$$\left(\sum_{j \in E}[\sigma GR_{ij}]\right)(T_i^4 - T_{S,r}^4) = \sum_{j \in E}[\sigma GR_{ij}(T_i^4 - T_j^4)]$$

  - linear sink temperature $T_{S,l}$

$$\left(\sum_{j \in E} GL_{ij}\right)(T_i - T_{S,l}) = \sum_{j \in E}[GL_{ij}(T_i - T_j)]$$

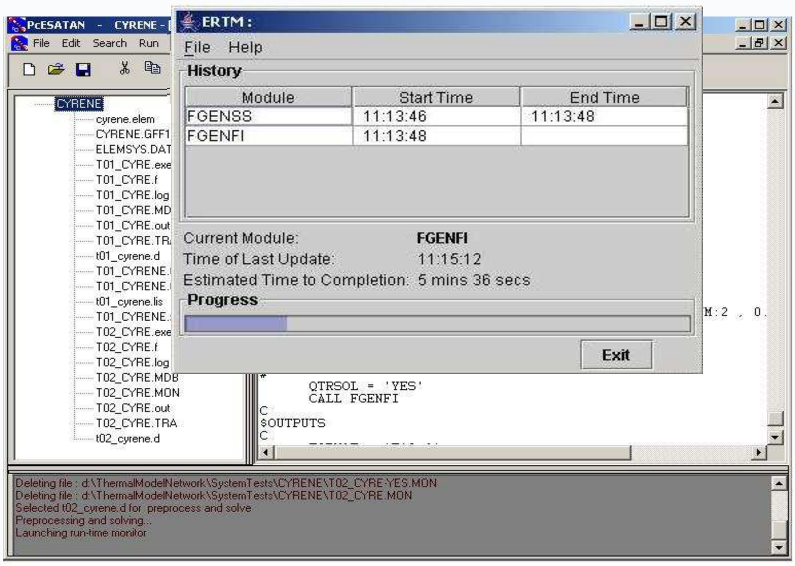
Contents: ESATAN

ESATAN v9.2

- FHTS solver enhancements
- New Elements
- Groups, Events & Phases
- Sink temperature
- Solution run-time monitor
- Thermal Network Viewer

ESATAN Developments

Solution run-time monitor



- Read *monitor* file
- Monitor progress
  - current module
  - last update time
  - est. time to complete
- See solution history
- Report successful completion
- All platforms supported

Contents: ESATAN

ALSTOM

ESATAN v9.2

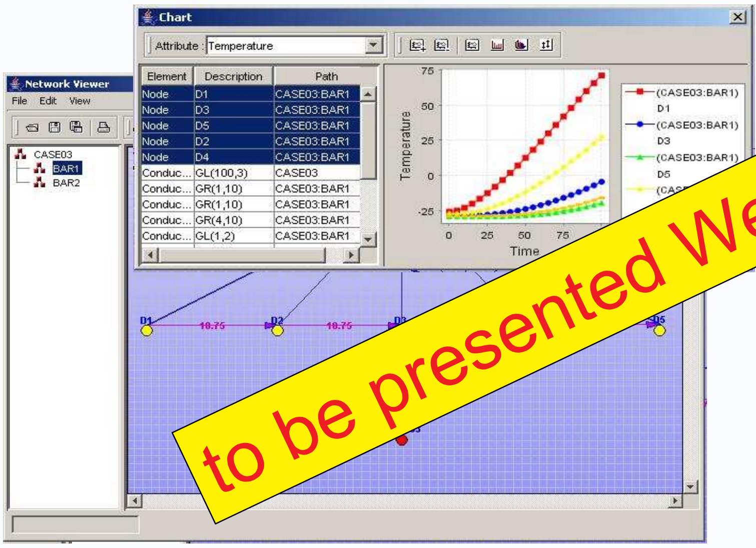
- FHTS solver enhancements
- New Elements
- Groups, Events & Phases
- Sink temperature
- Solution run-time monitor
- Thermal Network Viewer

- ESATAN Version 9.2 -

ESATAN Developments

ALSTOM

Thermal Network Viewer - ThermNV



to be presented Wednesday

- Viewing n...
  - ...ing
  - ...dation
  - ...orting data
  - simplify model using groups
- Reporting & charting
  - any result data
  - average group/model data
- Post-process
  - heat flow & heat balance
  - visualise heat flows

- ESATAN Version 9.2 -

Contents: ESARAD

ALSTOM

ESARAD v5.6

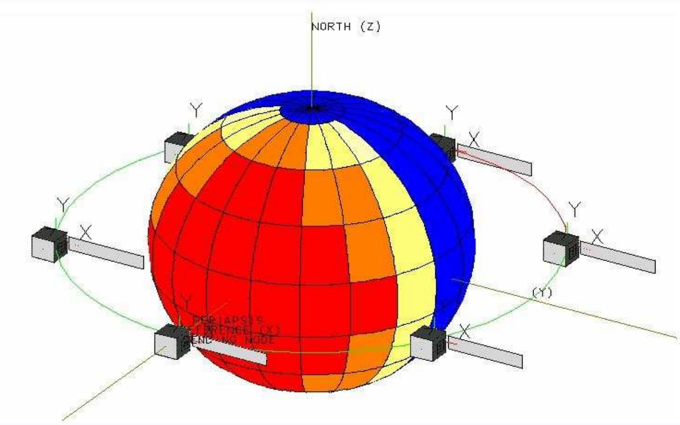
- Planet temperature map
- Sun finite distance
- Performance enhancement
- Optical property sets

ESARAD Developments

ALSTOM

Planet flux calculation enhancement

- Planet temperature map
  - used in planet flux calculation
  - uniform temperature option retained



New options ….

- Matrix of temperature
  - T vs longitude/latitude
- Auto calculate map from,
  - solar absorptivity
  - infra-red emissivity
  - minimum night side temp

Contents: ESARAD

ALSTOM

ESARAD v5.6

- Planet temperature map
- Sun finite distance
- Performance enhancement
- Optical property sets

ESARAD Developments

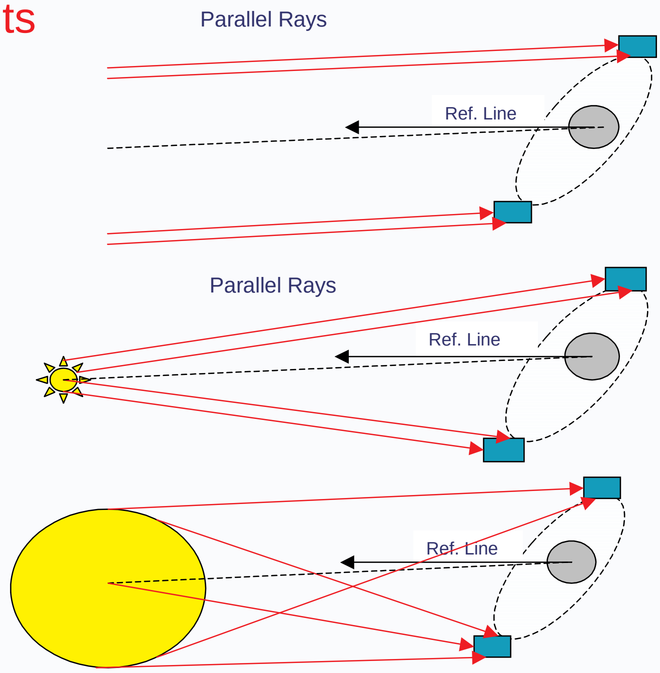
ALSTOM

Modelling near sun orbits

Rays from sun at infinite distance

Rays from sun at finite distance

Rays from finite sun at finite distance



Contents: ESARAD

ALSTOM

ESARAD v5.6

- Planet temperature map
- Sun finite distance
- Performance enhancement
- Optical property sets

ESARAD Developments

ALSTOM

Ray-tracing performance improvement

- Analysis of ray-tracing algorithm performed
- Octree approach to mesh analysis domain
  - widely accepted approach
  - mesh breakdown according to contained geometry
  - avoids unnecessary processing whilst tracing a ray
  - avoids mesh definition by user
- Performance results model dependant,
  - Over 3 times speed improvement seen for industrial models

Contents: ESARAD

ALSTOM

ESARAD v5.6

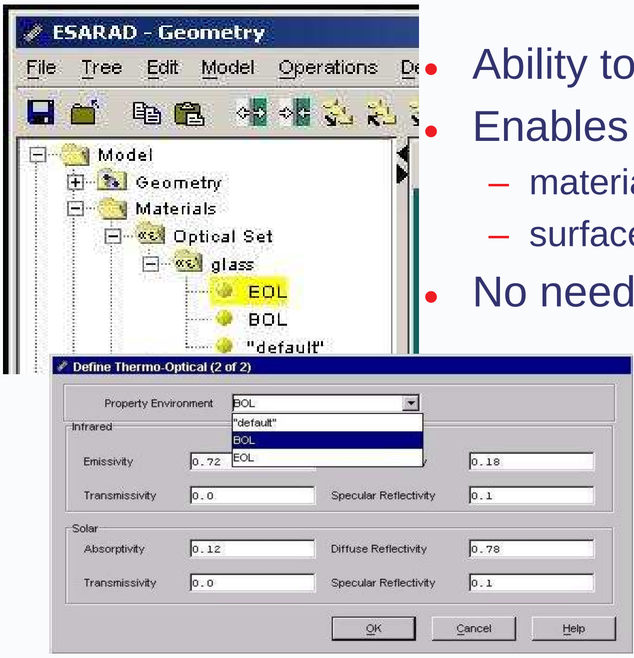
- Planet temperature map
- Sun finite distance
- Performance enhancement
- Optical property sets

- ESARAD Version 5.6 -

ESARAD Developments

ALSTOM

Application of optical property sets



- Ability to define optical property sets
- Enables easy simulation of,
  - material degradation
  - surface finish effects
- No need to duplicate geometry

- Select set within radiative case
- Default property ("default")
- Visualisation of property set
- Dynamic binding of properties

- ESARAD Version 5.6 -

Contents: ThermXL

ALSTOM

ThermXL v3.0

- Modelling enhancements

ThermXL Developments

ALSTOM

Modelling enhancements

- Improved solver performance
- Flexible interpolation function
- Import of radiative data
  - import from *csv* file
  - map radiative data onto ThermXL model
- Sensitivity analysis
  - user defined parameters and variations
  - user defined results

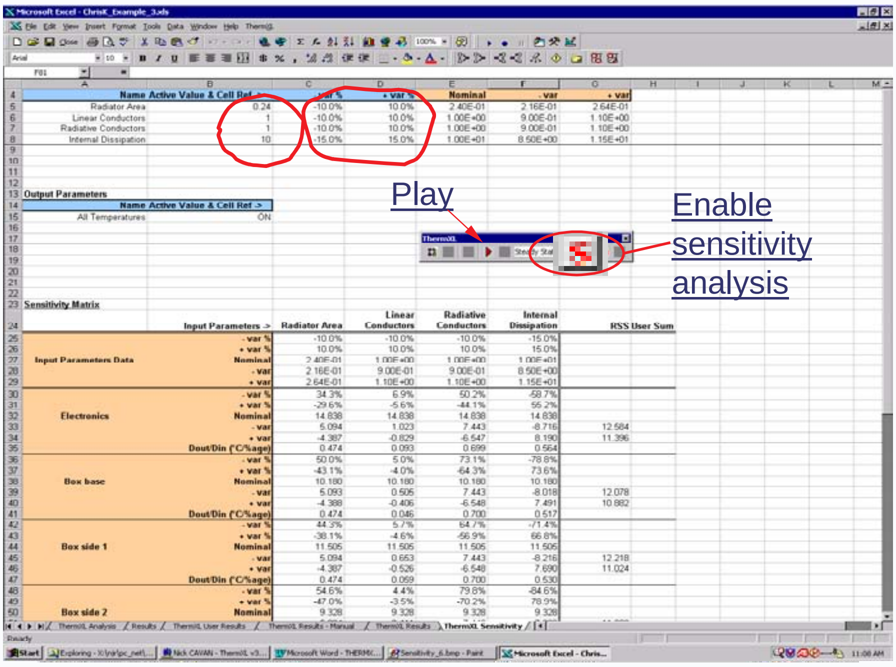
ThermXL Developments

ALSTOM

Selected parameters and variation

Selected output parameters

Output



Play

Enable sensitivity analysis

- ThermXL Version 3.0 -

Contents: Current Developments

ALSTOM

Current developments

- Orbital arc support
- Linux support
- Fluid property definition
- Wet-air transient simulation

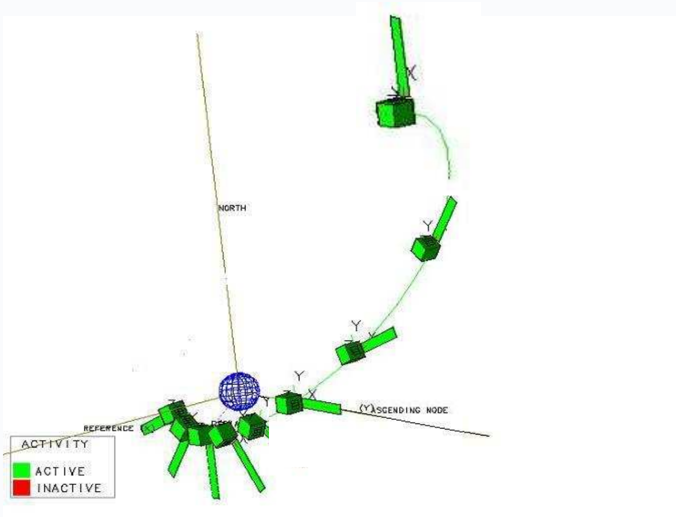
- Current Developments -

Current Developments

Further ESARAD Modelling enhancements

Orbital Arcs Support

- define orbit segment
- additional options for orbit definition
- associate orbit segment to radiative case
- associate radiative case(s) to an analysis case



Contents: Current Developments

Current developments

- Orbital arc support
- Linux support
- Fluid property definition
- Wet-air transient simulation

Current Developments

ALSTOM

Products on Linux

- ESATAN currently available on Linux ü
- ESARAD ported to Linux
  - 3D graphics using OpenGL
  - no third-party licence restrictions
  - makes use of hardware graphics accelerator
    - performance improvements
  - potential for powerful 3D graphics
    - functionality enhancements to be defined

Contents: Current Developments

ALSTOM

Current developments

- Orbital arc support
- Linux support
- Fluid property definition
- Wet-air transient simulation

Current Developments

ALSTOM

Open fluid property definition

- Defined through property files (ASCII)
- Simple to define and modify
- Definition can take the form of,
  - a constant
  - interpolation (1D, 2D or fixed interval)
  - procedure (FORTRAN + reserved variables PROPL, …)
- Defined on a per regime basis
- System properties can be overridden

Current Developments

ALSTOM

Open architecture for fluid property definitions

```
$FLUID WATER
  $RHO
    $LIQUID
      definition
    $SAT_LIQ
      definition
    $SAT_VAP
      definition
    $TWO_PHASE
      definition
    $VAPOUR
      definition
  $CP
```

Region

Property

Fluid Type

Contents: Current Developments

ALSTOM

Current developments

- Orbital arc support
- Linux support
- Fluid property definition
- Wet-air transient simulation

- Current Developments -

Current Developments

ALSTOM

Solver Developments

- Steady-state humidity simulationü
- Single-phase transient humidity solution
  - fltntf, fltnts and fltmts being extended to handle wet air
  - hydraulic steady-state assumed (P & W)
  - water vapour inertia term to be included

- Current Developments -

Conclusion

ALSTOM

- Outlined our current developments
  - ESATAN & ESARAD being finalised for release
- Developments driven in response to needs
  - user survey performed Dec 2003
  - customer visit an on-going activity
  - user survey 2004 being planned
  - training courses & workshops
- Help us provide what you want & when you want
  - team present here today
  - user support system
    - web support system rolled out 2003

- Conclusion -

ALSTOM

www.alstom.com

Appendix F: Feasibility of using a Stochastic Approach for Space Thermal Analysis

Feasibility
of using a
Stochastic Approach
for
Space Thermal Analysis

M. Gorlani
Blue Group

FEASIBILITY OF USING A STOCHASTIC APPROACH FOR SPACE THERMAL ANALYSIS

Matteo Gorlani, Danilo Lazzeri
Blue Engineering, Torino, Italy

Vincenzo Mareschi, Valter Perotto

Alenia Spazio, Torino, Italy

Olivier Pin
European Space Agency, Noordwijk, The Netherlands

OVERVIEW

- Background
- Stochastic Method Retained (Following Literature Survey)
- Stochastic S/W Selected (Following Market Survey)
- Practical Applications of Stochastic Method
- TCS Activity Change with Stochastic Method
- Conclusions
- Distribution of Results

BACKGROUND - 1/3

- **APPLICATION OF STOCHASTIC METHODS (SM) TO TCS IS STILL LIMITED, WHY ?:**

- Small number of specialists compared to other disciplines;
- Consolidated design procedures, often imposed by clients;

PRESSURE TO IMPROVE THIS STATIC SCENARIO:

- Need to achieve design with lower costs in shorter time;
- Awareness of limits in consolidated approach:
  – frequent over-design;
  – tests and correlation costs;
  – increasing complexity of space system and missions;
  – limited flexibility to accommodate design changes;
- Decreasing computational costs;

BACKGROUND – 2/3

BENEFITS OF STOCHASTIC FOR S/C THERMAL DESIGN:

- Possibility to account for distribution of parameters
- Association of probability to design
- Worst cases determination
- Design robustness assessment
- Design optimisation
- Test correlation
- Multidisciplinary optimisation
- Mission risk analysis

BACKGROUND – 3/3

ESA AWARDED A CONTRACT TO BLUE ENGINEERING AND ALENIA SPAZIO WITH THE FOLLOWING OBJECTIVES:

- Literature survey on SM;
- Survey of stochastic S/W and trade-off between make / buy;
- Verify usefulness of SM for TCS analysis/design/verification;
- Assess of pro's/con's of SM versus classical process;
- Identify requirements posed to TCS by introduction of SM;
- Produce handbook with guidelines of use of SM for TCS;

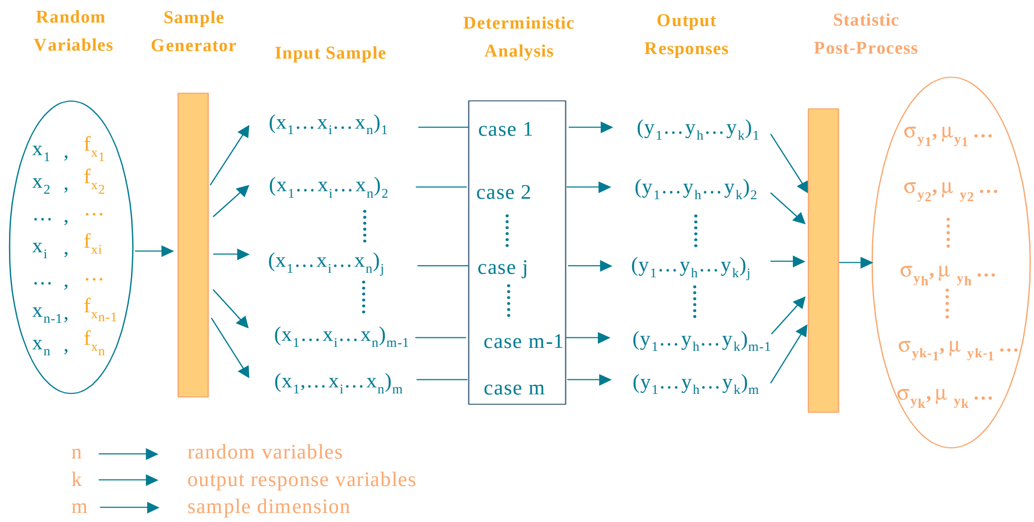
Activity started in Jan. 2003 and finalised in Sept. 2004

STOCHASTIC METHOD RETAINED (FOLLOWING LITERATURE SURVEY) – 1/3

- Random System

$\underline{y}=f(\underline{x})$ where: $\underline{y}$ response of the system
$\underline{x}$ random input variables

- MONTE CARLO SIMULATION (MCS) Analysis



STOCHASTIC METHOD RETAINED (FOLLOWING LITERATURE SURVEY) – 2/3

Main steps of a MCS:

1. Definition of **STOCHASTIC PROPERTIES** of input variables.
   - *Association of Probability Distribution Functions (PDF) to input variables*
   - *Association of an interval of variation to an input variable*

   ⇨ RELEVANT DATA ARE NECESSARY

2. **GENERATION OF A SAMPLE** from the input data.
   - *Generation of sets of values of input variables from PDF*
   - *Generation of numerical models*

   ⇨ SPECIFIC TOOL COULD BE NECESSARY

STOCHASTIC METHOD RETAINED (FOLLOWING LITERATURE SURVEY) – 3/3

3. Execution of ***N* ANALYSES CASES** to generate the output sample.
   - *Management of remote machines*
   - *Management of analyses cases in parallel*

   ⇨ SEVERAL CPUS AND LICENCES COULD BE NECESSARY

4. **STATISTICAL POST-PROCESSING** of output responses.
   - *Management of great amount of data*
   - *Calculation of statistical properties of variables*

   ⇨ SPECIFIC TOOL COULD BE NECESSARY

⇩ **DATA FOR PDF GENERATION**

⇩ **CPU RESOURCES**

⇩ **STOCHASTIC S/W**

SURVEY OF STOCHASTIC S/W

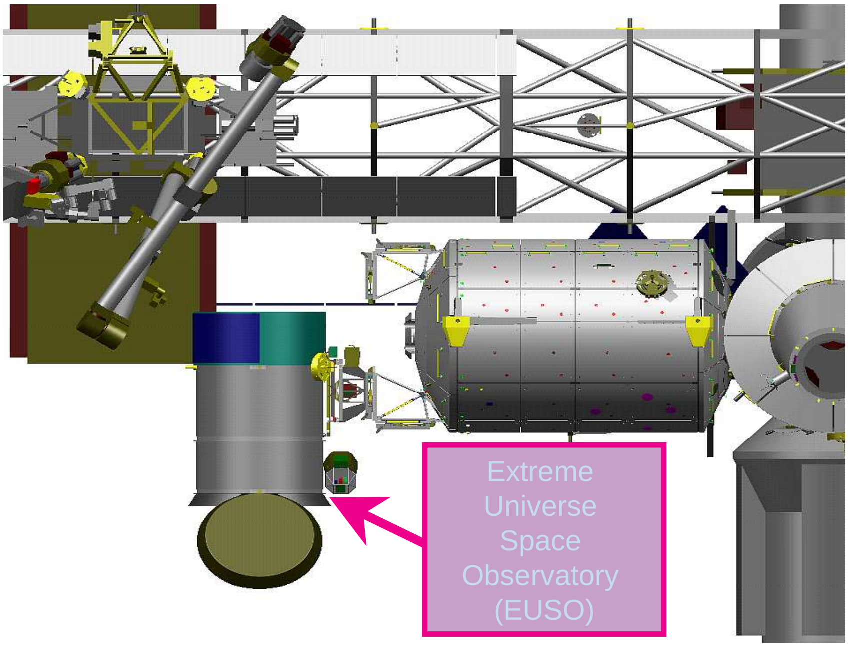
- ESA request was to select possible stochastic COTS compatible with main thermal tools
  - Still looking at possible Open Source S/W as a backup solution
- Several stochastic S/W assessed, in particular:
  - BossQuattro (Samtech);
  - Dakota (SANDIA);
  - ST-ORM (Easy Engineering);
- Performances of these tools were found adequate.
- ST-ORM was selected to assess SM for TCS design in a number of test cases, representative of the typical S/C and scenarios.

PRACTICAL APPLICATIONS OF THE STOCHASTIC APPROACH

The following test cases have been identified:

1. **Identification of worst thermal cases for ISSA P/L**
2. **Design margin assessment for scientific satellite**
3. **Test correlation for scientific satellite**
4. **Multidisciplinary application - thermoelastic analysis**
   a. **Worst Cases Identification for a scientific satellite**
   b. **Structural and TCS optimisation for a radiator**
5. Mission risk analysis for a lander
6. Sensitivity/uncertainty analyses for a reentry vehicle and optimisation of thermal protections
7. Preliminary radiator sizing of a S/C

IDENTIFICATION OF WORST THERMAL CASES
EUSO – (1/10)



EUSO:

Study interaction between cosmic rays and athmosphere.

Main components: telescope and detectors (scintillators)

Detector temperature < temperature stability <

Operation during ISSA eclipse

Project in Phase A

IDENTIFICATION OF WORST THERMAL CASES
EUSO – (2/10)

Extreme thermal cases of EUSO depends on several parameters: ISSA altitude, attitude (yaw, pitch, roll), season, position of P/L on ISSA, overall ISSA configuration (with/without STS), age of components (optical properties degradation).

- Initial assessment of thermal cases was made with a large database built during several years by running some thousands of cases exploring many combinations of parameters; database was not tailored for EUSO but generic.
- Improvement of the traditional search with the stochastic method:

  1 - identification of influent parameters (1st stochastic analysis)

  2 - identification of worst cases (1st + 2nd stochastic analyses)
- Step forward with the stochastic method

  3 - optimisation of P/L mission & TCS (3rd stochastic analysis)

IDENTIFICATION OF WORST THERMAL CASES EUSO – (3/10)

Improvement of traditional approach: first scan

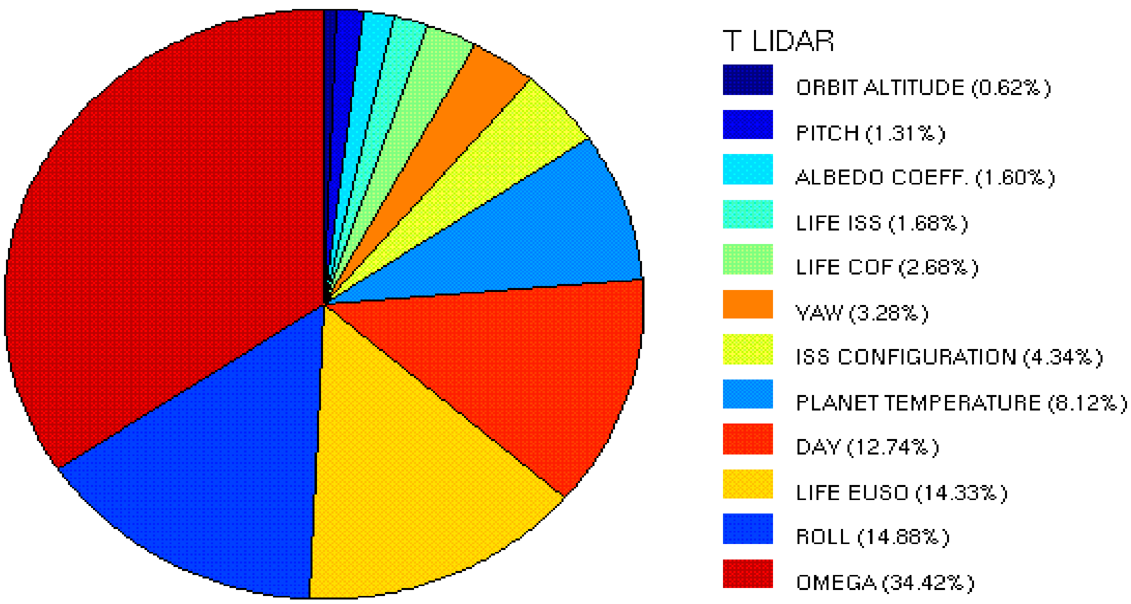
Parameter Name	Description	File	Distribution	Min	Max
Sun and Epoch parameters					
	Day of the Year	kernel	Uniform	1	360
	Solar Constant [W]	kernel	Day Dependent	1321	1423
	Solar Declination [°]	kernel	Day Dependent	-23.5	23.5
Earth parameters					
	Albedo Coefficient	kernel	Uniform	0.22	0.35
	Earth Temperature [K]	kernel	Uniform	240	257.2
Orbit parameters					
	Orbit Altitude [m]	kernel	Uniform	333E3	500E3
	Omega (1)	kernel	Uniform	0	360
ISS attitude					
	Yaw [°]	kernel	Uniform	-15	15
	Pitch [°] (2)	kernel	Uniform	-20	25
	Roll [°]	kernel	Uniform	-15	15
Optical Properties of external surfaces (3)					
	EUSO life parameter	geometric	Uniform	0	1
	Columbus life parameter	geometric	Uniform	0	1
	ISS life parameter	geometric	Uniform	0	1
ISS Configuration					
	ISS configuration parameter	geometric	Uniform	101	108

(1) Right ascension of ascending node of ISS Orbit.
(2) The range covers both ISS configurations: with and without the Shuttle.
(3) The extreme values of the life parameters correspond to:
0: BOL properties
1: EOL properties

- The Latin-Hypercube technique used, with 125 thermal analysis cases (compared to thousand of cases of traditional database)
- Different ISS configurations can be explored
- Optical Properties can be continuously explored

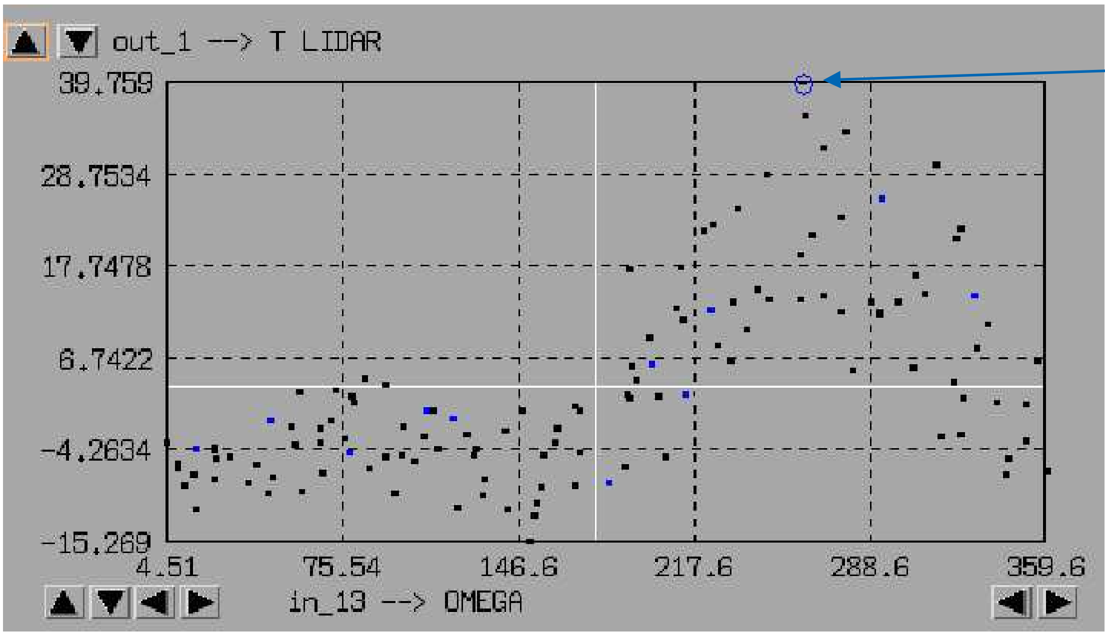
IDENTIFICATION OF WORST THERMAL CASES EUSO – (4/10)

Improvement of traditional approach: most influent parameters



IDENTIFICATION OF WORST THERMAL CASES
EUSO – (5/10)

Improvement of traditional approach: preliminary worst cases



EUSO max temp. 39,76 °C

IDENTIFICATION OF WORST THERMAL CASES
EUSO – (6/10)

Improvement of traditional approach: worst cases refinement

- select region of worst cases
- reduce no. of parameters to the most influent
- reduce variation interval of most influent parameters
- fix value of less influent parameters to
  - conservative value
  - value provided by previous case

	Descriptions of Input Parameters				
Parameter	**Min**	**Max**	**Fixed**	**Distribution**	**Comments**
Omega [°]	242	282		Uniform	Pie Chart Area > 10%
EUSO life parameter	0.8	0.9		Uniform	Pie Chart Area > 10%
Day of the Year	240	320		Uniform	Pie Chart Area > 10%
Roll [°]	9	15		Uniform	Pie Chart Area > 10%
Albedo Coefficient			0.35		Traditional Hot Extreme
Earth Temperature [K]			257.2		Traditional Hot Extreme
Orbit Altitude [m]			333E3		Traditional Hot Extreme
Columbus life parameter			1.0		Traditional Hot Extreme
ISS life parameter			1.0		Traditional Hot Extreme
Yaw [°]			4.584		From First Stochastic Case
Pitch [°]			-6.58		From First Stochastic Case
ISS Configuartion	101	108		Uniform	Difficult Correlation

IDENTIFICATION OF WORST THERMAL CASES
EUSO – (7/10)

Improvement of traditional approach: comparison of worst cases

	Traditional		First Scans		Refinement	
	Lidar	EUSO	Lidar	EUSO	Lidar	EUSO
Temperature [°C]	15	20	39.76	12.24	53.46	25.54
Parameter						
Day of the Year			283.9		294.4	292.4
Solar Constant [W]	*1423*		*1421.5*		*1418.4*	*1419.2*
Solar Declination [°]	*-23.5*		*-22.81*		*-21.4*	*-21.73*
Omega			261.78		277.18	272.7
Roll	-15		11.67		9.89	14.73
EUSO life parameter	1.0		0.66		0.86	0.86
ISS configuration parameter	108		105		105	104

Results of the SM are different with classic method; this is partly due to old database not tailored for EUSO, but similar change in worst cases due to SM was found also on other ISSA P/L

IDENTIFICATION OF WORST THERMAL CASES
EUSO – (8/10)

Step Forward:
Assessing a probability of compliance to requirement

CONSEQUENCE FOR EUSO THERMAL DESIGN FROM WORST CASES :
the updated worst hot case is so severe that thermal design is not compatible with allocated resources (mass, volume, heater power)

POSSIBLE SOLUTION:
EUSO will be “off” around extreme hot case, and identify less severe case for thermal design, still compatible with mission requirement.

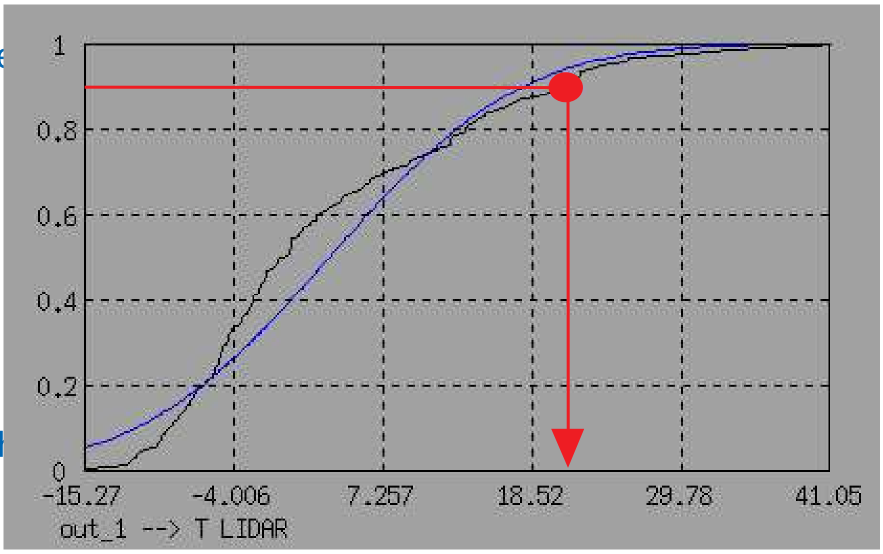
TECHNIQUE:
use SM to find probability of occurrence of a worst condition, by extending the initial set of 125 cases.

IDENTIFICATION OF WORST THERMAL CASES EUSO – (9/10)

Step Forward: Assessing a probability of compliance to requirement

In 90% of possible cases the LIDAR max. temp. is about 20 °C, thence this could be the goal for the thermal design, which would be sufficient for 90% of the mission

--> EUSO will be switched off only 10% of the time, with a TCS compliant with allocated resources



IDENTIFICATION OF WORST THERMAL CASES EUSO – (10/10)

Test Case Summary

Direct comparison with the traditional procedure:

- Identified the most influent parameters
- Identified global worst cases
- Identified extreme worst cases

⇨ STRONG REFINEMENT OF WORST CASES W.R.T. TRADITIONAL

Step forward with the stochastic approach:

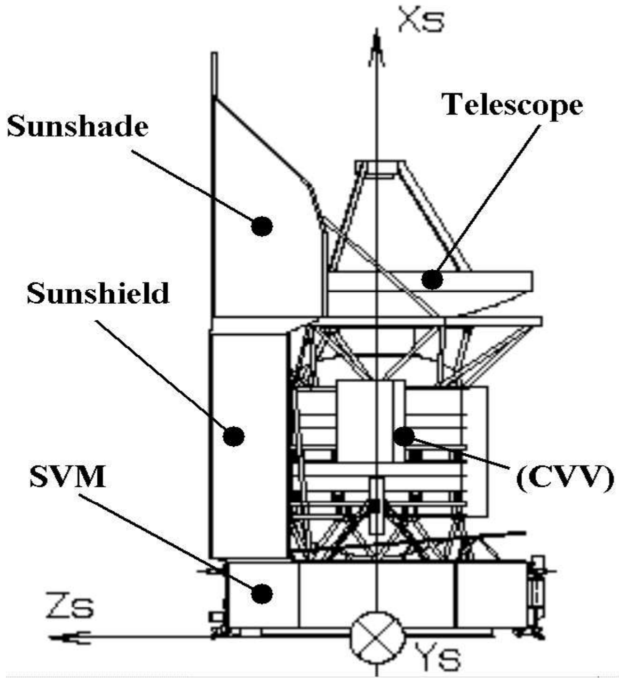
- Assessed a probability of compliance to requirement/worst cases

⇨ POSSIBILITY TO OPTIMISE P/L MISSION

DESIGN MARGIN & ROBUSTNESS ASSESSMENT HERSCHEL – (1/7)

Herschel satellite main components are:

- The SVM
- The Cryostat Vacuum Vessel (CVV, Elium II tank used to cool down the telescope)
- The Telescope
- Sunshade (Telescope sun shield)
- The Sunshield (CVV sun shield)

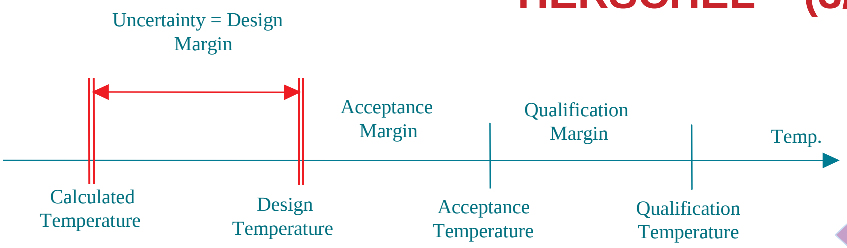


DESIGN MARGIN & ROBUSTNESS ASSESSMENT HERSCHEL – (2/7)

Design margins are used to account for uncertainties in the model prediction and test/flight condition.

- **MARGINS DEFINED** at the beginning of a phase, by experience and sensitivity/uncertainty analysis with available models;
- **MARGINS VERIFIED** / **REFINED** during the phase, from updated models;
- **DESIGN REFINED** following evolution of margins.

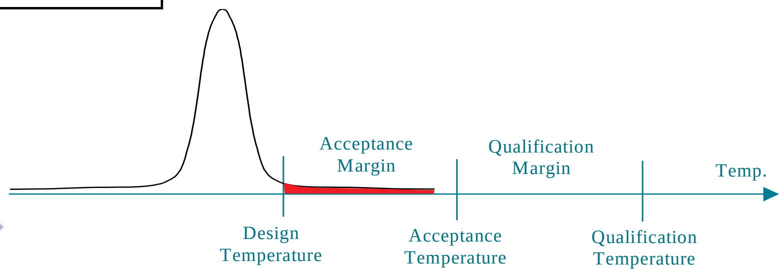
DESIGN MARGIN & ROBUSTNESS ASSESSMENT HERSCHEL – (3/7)



Design margins with traditional method

Traditional Approach:
T Calculated < Design Temperature - Design Margin

Design margins with stochastic method: design to fit with specific probability to remain within limits



Stochastic Approach:
T Calculated < Design Temperature with a determined confidence level

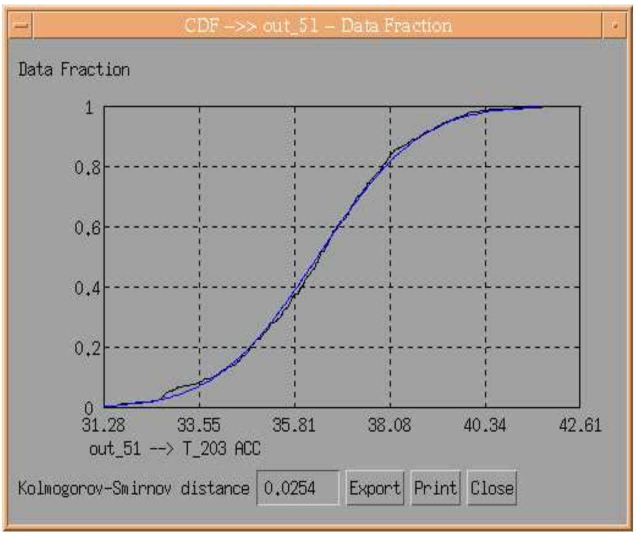
DESIGN MARGIN & ROBUSTNESS ASSESSMENT HERSCHEL – (4/7)

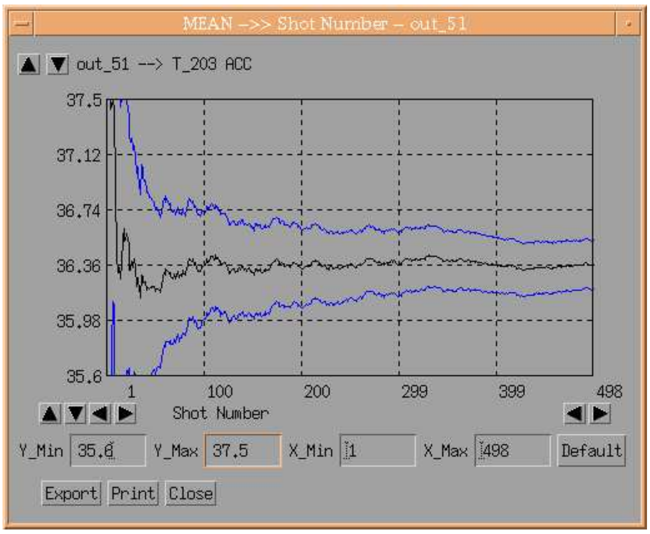
Initial sensitivity/uncertainty analysis

	Inaccuracy	
Parameter	**Traditional Approach**	**Stochastic Approach**
	Absolute Value or Percentage	Standard deviation of gaussian distribution
Absorptivity	+0.03	0.015
Emissivity	-0.03 for emissivity ≥0.2 -0.02 for emissivity <0.2	0.015 for emissivity ≥0.2 0.01 for emissivity <0.2
MLI conductance	±25%	12.76%
Thermal conductivity	+20% homogenous materials +30% fibre panels and composites	10.2% homogenous materials 15.3% fibre panels and composites
Radiating area	±5%	2.55%
Linear conductivity between unit and structure	±25% internal units ±50% external units	12.76% internal units 25.51% external units
Dissipation	+10% warm units +10% for dissipation < 10 W +5% for dissipation > 10 W	5.1% warm units 5.1% for dissipation < 10 W 2.55% for dissipation > 10 W

DESIGN MARGIN & ROBUSTNESS ASSESSMENT HERSCHEL – (5/7)

Cumulative Distribution Function (CDF) vs no. of thermal analysis cases, stabilisation after 100 cases, the sample of 500 cases is adequate





DESIGN MARGIN & ROBUSTNESS ASSESSMENT HERSCHEL – (6/7)

Stochastic analysis: 500 cases Latin Hypercube with ST-ORM
Comparison of traditional/stochastic results:

			Traditional Approach			Stochastic Approach		
Item	Nominal Temp. [°C]	Design Temp. [°C]	Temp. Uncertainty [°C]	Temp. Max Predicted [°C]	Temp. Diff. [°C]	Probability of compliance with Design Temperature	Temp. with 97.5% probability	Temp. Diff. at 97.5% probability [°C]
ACC	36,30	42,00	5,00	41,30	0,70	99.80 %	39.95	2.05
FHWOV	5,05	12,00	6,14	11,19	0,81	99.20 %	10.25	1.75
FHWEV	20,50	27,00	5,79	26,29	0,71	98.80 %	26.10	0.90
FHWOH	5,06	12,00	6,12	11,18	0,82	99.60 %	10.25	1.75
FHWEH	20,80	27,00	5,82	26,62	0,38	97.99 %	26.60	0.40
RWL1	45,70	52,00	5,44	51,14	0,86	99.40 %	49.70	2.30
RWL3	46,30	52,00	5,45	51,75	0,25	99.20 %	50.25	1.75
RWL4	46,20	52,00	5,22	51,42	0,58	99.60 %	50.28	1.72

DESIGN MARGIN & ROBUSTNESS ASSESSMENT HERSCHEL – (7/7)

Test Case Summary

Direct comparison with the traditional approach:

- Provided higher temperature margins

→ RISK OF OVERDESIGN WITH TRADITIONAL CALCULATION OF UNCERTAINTY

Step forward with the stochastic approach:

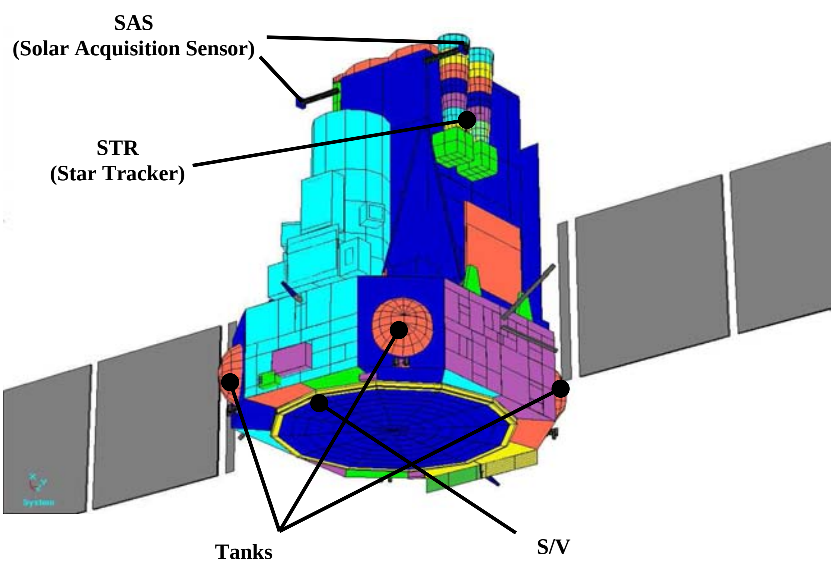
- Assessed a probability of compliance to requirement

→ POSSIBILITY TO ASSOCIATE PROBABILITY VALUES TO UNCERTAINTY OF TEMPERATURES

TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (1/11)

INTEGRAL satellite main components are:

- The S/V
- The INTEGRAL Soft Gamma Ray Imager (ISGRI).
- The INTEGRAL Radiation Environment Monitor (IREM)
- The Joint European X-Ray Monitor (JEM-X)
- The Optical Monitoring Camera (OMC)
- The Imager on Board INTEGRAL Satellite (IBIS).



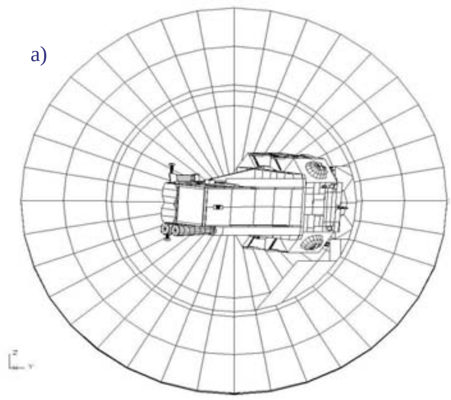
TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (2/11)

Correlation Analysis Cases

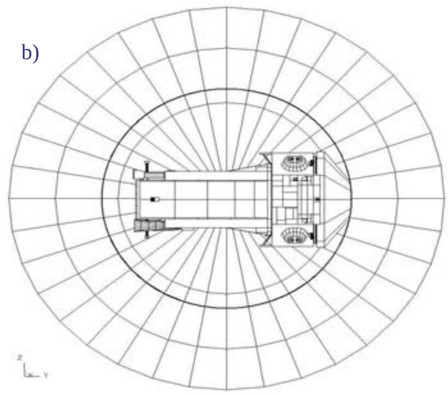
Correlation accounts for two different cases:

a) Hot Case - Units close to maximum operative acceptance temperature.

b) The Cold Case - Added when it was clear that the hot case only was not sufficient to obtain good correlation of results.



Hot Case



Cold Case

TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (3/11)

Analysis of Measurement

Temperature Differences $T_{Mi} - T_{Pi}$ [°C]

where:
$T_{Mi} \longrightarrow$ *Measured Temperature*
$T_{Pi} \longrightarrow$ *Calculated Test Temperature*

Temperature Deviation

$$\Delta T = \frac{1}{N}\sum_{N} T_{Mi} - T_{Pi} \quad [°C]$$

Standard Deviation

$$\sigma = \sqrt{\frac{\sum_{N}\left[\left(T_{Mi} - T_{Pi}\right) - \Delta T\right]^{2}}{N-1}} \quad [°C]$$

When

N = Ntot With Ntot equal to the number of all measured temperatures, the above parameters can be referred as *Global Temperature Deviation* and *Global Standard Deviation*.

N = ni With ni < Ntot and equal to the number of a particular group of measured temperatures, the above parameters can be referred as *Group Temperature Deviation* and *Group Standard Deviation*.

TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (4/11)

Correlation Criteria

- **Correlation performed for groups of units:**
  S/V, P/L, TANK, JEM-X, STAR TRACKER, SAS, IBIS

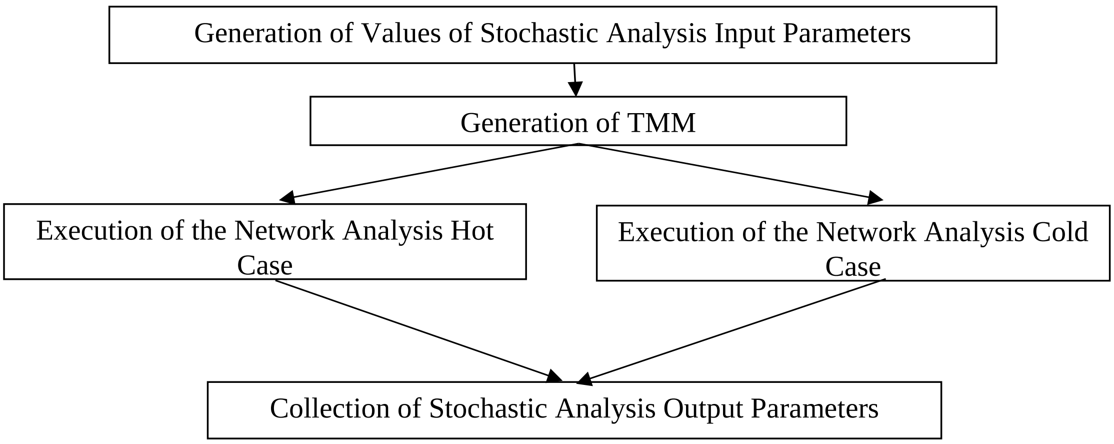
- **Criteria for traditional approach:**
  - All *Group Temperature Deviations* ≤ 7 °C for Hot Case
  - All *Group Temperature Deviations* ≤ 6 °C for Cold Case

- **Criteria for stochastic approach:**
  1. Temperature level criteria
  - ***Global Temperature Deviation*** ≤ 2 °C for Cold and Hot Cases
  2. Standard deviation criteria
  - ***Global Standard Deviation*** ≤ 3 °C for Cold and Hot Cases
  3. Individual unit success criteria
  - All ***Group Temperature Deviations*** ≤ 7 °C for Hot Case
  - All ***Group Temperature Deviations*** ≤ 6 °C for Cold Case

TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (5/11)

Stochastic Optimisation:

ST-ORM stopped after 37 Runs (15 Shots):



TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (6/11)

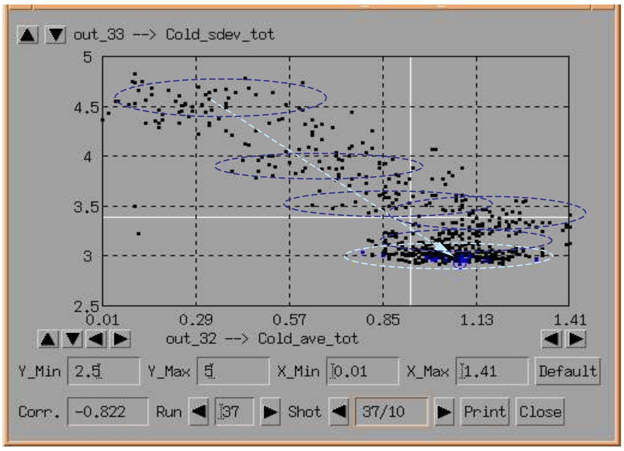
Input Variables

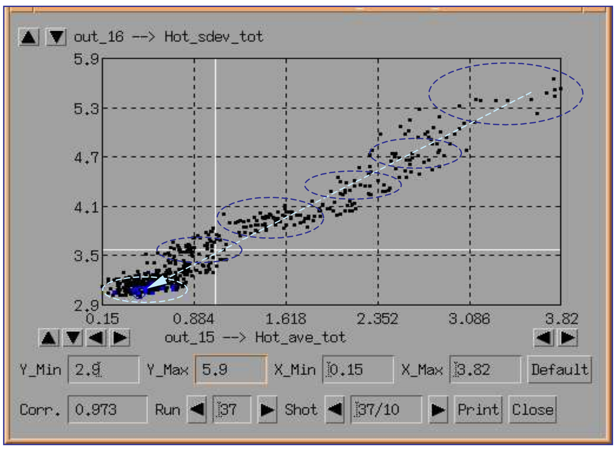
Parameter	Min	Max	Distribution
Fine Sun Sensor Head (α)	0.36	0.6	Uniform
Fine Sun Sensor Head (ε)	0.833	0.859	Uniform
ACC Radiator Efficiency Factor	0.8	1.0	Uniform
CAE Radiator Efficiency Factor	0.8	1.0	Uniform
IREM external Radiative Coupling Factor	1	14	Uniform
MRU Contact Conductance [W/m²K]	100	200	Uniform
SAS Bracket Conductance Factor	1	10	Uniform
SAS +Y Cold Case Heater Power [W]	1.12	4.48	Uniform
SAS -Y Cold Case Heater Power [W]	1.12	4.48	Uniform
SAS +Y Hot Case Heater Power [W]	1.12	4.48	Uniform
SAS -Y Hot Case Heater Power [W]	1.12	4.48	Uniform
STR/Panel GL Factor	1	2	Uniform
Honeycomb Panel Conductivity Factors[1]	1	3	Uniform

(1) A total of 28 independent factors have been defined. One for each thermal conductivity parameter of honeycomb panels defined in the TMM

TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (7/11)

Stochastic Correlation: Results

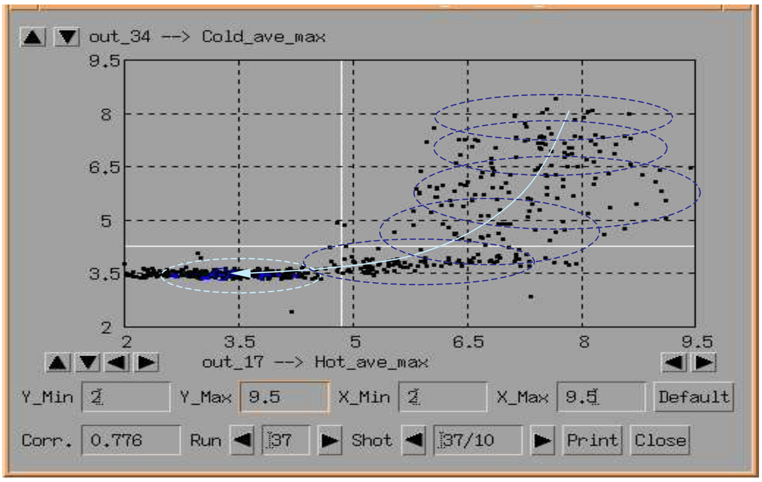




Compliance of the Correlated Model with
Temperature Level Criteria and **Standard Deviation Criteria**

TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (8/11)

Stochastic Correlation: Results

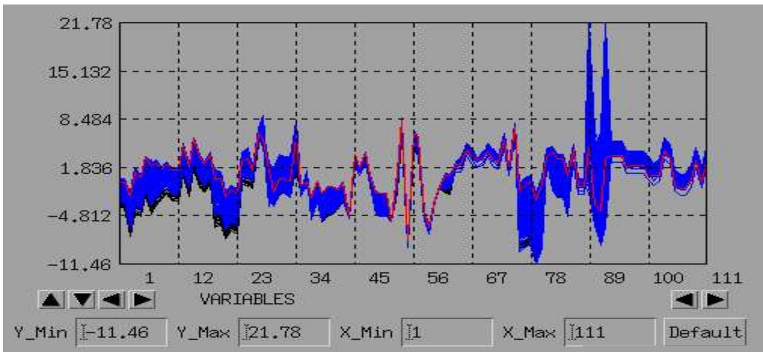


Compliance of the Correlated Model with

Individual Unit Success Criteria

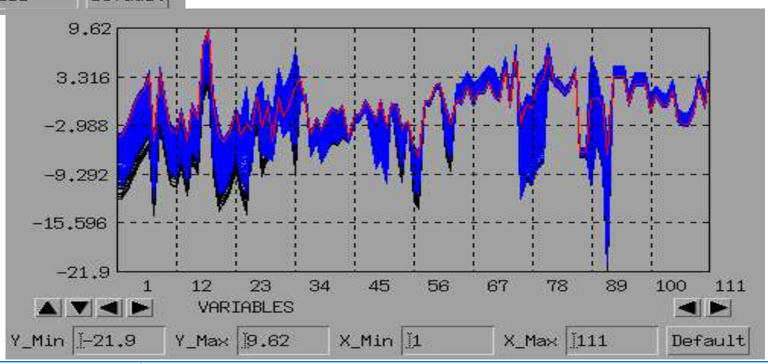
TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (9/11)

Stochastic Correlation: Evolution of Temperatures



Evolution of the Monitored Temperatures during the Correlation Analysis in **Cold Case**

Evolution of the Monitored Temperatures during the Correlation Analysis in **Hot Case**



TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (10/11)

The stochastic approach provides the lowest maximum absolute values (highlighted in bold) for all the parameters

GROUP	Hot Case				Cold case			
	Traditional		Stochastic		Traditional		Stochastic	
	ΔT [°C]	σ [°C]	ΔT [°C]	σ [°C]	ΔT [°C]	σ [°C]	ΔT [°C]	σ [°C]
SVM UNITS	-3.2	3.8	-1.05	3.40	1.0	2.8	1.56	2.39
PLM UNITS	-3.0	3.0	-1.54	1.79	0.1	2.7	-0.54	2.04
TANK	-2.3	3.2	-1.62	2.82	-0.8	**5.4**	-0.46	**5.17**
JEM-X	**4.5**	2.4	1.53	1.86	**5.5**	2.5	**3.47**	1.53
STAR TRACKER	-0.1	4.4	1.72	2.31	0.5	3.6	1.12	2.28
SAS	0.0	**4.5**	**-3.27**	**3.41**	0.2	1.7	-0.31	3.16
IBIS	3.8	2.1	0.74	2.13	5.0	2.0	1.56	1.63

TEST CORRELATION ANALYSIS ASSESSMENT INTEGRAL - (11/11)

Test Case Summary

Direct comparison with the traditional approach:

- Model correlated vs. Global and Group Criteria
- Model correlated in Hot and Cold cases
- Automatic correlation with stochastic optimisation

SOLVED THE PROBLEMS ENCOUNTERED WITH TRADITIONAL ANALYSIS (GLOBAL CRITERIA, HOT CASE)

Step forward with the stochastic approach:

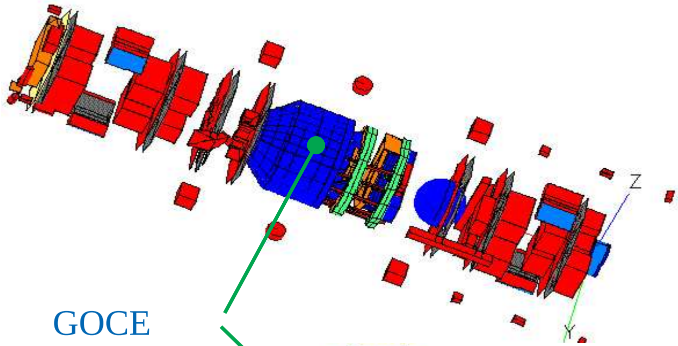
- Stochastic optimisation with concurrent consideration of Hot and Cold cases

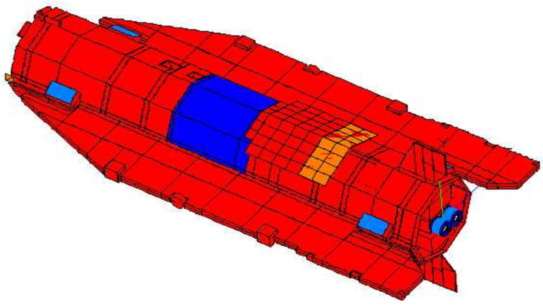
MODEL DIRECTLY CORRELATED IN DIFFERENT CASES WITH A SINGLE STOCHASTIC ANALYSIS

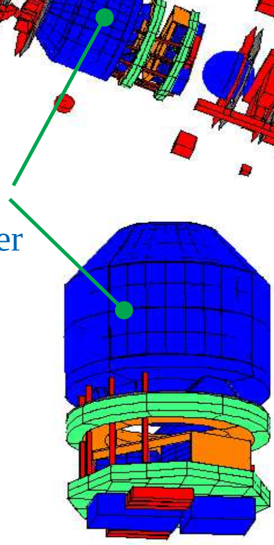
IDENTIFICATION OF WORST CASES IN MULTIDISCIPLINARY ANALYSIS – GOCE - (1/4)

GOCE (Gravity field Ocean Circulation Explorer) satellite is constituted by two main payloads:

- Electrostatic Gravity Gradiometer
- Satellite to Satellite Tracking Instrument.







IDENTIFICATION OF WORST CASES IN MULTIDISCIPLINARY ANALYSIS – GOCE - (2/4)

Input Parameters And Distributions

Variable	Distrib.	Min	Max	File	Note
Day of the Year	Uniform	1	360	GOCE_k.t	Sun and Epoch parameters. See following comments
Solar Constant [W]	Dependent on the Day				
Solar Declination [°]	Dependent on the Day				
Albedo Coefficient	Uniform	0.2	0.4		Earth Parameters
Earth Temperature [K]	Uniform	240	257.2		
Omega	Discrete	90	270		Right ascension of ascending node. Only two values are possible : 90° 270°
EUSO life parameter	Uniform	0	1	GOCE_g.t GRADIO_g.t	Optical Properties of surfaces See following comments
Operative Mode	Discrete	1	6	GOCE.tpl	Goce operative modes are six, corresponding to different levels of heat dissipation of the units.
Average Thrust level	Discrete	1	4		Four different average thrust level are possible, corresponding to: 1. 1.7 2. 5.8 3. 8.3 4. 200
Thruster profile	Discrete	1	3		Three different thrust profile are possible.

IDENTIFICATION OF WORST CASES IN MULTIDISCIPLINARY ANALYSIS – GOCE - (3/4)

Output Variables

Three independent Star Sensors are mounted on GOCE:

The alignment of the 3 Star Sensor Reference Frame (SSRF) with the Gradiometer Reference Frame (GRF) shall be verified (Not applicable to Operative Modes 4 and 5)

$$(\varphi,\theta,\psi)_j \quad \text{(with } j = 1 \text{ to } 3\text{)}$$

$$\leq$$

$$\mathbf{2 \cdot 10\text{-}4\ rad}$$

Identification of extreme cases:

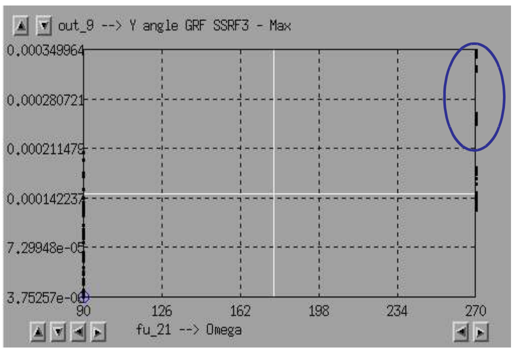
Latin Hypercube 120 function evaluations constituted by

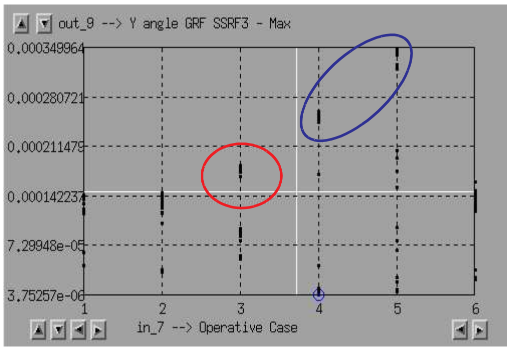
- 1 thermal radiative analysis case (ESARAD run)
- 1 thermal network analysis case (ESATAN run)
- 1 structural analysis case (NASTRAN run)

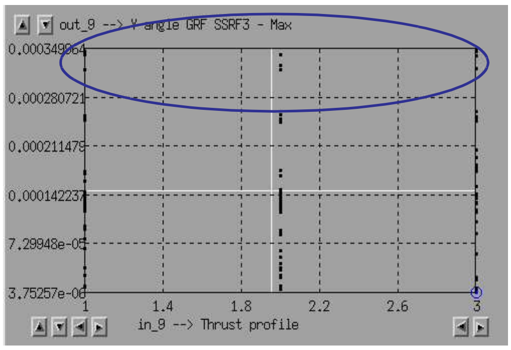
IDENTIFICATION OF WORST CASES IN MULTIDISCIPLINARY ANALYSIS – GOCE - (4/4)

Worst Case:

- Omega Angle = 270°
- Operative case = 3

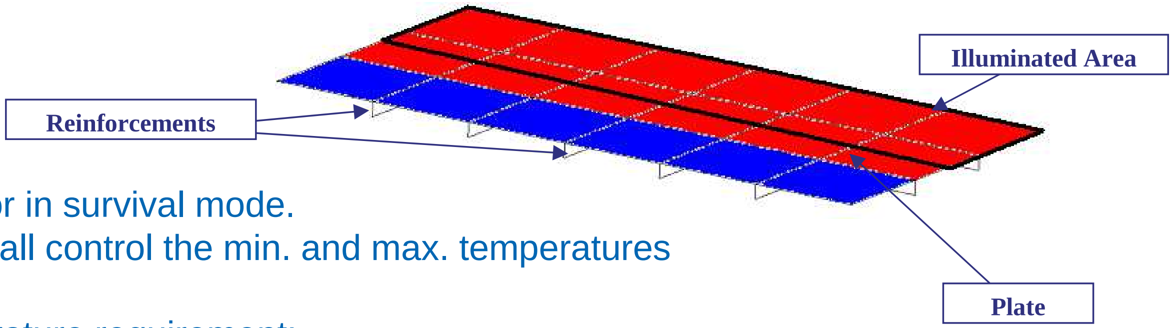






STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (1/9)

Structural and TCS optimisation for a radiator



Radiator in survival mode.
TCS shall control the min. and max. temperatures

Temperature requirement:

- Red Area with temperature limits 0/40°C.
- Blue Area with temperature limits –10/30°C.

Radiator black bound Area is partially illuminated by the sun (100 W/m2).

Maximum deformation Requirements shall be satisfied

STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (2/9)

SM to optimise structure and TCS:

- Find minimum heater power to satisfy requirements.
- Define best heater and temperature sensor positions
- Evaluate the radiator thickness and thermo-structural characteristics.

TEST PROCEDURE:

1. Stochastic Optimisation: definition of best combination of input parameters to satisfy thermal and structural requirements

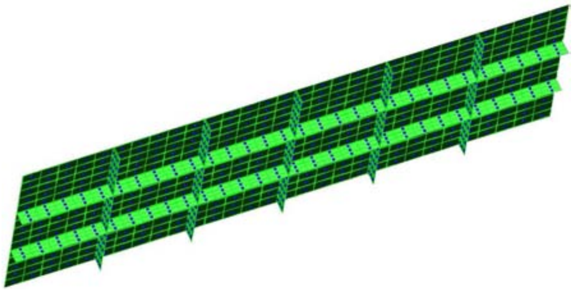
2. Material selection: selection of a material with characteristics as similar as possible to those obtained in the previous phase

3. Uncertainty/sensitivity analysis: performed considering:
   - Inaccuracy for the material selected in phase 2
   - best heater and sensor positions evaluated in phase 1

STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (3/9)

SM: input parameters

Variable	Minimum Value	Maximum Value
Single Heater Power [W]	0.	100.
Heater X positions (1)	1	30
Heater Y positions (1)	1	15
Sensor X position (2)	1	30
Sensor Y position (2)	1	15
Plate Thickness [mm]	1	7
Reinforcement Thickness [mm]	1	7
Thermal Conductivity [W/m/k]	100	200
Specific Heat [J/Kg/K]	600	1000
Density [Kg/m3]	2500	3000
Modulus of Elasticity [N/mm^2]	72000	206000
Coefficient of Thermal Expansion (CTE) [°C^{-1}]	$1.2 \cdot 10^{-5}$	$2.6 \cdot 10^{-5}$



Y \ X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
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4	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
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15	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450

Input Variables: Uniform PDF

STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (4/9)

Stochastic Optimisation: Output parameters

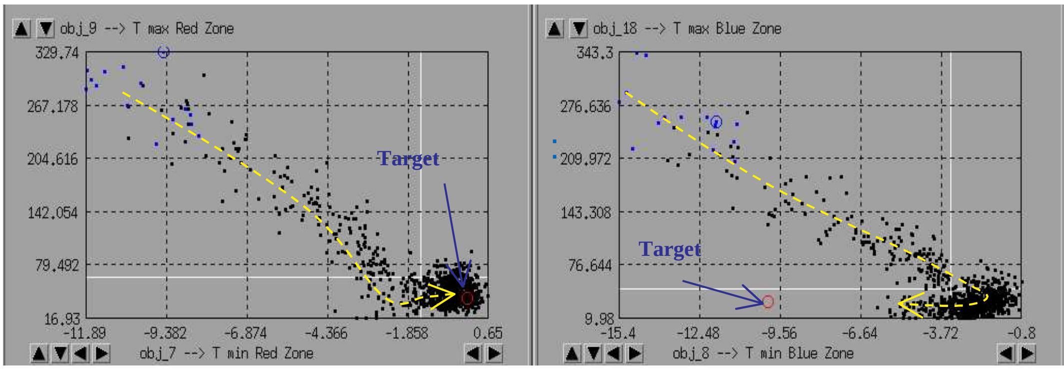
Variable	Target Value
Minimum Temperature Red Area [°C] (1)	=0
Minimum Temperature Blue Area [°C] (1)	=-10
Maximum Temperature Red Area [°C] (1)	<40
Maximum Temperature Blue Area [°C] (1)	<30
Heater Duty Cycle(2)	=80%
Maximum Displacement [mm] (3)	=0.15

1) Temperatures reached in transient simulation (10,000 sec). Requirements are $0 \le T \le 40$ and $-10 \le T \le 30$, equality option minimise the heater power.
2) Calculated during the last 5000 sec of transient simulation.
3) Displacement reached in transient simulation (10,000 sec). Requirement is Displ ≤ 0.15

STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (5/9)

Stochastic Optimisation: ST-ORM stopped after 60 Runs (15 Shots)

- Red Zone temperatures: Both temperature targets reached
- Blue zone temperatures: Only Maximum temperature target reached

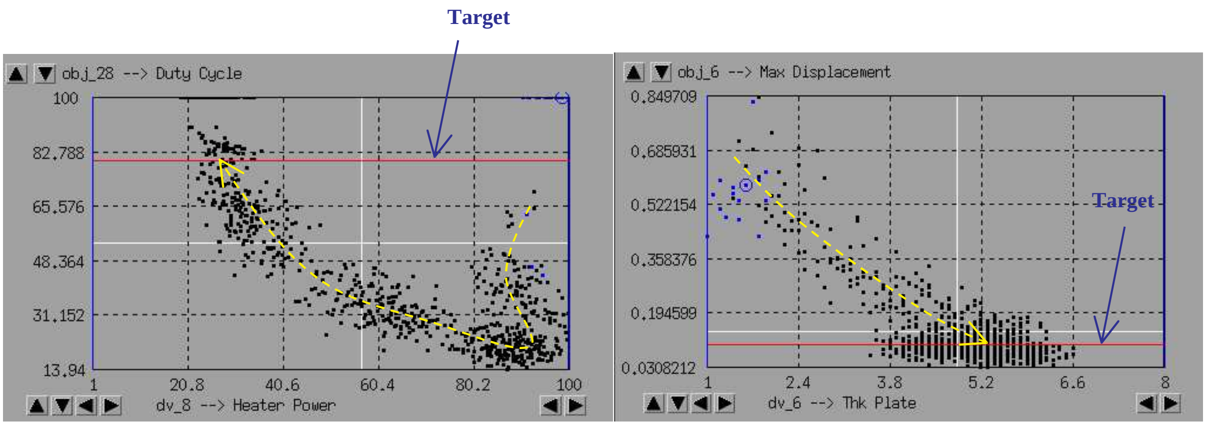


➡ Difficult to obtain high temperature gradient (10°C) in areas very close and strongly linearly coupled

STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (6/9)

Stochastic Optimisation: ST-ORM stopped after 60 Runs (15 Shots)

- Duty cycle: Target reached
- Maximum displacement: Target reached



STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (7/9)

Stochastic Optimisation:

Results

Heaters and sensor positions

Y \ X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
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Heater   Sensor

Input Variable	Value from Optimisation	Al2219-O value
Single Heater Power [W]	26	
Plate Thickness [mm]	4.3	
Reinforcement Thickness [mm]	1.5	
Thermal Conductivity [W/m/k]	168	171
Specific Heat [J/Kg/K]	916	864
Density [Kg/m3]	2593	2840
Modulus of Elasticity [N/mm^2]	74237	73100
Coefficient of Thermal Expansion (CTE) [°C^{-1}]	$1.8{\cdot}10^{-5}$	$2.23{\cdot}10^{-5}$

Geometrical and Physical Variables

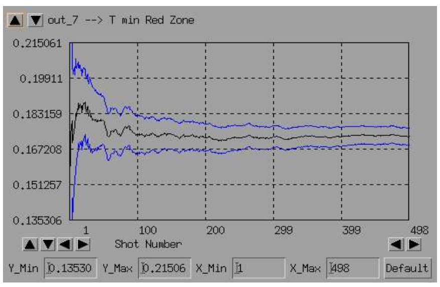
STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (8/9)

Uncertainty / Sensitivity analysis

Physical property	Mean	Standard deviation
Thermal Conductivity [W/m/k]	171	5
Specific Heat [J/Kg/K]	864	26
Density [Kg/m3]	2840	85
Modulus of Elasticity [N/mm^2]	73100	2193
Coefficient of Thermal Expansion (CTE) [°C^{-1}]	$2.23{\cdot}10^{-5}$	$0.07{\cdot}10^{-5}$
Single Heater Power [W]	26	0.8
Plate Thickness [mm]	4.3	0.13
Reinforcement Thickness [mm]	1.5	0.04

Input Variables: Gaussian PDF

STORM used to generate a sample of 500 thermal analysis cases



Mean Outputs stabilised: Sample dimension adequate

STOCHASTIC OPTIMISATION IN MULTIDISCIPLINARY ANALYSIS – PAYLOAD RADIATOR - (9/9)

Uncertainty / Sensitivity analysis

Description	X_Min	X_Max	Mean	Std	CV(%)	$Min_{95\%}$	$Max_{95\%}$	Requirement
Max Displacement	0.093	0.13	0.11	0.0062	5.6	0.098	0.12	≤ 0.15
T min Red Zone	0.04	0.28	0.173	0.0433	25	0.09	0.2	≥ 0
T min Blue Zone	-3.31	-2.41	-2.75	0.136	4.9	-3.0	-2.5	≥ -10
T max Red Zone	34	42.2	37.4	1.24	3.3	34.9	39.9	≤ 40
T max Blue Zone	22.4	28.1	24.8	0.86	3.5	23.0	26.5	≤ 30
Duty Cycle	69.5	100	80.9	5.53	6.8	69.8	91.9	80%

For all the Output variables the requirements are satisfied with a probability of 95%.

STOCHASTIC APPROACH IN MULTIDISCIPLINARY ANALYSIS - SUMMARY

Multidisciplinary Test Cases Summary

- Considered inaccuracy/variation of structural parameters
- Considered inaccuracy/variation of thermal parameters
- Considered inaccuracy/variation of configuration parameters (positions)
- Direct assessment of structural sensitivities w.r.t. structural and non structural parameters
- Direct assessment of structural uncertainties due to inaccuracy of structural and non structural parameters
- Concurrent optimisation of structure and TCS design

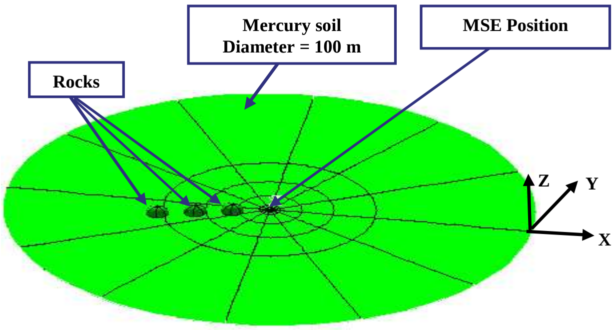
→ POSSIBILITY OF CONCURRENT DEVELOPMENT OF STRUCTURE AND TCS

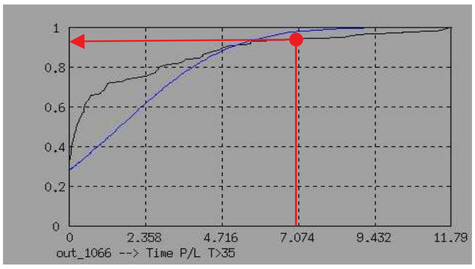
MISSION RISK ANALYSIS - BEPICOLOMBO MSE

Test Case Summary

- Considered inaccuracy/variation of:
  - a. Mercury soil characteristics
  - b. Inaccuracy of Aluminium properties
  - c. Variations of thermo-optical properties of materials
- Assessed the probability of survival
- Found the most influent parameters to reduce the risk of failure of the mission

POSSIBILITY TO ASSESS THE RISK OF THE MISSION AND FIND PARAMETERS FOR REDUCING IT





Probability that the P/L temperature exceeds 35°C before 7 days is about 97%

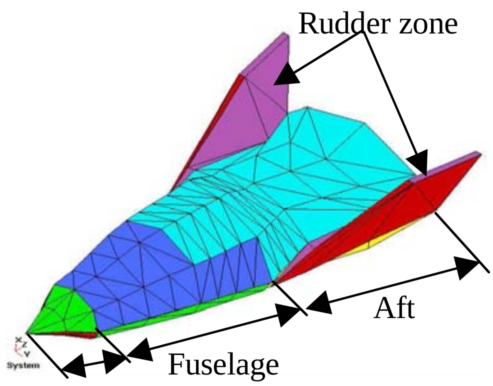
SENSITIVITY/UNCERTAINTY ANALYSIS AND DESIGN OPTIMISATION OF SPHYNX

Test Cases Summary

Direct comparison with the traditional approach:

- Considered inaccuracy/variation of more than 60 parameters
- Assessed the sensitivity to the input parameters
- Assessed the uncertainty of temperature results

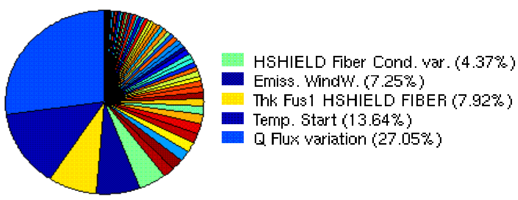
FOUND AREAS OF TPS OVER-DESIGN AND UNDER-DESIGN



Step Forward with the stochastic approach:

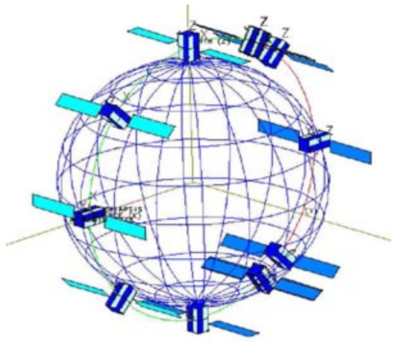
- Applied the stochastic optimisation to TPS design

17% REDUCTION OF THE TPS MASS BUDGET



PRELIMINARY RADIATOR SIZING - VENUSSAT

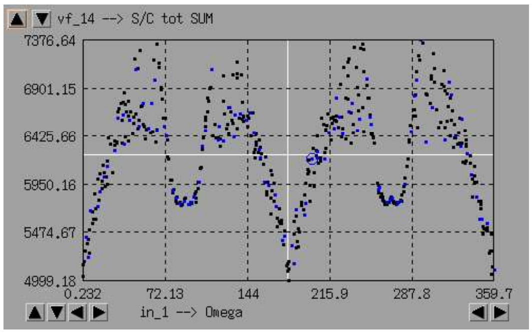
Test Case Summary



Direct comparison with the traditional approach:

- Assessed worst cases
- Preliminary radiators sized with a stochastic optimisation

⇨ FAST AND AUTOMATIC SIZING OF RADIATORS ACCOUNTING FOR REQUIREMENTS



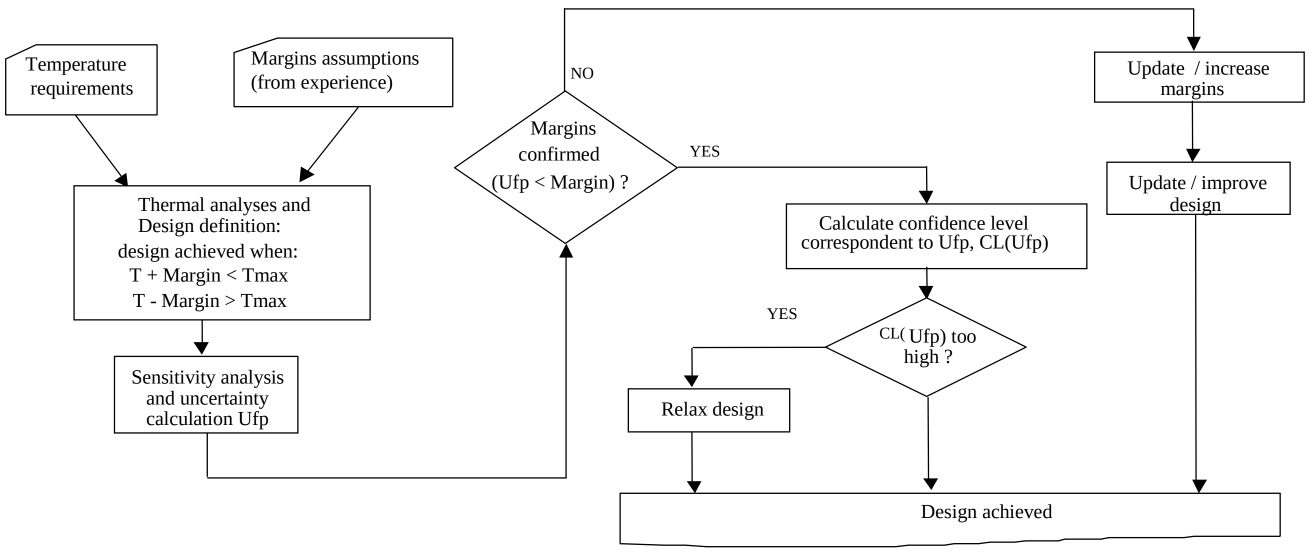
Step forward with the stochastic approach:

- Stochastic optimisation accounting for 3 different external environments

⇨ POSSIBILITY TO SIZE RADIATORS FOR DIFFERENT EXTERNAL LOADS AND REQUIREMENTS

TCS ACTIVITY CHANGE
TO INCORPORATE STOCHASTIC METHODS – (1/2)

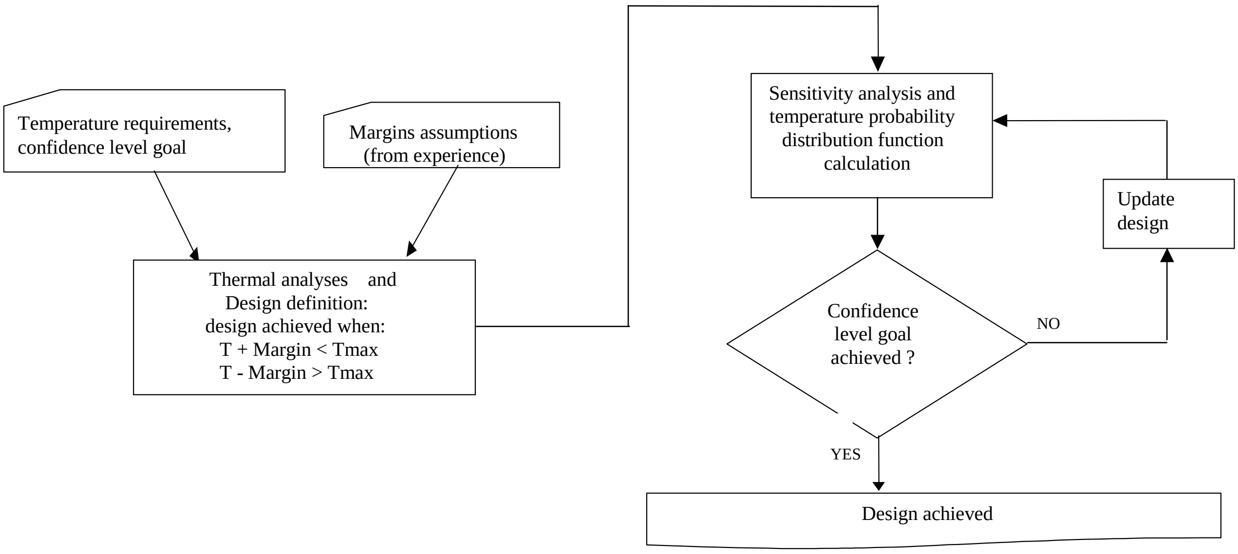
FROM: satisfy the thermal requirements accounting for uncertainty of parameters



NO

TCS ACTIVITY CHANGE
TO INCORPORATE STOCHASTIC METHODS – (2/2)

TO: satisfy the thermal requirements accounting for uncertainty of parameters, with a specified level of confidence, i.e. probability to meet the requirements must be higher than a given value



CONCLUSIONS
Application of the Stochastic Approach

MCS is effectively applicable in the frame of real space projects.

- The method is of general application and the theory is well known and developed
- The application of the method is not difficult and does not require a complicated theoretical background
- During tests the application of the MCS allowed to:
  a. Account for inaccuracy
  b. Solve and/or optimise the solution of TCS design problems
- During tests the MCS provided advantages in terms of:
  a. Activity duration
  b. Man-hours
  c. Design optimisation
  d. Possibility to derive additional information form the amount of data that the MCS analysis makes available

CONCLUSIONS
Comparison of Possible Stochastic Methodologies

Stochastic methodology focused on single activities of TCS		Global stochastic methodology for TCS
+	Feasible when subcontractors are involved	−
+	Feasible when interface with other subsystems is necessary	−
+	Possible use of small samples for some types of analyses	−
+	Feasible in all phases of development	−
+	Reduced change of engineering approach	−
−	Always accounting for inaccuracy	+

CONCLUSIONS
Recommendations For Future Activities

- **INACCURACY OF PARAMETERS:**

  Studies dedicated to advanced methods for testing and measuring properties of materials in order to generate specific data relevant to inaccuracy would be useful.

- **OPTIMISATION PROCEDURES:**

  It would be interesting the evaluation of the use of the MCS for accounting of inaccuracy together with different optimisation procedures (e.g. procedures based on emulators rather than on simulators).

DISTRIBUTION OF RESULTS

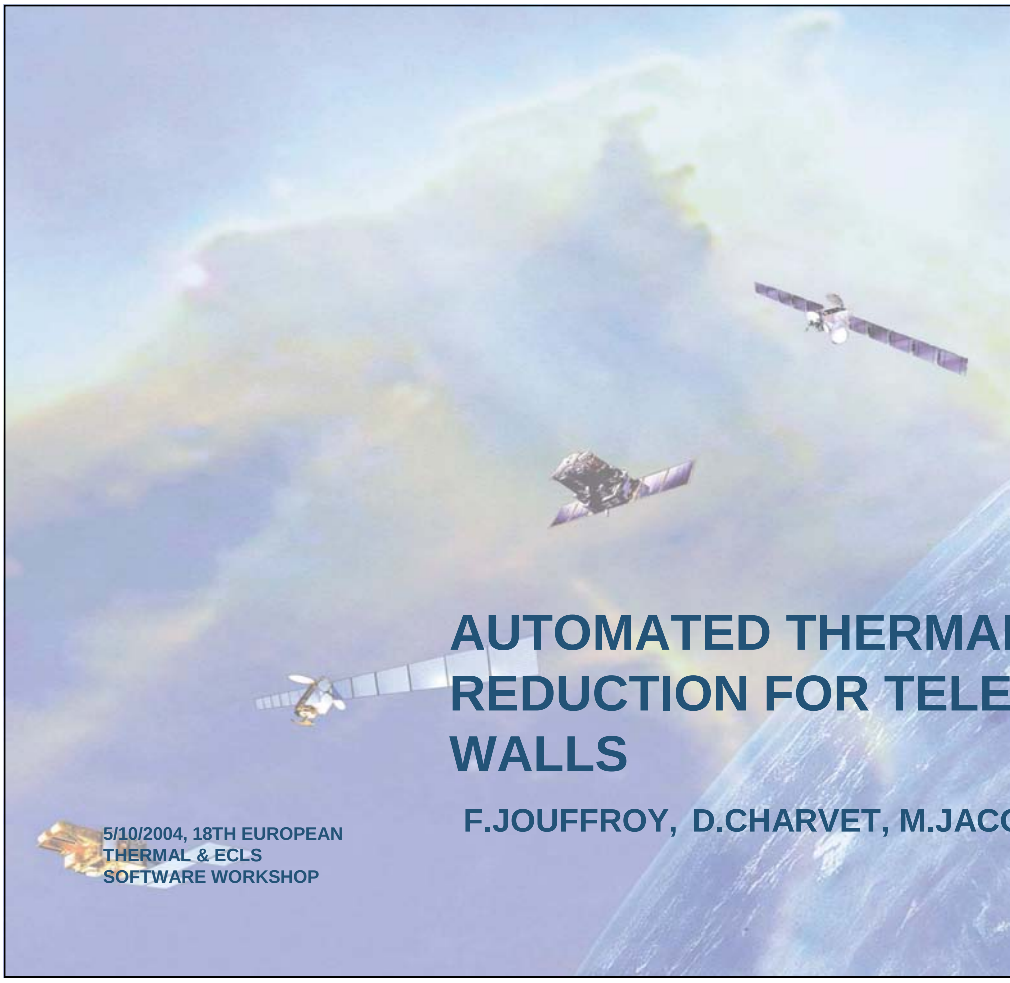
In ESA website will be available the results of the project :

- The Final Report: “Analysis and Assessment”, 02.07.035/TN4, issue 1, 30/9/2004
- The Handbook: “Guidelines for the Assessment and Implementation of Stochastic Methods for Space Thermal Analysis”, 02.07.035/TN5, issue 1, 30/9/2004
- The Executive Report: “Executive Report”, 02.07.035/TN6, issue 1, 30/9/2004
- The HTML version of the Handbook
- Some examples of the models implemented and used during the project

Appendix G: Automated Thermal Model Reduction for Telecom S/C Walls

Automated
Thermal Model Reduction
for
Telecom S/C Walls

F. Jouffroy
EADS Astrium



AUTOMATED THERMAL MODEL REDUCTION FOR TELECOM S/C WALLS

F.JOUFFROY, D.CHARVET, M.JACQUIAU, A.CAPITAINE

5/10/2004, 18TH EUROPEAN THERMAL & ECLS SOFTWARE WORKSHOP

EADS ASTRIUM

Summary

- Telecom spacecraft modelling process in EADS ASTRIUM
- Model reduction usual approach in EADS ASTRIUM
- Automatic method reduction for panels
- Application for Telecommunication panels
- Perspectives and conclusions

TELECOM S/C modelling process (1/2)

- Continuous increase in size and complexity vs development duration cut

⇒ Improvement of development process is a key issue.

- EADS-ASTRIUM answer for the thermal field: GENASSIST internal tool for TELECOM S/C wall modelling, developed for 10 years.
  - High level -but detailed- wall definition for sandwich panel, units, doublers, heat pipes : geometry, location, contact conduction & thermo-optical properties inputs.
  - This definition is used to automatically generate a whole ESATAN model based on a grid meshing (150x150, for each skin).

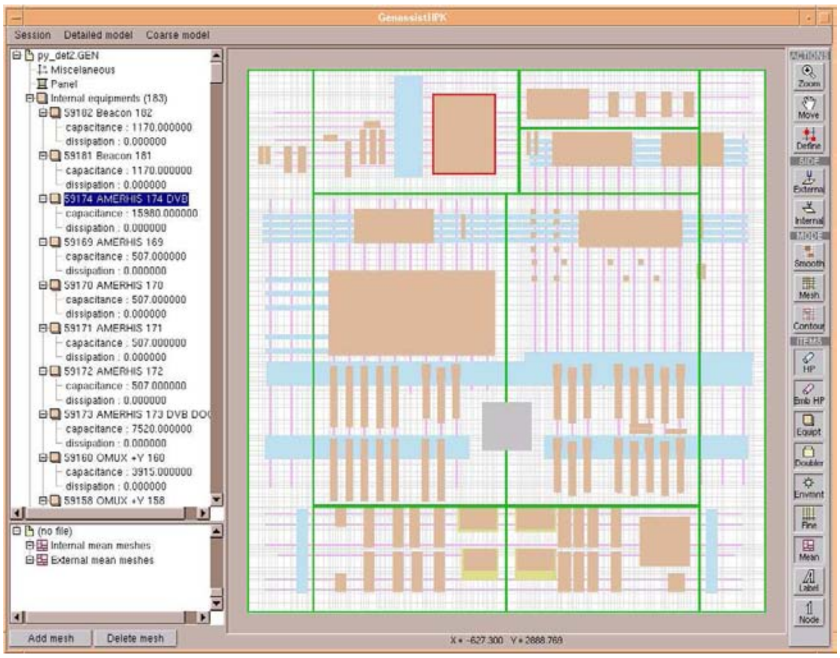
But …

  - Required thermal accuracy (due to high heat flux density) needs fine meshing to model every geometrical transition with only linear conduction (no spreading effect formula)

⇒ Huge Model : >40 000 nodes per wall which leads to unacceptable computation times :

MODEL REDUCTION IS MANDATORY FROM INDUSTRIAL POINT OF VIEW

TELECOM S/C modelling process (2/2)



Typical detailed wall modelling in GENASSIST

Model reduction usual approach (1/2)

1) Definition of a simplified meshing by gathering nodes.

- **Some experience is requested for node selection to get a satisfying reduction (isothermal nodes, spreading effect)**
- **Automatic procedure developed under Thermica environment**

2) Computation of the coupling network for the reduced model.

- **Automatic generation of radiative couplings.**
- **Manual/assisted/automatic generation of conductive couplings.**

3) Iterative correlation of obtained reduced model

- **temperature comparison with detailed model for one hot and one cold case**
- **manual update of conductive couplings to get an acceptable thermal flux spreading over the model**

REAL NEED FOR A FASTER & BETTER QUALITY PROCESS

Model reduction usual approach (2/2)

Advantages :

- « Classical » thermal model with conductive links between neighbour node
- Not heavy numerical tools are needed for model reduction

Disadvantages - Drawbacks

- Correlation is made only for one or two cases
- Physical properties are lost during correlation procedures
- Updating procedures after tests are approximate
- Reduction is dependant on the thermal engineer
- No possibility to recover temperature on the detailed model
- Process has to be re-run if some configuration is changed
- Number of nodes is quite important to have a good accuracy : 1800 nodes by panel
- Difficulties to obtain an accuracy better than 2°C
- Heavy process

REAL NEED FOR A FASTER & BETTER QUALITY PROCESS

A method for model reduction (1/4)

- The goal of the method is to mathematically generate, for reduced model, an <u>equivalent conductive matrix</u>, corresponding to conductive transfer of original detailed model.

⇒ No more manual conductive coupling calculation or iterative update should be required: the best solution for the problem is directly got from numerical calculation.

- The reduced model is built with two different kinds of nodes:
  - 'Thermal control' nodes: kept 'as is' from detailed model, for thermal control or accuracy needs: units, heated area, heat pipe vapor nodes.
  - 'Condensed nodes' gathering several detailed model nodes.

A method for model reduction (2/4)

<u>Spirit of the method</u>

- The steady-state heat transfer equation for a given node i is written in a linear manner, as following $\sum_{j \neq i} C(i,j).(T_j - T_i) + P_i = 0$

Where P_i includes the radiative transfer: $P_i = Q_i + \sigma \sum_{j \neq i} GR(i,j).(T_j^4 - T_i^4)$

- This can be written using linear algebra formulation, separating kept 'thermal control' nodes N_i from 'eliminated' ones N_j.

$$\begin{bmatrix} C_{ii} & C_{ij} \\ C_{ji} & C_{jj} \end{bmatrix} * \begin{bmatrix} T_i \\ T_j \end{bmatrix} + \begin{bmatrix} P_i \\ P_j \end{bmatrix} = \begin{bmatrix} O \end{bmatrix}$$

$C_{ii}.T_i + C_{ij}.T_j + P_i = 0$

$C_{ji}.T_i + Cjj.T_j + P_j = 0$

A method for model reduction (3/4)

- **Then, 'condensed' nodes Nk to be created for the reduced model are added to the equation system, with following assumptions:**
  - Temperature of a 'condensed node' k is the surface-weight averaged temperature of corresponding detailed model nodes.

$$T_k = \sum_j a_{kj}.T_j \qquad \sum_j a_{kj} = 1 \text{ and } \sum_j a_{kj}.(T_j - T_k) = 0$$

  - Radiative fluxes of a detailed model node is the surface-weight fraction (a_{jk}) of the total radiative flux of the corresponding 'condensed node' k:

$$P_j = a_{jk}.P_k$$

- **This leads to a larger equation system gathering:**
  - N_i kept nodes.
  - N_j eliminated nodes.
  - N_k condensed nodes built from Nj eliminated nodes.

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A method for model reduction (4/4)

- **By reorganizing this equation system, it is possible to find a relationship linking temperatures and fluxes for the new reduced model:**

$$M_{ll} T_l + P_l = 0 \quad (1)$$

T_l is the reduced model temperature vector, ie T_i and T_k
P_l is the reduced model power vector, ie P_i and P_k
M_{ll} is the linear coupling matrix of the reduced model

- **In addition, an another interesting relationship can be highlighted from the reorganized equation system:**

$$X_j = C_{jl} T_l \quad (2)$$

where **X_j is a vector containing the T_j vector**
C_{jl} is a transformation matrix linking reduced model temperatures to detailed model temperatures

EADS ASTRIUM

Remarks (1/2)

- **The final matrix obtained M_{ll} is symmetric and for each line we have**

$$\sum_n M_{ln} = 0$$

- **This matrix is introduced in TMM as GL(l,n)=M_{ln}**

- **Eq. (2) allows to get eliminated nodes temperatures T_j from reduced model temperatures T_l.**
  - to compute heatpipe transport capacity.
  - to get detailed T° map of the panel
  - to get flux exchanges
  - Inputs for thermoelastic analysis
- **Model reduction is exact for conductive transfer**
- **Need to inverse a matrix nxn where n is the size of the detailed model.**
- **Not emitting nodes (P_j=0) are useless to define 'condensed nodes' (a_{kj}= 0) and can be directly reduced.**

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Remarks (2/3)

For a node k, the average radiated flux difference is proportional to $\sum_j a_{kj} T_j^4 - T_k^4$

Defining $T_j = T_k + \Delta T_j$ with $\sum_j a_{kj} = 1$ and $\sum_j a_{kj}.\Delta T_j = 0$

The average error is a second order and proportional to $6\left(\sum_j a_{kj}.\Delta T_j^2\right) T_k^2$

The ratio is then $$6\frac{\left(\sum_j a_{kj}.\Delta T_j^2\right)}{T_k^2}$$

This error may be illustrated by a very simple model

Example: average of 2 nodes: 0°c ,10°c				T env=0°K
T_{kred}(°C)=	5.00	T_{kdet}(°C)=	5.13	$\Delta\phi_{rad.exch}$ (%)
$\phi_{rad.exch}$=	339.0	$\phi_{rad.exch}$=	339.6	0.2%

EADS ASTRIUM

Remarks (3/3)

- Some GL terms may be negative !!
- Let's try to watch the model reduction problem from an other point of view:
- The goal is to get, with a reduced model network, the same conductive fluxes between kept nodes, as with initial detailed model network…
- this, although less parameters -i.e. nodes & couplings- are available …

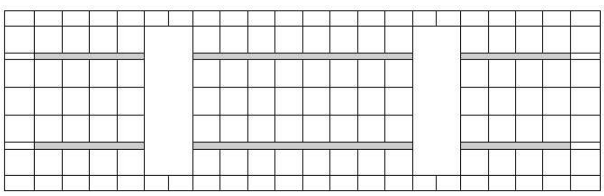
⇒ Linear couplings in the obtained matrix may be negative. They can't be called 'conductive couplings',

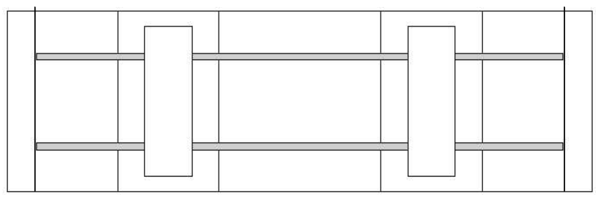
but …

the whole linear coupling matrix provides for kept nodes the same conductive thermal behaviour as detailed model

Examples of results

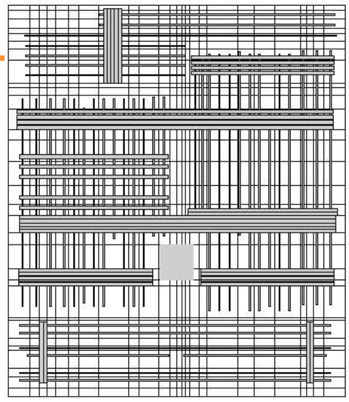
- 400 nodes wall simplified model: reduced to 22 nodes (1/18 ratio)
  - Realistic flux density : 2 * 40 W, for S_{rad} = 0,3 m2
  - Environnement : T_{sink} front side = -120°C / T_{sink} rear side = 40°C
  - Longitudinal thermal gradient in the skin : 15°C.
  - Delta reduced/detailed model : 0.2/0.3°C for unit and heat pipe nodes.





- 43000 nodes wall detailed model: reduced to 750 nodes (1/57 ratio)
  - Max delta reduced/detailed <0.°7C for all units and heat pipes.

Comparison with previous reduction method

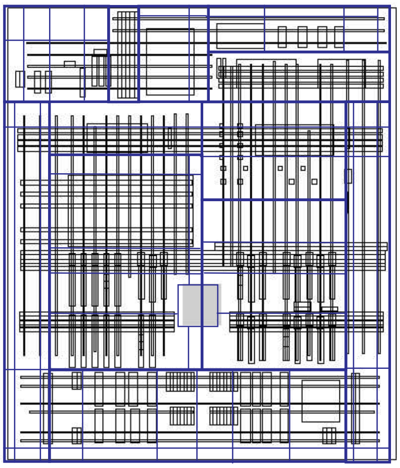


- Model correlation is excellent on every node,

and not only for ‘manually correlated’ nodes as previously

- Reduced model size can be significantly decreased:

- previous method: 43000 -> 1740 nodes (1/25 ratio)



1500 skin reduced nodes (manual spreading calc.)

80 kept heat pipe nodes

160 kept unit nodes

- New method: 43000 -> 460 nodes (1/93 ratio)

160 skin ‘condensed’ nodes

60 kept skin nodes facing integrated heat pipes.

80 kept heat pipe (integrated +surface) heat pipes.

160 kept unit nodes.

NEW METHOD: LARGER SKIN NODES

& BETTER PRECISION

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Reduced meshing definition: the key step still requiring thermal engineer added value.(1/3)

- Rules to improve reduced model quality.
  - uniform radiative flux assumtion to be roughly respected to define ‘condensed’ skin nodes.

- Rules to ease further reduced model operation (for post-test correlation and sensitivity analysis).
  - skin nodes below units and heat pipes to be kept to allow direct trimming of contact conductances.
  - Condensed nodes to respect heater and radiator area definition.

  ⇒Reduced model allows direct sensitivity calculation for dissipations, contact conductances and radiator areas.

  But…

  sensitivity on panel conductivity requires to run the whole computation chain from detailed model.

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Reduced meshing definition: the key step still requiring thermal engineer added value.(2/3)

- **Rules for model interfacing: interfaces shall be clearly defined prior to reduction.**

  Beware: Condensed nodes are not isothermal so not representative of local temperatures.

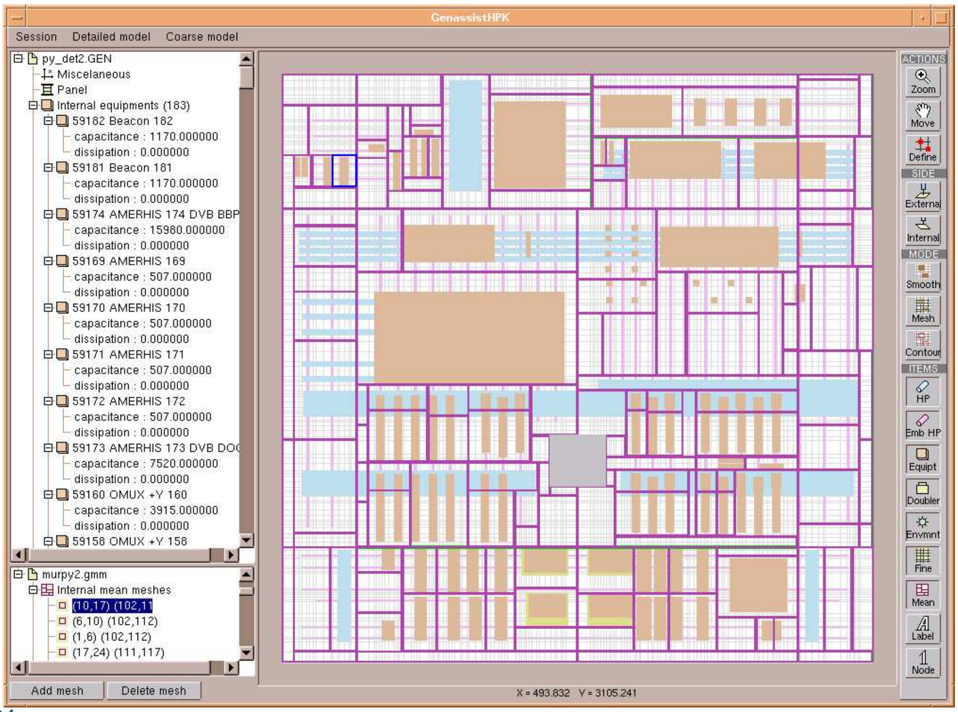
  => Local detailed modelling to be kept at interface location:

  - **Interface points where subsystems are mounted.**
  - **wall interface => use of strip nodes on panel border to separate contact from thermal path within the panel.**

- **GENASSIST provides a user-friendly interface to define a reduced meshing mapped on detailed model (picking of opposite corner points for 'condensed' areas).**

EADS ASTRIUM

Reduced meshing definition: the key step still requiring thermal engineer added value (3/3)



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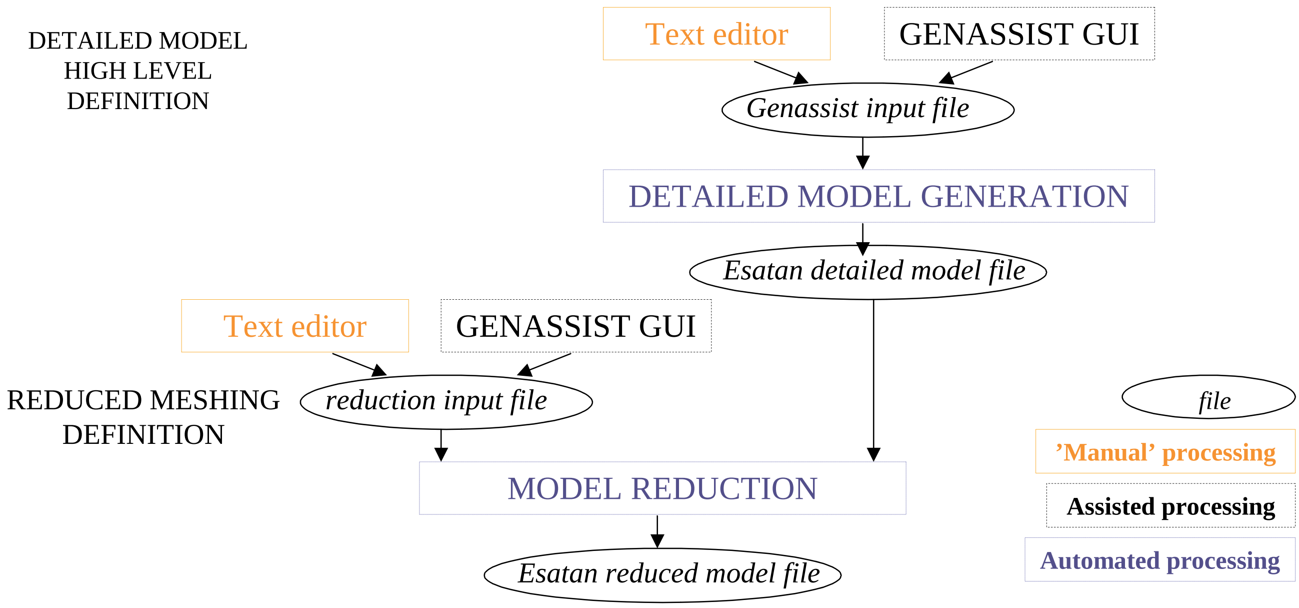
GENASSIST PROCESS SUMMARY



REDUCTION is a separate module: it can be performed out of GENASSIST

Conclusion

- **Reduction process no longer requires manual conductive coupling calculation and iterative update : the best solution for the problem is directly obtained from numerical calculation,**
- **Less manpower required; model reduction requires heavy computations but not a critical issue,**
- **Better quality results obtained everywhere in the model,**
- **Possible smaller size obtained for reduced model speeds up analysis computation,**
- **Reverse engineering capabilities: Possibility to get specific information within detailed model from reduced model computation results,**
- **Meshing simplification definition is now the key step: thermal engineer added value is still necessary.**

Perspectives

- **Flexible method adaptable to different problems, although radiative flux assumption is not strictly verified. Reduction module can be used independantly from GENASSIST.**
- **Generalisation in order to be able to reduce 3D models with specific methodology for**
  - Interfaces
  - Non flat surfaces
  - Non uniform environmental boundary conditions
- **Use of sub systems assembly at system levels with detailed models from sub**
- **Use of reduction method for real time model correlation**

Appendix H: Advances in the Thermal Analysis in the frequency domain: Algorithms development, integrated software tools and post-processing

Advances in the Thermal Analysis in the frequency domain: Algorithms development, integrated software tools and post-processing

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Advances in the Thermal Analysis in the frequency domain
Algorithms development, integrated s/w tools and postprocessing

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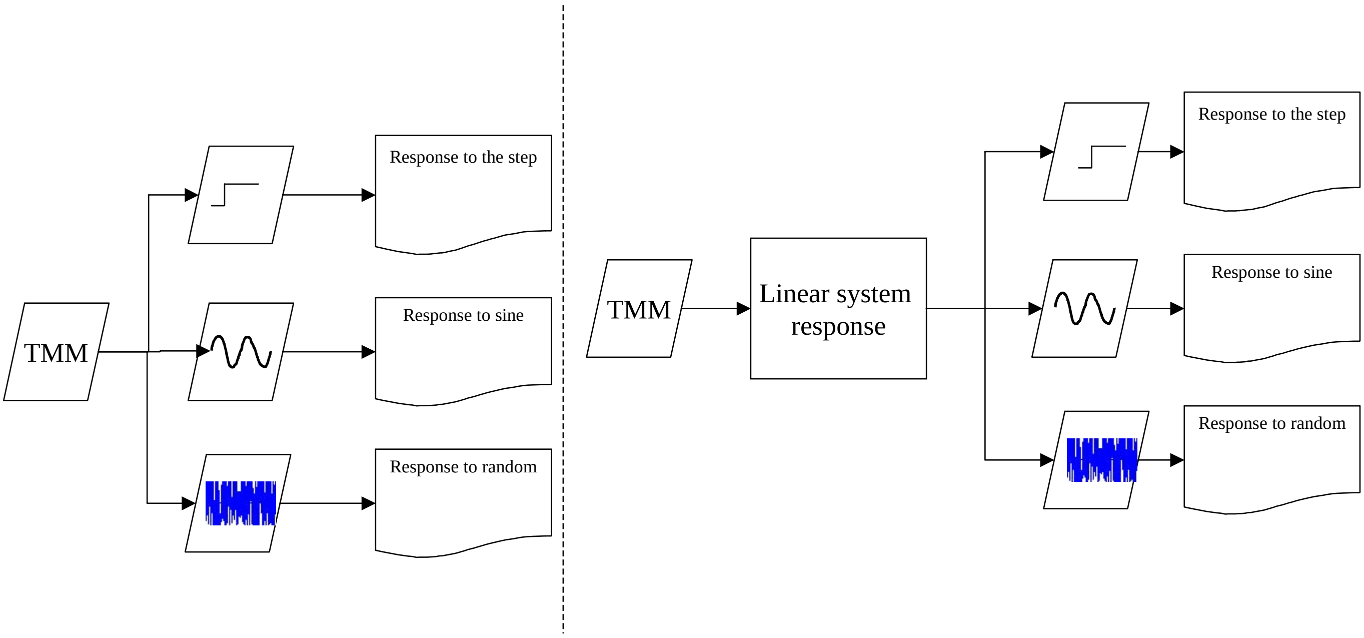
Introduction

- New physics (gravitational waves, geodesic characterisation) demands for new thermal tools
  – THERMAL “ON DEMAND”
- mK, μK (nanokelvin?) fluctuations
  – Numerical problems
  – Linearization possible!
- A unique tool is needed to allow calculation of the response of a thermal system to:
  – a constant perturbation, or Steady State response (step function)
  – a periodic perturbation (monochromatic frequency response)
  – a random perturbation
  – a combination of what above

Standard vs. linear system approach



Physical quantities definition

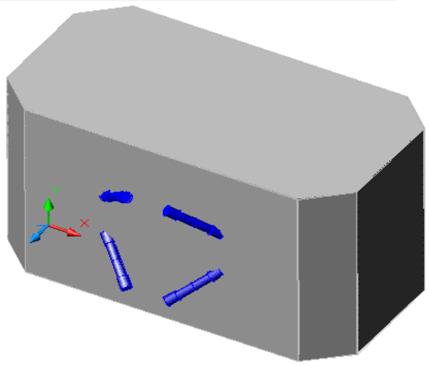
- The method presented hereafter can be applied to any set of CONSISTENT UNITS
  - K
  - °F
  - Sqrt(TSD)

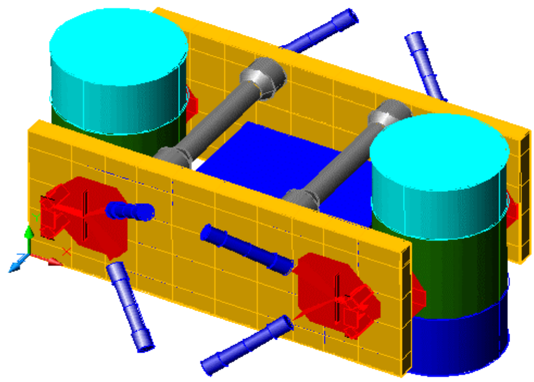
    - TSD = Temperature Spectral Density = [K^2/Hz]

$$TSD \equiv \lim_{\Delta f \to 0} \frac{T^2}{\Delta f}$$

Application
(the Test case)

LISA TECHNOLOGY PACKAGE





Optical Bench requirements

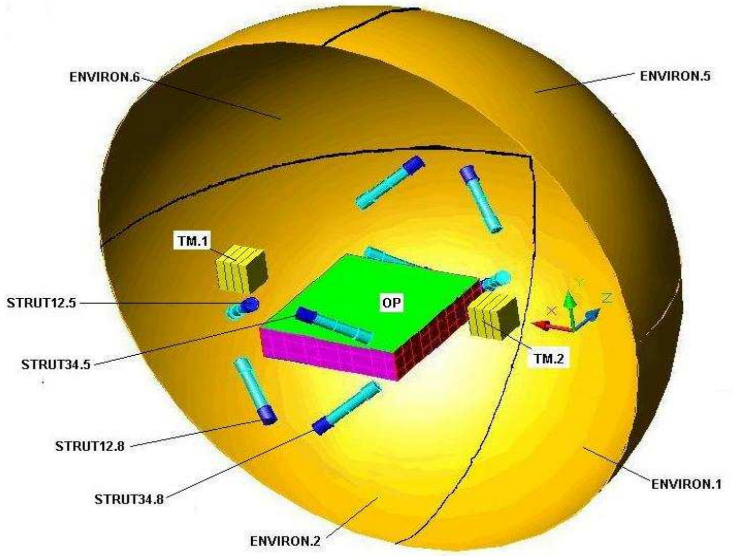
REQUIREMENTS	*REQ. VALUE*
OB temperature	20 ± 10°C
OB temperature stability	10^{-4} K/ $\sqrt{\text{Hz}}$
OB temperature gradient stability	10^{-4} K/ $\sqrt{\text{Hz}}$

FREQUENCY RANGE: $10^{-1} \div 10^{-4}$ Hz

Interfaces definition

• RADIATIVE INTERFACES :
LTP has been put into a sphere (8 nodes), simulating satellite environment
•CONDUCTIVE INTERFACES:
  •Struts
  •Cables

TOTALLY 40 boundary nodes



MIMO (Multi-Input-Multi-Output) systems theoretical background

Heat transfer equations

$$
\begin{cases}
C_1\dot{T}_1 = \sum_{i=1}^{N} GL_{1-i}(T_1 - T_i) + \sum_{i=1}^{N} GR_{1-i}\left(T_1^{\,4} - T_i^{\,4}\right) + Q_1 \\
C_2\dot{T}_2 = \sum_{i=1}^{N} GL_{2-i}(T_2 - T_i) + \sum_{i=1}^{N} GR_{2-i}\left(T_2^{\,4} - T_i^{\,4}\right) + Q_2 \\
\vdots \\
C_j\dot{T}_j = \sum_{i=1}^{N} GL_{j-i}(T_j - T_i) + \sum_{i=1}^{N} GR_{j-i}\left(T_j^{\,4} - T_i^{\,4}\right) + Q_j \\
\vdots \\
C_N\dot{T}_N = \sum_{i=1}^{N} GL_{N-i}(T_N - T_i) + \sum_{i=1}^{N} GR_{N-i}\left(T_N^{\,4} - T_i^{\,4}\right) + Q_N
\end{cases}
$$

Linearized equations

$$[C]\{\delta\dot{T}\} = [K]\{\delta T\} \quad \Rightarrow \{\delta\dot{T}\} = \left[C^{-1}\right][K]\{\delta T\} = [A]\{\delta T\}$$

Linearized system equations and transfer function

$$\{\delta\dot{T}\} = [A]\{\delta T\} \quad \Rightarrow \quad \begin{Bmatrix} \delta\dot{T}_V \\ 0 \end{Bmatrix} = \begin{bmatrix} A_{VV} & A_{VB} \\ A_{BV} & A_{BB} \end{bmatrix} \begin{Bmatrix} \delta T_V \\ \delta T_B \end{Bmatrix} \quad \Rightarrow \quad \delta\dot{T}_V = A_{VV}\delta T_V + A_{VB}\delta T_B$$

- Standard format for dynamic system equations

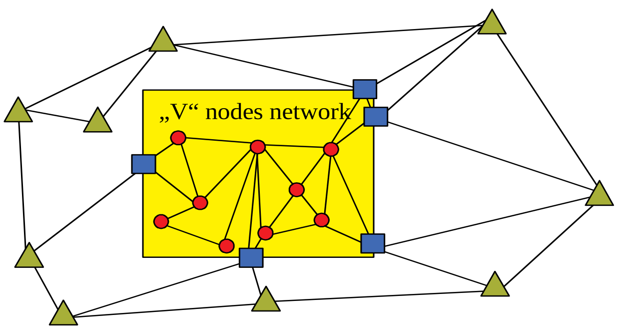
$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$

- In the frequency domain

$$\begin{cases} sX = AX + BU \\ Y = CX + DU \end{cases}$$

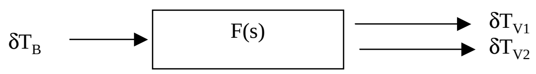
- Transfer function

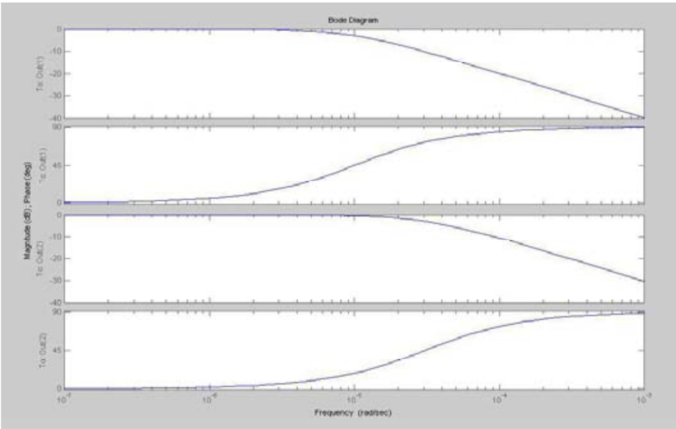
$$\frac{Y(s)}{U(s)} = F(s) = C(sI - A)^{-1}B + D$$



X= Status of the system
Y= Output of the system
U= Input

A first simple example





- Single Input, Double Output (SIDO)
  - For thermal engineers: 1 boundary+ 2 diffusion nodes
- 1 Bode diagram per diffusion node (d.o.f.)
  - Gain
  - Phase

Ready for any possible number of degrees of freedom

$$\begin{Bmatrix} \delta \dot{T}_V \\ 0 \end{Bmatrix} = \begin{bmatrix} A_{VV} & A_{VB} \\ A_{BV} & A_{BB} \end{bmatrix} \begin{Bmatrix} \delta T_V \\ \delta T_B \end{Bmatrix}$$

$$\frac{Y(s)}{U(s)} = F(s)$$

- If the thermal system has V “stati”, namely V different temperatures, one per node, the matrix A_{VV} size is *V* x *V*.
- If the number of (independent) inputs is B (number of bounday nodes) then the transfer function matrix *F(s)* is a rectangular matrix *V* x *B*.

Each component of this matrix F_{ij} provides the effect on the node *i* given by the variation of the temperature of the *j* boundary node.

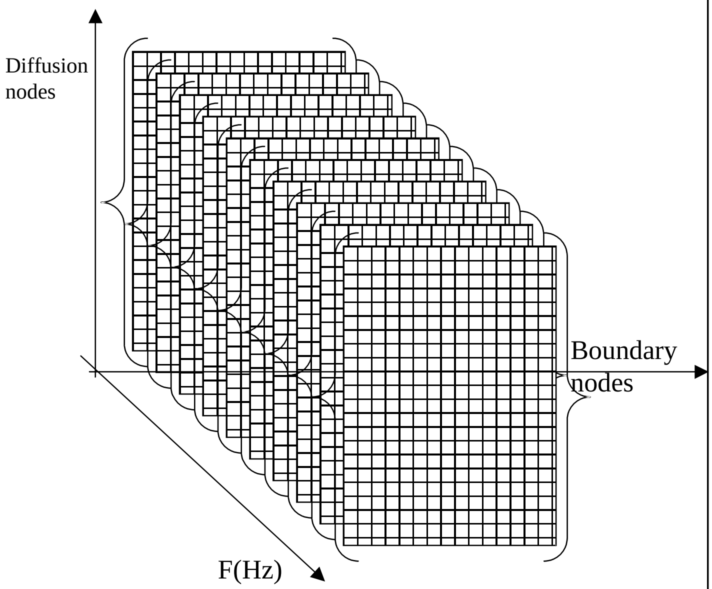
Test case features

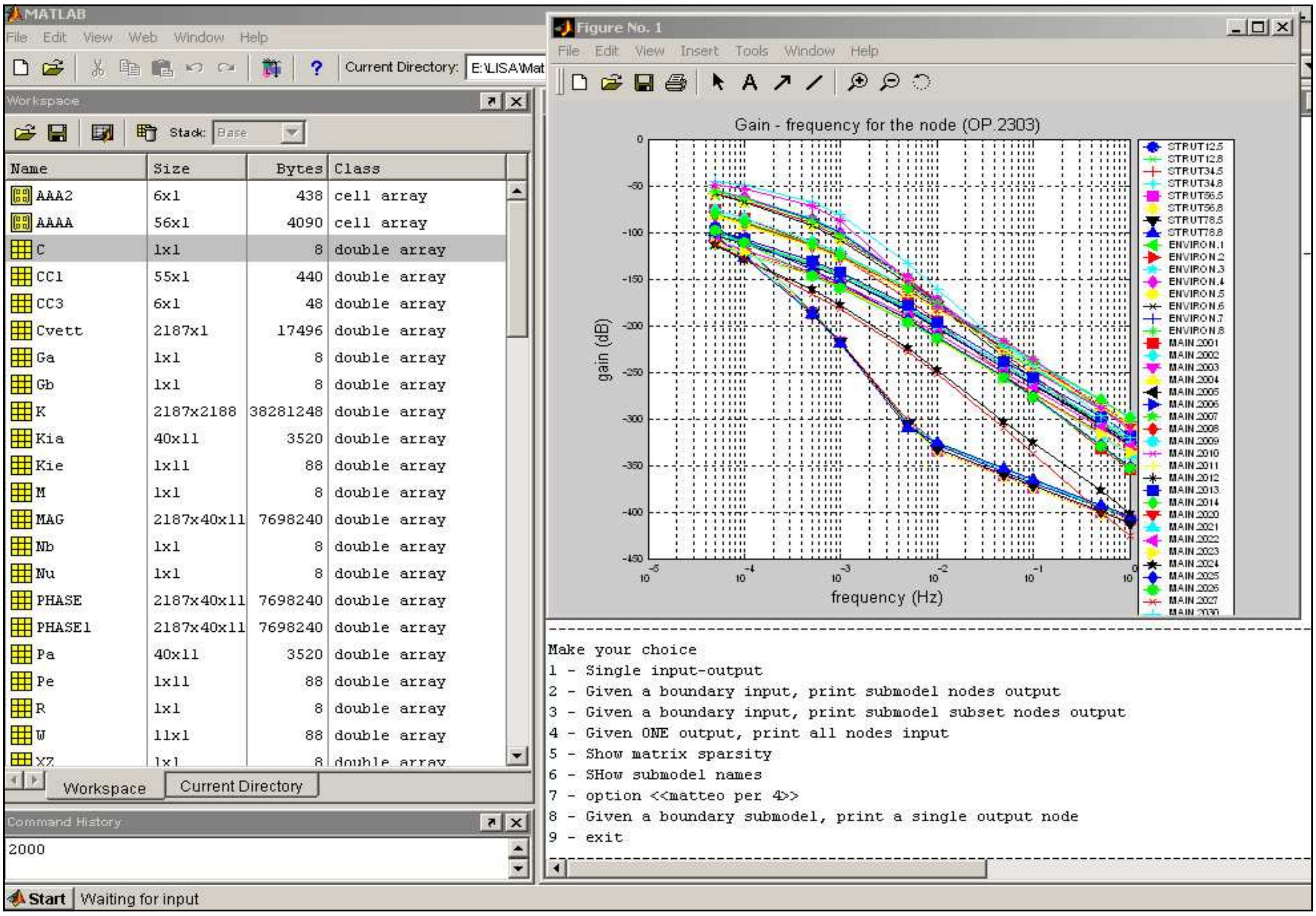
- LPT thermal network is :
  - 2280 diffusive nodes (V=2280)
  - 40 boundary nodes (B=40)
- According with the above description the matrix will have the following dimension:
  - Size(A_{VV}) = 2280 x2280
  - Size(A_{VB}) = 2280 x 40
- *F(s)* transfer function matrix size is 2280 x 40
  - It contains complex numbers (i.e. Phase and modulus are given)
  - It is frequency dependent

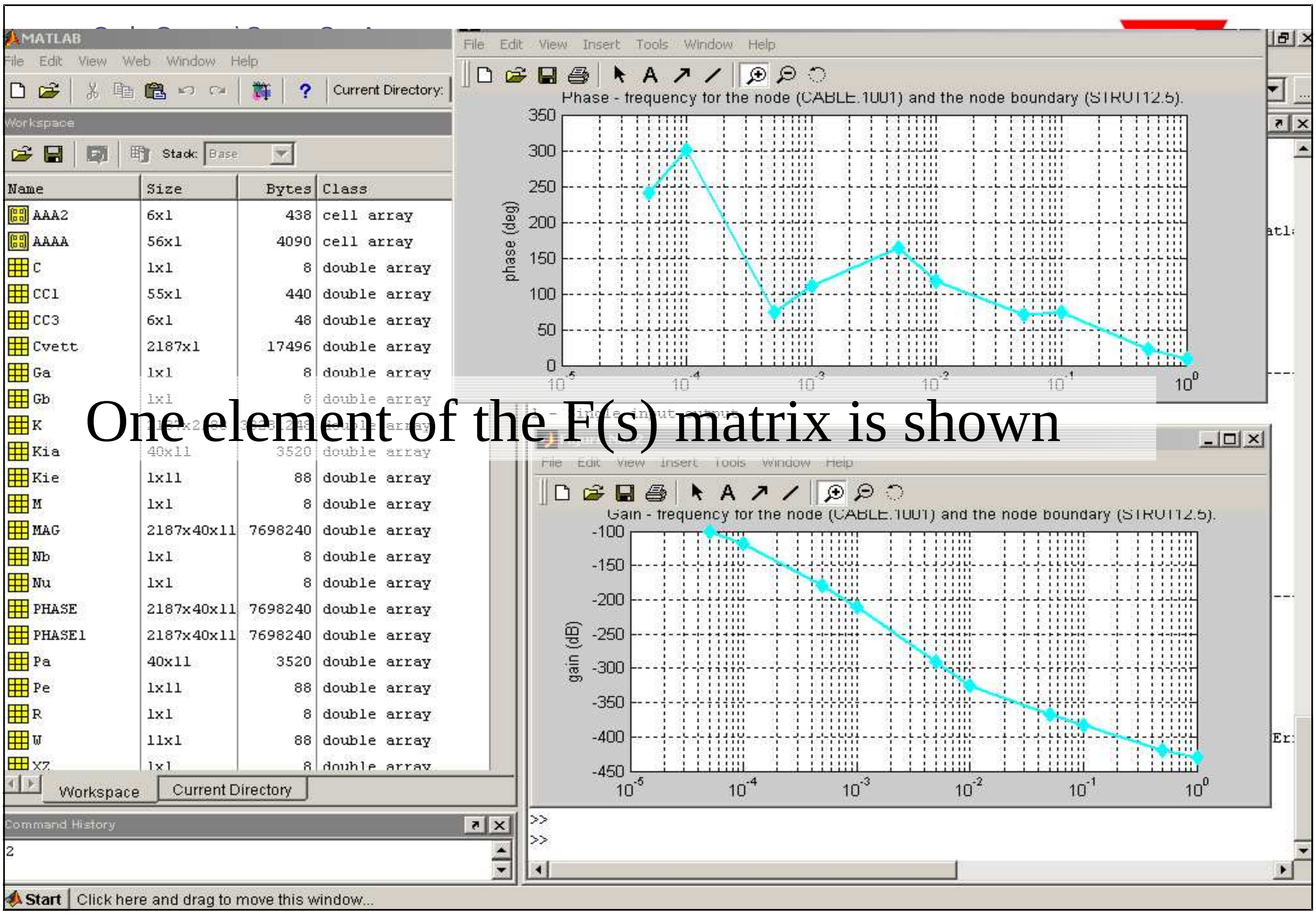
MATLAB tool to calculate F(s) and extract data from the matrix

- Gain Node-to-node
- Gain Node-to-Submodel
- Gain Submodel-to-Node
- Gain All boundaries-to-Node

- AVV or connectivity matrix is also given

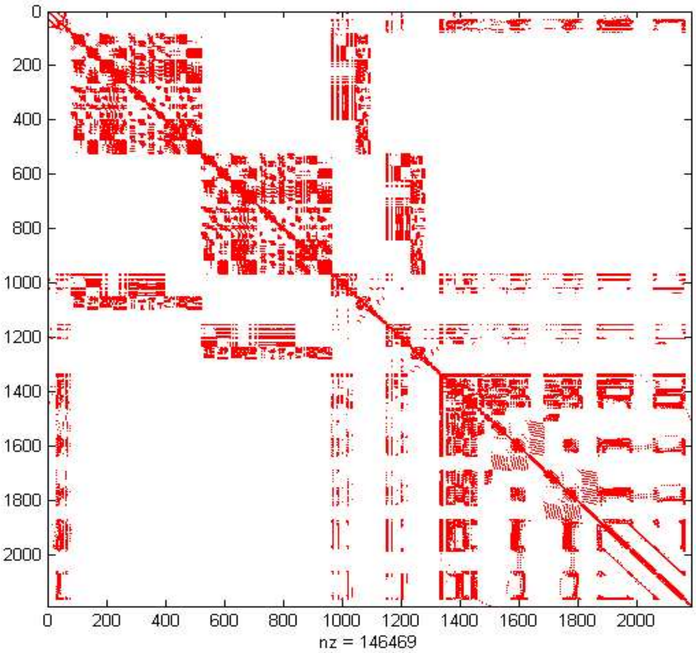




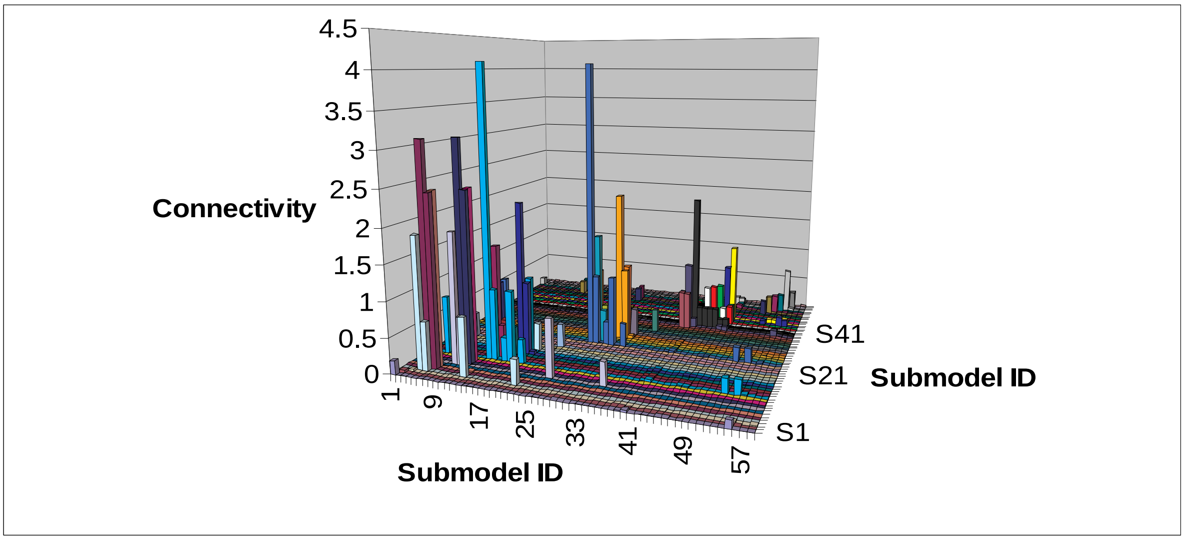


One element of the F(s) matrix is shown

AVV Matrix sparsity



Connectivity among Submodels



Physical meaning of the results

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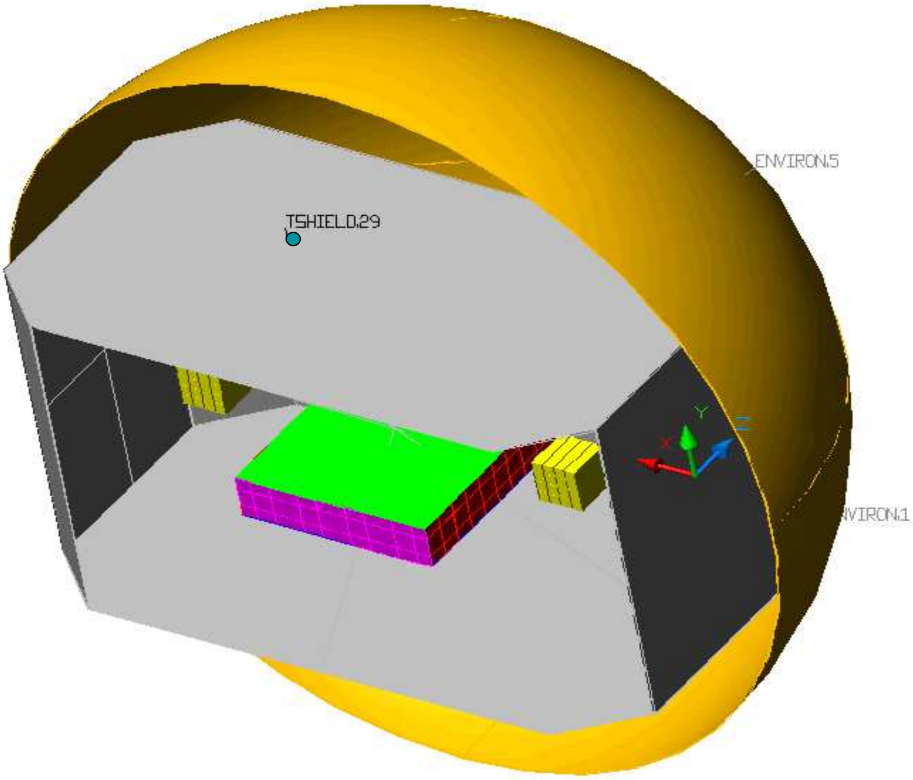

Test node location

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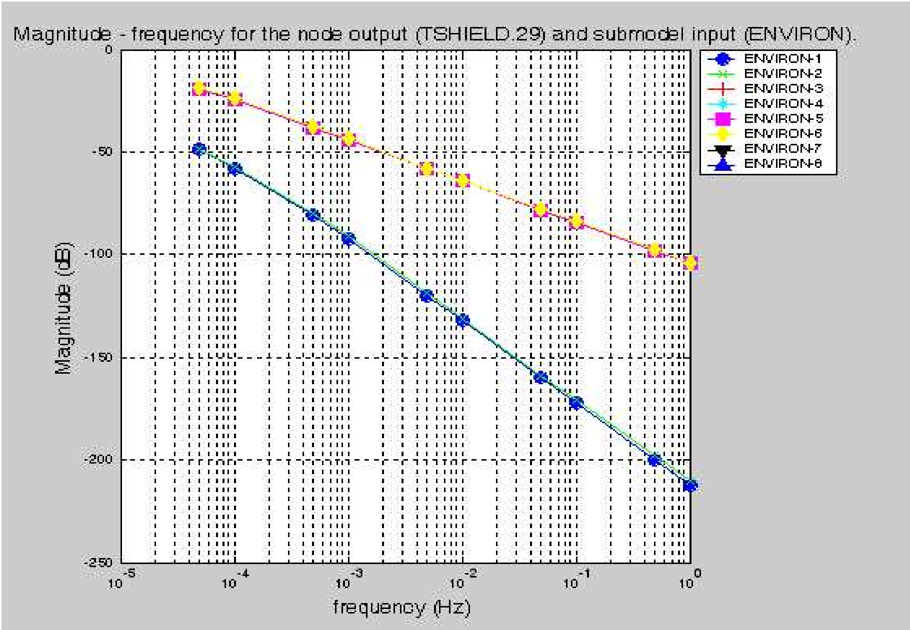
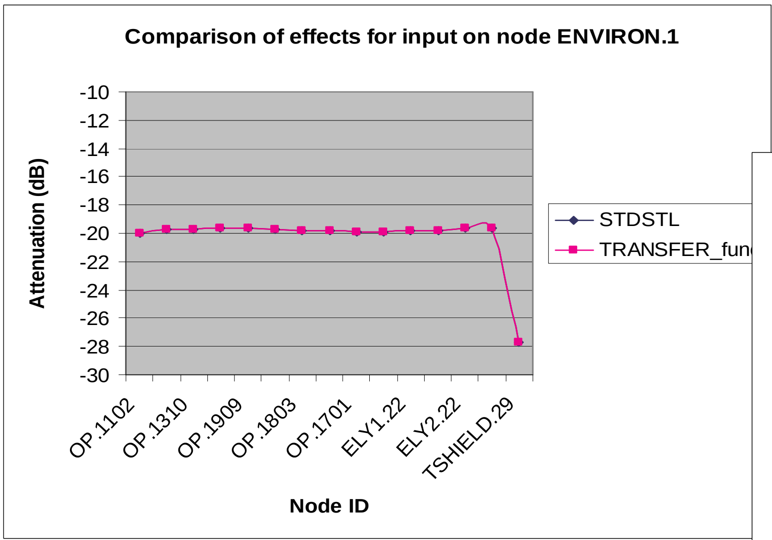
8 Sphere-nodes -to-a-single node on the thermal shield Gain

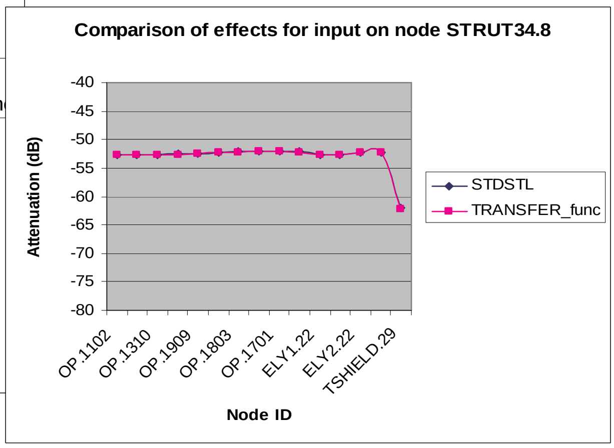


Tool check

- The results of the steady state TMM simulation were compared with the 0 Hz results coming from the Bode diagram.
- The results with TMM of transient simulations driven by periodical boundary fluctuations were compared with the Bode diagrams at 10^{-4} and 10^{-3} Hz.

Check Bode @0 Hz with STDSTL





10^{-4} Hz and 10^{-3} Hz comparison

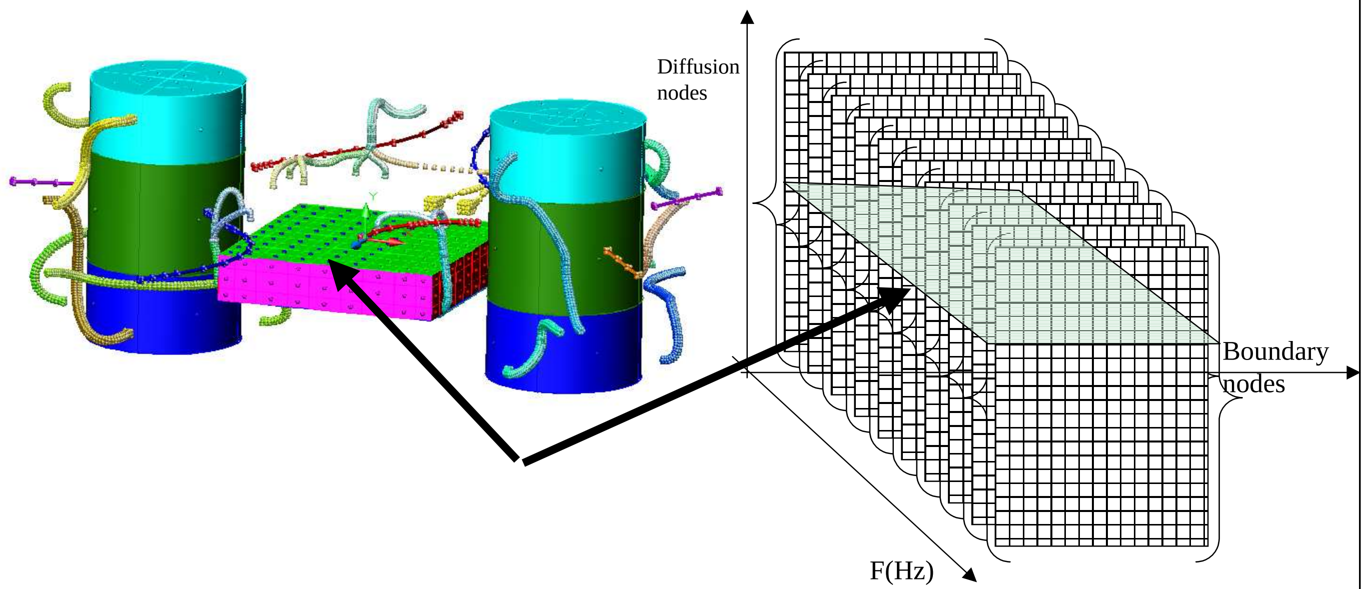
CASE	Input NODE	Frequency [Hz]	Input Amplitude (°C)
1	ENVIRON.1	10^-4	1
1b	ENVIRON.1	10^-4	1
2	ENVIRON.3	10^-3	1
4	STRUT78.5	10^-4	2
4b	STRUT78.5	10^-4	2
5	MAIN.2030	10^-4	1
6	MAIN.2030	10^-3	1

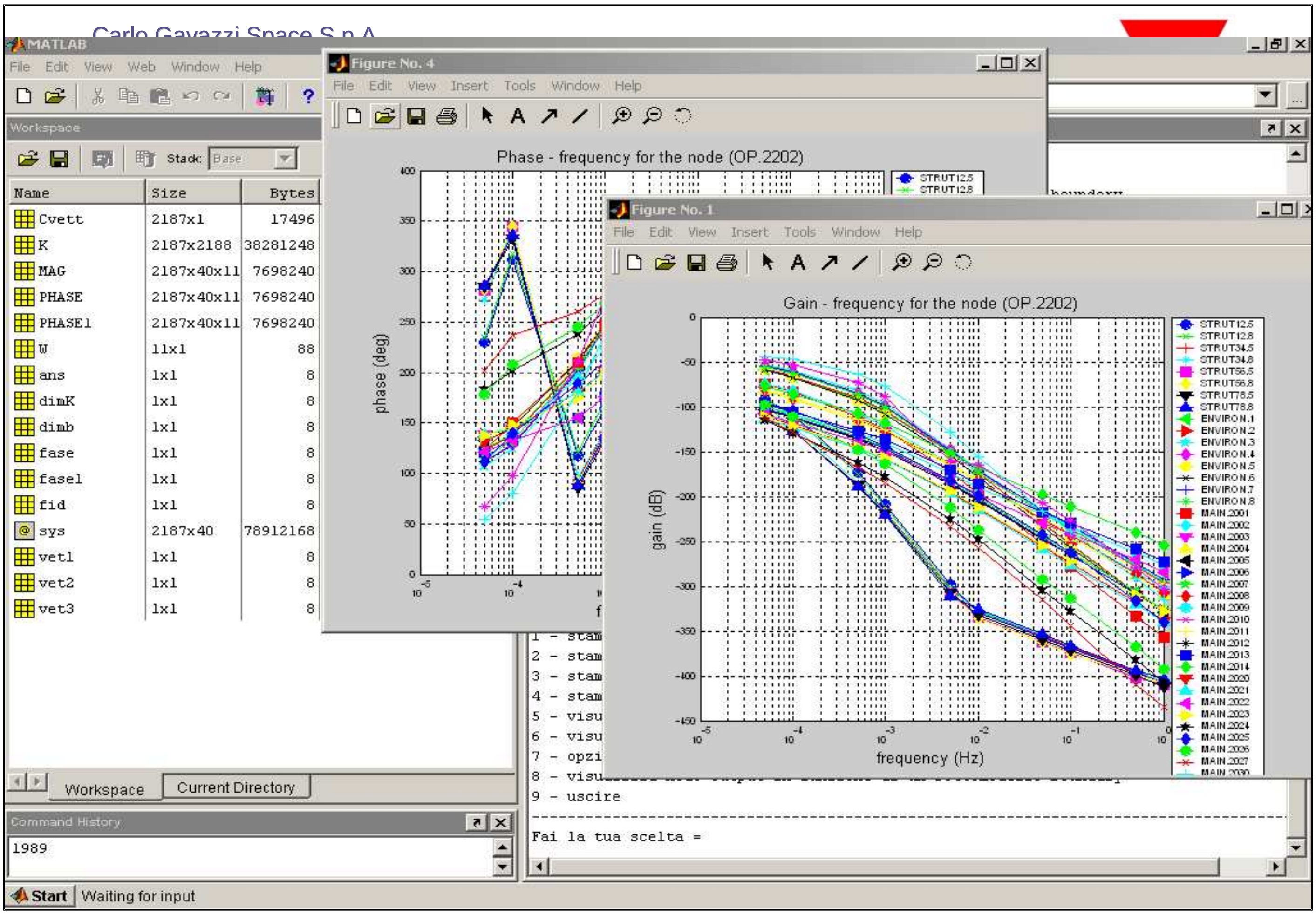
It is also a linearity limit check

		Attenuation			PHASE (deg)		
	Output node	SINDA	BODE	Relative difference	SINDA	BODE	Relative difference
1	TSHIELD.21	6.55E-03	6.51E-03	0.64 %	34.99	35.0	-0.08 %
1b	OP.1101	5.05E-04	5.19E-04	-2.77 %	134.8	135.4	-0.45 %
2	TSHIELD.10	1.30E-03	1.29E-03	0.52 %	104.4	104.5	-0.06 %
4	FLANGE4.6	2.45E-03	2.49E-03	-1.44 %	175.1	174.2	0.55 %
4b	TSSTR.34140	5.46E-05	5.66E-05	-3.70 %	191.7	194.8	-1.59 %
5	OP.1101	4.75E-03	4.76E-03	-0.12 %	87.84	87.1	0.84 %
6	OP.1301	5.05E-03	5.10E-03	-0.89 %	104.04	103.0	1.03 %

Typical output

All boundaries effect to a single node





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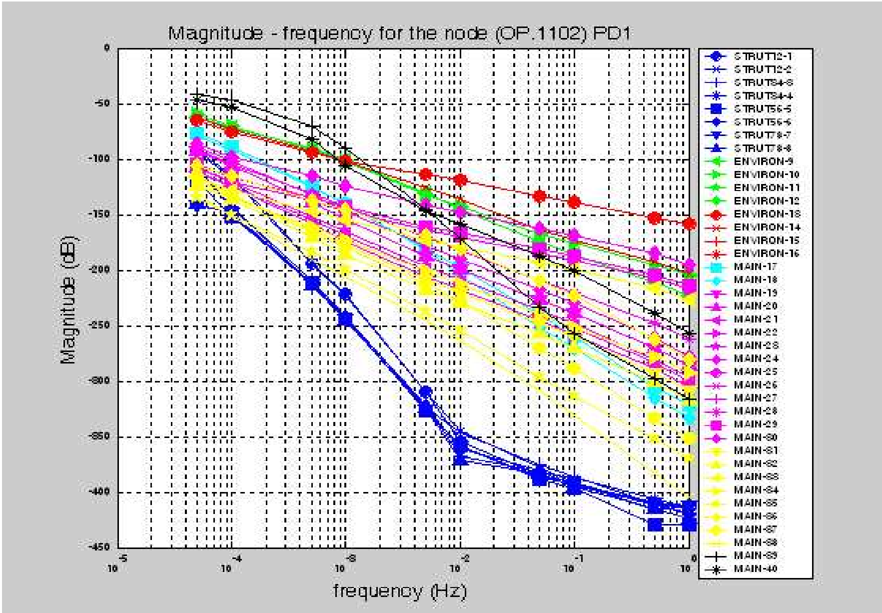
Gain of all the boundaries to a single node



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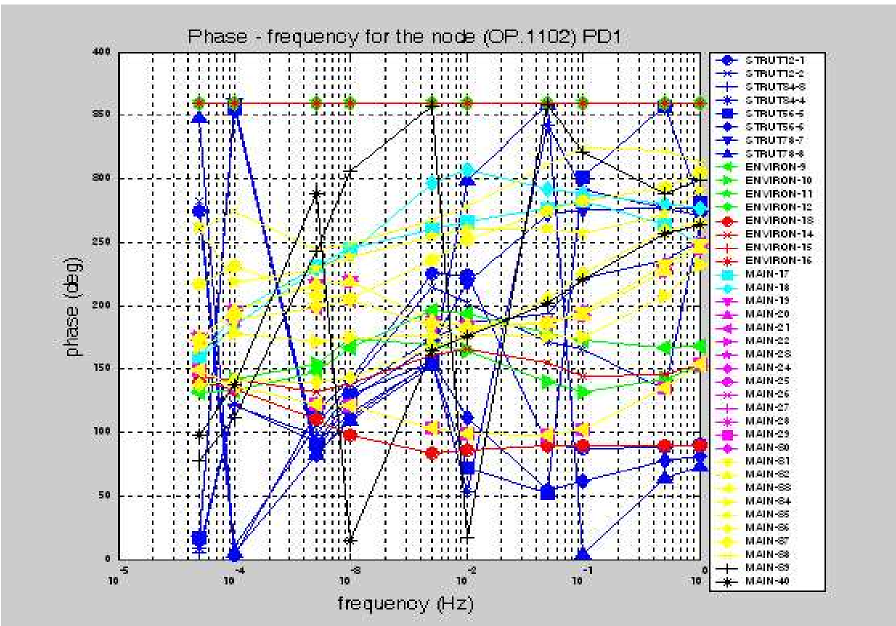
Phase of all the boundaries to a single node



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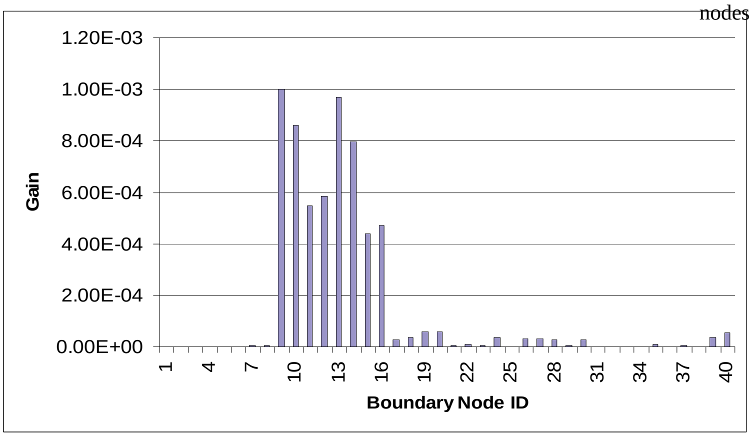
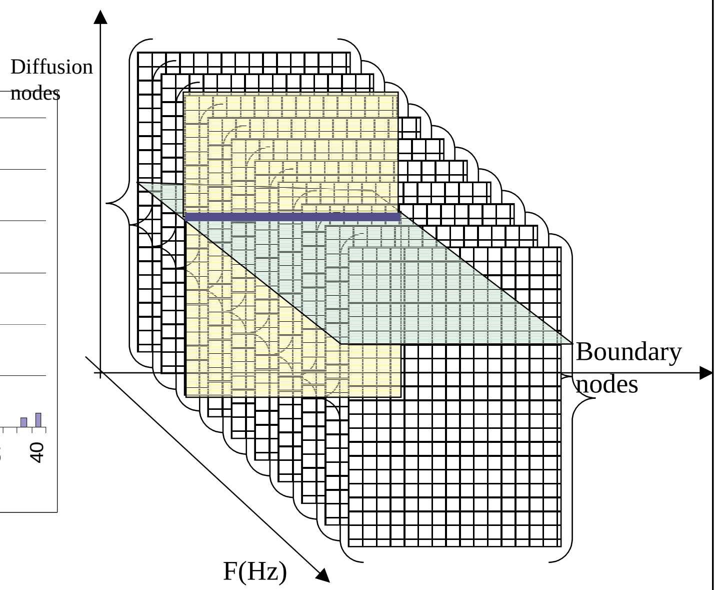
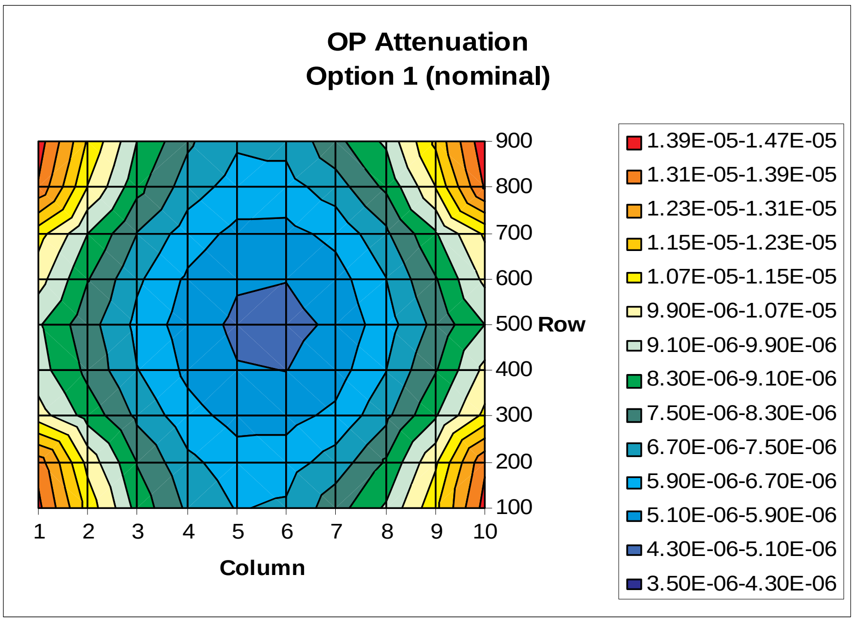
Gain of boundaries on a single node (of the Optical bench) at 10^{-4} Hz





Carlo Gavazzi Space S.p.A.

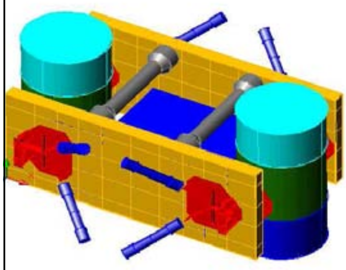
Gain due to the struts only on the Optical bench nodes (at 10^{-4}Hz)

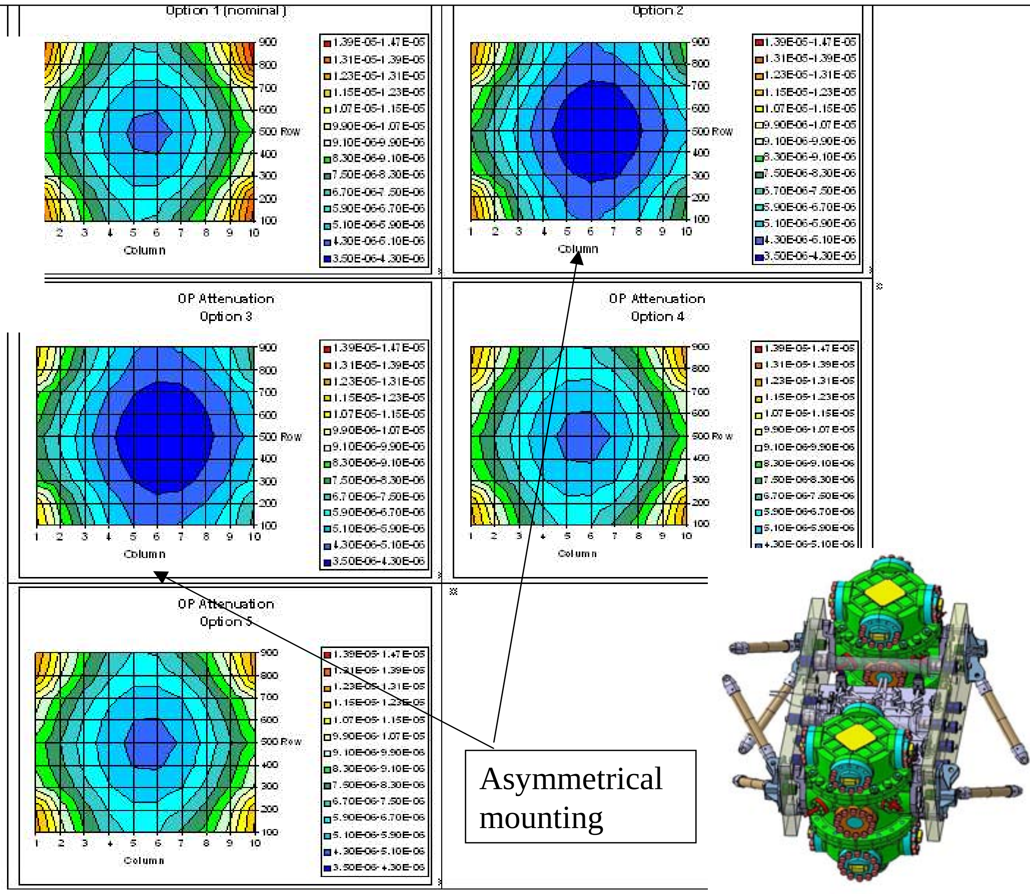


- In phase effects are considered as worst case

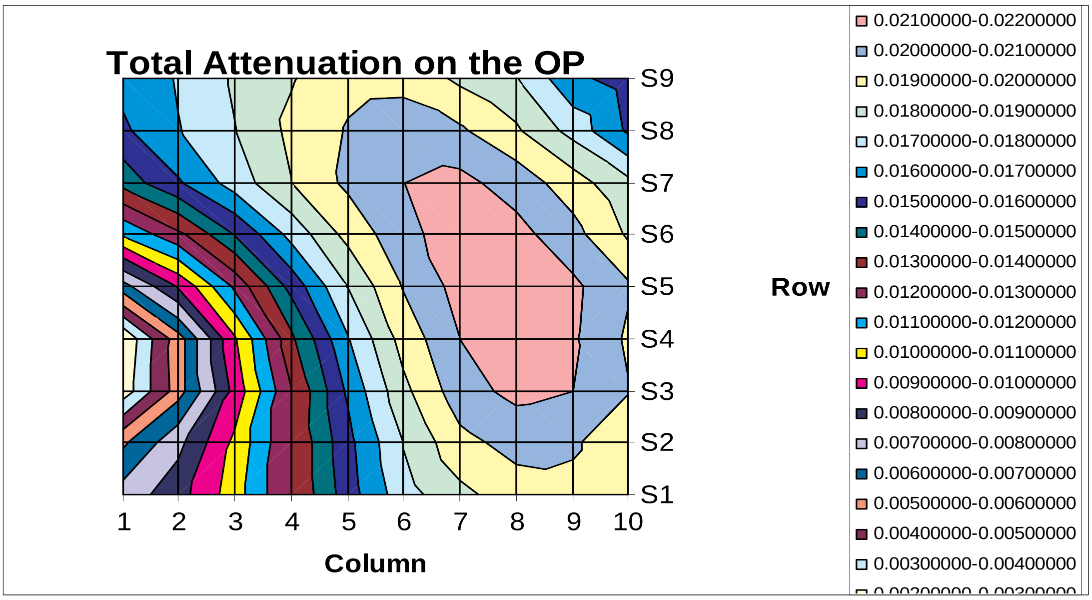
18th Workshop on Thermal and ECLS Software-ESTEC, 5-6 October, 2003

Trade off among mounting options





Gain due to all the boundaries on Optical bench nodes (at 10^{-4}Hz)



Conclusion

- Linear system theory has been successfully applied to a linearized TMM.
- Test cases have shown a very satisfactory agreement, under a heterogeneous set of test cases (steady state perturbations, transient perturbation at different frequencies).

F(s), or THE MATRIX

- The Transfer Function matrix, once calculated, allows
  – trade off evaluations
  – Checks possible to the PI, without any thermal tool (it is a matrix, sometimes called THE Matrix)
- The Matrix is a “deliverable”
- It is possible to apply any combination of disturbances with algebraic only computation effort

Appendix I: LHP Transient Modelling with EcosimPro

LHP
Transient Modelling
with
EcosimPro

C. Gregori de la Malla
Empresarios Agrupados

LHP TRANSIENT MODELLING WITH ECOSIMPRO

CARMEN GREGORI DE LA MALLA
EAI

CONTENTS

INTRODUCTION

INTRODUCTION (1)

- Loop heat pipes (LHP) are two-phase capillary heat transfer devices that are becoming very interesting for space thermal control applications because of:
  - High power transport capability
  - High temperature stability
  - Fast and strong diode action
  - Design flexibility
  - Robustness and reliability

INTRODUCTION (2)

- Important modelization efforts have been performed in order to predict thermal performances and transient behaviour of LHPs.
- LHP performances are usually obtained by using steady state calculations. The results fit quite well to experimental data.
- However, the current mathematical models do not reproduce LHP transient behaviour satisfactorily (start-ups, temperature oscillations)
- The current approach aims to catch these phenomena using the powerful ECOSIMPRO capabilities.

LHP LIBRARY

EMPRESARIOS AGRUPADOS

LHP LIBRARY (1)

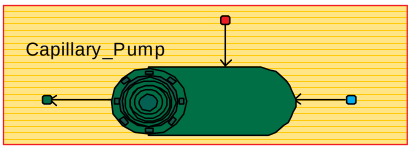
- **General considerations:**

- This library consist of typical components that model the parts of a LHP: Capillary Pump (Evaporator Casing, Grooves and Primary Wick), Compensation Chamber, Condenser and Transport Lines.
- The working fluid is considered as a two phase fluid (homogeneous flow).
- The fluid properties are interpolated from NIST tables for real fluids.
- The capillary pressure is calculated using the Leverett's correlation that uses fluid saturation.

EMPRESARIOS AGRUPADOS

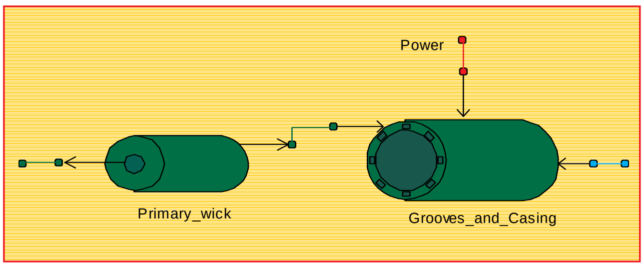
LHP LIBRARY (2)

- **Capillary Pump**



– This component is modelized using two basic components:

- *Primary wick*
- *Grooves and casing*



LHP LIBRARY (3)

- **Primary Wick:**

- This component simulates several phenomenon in a porous media.
- It is modelized by using mass and energy conservation equations in one dimension (radial) .
- The Leverett´s function *J* is calculated within the wick. Then, capillary pressure differences between wick and grooves and wick and compensation chamber can be obtained. The resulting values are introduced in the momentum equations.

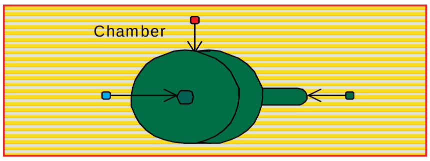
LHP LIBRARY (4)

- **Grooves and Casing:**

- This component simulates the evaporator casing, the vapour grooves and the outer layer of the wick.
- The equations included in this component are mass conservation, energy conservation, momentum (including capillary pumping, head losses and height effect), fluid properties (allowing two phase mixtures) and heat transfer with walls and through the wick (effective conductivity)..

LHP LIBRARY (5)

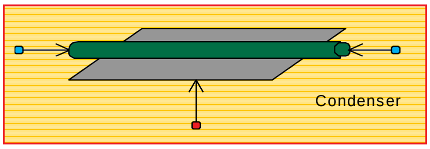
- **Compensation Chamber:**



- This component simulates the compensation chamber and the inner layer of the wick.
- The equations included in this component are mass conservation, energy conservation, momentum (including capillary pumping, head losses and gravity effect), fluid properties (allowing two phase mixtures) and heat transfer with walls and through the wick (effective conductivity).
- The capillary pumping is calculated considering the Leverett's function in the component "wick" and assume the presence of liquid in the chamber.

LHP LIBRARY (6)

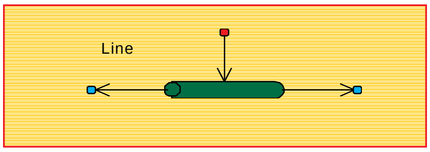
- **Condenser:**



- This component simulates the pipe circuit in a condenser. It is divided in *n* control volumes.
- The equations considered in this component are energy conservation, momentum (including fluid inertia, head losses and height effect), fluid properties (allowing two phase mixtures) and heat transfer with walls.
- The head losses and the film coefficient for heat interchange with walls are calculated using typical correlations.
- The wall energy nodes can be connected to an ambient node and/or to a sink node.

LHP LIBRARY (7)

- **Lines:**



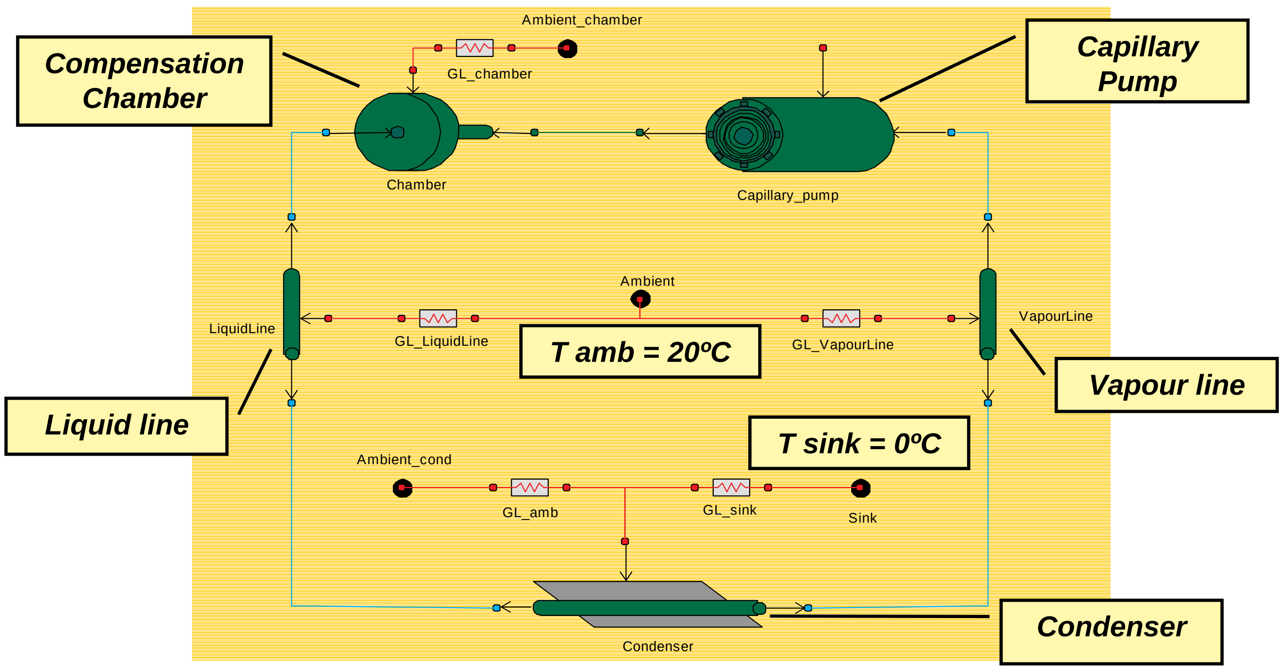
- These nodal components are used to simulate the transport lines that connect the LHP pump and the condenser.
- The equations considered in this component are energy conservation, momentum (including head losses and height effect), fluid properties (allowing two phase mixtures) and heat transfer with walls.
- The head losses and the film coefficient for heat interchange with walls are calculated using typical correlations.
- The heat exchange between the pipe and the ambient can be simulated by means of a GL (is a vector) between the thermal port of the "Line" and the ambient node.

EXAMPLES

EXAMPLES (1)

- A real LHP model have been used as library test bench.
- Ammonia has been considered as working fluid.
- The behaviour of the loop has been checked in different conditions such as power dissipation and sink and ambient temperatures variations.

EXAMPLES (2)



EXAMPLES (3)

- **Model data:**

Capillary Pump	
Active Length (m)	0.305
Wick Porosity	0.6000
Wick Outer Diameter (m)	0.0239
Wick Inner Diameter (m)	0.0076
Wick Thermal Conductivity (W/m-K)	25.00
Wick Permeability (m2)	6.45E-18
Wick effective pore radius	1.2000
Vapor Line	
Outer Diameter (m)	0.0048
Wall Thickness (m)	0.0007
Length (m)	1.016

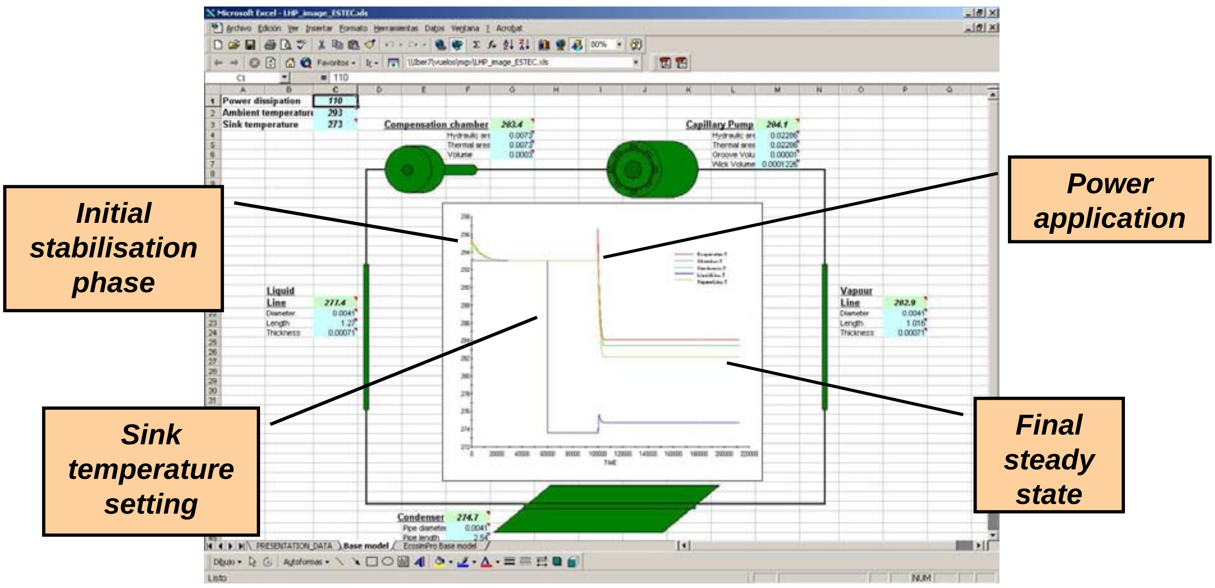
Condenser	
Outer Diameter (m)	0.0048
Wall Thickness (m)	0.0007
Length (m)	2.540
Liquid Line	
Outer Diameter (m)	0.0048
Wall Thickness (m)	0.0007
Length (m)	1.270
Compensation Chamber	
Outer Diameter (m)	0.0254
Length (m)	0.127

- **Runs data:**

  * T ambient = 20ºC , T sink = 20 / 0 ºC (applied at t=60000s)
  * Power: From 10 to 510 W (applied at t=100000s)

EXAMPLES (4)

- **Transient phenomena: Fixed power run**



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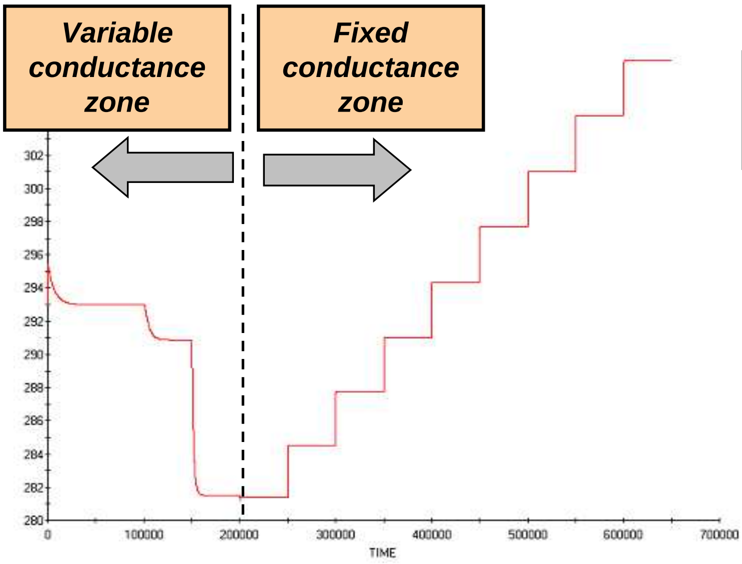
EXAMPLES (5)

- LHP performance: T_vs_TIME plot



Power profile (W)
0-10-60-110-160-210-260-310-360-410-460-510

Tsink = 273 K
Tamb = 293 K

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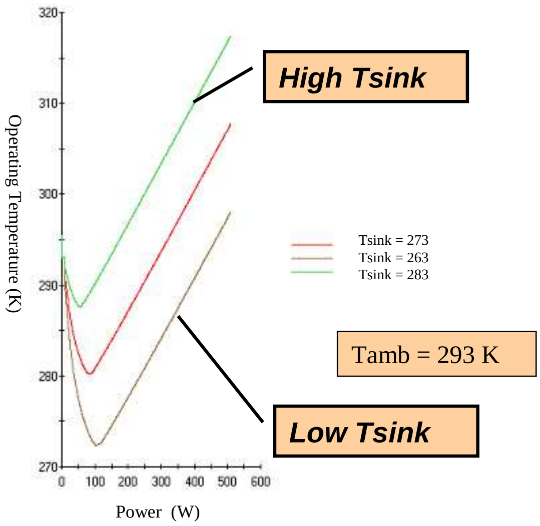
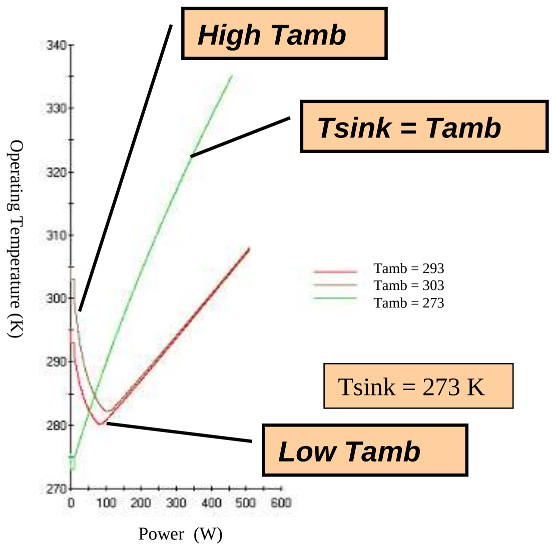
EXAMPLES (6)

- Variation of Sink Temperature: T_vs_Power plot



- Variation of Ambient Temperature: T_vs_Power plot



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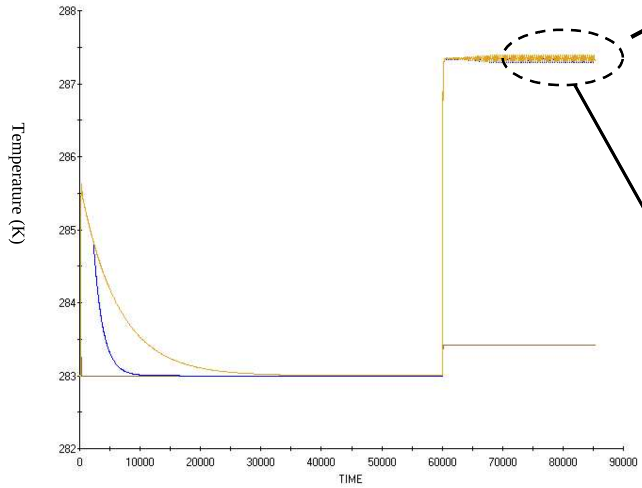
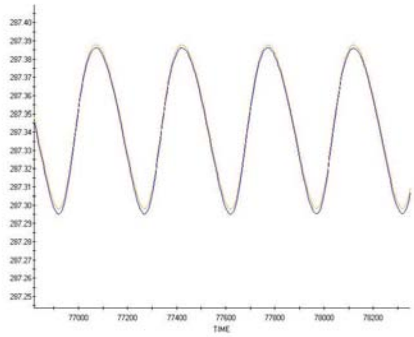
EXAMPLES (7)

- **Oscillations: Temperatures plot**

Power: 65 W
Tsink = Tamb = 283 K





High frequency oscillations:
Period ~ 350s / Amplitude < 1 K

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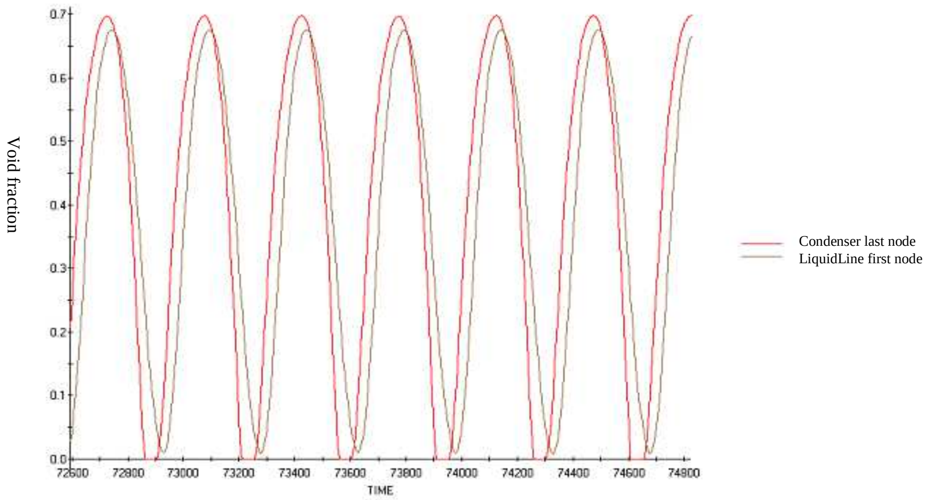
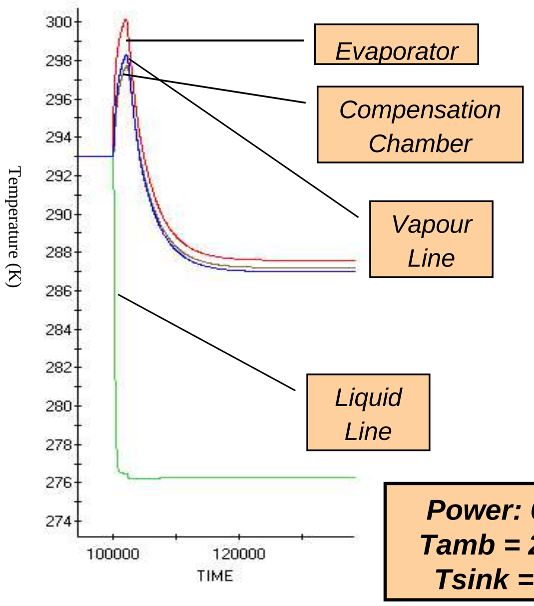
EXAMPLES (8)

- **Oscillations: Void fractions plot**

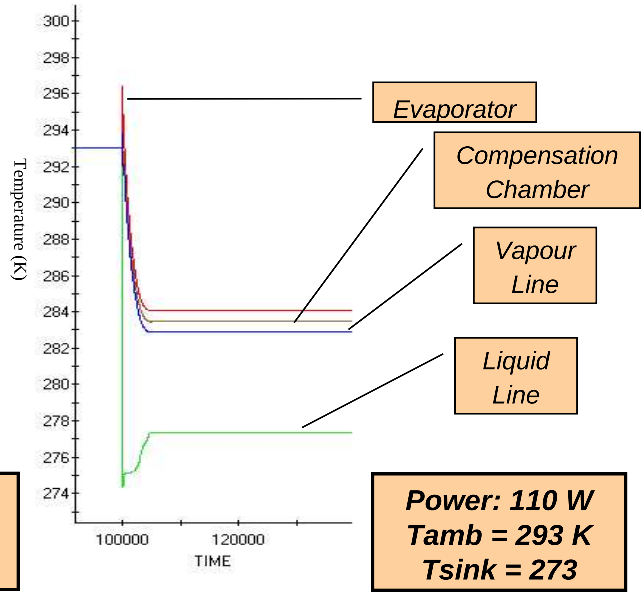


EXAMPLES (9)

- **Transient phenomena: Start - up**



Power: 60 W
Tamb = 293 K
Tsink = 273



Power: 110 W
Tamb = 293 K
Tsink = 273

FUTURE IMPROVEMENTS

FUTURE IMPROVEMENTS

- Implementation of the secondary loop to improve the determination of heat leak to catch the superheat precisely.
- To perform additional validation of the model
- Several nodes at the primary wick are already implemented to determine the fluid distribution. Some refinement are under development.
- To improve the correlations for two-phase flow.
- Friendly user interface.

Appendix J: Designing for milli- and micro-kelvin revisited

Designing
for
milli- and micro-kelvin

revisited

V.Perotto
Alenia Spazio

Designing for mK / μK
A challenge also for thermal solvers ?

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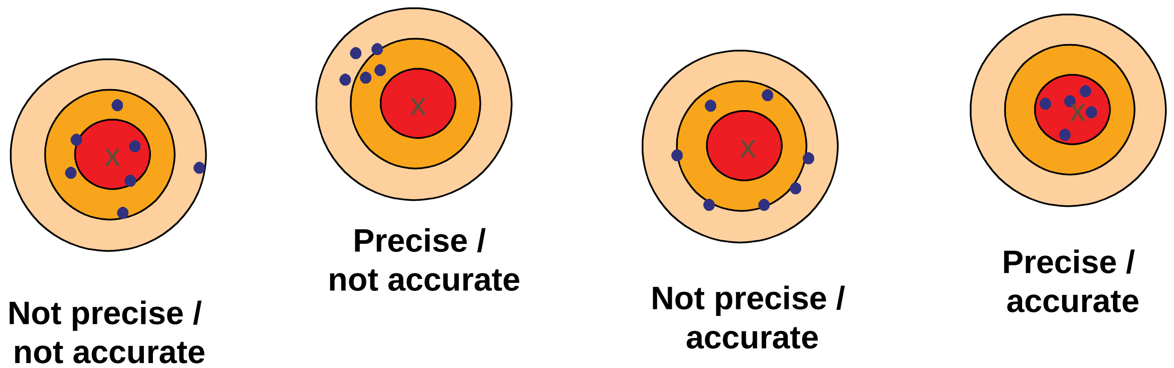
INTRODUCTION

- **In some space programs *(e.g. GAIA, GOCE)* a high accuracy and precision are requested to numerical simulations, down to the levels of milli-Kelvin or even to micro-Kelvin (for temperatures and gradients).**



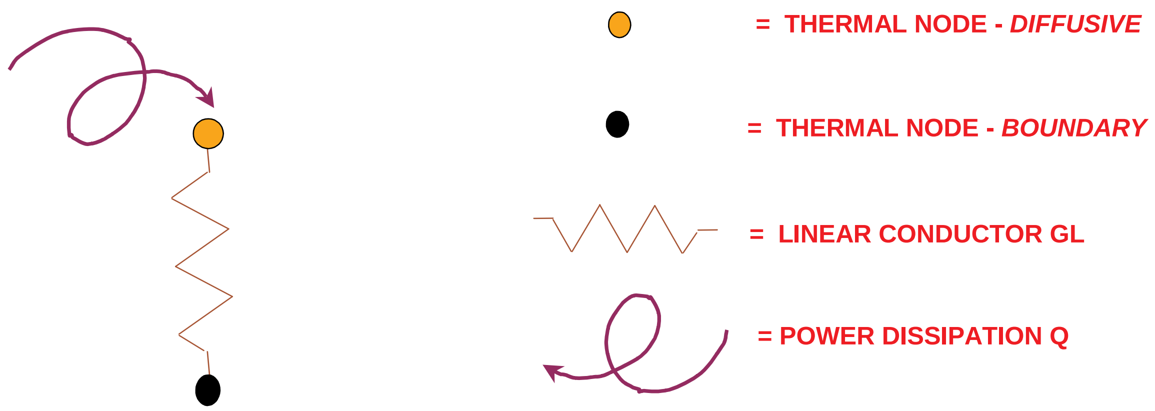
Accuracy -> average deviation **Precision -> standard deviation**

INTRODUCTION

- **Are the available solvers able to guarantee adequate results in front of these requirements ?**
- **To verify this, a simple 2-nodes model has been built to compare the ESATAN numerical solution with the analytical one.**
- **This very simple problem allows to assess the ESATAN numerical precision and accuracy and also to identify the parameters which affect them.**

Designing for mK / µK - A challenge for thermal solvers ?

2-NODES MODEL WITH IMPOSED THERMAL POWER



Thermal balance equation:

$$C * dT(t) / dt = Q(t) + GL \cdot [\, T_{boundary} - T(t) \,]$$

with: $Q(t) = A \cdot (1 + \cos \omega \cdot t)$

2-NODES MODEL WITH IMPOSED THERMAL POWER (cont'd)

- **Analytical solution:**

$$T(t) = T_{boundary} + \left\{ \left[T_{t=0} - T_{boundary} \right] - \frac{A}{C}\left(\frac{1}{\alpha} + \frac{\alpha}{\alpha^2 + \omega^2} \right) \right\} \cdot \exp(-\alpha t) + \frac{A}{C \cdot \alpha} + \frac{A}{C} \cdot \frac{1}{\alpha^2 + \omega^2} \cdot (\alpha \cos \omega t + \omega \sin \omega t)$$

where: α = GL / C, $\omega = 2\pi$ / T

- **Several test cases have been made, each characterized by different values of parameters (linear conductor GL, specific heat, mass, boundary temperature, dissipated power)**

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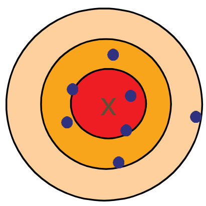
Designing for mK / μK - A challenge for thermal solvers ?

2-NODES MODEL WITH IMPOSED THERMAL POWER (cont'd)

- **For each test case several runs have been made to assess the effect of the ESATAN convergence control parameters.**
- **The difference ESATAN – analytical solution is the accuracy (actually the accuracy should be the average deviation of error for all runs with different values of control parameters, but in an analysis campaign such parameters are not explored estensively).**
- **The deviation of the accuracy with the convergence control parameters corresponds to the precision.**

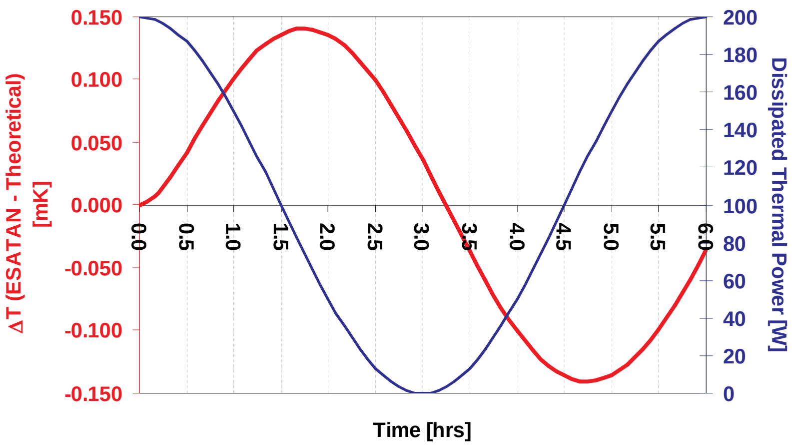


VERIFICATION OF ESATAN PERFORMANCES

Case with:

A = 100 W, m = 1 kg, c = 900 J/kg·K, Tb = T0 = 20 °C, GL = 1 W/K

Integration time step Δt = 0.01 s, Period T = 6 hrs



Time [s]	ESATAN Solution [°C]	Theoretical Solution [°C]	Difference [°C]
0	20.000000	20.000000	0.000000
1200	165.292930	165.292908	0.000022
2400	193.988628	193.988565	0.000063
3600	184.465538	184.465438	0.000100
4800	159.444963	159.444835	0.000128
6000	**127.631248**	**127.631107**	**0.000141**
7200	94.360541	94.360405	0.000136
8400	64.040898	64.040784	0.000114
9600	40.433468	40.433388	0.000080
10800	26.413110	26.413074	0.000036
12000	23.678121	23.678134	-0.000013
13200	32.560291	32.560351	-0.000060
14400	51.988800	51.988900	-0.000100
15600	79.620417	79.620545	-0.000128
16800	112.122395	112.122536	-0.000141
18000	145.574526	145.574662	-0.000136
19200	175.941990	175.942105	-0.000115
20400	199.562024	199.562104	-0.000080
21600	213.585703	213.585739	-0.000036

VERIFICATION OF ESATAN PERFORMANCES (cont'd)

Maximum ΔT [mK] ESATAN - Analytical solution	Integration time step [s]	
Relaxation Constant	*0.01*	*0.1*
1.00E-10	0.141	1.403
1.00E-05	0.141	1.403
1.00E-03	0.141	1.403

From all the test cases:

- **No effect of RELXCA on solution accuracy can be appreciated for little models**
- **Very small time steps and RELXCA not compatible with ESATAN internal limit (one million steps maximum)**

CONCLUSIONS

- For this very simple linear model (no GR) the accuracy of ESATAN is of the order of 0.1 mK
- Accuracy can be somewhat reduced (not to µK levels) using very small time steps, but <u>this is unfeasible with large models</u>
- Accuracy for complex models can not be assessed, but it is reasonable to assume it is higher than mK
- With networks containing GR instead of GL, error is expected to increase as effect of non-linearity and necessary iterations within ESATAN

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CONCLUSIONS

OPEN POINTS:

- Is it possible to design a TCS with requirements in terms of mK / µK with the standard solvers ?
- Is it possible to improve the standard solvers accuracy ?
- Is it necessary to calculate also precision?
- Is it possible to achieve a TCS with requirements in terms of mK / µK with the classic procedure based on analysis (iterations design/analysis and subsequent tests) ?

Appendix K: GAETAN Usage at Alcatel Space

GAETAN Usage
at
Alcatel Space

K. Caire
Alcatel Space

Gaetan Usage at Alcatel Space

Alcatel Space
K. Caire

Gaetan Usage at Alcatel Space

What is the goal of this presentation?

~~--> an exhaustive view of GAETAN~~

~~--> a training session on the software~~

--> a synthetic view of the advantages of a pre/post-processing tool

--> a global view of a daily usage

Gaetan Usage at Alcatel Space

Which use for GAETAN?
--> Global environment for ESATAN -->Thermal analysis of Antennas and Payload

What interest do we find in GAETAN?

--> Management of THERMICA computations and results
--> Pre- and post-processing of ESATAN
--> Automated multi-case computation with low risk of « human » error
--> A common architecture for each project to make it easy for any colleague to re-use the model and the results
--> An easy archiving process

Gaetan Usage at Alcatel Space

Management of THERMICA computations and results --> gaetanflux module

Our need : to compute a great number of cases and to manage their results

--> use of a command file to do a sequence of THERMICA run
--> definition of a case name for each computation, to be reused in ESATAN run
--> storage of the GR.TAN and H.TAN files in pre-defined directories
--> possible translation of the H.TAN file in specific format

Gaetan Usage at Alcatel Space

Example of GAETAN command file for THERMICA :

```
#
####### case1 : winter solstice BOL
$CAS='WSbol'#

        @GEOMETRIE='CDRBOL.SYSBAS'
        @POINTAGE='nominal.PNTINP'
        @TRAJECTOIRE='WSBOL.TRJINP'
        @SIMULATION='WSBOL.THER'
#
####### case2 : Sun declination of -20° BOL
$CAS='m20bol'#

        @GEOMETRIE='CDRBOL.SYSBAS'
        @POINTAGE='nominal.PNTINP'
        @TRAJECTOIRE='m20.TRJINP'
        @SIMULATION='m20BOL.THER'
#
####### case3 : Sun declination of -20° EOL
$CAS='m20eol'#

        @GEOMETRIE='CDREOL.SYSBAS'
        @POINTAGE='nominal.PNTINP'
        @TRAJECTOIRE='m20.TRJINP'
        DTHETN = 144.
        @SIMULATION='m20EOL.THER'

####### case4 : Sun declination of -20° EOL with more steps
$CAS='m20eolT144'#

        @GEOMETRIE='CDREOL.SYSBAS'
        @POINTAGE='nominal.PNTINP'
        @TRAJECTOIRE='m20.TRJINP'
        DTHETN = 144.
        @SIMULATION='m20EOL.THER'
```


Gaetan Usage at Alcatel Space

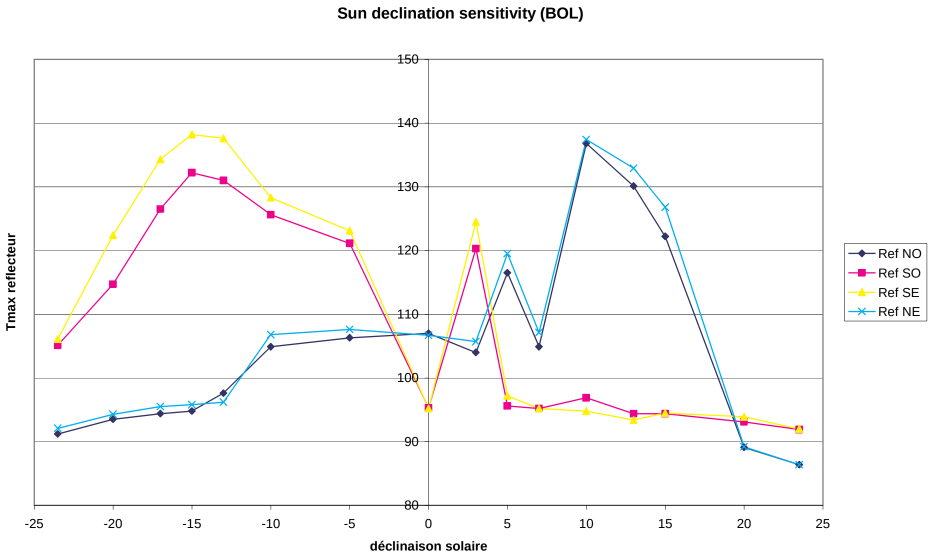
For us, what advantage of GAETAN command file for THERMICA ?

Current use :
- two geometrical models (before and after deployment)
- two thermo-optical properties
- parametric study on sun declination to search dimensioning case
- sensitivity analysis on geometrical model

Specific use :
- steerable antenna (multiplication of geometrical models)
- global computation on life duration (parametric study on thermo-optical properties)

Gaetan Usage at Alcatel Space

An example of parametric study : maximum temperature according to sun declination



ALCATEL

Gaetan Usage at Alcatel Space

Pre-processing of ESATAN :

- Key-words to do parametric study --> notion of « case »
  - to choose the files to read
  - to choose Thermica results
  - to choose boundary conditions or electrical conditions
  - to define any other condition

- High level study
  - a unique file with the description of all these cases
  - the possibility to launch different GAETAN run in sequence, in specified order

What interest for the user?

--> ONE single ESATAN model

--> ONE single command file easy to re-find and to re-run

ALCATEL

Gaetan Usage at Alcatel Space

Management of ESATAN computation :

- ESATAN run parameters
  - to choose ESATAN sub-routine and all associated parameters
  - to give initial conditions issued from tables (given by GAETAN from a previous run)
  - to do several computations (with initial conditions for following run issued automatically from the previous one)

- Iterative process for cyclic computation
  - to pilot a transient analysis on an orbit

    A first transient run

    --> final temperature and initial one are compared for each node

    --> the highest difference must be under a user-defined value

    --> if not, a new run is done, taking final temperature as new initial one

  The user defines the success criteria and the maximum number of cycle

- A file to follow in real time computation progress

ALCATEL

Gaetan Usage at Alcatel Space

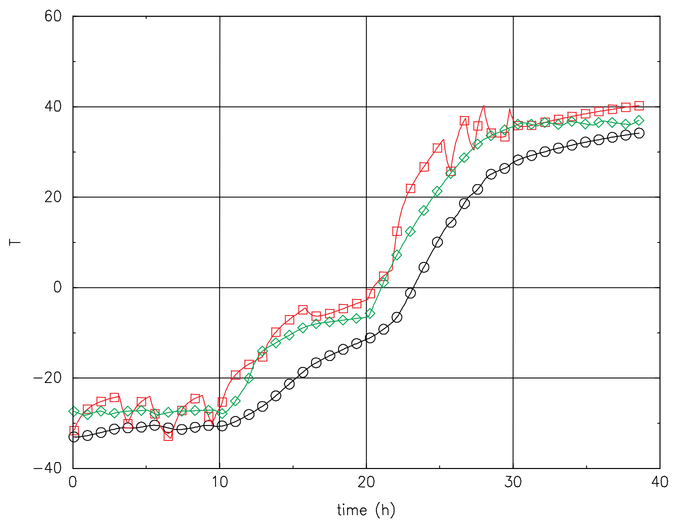
An example of ESATAN run parameters : thermal balance test with 3 different heating power

```
$RUN_ESATAN

     @TRANSIENT
          CALCULATION_CASE_NAME =              'COLD OP';
          CHARGE_CASE_NAME =                   COLD OP;
          CHRONOLOGY_INITIAL_TIME =            36001.;
          CHRONOLOGY_FINAL_TIME =               72000.;
          TIME_STEP =                           300.;
          ESATAN_SOLUTION_ROUTINE_NAME =       'SLFWBK' ;
          ESATAN_CONTROL_CONSTANT =            'RELXCA = 0.0006' ;
          ESATAN_CONTROL_CONSTANT =            'NLOOP = 30000' ;

     @TRANSIENT
          CALCULATION_CASE_NAME =              'TRANS';
          CHARGE_CASE_NAME =                   'TRANS';
          CHRONOLOGY_INITIAL_TIME =            72001.;
          CHRONOLOGY_FINAL_TIME =               91800.;
          TIME_STEP =                           300.;
          ESATAN_SOLUTION_ROUTINE_NAME =       'SLFWBK' ;
          ESATAN_CONTROL_CONSTANT =            'RELXCA = 0.0006' ;
          ESATAN_CONTROL_CONSTANT =            'NLOOP = 30000' ;

     @TRANSIENT
          CALCULATION_CASE_NAME =              'HOT OP';
          CHARGE_CASE_NAME =                   'HOT OP';
          CHRONOLOGY_INITIAL_TIME =            91801.;
          CHRONOLOGY_FINAL_TIME =               144000.;
          TIME_STEP =                           300.;
          ESATAN_SOLUTION_ROUTINE_NAME =       'SLFWBK' ;
          ESATAN_CONTROL_CONSTANT =            'RELXCA = 0.0006' ;
          ESATAN_CONTROL_CONSTANT =       'NLOOP = 30000' ;
```


ALCATEL

Gaetan Usage at Alcatel Space

An example of ESATAN run sequence : thermal balance test with 3 different heating power



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Gaetan Usage at Alcatel Space

An example of convergence file : to follow in real time the computation in progress

IORB	TIMEO	TIMEM	TIMEN	TIM1	DTIMEI	DTIMEU	NLOOP	LOOPCT	NBALA	NBALR	
V1	1	0.0	150.0	300.0	150.0	300.0	300.0	30000	0	0.0000	0.0000
V1	1	0.0	150.0	300.0	150.0	300.0	300.0	30000	1	0.0000	0.0000
V2	1	0.0	150.0	300.0	150.0	300.0	300.0	30000	635	0.0000	0.0000
V1	1	300.0	450.0	600.0	450.0	300.0	300.0	30000	635	0.0000	0.0000
V2	1	300.0	450.0	600.0	450.0	300.0	300.0	30000	629	0.0000	0.0000
V1	1	600.0	750.0	900.0	750.0	300.0	300.0	30000	629	0.0000	0.0000
V2	1	600.0	750.0	900.0	750.0	300.0	300.0	30000	669	0.0000	0.0000
V1	1	900.0	1050.0	1200.0	1050.0	300.0	300.0	30000	669	0.0000	0.0000
V2	1	900.0	1050.0	1200.0	1050.0	300.0	300.0	30000	665	0.0000	0.0000
V1	1	1200.0	1350.0	1500.0	1350.0	300.0	300.0	30000	665	0.0000	0.0000
V2	1	1200.0	1350.0	1500.0	1350.0	300.0	300.0	30000	691	0.0000	0.0000
V1	1	1500.0	1650.0	1800.0	1650.0	300.0	300.0	30000	691	0.0000	0.0000
V2	1	1500.0	1650.0	1800.0	1650.0	300.0	300.0	30000	681	0.0000	0.0000
V1	1	1800.0	1950.0	2100.0	1950.0	300.0	300.0	30000	681	0.0000	0.0000
V2	1	1800.0	1950.0	2100.0	1950.0	300.0	300.0	30000	703	0.0000	0.0000
V1	1	2100.0	2250.0	2400.0	2250.0	300.0	300.0	30000	703	0.0000	0.0000
V2	1	2100.0	2250.0	2400.0	2250.0	300.0	300.0	30000	692	0.0000	0.0000
V1	1	2400.0	2550.0	2700.0	2550.0	300.0	300.0	30000	692	0.0000	0.0000
V2	1	2400.0	2550.0	2700.0	2550.0	300.0	300.0	30000	711	0.0000	0.0000
V1	1	2700.0	2850.0	3000.0	2850.0	300.0	300.0	30000	711	0.0000	0.0000

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Gaetan Usage at Alcatel Space

Post-processing of ESATAN results :

Management :
- an exhaustive data-base is available for further treatment by different module
- command file make it easy to run and re-run post-processing

Computation :
- management of groups of nodes
- heat flow exchange between nodes and/or groups of nodes (including towards boundary node)
- min/max values (temperature and heat flow exchange)
- maximum gradient in a group of node, or between groups of nodes
- storage of temperature/flux results to use them further as initial conditions

Outputs :
- tables to sum up all these results
- specific file for thermo-elastic analysis (formatted file to be delivered at mechanical engineers)
- specific file for 3-D visualisation (formatted for THERMICA)
- curves

Gaetan Usage at Alcatel Space

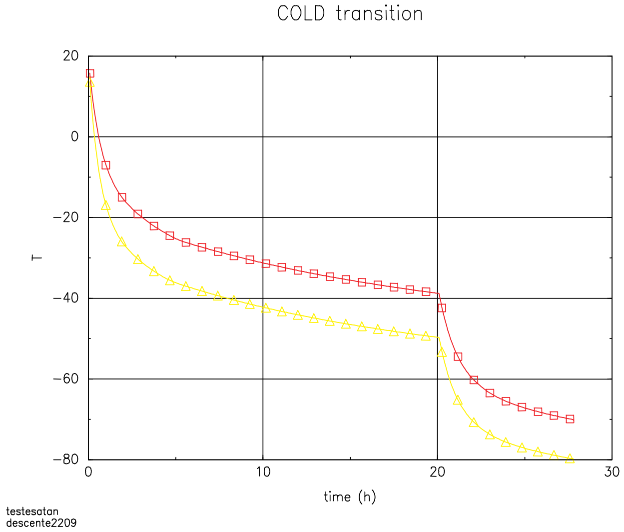
Post-processing of ESATAN and THERMICA results :

Gaetangraph module developed for Alcatel :
--> use of xmgr tool
--> a command file to define a list of curves and to re-run them without effort (nor errors!)
--> several thermal analysis results on the same curve

Available curves :
- all node attribute (T, QI, QR, QS, etc…)
- min/max temperature for a group of nodes
- average temperature, gradient in a group of nodes or between two groups of nodes
- heat flow exchange

Gaetan Usage at Alcatel Space

An example of curve : temperature of the same node for two different computations



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Gaetan Usage at Alcatel Space

CONCLUSION

Which advantage of a General Automated Environment for Alcatel?

--> *technical advantages*

to run and re-run lot of cases
to extract the relevant results
to make a powerful presentation to our customer

-->*human advantages*

to limit errors
to run the colleague 's model
to exchange model with our sub-contractor

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Gaetan Usage at Alcatel Space

As thermal engineers, we always need more functionnalities in pre/pro aspects.

Pre-pro aspects : GAETAN advantages are numerous, we ask for improvements

Post-pro aspects : additional computations are useful, but new functionalities are welcome; specific demand on visualisation are developed in an extra-module

Ask to the users and they will demand more!

Appendix L: Thermal Analysis of the Mechanical Structure of the Solar Telescope GREGOR

Thermal Analysis of the
Mechanical Structure
of the
Solar Telescope
GREGOR

T. Bornkessel
TU Darmstadt

Thermal Analysis of the Mechanical Structure of the Solar Telescope GREGOR

T. Bornkessel & M. Schäfer
Department of Numerical Methods in Mechanical Engineering
Technical University Darmstadt, Germany

in cooperation with

MAN Technologie AG, Mainz

18TH EUROPEAN THERMAL & ECLS SOFTWARE WORKSHOP
5 – 6 October 2004
ESA/ESTEC, Noordwijk - The Netherlands

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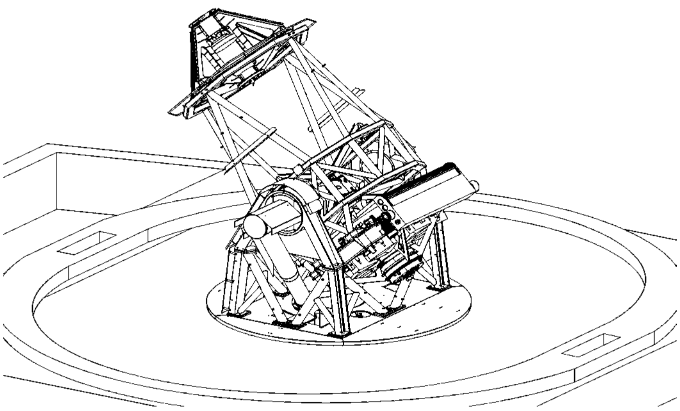
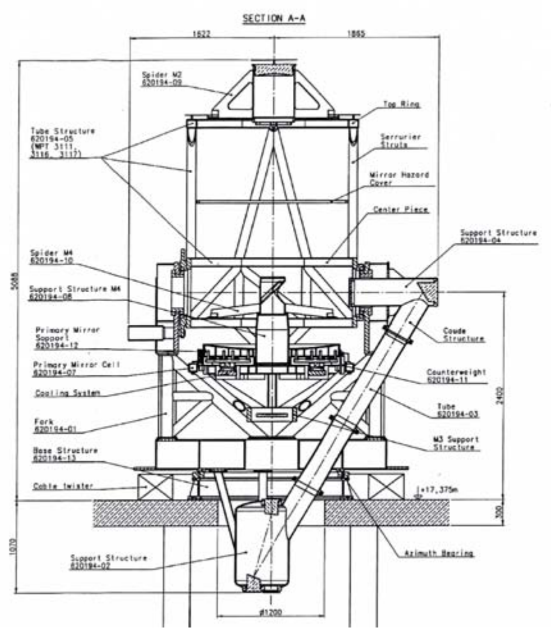


Thermal Analysis of the Solar Telescope GREGOR

Motivation

Telescope building



Telescope structure

Thermal Analysis of the Solar Telescope GREGOR

Thermal Requirements

- The telescope structure and the main mirrors are expected to be heated up by a solar radiation of 750 through 1100 W/m² depending on the time of day.
- The mechanical structure must maintain a minimal temperature deviation in order not to introduce thermal inhomogeneity of ambient air (“internal seeing”).
- The telescope structure shall therefore maintain a temperature deviation to the ambient air within -0.5K through +0.2K by passive means.
- Use of reflecting sun-shields which are thermally isolated from the remaining structure to improve the thermal behaviour of the main structure.

- The main mirror requires an active thermal control to maintain its surface temperature within given limits from the temperature of the ambient air.
- Temperature difference ΔT of less than 2K from ambient temperature with an accuracy of $\pm$ 0.1K across the mirror surface.

Thermal Analysis of the Solar Telescope GREGOR

Thermal Design Features

- Sun-shields at all surfaces directly exposed to the sunlight.
- Largely open steel truss structure allowing the wind to go through and to cause air turbulences and thus contributing to the avoidance of internal seeing.
- Surface coatings:
  - TiO_2 paint on sun-shields; high emissivity in the infrared domain
  - Metallic foil on Serruier struts
  - Paint with low infrared emissivity on remaining structure
- The Cesic main mirror is actively cooled by a nozzle system of six integrated cooling segments. Each nozzle cools one triangular cell of the primary mirror rear side by conditioned air.

Thermal Analysis of the Solar Telescope GREGOR

Thermal Analysis

- The analysis was performed with the finite element program ANSYS using a detailed finite element model of the telescope and of the environment.
- Due to the fact that the used program can not consider the wavelength dependence of the emissivities the analysis was only performed in the infrared domain.
- The finite element model contains all structural parts and optical elements which are necessary for a realistic thermal analysis of the whole structure.
- The absorbed heat flux of the sun-shields was applied as thermal load with 15 percent of the relevant sun radiation
- The analysis considers the heat conduction in the telescope structure, the convection between the telescope structure and the ambient air, the radiation heat transfer between the telescope structure and the environment (earth and cold sky) and between the telescope's structural parts as well.

Materials

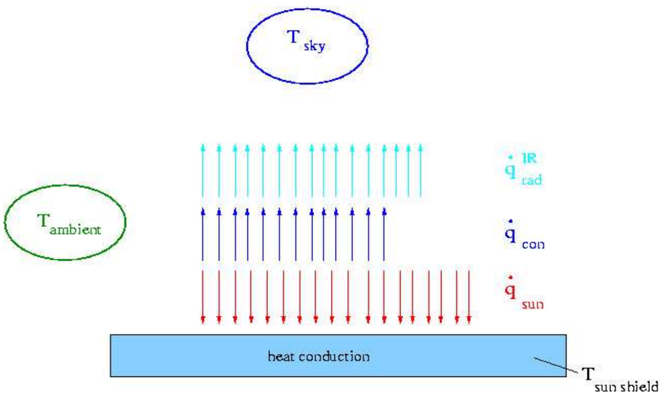
- Telescope structure is made of steel: standard material parameters
- Aluminium sun-shields: standard material parameters
- Emissivity coefficient:

Emissivity	Paint Steel Structure	Titan dioxide Sun-Shields	Reflecting Foil Serrurier Struts
ε_{IR}	0, 25	0,91	0,1

Boundary Conditions

- Sky temperature: 220K
- Earth temperature and ambient temperature: 288K
- Heat flux: elevation 90° ~ 165 W/m²; elevation 45° ~ 112 W/m²
- Wind velocity: 4 m/s => heat coefficient α= 20W/m²K :

Scheme of the heat fluxes



$$\dot{q}^{IR}_{rad} = \varepsilon_{IR} \cdot \sigma (T^4 - T^4_{sky}) \,, \qquad (1)$$

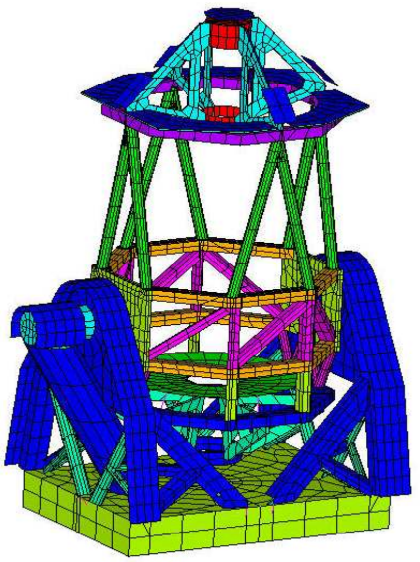
$$\dot{q}_{con} = \alpha \cdot (T - T_{amb}) \,, \qquad (2)$$

$$\dot{q}_{sun} = \varepsilon_{VL} \cdot S_r \,, \qquad (3)$$

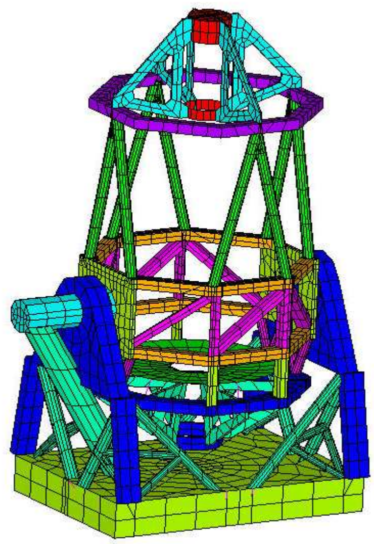
whereas ε_{IR} is the emissivity of the sun-shields, σ is the Stefan-Boltzmann constant, α is the heat transfer coefficient, S_r is the reduced solar constant and ε_{VL} is the emissivity in the visible domain.

Thermal Analysis of the Solar Telescope GREGOR

Thermal FE model



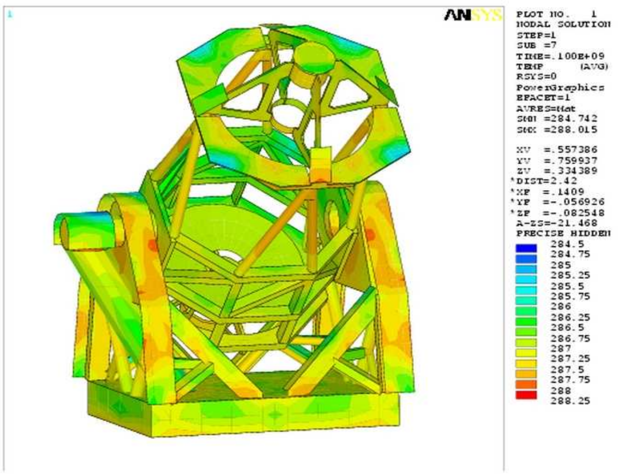
90° elevation; plus sun shields

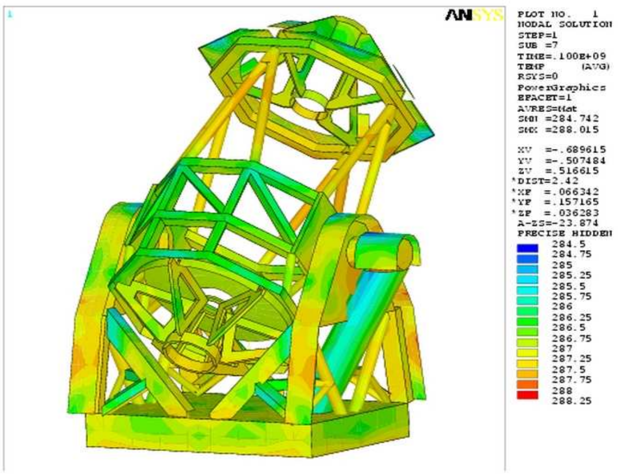


90° elevation; plus sun shields

Thermal Analysis of the Solar Telescope GREGOR

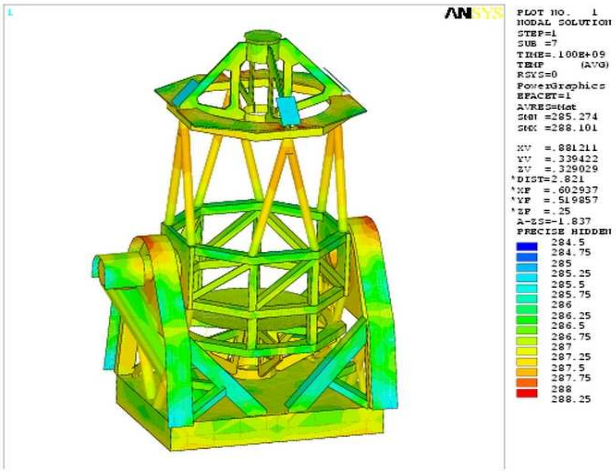
Temperature distribution for 45° elevation

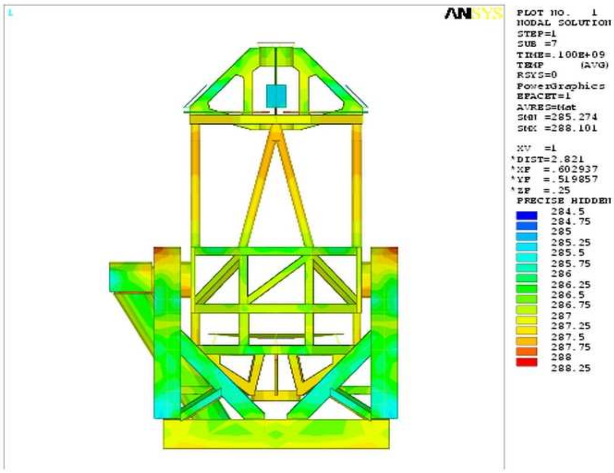




Temperature of the main telescope structure is within the requirements

Temperature distribution for 90° elevation





Temperature of the main telescope structure is within the requirements

Conclusion and Outlook

- The temperature of all structural parts is within a range of approximately 284.7 and 288.1K. The highest calculated structural temperature is 0.1K above the ambient temperature of 288K and thus fully within the requirement of +0.2K.
- The lowest temperatures can be found on the sun-shields.
- The top ring and the Serrurier struts which are in the critical path of the light are due the selected surface coatings also within the required temperature range of not more than 0.5K below the ambient temperature.
- The small temperature gradient across the struts has a negligible influence on the pointing of the telescope.
- First light at the beginning of 2005.
- Temperature measurements to verify the numerical results.

Appendix M: Modelling of Cryocoolers

Modelling
of
Cryocoolers

M. Linder
ESA/ESTEC

Modelling of Cryocoolers

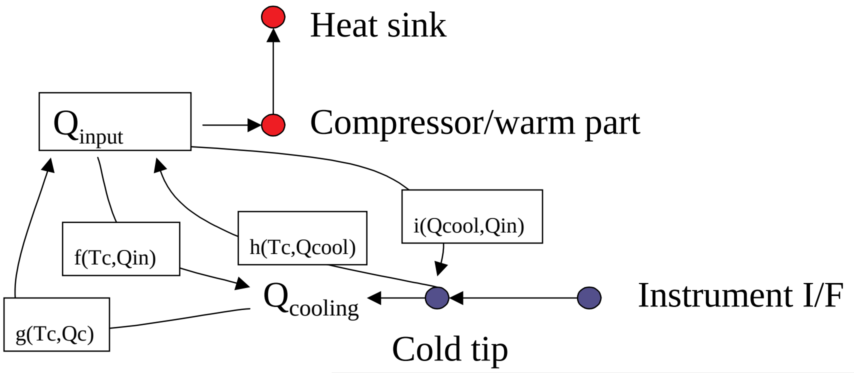
Introduction

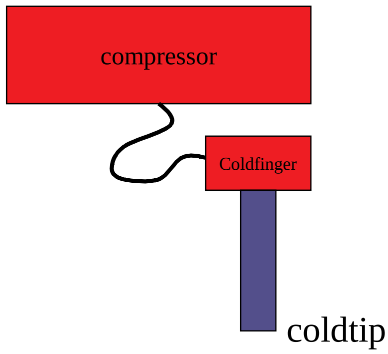
- *Current cryocooler models in ESATAN make use of polynomial fit functions in combination with boundary nodes*
- *This limits the number of free parameters (e.g heat sink temperature)*

therefore

- *Leading to a conservative design only considering worst cases*
- *It is difficult to perform sensitivities or assess the impact of sub-systems (e.g. compressor performances)*
- *A correct heat balance is not always obtained*

Stirling/ Pulse Tube models





$h(T_c,Q_{cool})$:

$$Q_{input} = a\, Q^2_{cool} + b\, Q_{cool} + c$$

$$a = a_1\, T^2_{cold\ tip} + a_2\, T_{coldtip} + a_3$$

$$b = b_1\, T^2_{cold\ tip} + b_2\, T_{coldtip} + b_3$$

$$c = c_1\, T^2_{cold\ tip} + c_2\, T_{coldtip} + c_3$$

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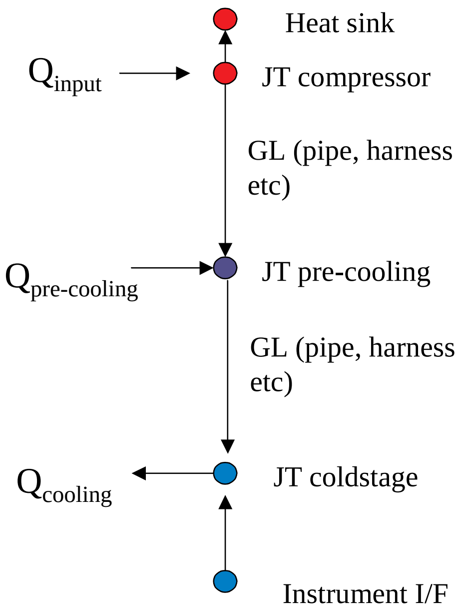
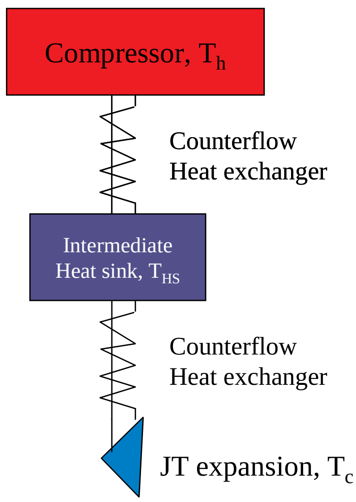
Joule Thomson coolers

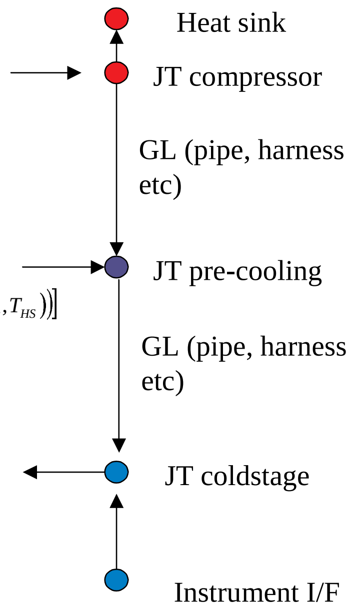
$Q_{pre\text{-}cooling}$ and $Q_{cooling}$, depending on the Hx efficiency and the fluid, are provided only by polynomial fits





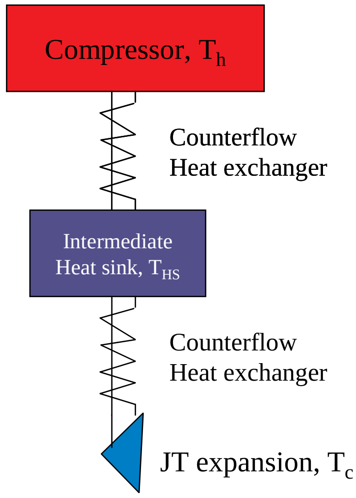
Joule Thomson coolers including Physics

Q_{input}



$$Q_{pre-cooling} = \dot{m}\left[\left(H\left(p_{high},T_{high}\right)-H\left(p_{high},T_{HS}\right)\right)-\varepsilon\left(H\left(p_{low},T_{high}\right)-H\left(p_{low},T_{HS}\right)\right)\right]$$

$$Q_{cooling} = \dot{m}\left[H\left(p_{high},T_{HS}\right)-\varepsilon H\left(p_{low},T_{HS}\right)\right]$$



Requirements for Cooler models

- *In most cases the coldtip temperature is specified by the system (coming from detector needs etc)*
- *The required cooling power is obtained by the TMM*
- *For sizing the thermal system the cooler model must provide* $Q_{input} = f(T_{coldtip}, Q_{cooling})$
- *For transient verification, the cooler model must be able to calculate* T_{cold} *for a given* Q_{input}*. The following function is required within a TMM:* $Q_{cooling} = g(T_{coldtip}, Q_{input})$

Requirements for Cooler models

- *Cooler model shall consider as a minimum the following parameters:*
  - *For single stage cooler $T_{heat\ sink}$, $T_{coldtip}$, Q_{input}, $Q_{cooling}$*
  - *For multistage coolers, the influence of the intermediate cooling stages for different operating conditions needs to be implemented*
- *This can not be handled by polynomial fits or would require a large amount of data points at specific conditions (e.g. isothermal points)*

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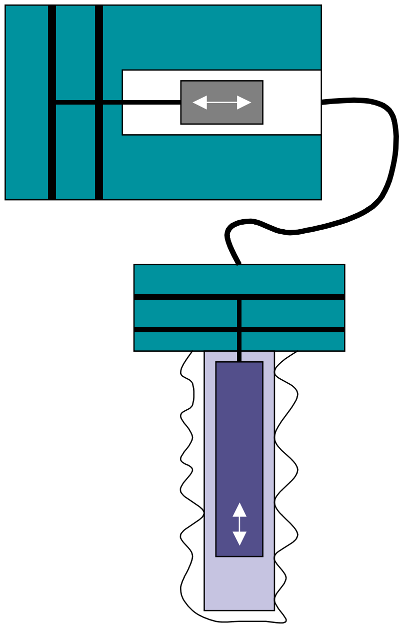
Requirements for Cooler models

- *Overall heat balance needs to be correct*
  - *Common approach is: $Q_{dissipated} = Q_{input}$*
  - *For Stirling, PT and reverse Turbo-Brayton correct approach is: $Q_{dissipated} = Q_{input} + Q_{cooling}$*
- *Use of boundary nodes shall be limited, where required link them correctly with the TMM*
- *Shall be simple, fast and robust*

Stirling cooler

- Compressor transform electrical Energy into pneumatic Work (pV work). For high efficient space coolers one can assume: $pV = Q_{in} - I^2R$
- Pressure wave generated passes through a regenerative heat exchanger (= Regenerator)
- At the cold end the pressure wave and massflow wave are shifted such, that the following cooling occurs: $q_{gross} = T_{cold}/(T_{hot} - T_{cold}) * pV$
- The available cooling power is: $q_{net} = q_{gross} – losses$
- Main losses are: conductive, radiative, regenerator and shuttle losses



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Stirling cooler losses

- Conductive/radiative losses are equal to parasitic loads of a non-operating cooler.
- Regenerator losses: $Q_{regenerator} = dm/dt * c_p * (T_{hot} - T_{cold})\ (1-\varepsilon)$ with $dm/dt \sim pV/T_{hot}$
- Shuttle losses $Q_{shuttle} \sim (T_{hot} - T_{cold})/stroke$

Stirling cooler equation

- *It should be possible to describe the Stirling cooler with the following equation:*

$$\frac{T_{cold}}{T_{hot}-T_{cold}}pV - c(T_{hot}-T_{cold}) -$$
$$a(1-\varepsilon_{reg})\frac{pV}{T_{hot}}(T_{hot}-T_{cold}) - b\frac{T_{hot}-T_{cold}}{stroke} - q_{net} = 0$$

- *Approach has been tested with MIPAS 50-80k Astrium cooler data, assuming a constant compressor efficiency (due to the lack of I^2R data)*

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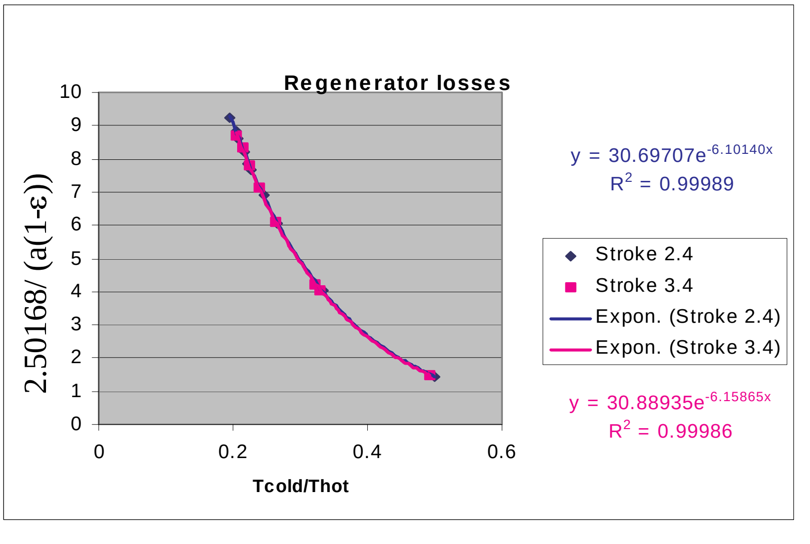
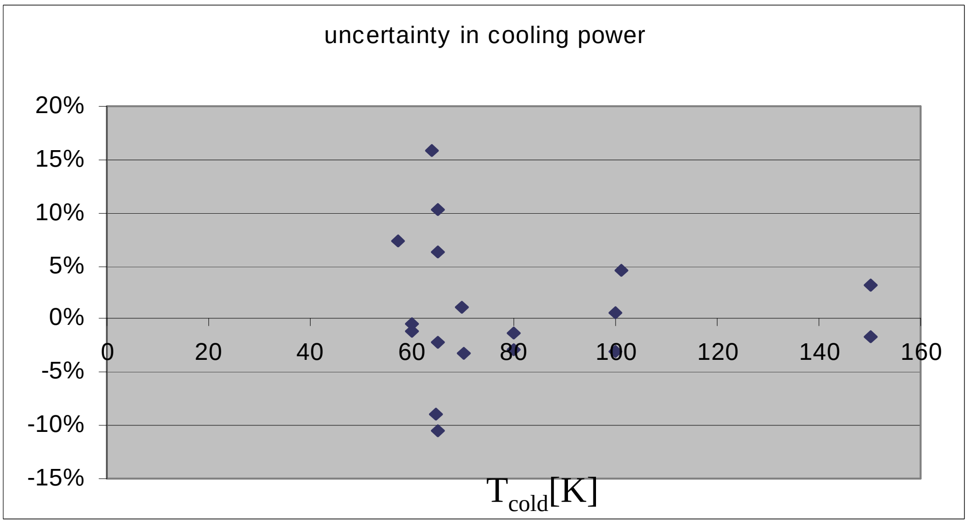
Stirling cooler extrapolation

- *Dataset includes 18 measurements from 57-150K and -10°C to 40°C heat sink*
- *pV = 0.8 *Q_{in}*
- *C = 220 mW /193K from parasitic measurements, refined during interpolation*
- *Distinguishing between regenerator and shuttle loss not possible, but regenerator loss as a function of displacer stroke*

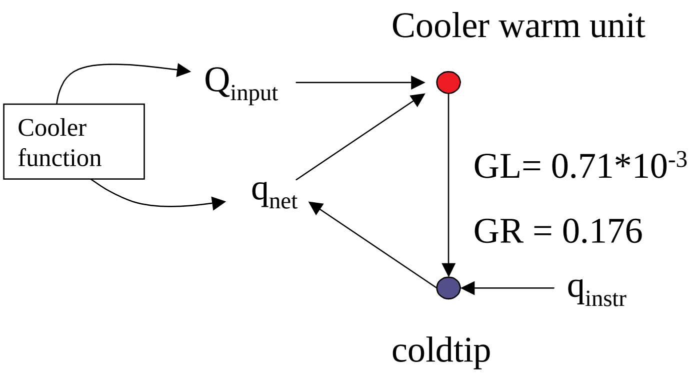


Stirling cooler extrapolation uncertainty

Strong deviations from measurements above 150K, additional correction for these temperatures required



Stirling cooler model



Result TMM:

(300mW q_{instr}, Cooler Wu 263K)

T_{cold} = 64.9K -> 12.19W input

Q_{in} = 11.17W -> 66.1K T_c

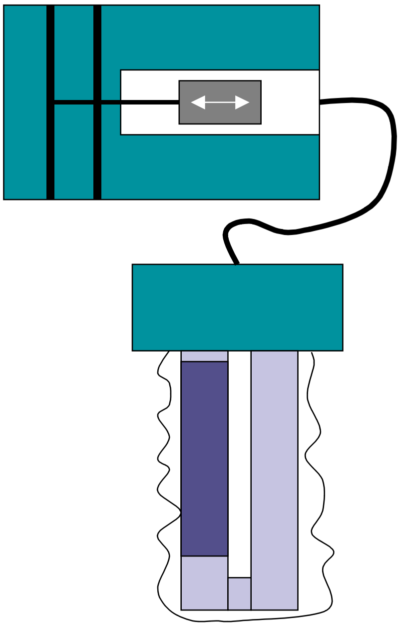
Cooler function:

$$0.8 * Q_{input}\left[\frac{T_{cold}}{T_{hot}-T_{cold}} - \frac{2.50168}{30.697}\, e^{6.101\, T_{cold}/T_{hot}}\, \frac{1}{T_{hot}}(T_{hot}-T_{cold})\right] - q_{net} = 0$$

Note: not valid for temperatures below 50K and above 150K

Pulse Tube cooler

- *Compressor transform electrical Energy into pneumatic Work (pV work). For high efficient space coolers one can assume:*
  $pV = Q_{in} - I^2R$
- *Pressure wave generated passes through a regenerative heat exchanger (= Regenerator)*
- *At the cold end the pressure wave and massflow wave are shifted such, that the following cooling occurs:*
  $q_{gross} = T_{cold}/T_{hot})*pV$
- *The available cooling power is:*
  $q_{net} = q_{gross} - losses$
- *Main losses are:*
  conductive, radiative, regenerator and pressure losses

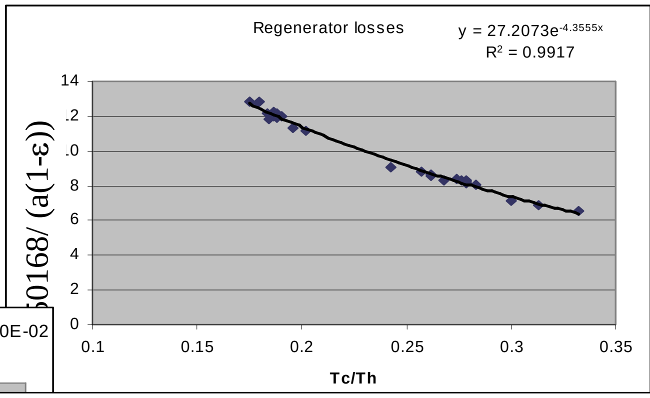


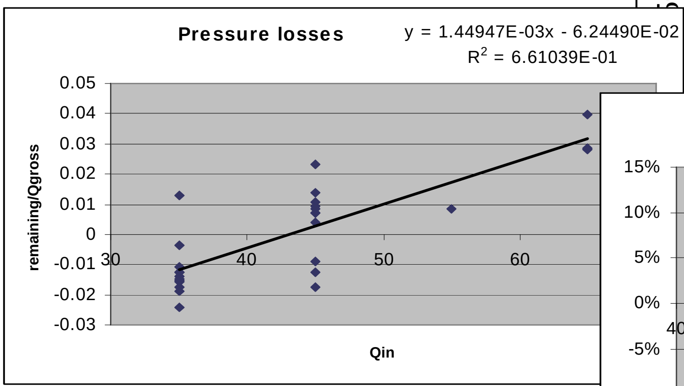
Pulse Tube cooler losses

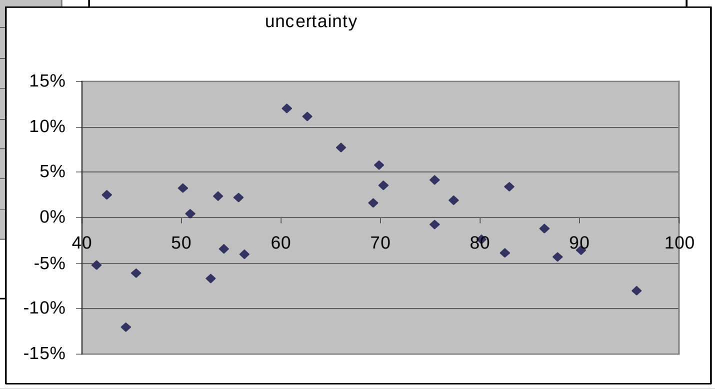
- *Conductive/radiative losses are equal to parasitic loads of a non-operating cooler.*
- *Regenerator losses:*
  $Q_{regenerator} = dm/dt * c_p *(T_{hot} - T_{cold}) (1-\varepsilon)$
  with $dm/dt \sim pV/T_{hot}$
- *Pressure losses* $Q_{press} \sim f(p_{ampl}) *T_c/T_h*pV$
  $p_{ampl} \sim Q_{in}$
- *Data taken from MPTC Air liquide TRP cooler*

Pulse Tube cooler extrapolation

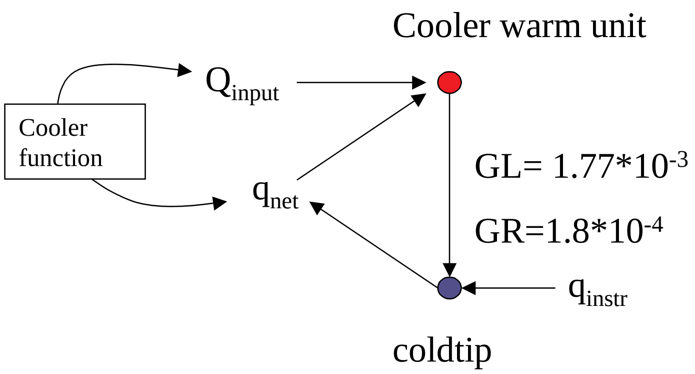
- *Dataset includes 23 measurements from 40-95K and -40℃ to 40℃ heat sink*
- *pV = 0.7 *Q_{in}*
- *C = 465 mW /208K from parasitic measurements*







Pulse Tube cooler model



Result TMM:

T_{cold} = 60.63K , T_{hot}=310K, q_{instr} =0

Q_{in} = 45W -> 58.7 K T_c

T_{cold} = 75.43K , T_{hot}= 273K, q_{instr} = 1W -> 36.3 W

Q_{in} = 35W -> 76.3 K T_c

Cooler function:

$$0.7 * Q_{input}\left[\frac{T_{cold}}{T_{hot}}\left(1.0637 - 1.479 * 10^{-3} * Q_{input}\right) - \frac{2.50168}{27.1518} e^{4.327\, T_{cold}/T_{hot}} \frac{(T_{hot} - T_{cold})}{T_{hot}}\right] - q_{net} = 0$$

Note: function not valid for input powers below 30W and $T_{coldtip}$ above 100K, not verified for high $T_{coldtip}$

Conclusion

- *Performance predictions of Stirling and PT coolers is feasible by interpolating the various loss mechanisms, requiring much less input data than polynomial fits*
- *Some additional effort is required for high cold tip temperatures, mainly for cool down predictions*
- *In addition to the classical thermal parameters, the compressor efficiency also needs to be measured*

Future work

- *Distinguish between Compressor and warm part of coldfinger and predict dissipated power on each*
- *Modelling of the gas temperature as a function of gross cooling power and I/F temperature (to improve high temperature performance)*
- *Extend model to multistage Stirling and Pulse Tube cooler*

Appendix N: Optimization of a Direct Condensing LHP Radiator with the Improved ALGOCAP

Optimization of a
Direct Condensing
LHP Radiator
with the
Improved ALGOCAP

R. Schlitt
OHB System

Optimization of a Direct Condensing LHP Radiator with the Improved ALGOCAP Code

Dr. Frank Bodendieck,
Dr. Reinhard Schlitt

OHB-System AG, Bremen, Germany

Introduction

- The ALGOCAP (Algorithms for CPL and LHP) code for inclusion of a LHP into a system thermal model was originally developed under ESA contract. Since then several improvements have been incorporated in order to utilize the package in a realistic hardware project.
- The presentation will explain:
  - the structure of the code and its interface to ESATAN/ESARAD
  - the implementation of the code into the system model of AMS (Alpha-Magnetic-Spectrometer)
  - the optimization process to obtain a suitable LHP condenser lay out

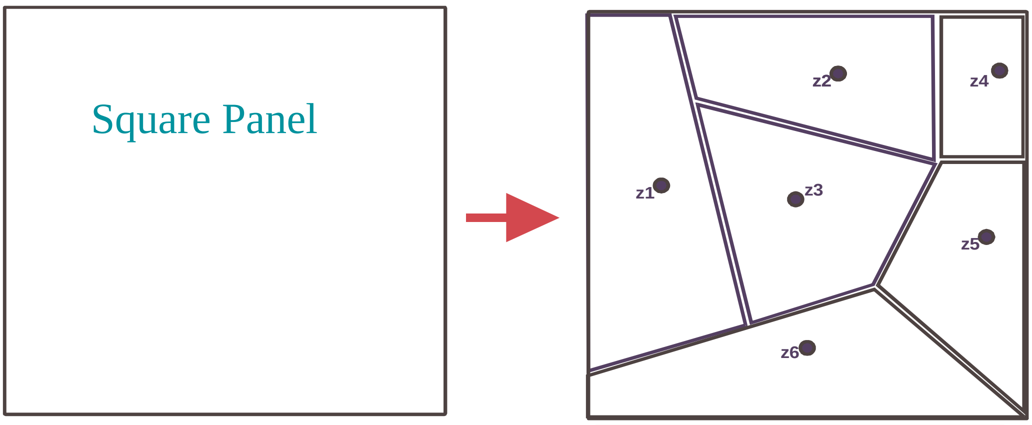
Introduction cont.

- The Thermal Mathematical Model (TMM) at subsystem and system level is usually executed with appropriate software (S/W), like ESATAN / SINDA or others, using the nodal approach.
- Capillary Pumped Two-phase loops (TPL) make significant impact on thermal behavior of involved components, wherefore the detailed TPL modeling is needed.
- Simulation of complex thermo-hydraulic processes in TPL requires at least a very small time step. The difference with TMM time step can reach several orders.
- We see solution in a separate and simultaneous execution of TPL and TMM models by such a way, that integration at system level with its large time step does not involve integration of detailed TPL model.

Conception of two-level modeling

1. Different nodal break-out for the same fragment

Different nodal division for the same fragment of the TPL radiator are performed. The coarse nodal division is used for the H-l model:



Example: Radiator-condenser panel

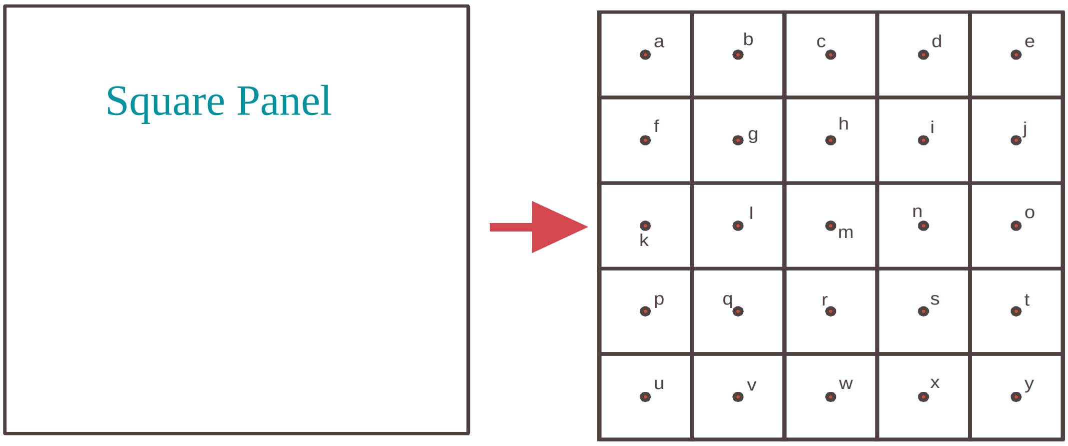
H-l model (6 nodes)

Nodes of H-l TPL model are included as part of global TMM model of satellite

Conception of two-level modeling

1. Different nodal break-out for the same fragment

The fine nodal division is used for the L-l model:

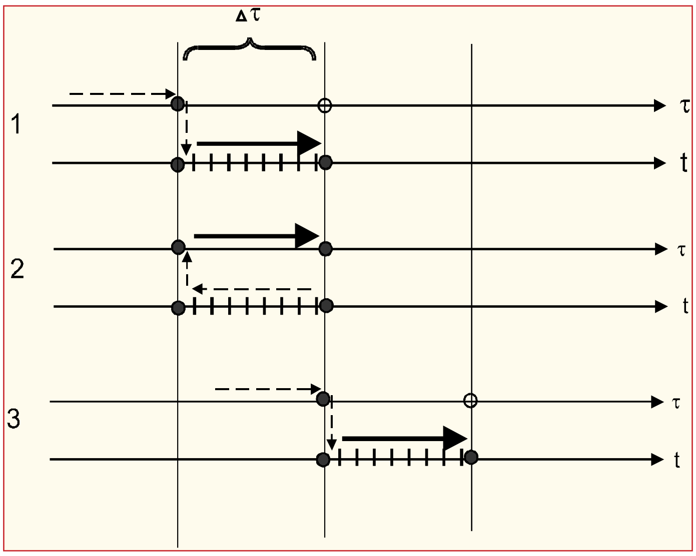


Example: Radiator-condenser panel

L-l model (25 nodes)

Conception of two-level modeling

2. Different time step for H-l and L-l models

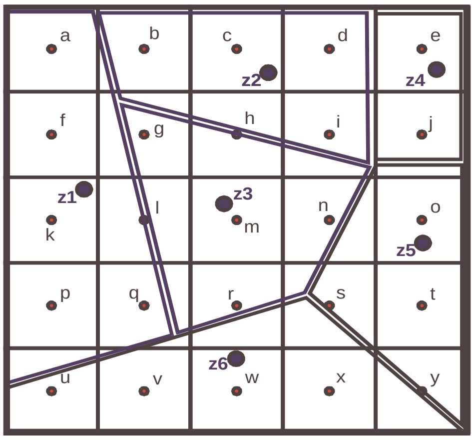


- **Baseline are large time steps of the H-1 model (TMM) Δτ**
- **The L-1 model is first executed for small time steps within the predicted duration of next large time step of H-1 (phase 1)**
- **During L-1 execution the TMM must be switched off**
- **Next, H-1 (TMM) is executed for the same large time (phase 2)**
- **Process is repeated (phase 3)**

Conception of two-level modeling

3. Inter-level interfacing through energy conservation

At each large time step, accumulated heat fluxes, calculated at L-l, enter as additional heat load to the corresponding H-l element.



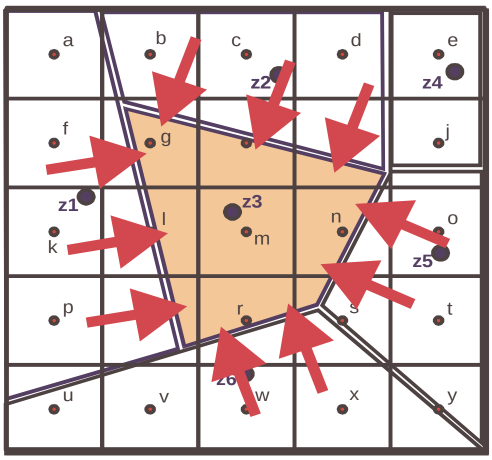
Optimization of a Direct Condensing LHP Radiator

Conception of two-level modeling

3. Inter-level interfacing through energy conservation

This additional heat load has two components. First, heat coming through perimeter of the H-l element.

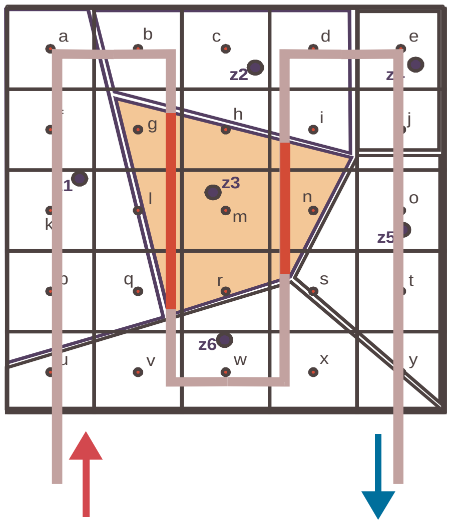
In this case conductive links between H-l elements do not need to be considered.



Conception of two-level modeling

3. Inter-level interfacing through energy conservation

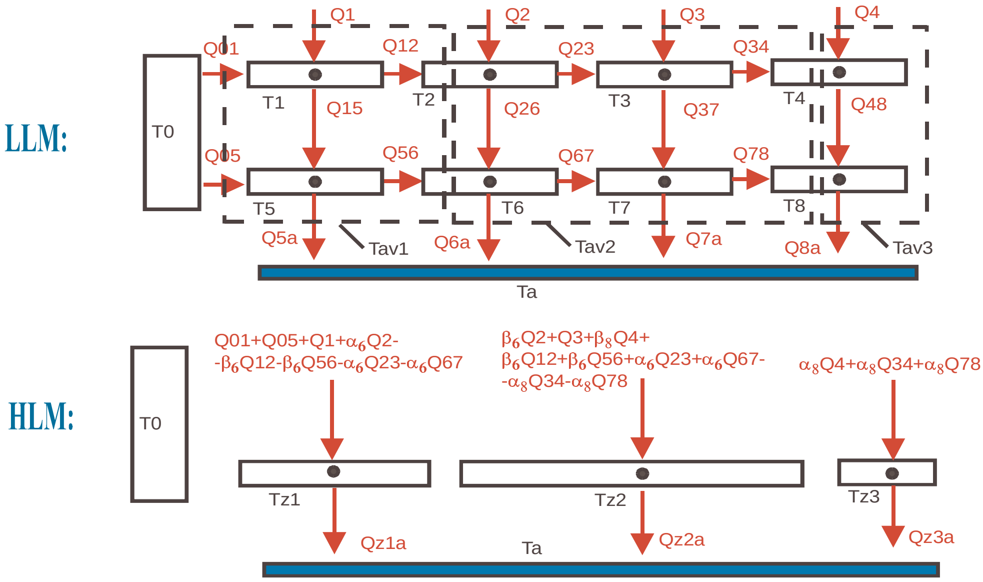
Second component is heat from internal heat sources or sinks of L-l model. For the radiator-condenser example it is the latent heat of condensation.



Conception of two-level modeling

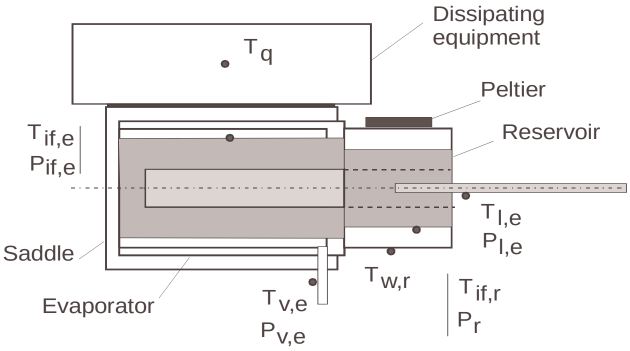
3. Inter-level interfacing through energy conservation

Example of interfacing of sandwich radiator panel at cross section



TPL Evaporator models

LLM

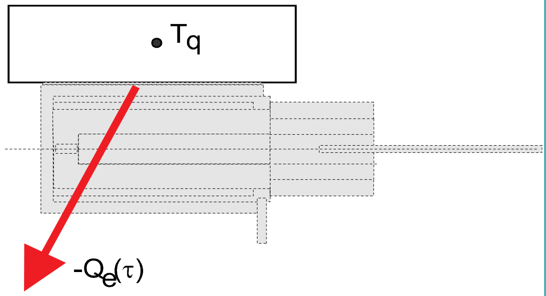


$$Cm_q \frac{dT_q}{dt} = Q_q(t) - G_{qw}(T_q - T_{we})$$

$$Cm_{we} \frac{dT_{we}}{dt} = G_{qw}(T_q - T_{we}) - G_{we}(T_{we} - T_{\&}) - G_{wr}(T_{we} - T_{wr}(t))$$

$$Cm_e \frac{dT_{\&}}{dt} = G_{we}(T_{we} - T_{\&}) - \lambda \dot{m}_e(t)$$

HLM



$$Cm_q \frac{dT_q}{d\tau} = Q_q(\tau) - Q_e(\tau)$$

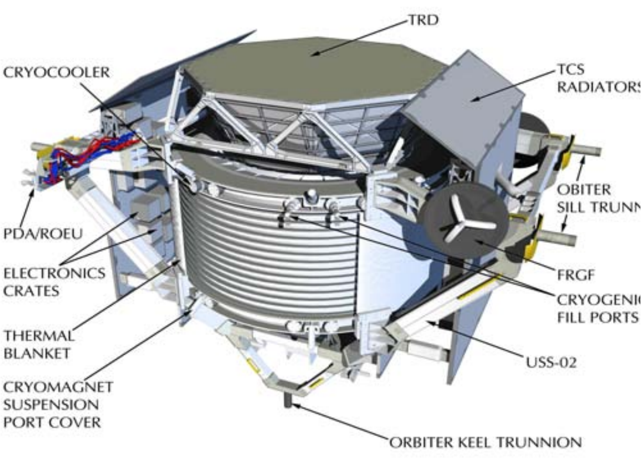
AMS-02

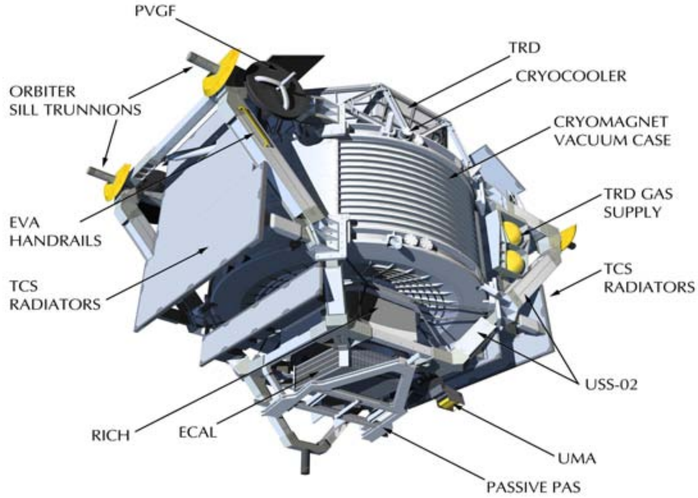
The international Alpha Magnetic Spectrometer experiment (AMS) is a particle detector for high-energy cosmic rays.

Several detectors and sub-detectors operate in a magnetic field, which is generated by a super-conductive Helium-cooled magnet.

AMS-02 System Overview

AMS includes 4 Stirling Cryogenic Coolers (Cryo-Coolers), which extract parasitic heat from one of the thermal protection shields: which are located around the Helium cooled AMS magnet

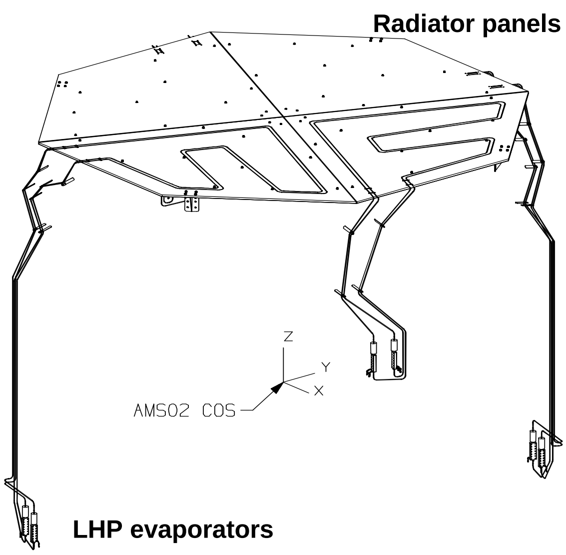


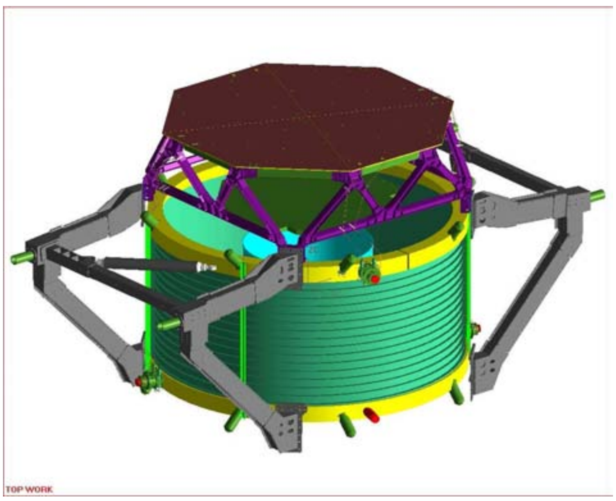


OHB SYSTEM
Optimization of a Direct Condensing LHP Radiator

AMS-02

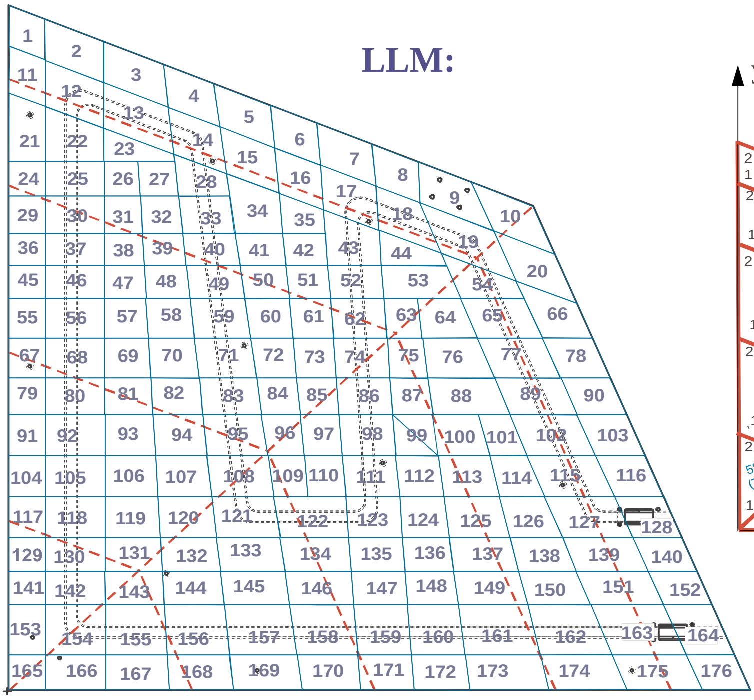
LHPs are employed to transfer the dissipative heat from the cryo-coolers to dedicated thermal radiators.



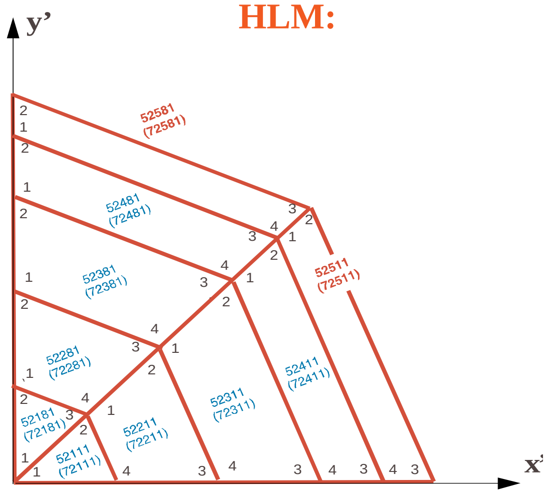


LLM and HLM nodal layout of the AMS cryo-cooler radiator

LLM:



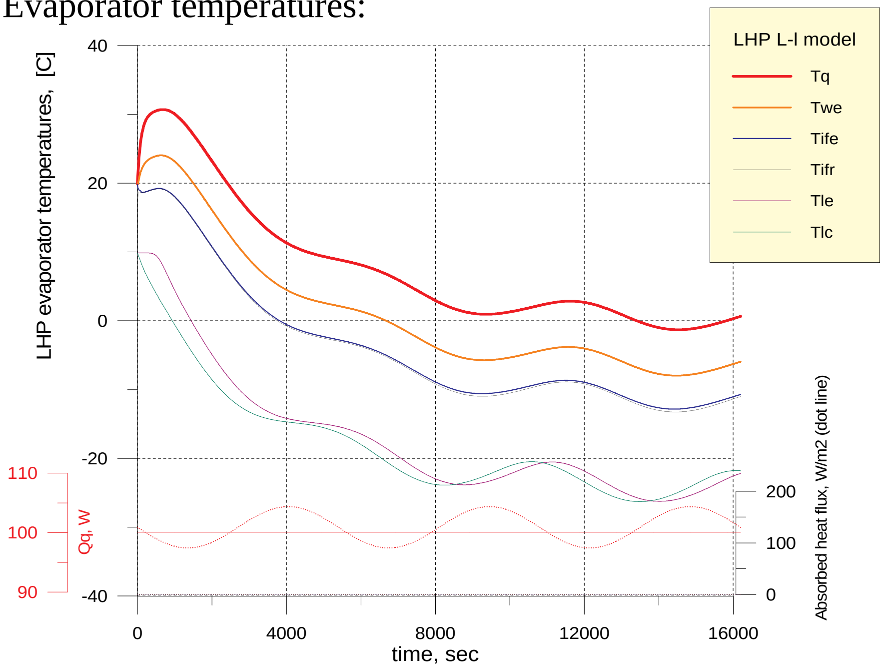
HLM:



LHP of AMS-02

case of variable qs

Evaporator temperatures:



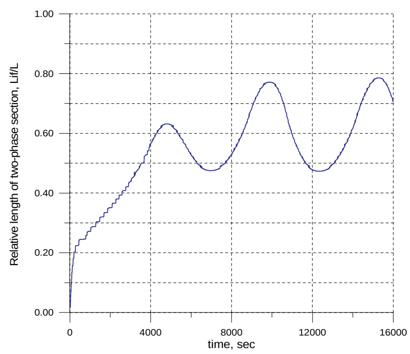
Qq= 100 W

qs = 90..170 W/m^2

Qr= 0 W

Rjk= 0 W/K^4

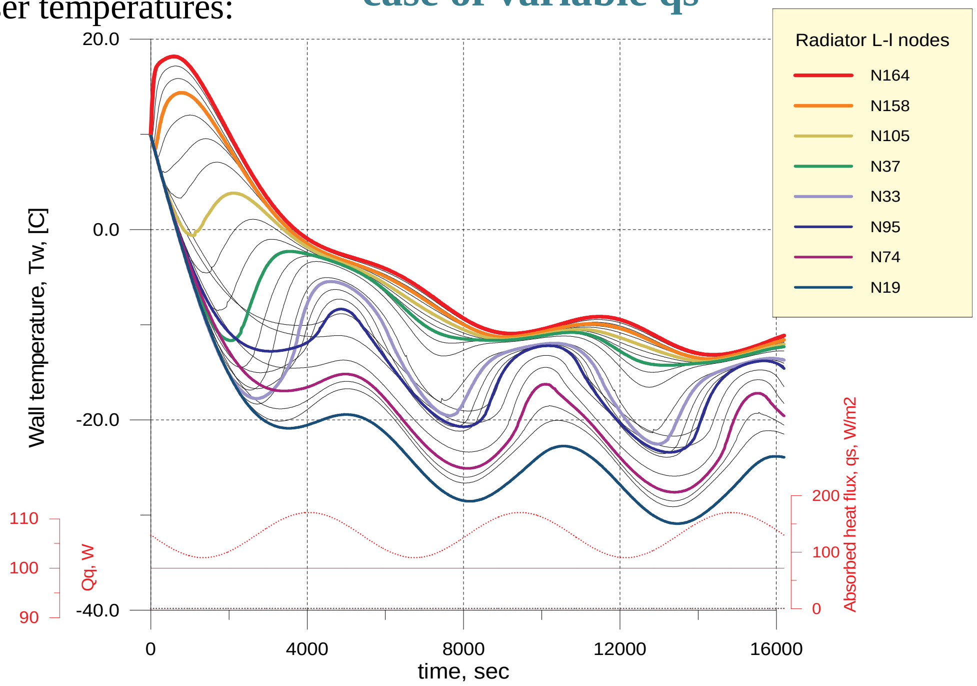
hj = 0 W/K/m2



LHP of AMS-02

case of variable qs

Condenser temperatures:

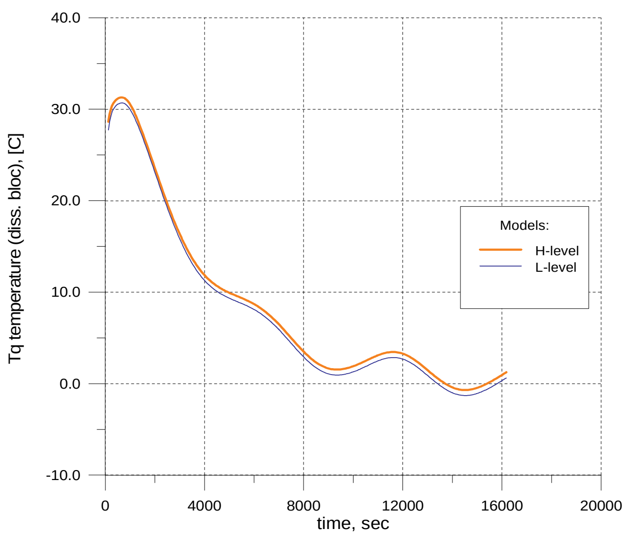


LHP of AMS-02

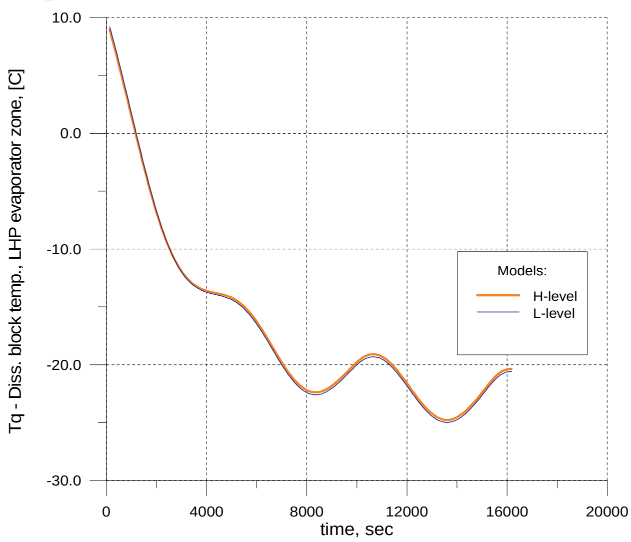
case of variable qs

H-l and L-l temperatures:

H-l and L-l Equipment temperatures:

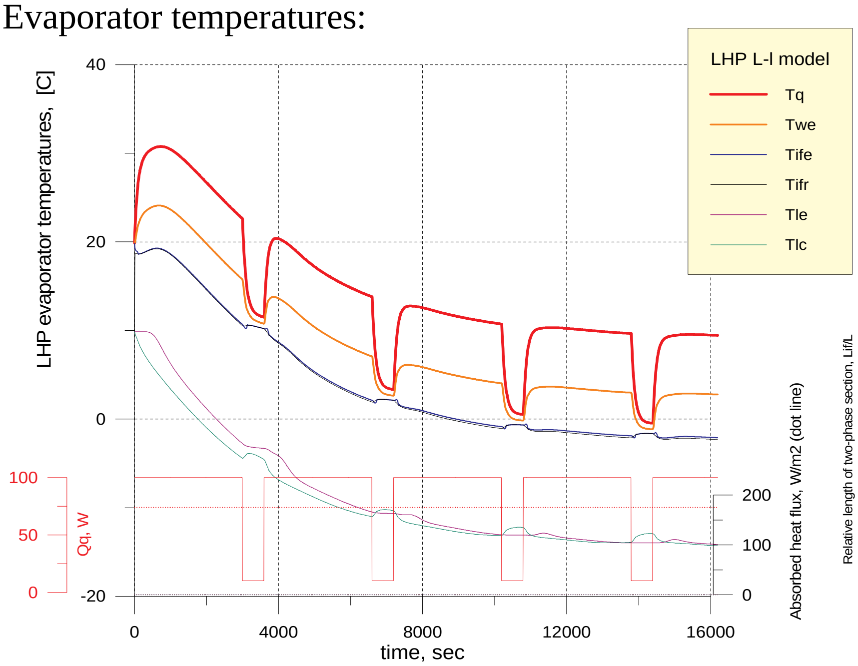


H-l T_{52581} and average of L-l temperatures composed this element:



LHP of AMS-02
case of variable Qq

Evaporator temperatures:



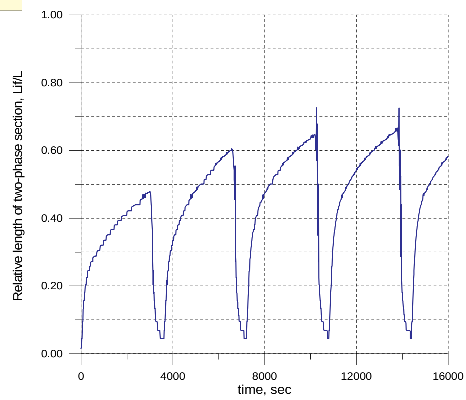
Qq= 10..100 W

qs = 175 W/m²

Qr= 0 W

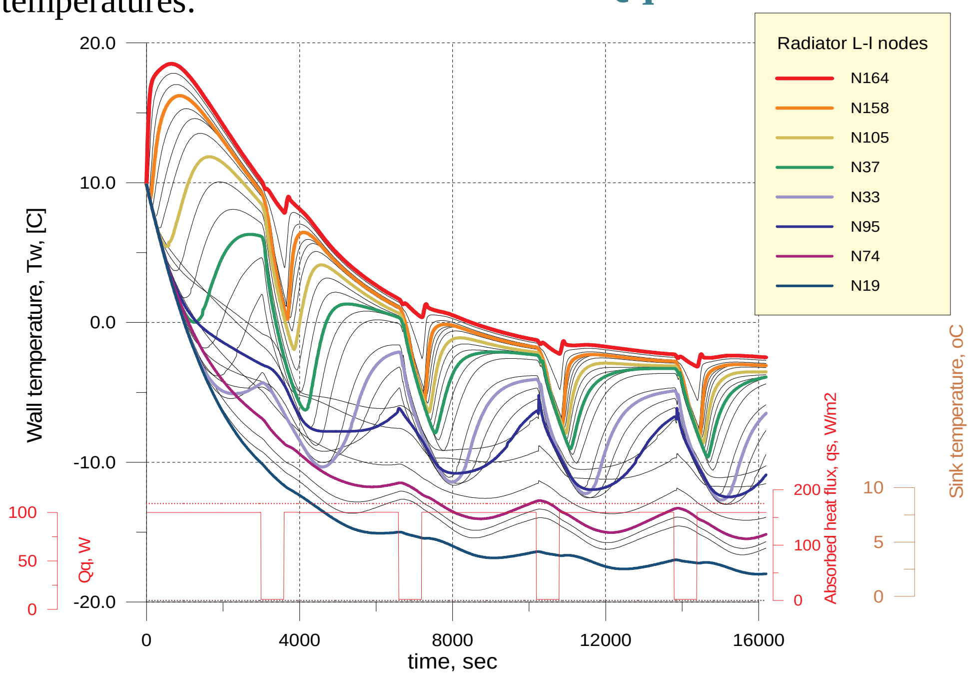
Rjk= 0 W/K⁴

hj = 0 W/K/m²



LHP of AMS-02
case of variable Qq

Condenser temperatures:

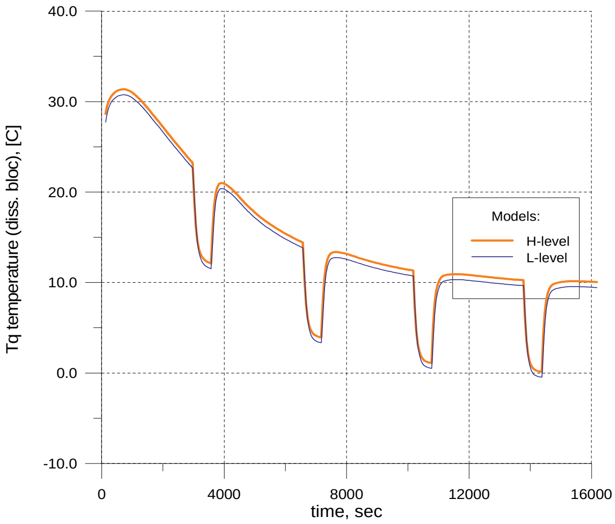


LHP of AMS-02

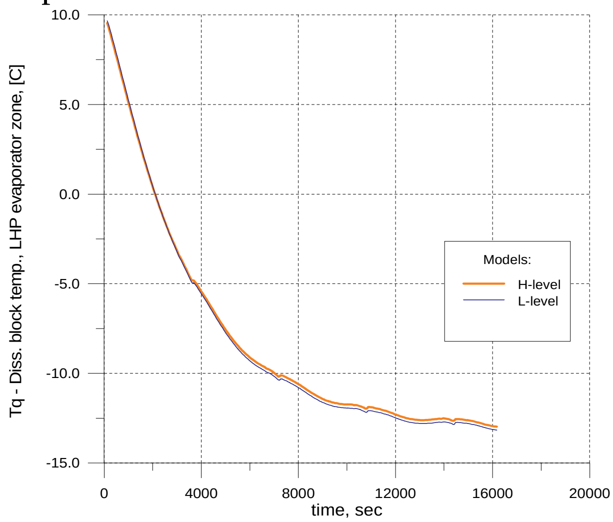
case of variable Qq

H-l and L-l temperatures:

H-l and L-l Equipment temperatures:

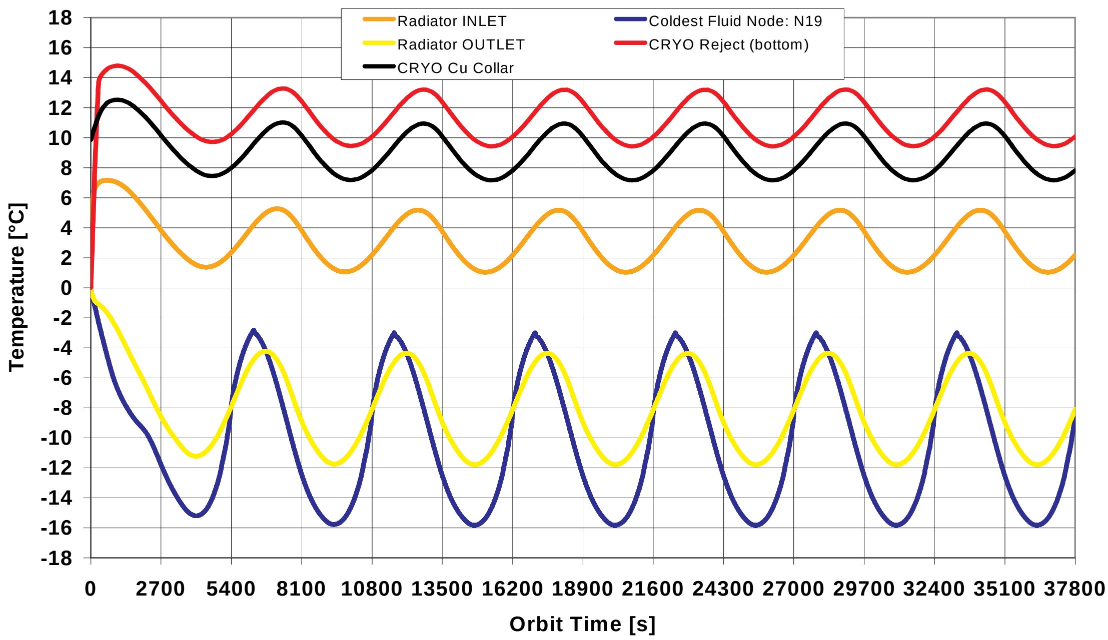


H-l T_{52581} and average of L-l temperatures composed this element:



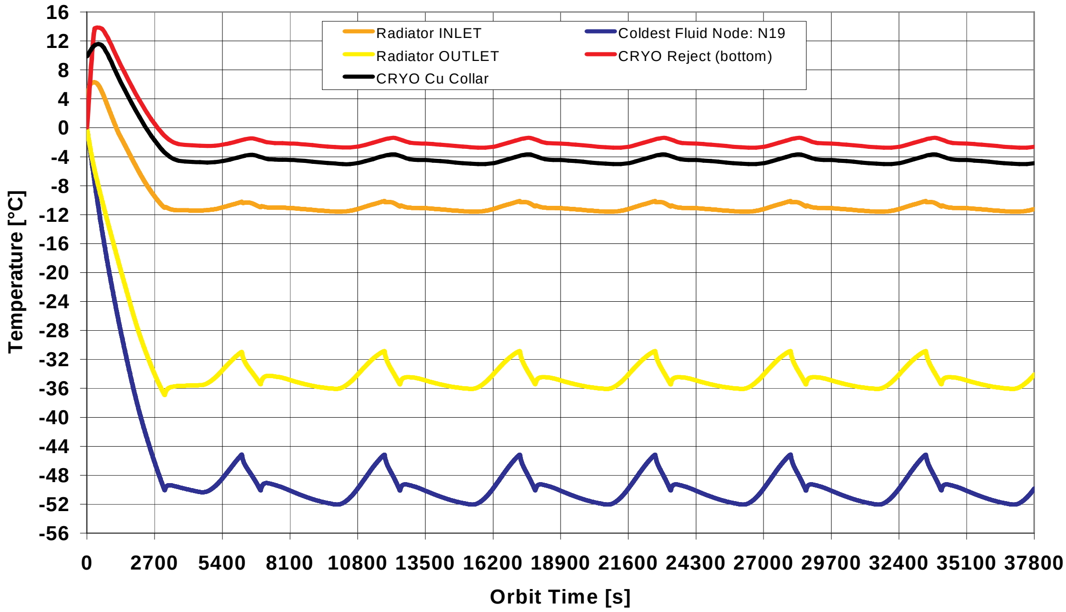
AMS-02

Hot environment case with 108 W cryo-cooler dissipation



AMS-02

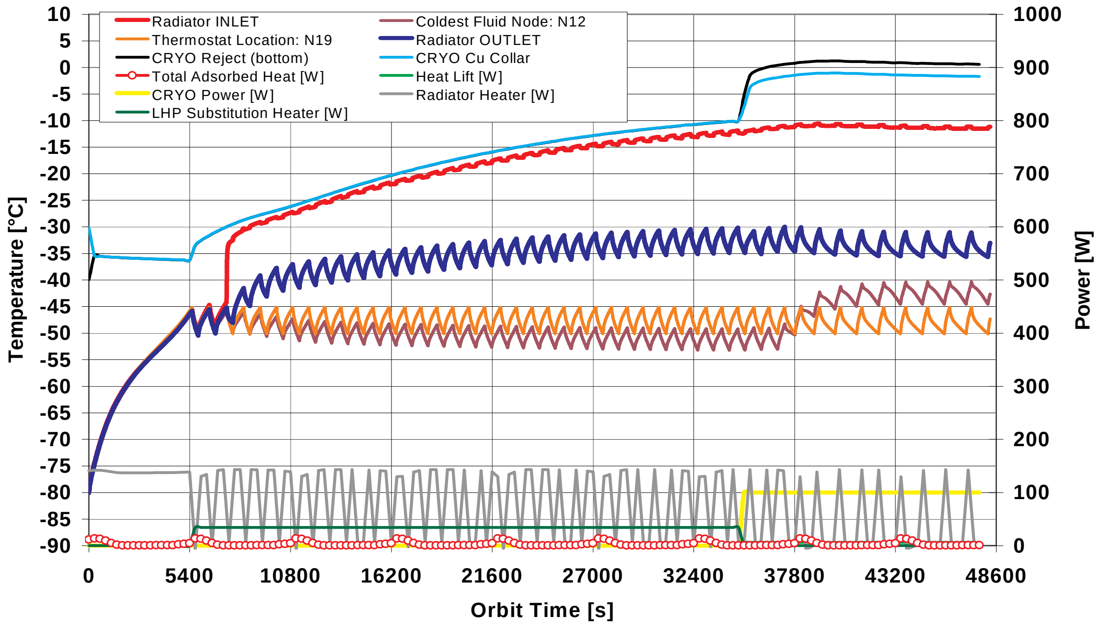
Operating of the cryo-cooler with 100 W during cold case plus thermostat regulated radiator heater of 75 W located near the fluid lines



Optimization of a Direct Condensing LHP Radiator

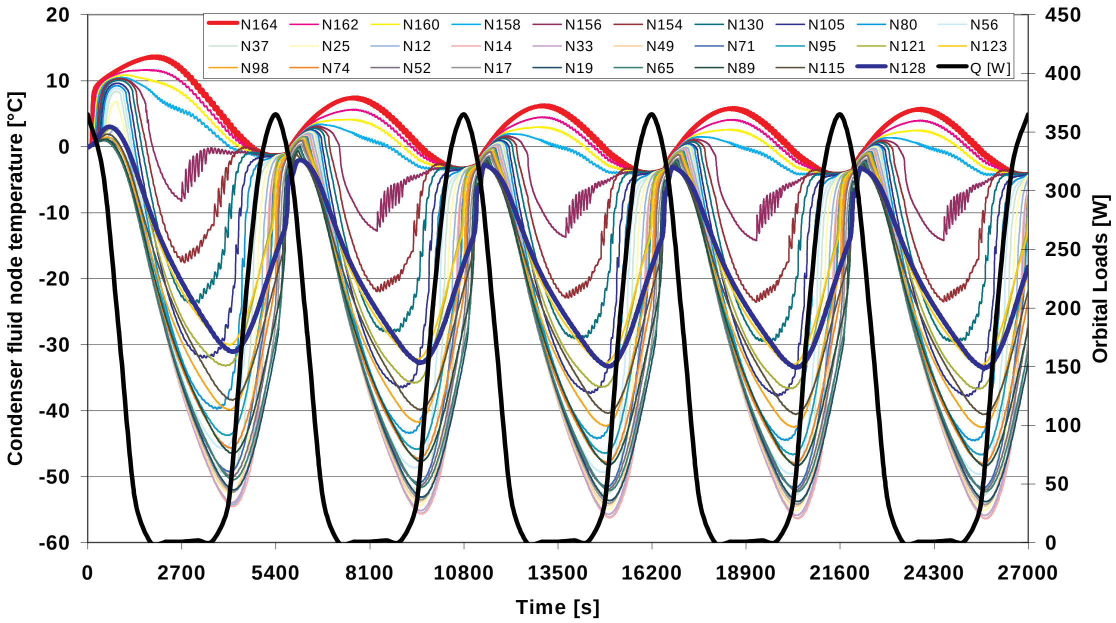
AMS-02

Defreezing of radiator with 137 W and warm-up cryo-cooler with substitution heater (34 W) to reach minimum switch-on temperature of –10°C



AMS-02

Resulting condenser fluid node temperatures at high absorbed orbital fluxes (Cryo dissipation = 100W). Radiator partially full open.



Conclusions

- The technique for including the TPL model into the TMM model of higher level is based on conception of two-level modeling of TPL.
- The two-level conception of TPL modeling permits separate and simultaneous integration of detailed TPL model during integration of TMM with its large time step.
- At high (system) level the TPL can be represented by only few nodes (minimum- 2 nodes).
- The interfacing algorithm (IFA) yields inter-level interaction based on energy conservation, thus, the H-l TPL model displays at system level practically the same precision as the detailed TPL model; the observed difference lies within ±1.5 ^{0}C.
- TPL User can adjust his L-l TPL model by TPL Supplier test results and substitute this L-l TPL model by keeping the entire TMM unchanged.
- The two-level modeling conception was verified during design practice of LHP of AMS-02 ISS experiment.
- Verification by test will be performed in 2005

Appendix O: Innovations in Thermica

Innovations
in
Thermica

M. Jacquiau
EADS Astrium

Innovations in Thermica

Marc JACQUIAU
Timothée SORIANO

Content

- Import of CAD geometry
- Temperature Solver
- Accurate modelling of Thermal Conduction

Import of CAD geometry
Emergence of needs

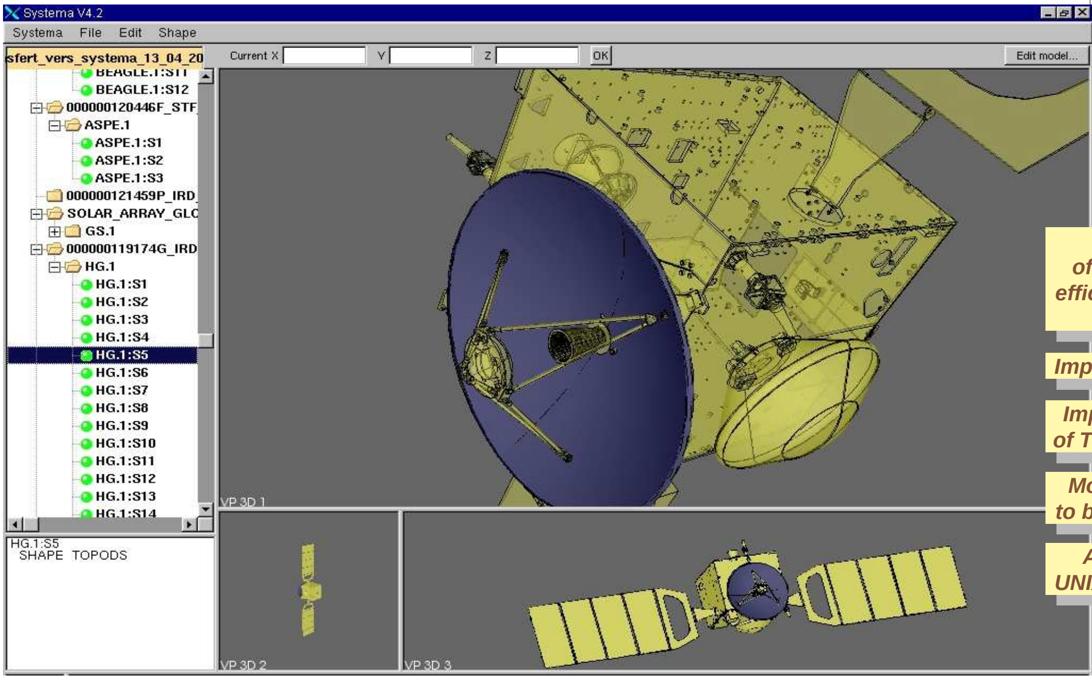
- **For many years**
  - Need to decrease human efforts to build a geometry
  - Need to have an integrated process involving CAD engineers and thermal engineers
- **Recent progress in software technology make possible an import of CAD geometry in a tool like Thermica**
- **However, the import of a CAD geometry is not an easy game**
  - The complexity degree of a CAD model is completely new for an analysis tool like Thermica
- **This means that a new process has to be defined**
  - The software must be compliant with the new needs

A new process for the import of CAD geometries
In search for a specific methodology

- **2002-2003 : Meetings with thermal analysts, design officers and project managers in EADS Astrium, in order to define the process to follow for the import of CAD models**
- **Process A : recurrent platforms**
  - Assemblies of existing models (previously translated from CAD to analysis)
  - Non-recurrent equipments : apply Process B
- **Process B : new geometries**
  - Software tool showing the CAD model in background
  - Automatic translation of standard surfaces
  - Use of specific points (picked on the CAD model) to build surfaces
  - Complex shapes : meshing into standard surfaces
- **Simplification decided by the thermal engineer**

A new tool to import and translate CAD geometry
Compliant with the process

❑ Main window *(import of Mars Express CAD model)*



Manipulation of CAD geometries efficient with classical computers

Import of STEP files

Import / export of Thermica files

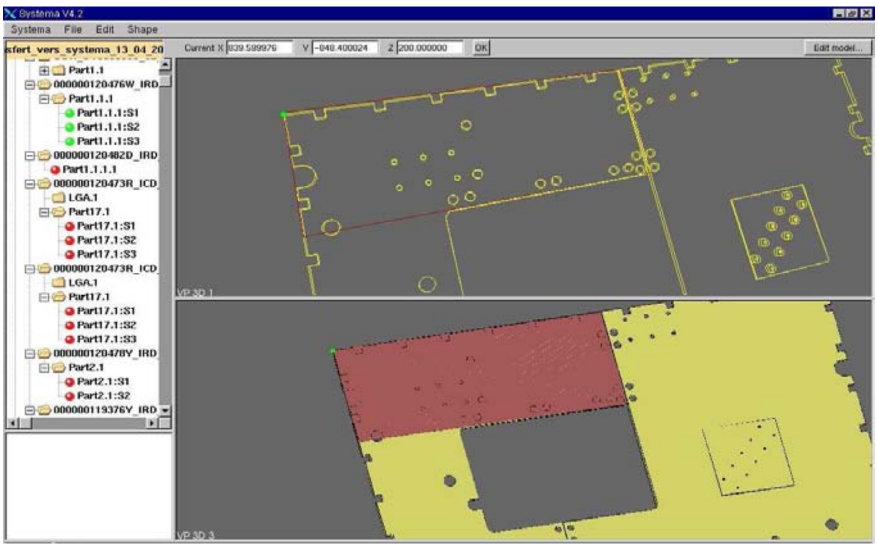
Modeler capabilities to build thermal model

Available on all UNIX & PC platforms

How to manage complexity of CAD geometry (1/2)
Pick of points on the CAD model to build Thermica shapes

❑ Semi-automatic simplification

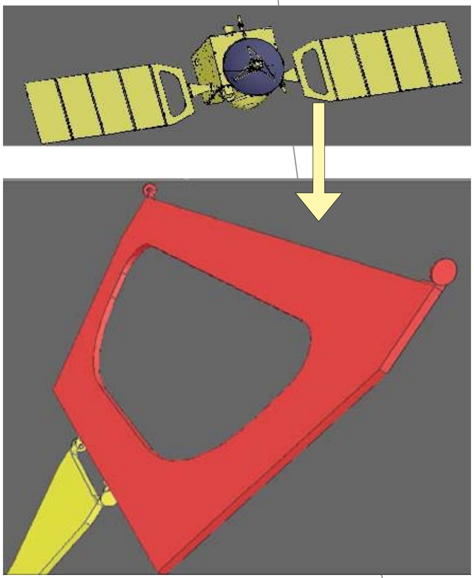
- ➢ CAD geometry is used as a <u>layer</u> which gives specific points
- ➢ Pick on specific points to define Thermica shapes



Interactive creation of a Thermica rectangle from the CAD layer

How to manage complexity of CAD geometry (2/2)
Translation of standard surfaces

- **Automatic translation of standard surfaces on request (under development)**
  - Thermica simple shapes will be automatically created from the equivalent CAD shapes
  - Complex shapes (i.e. Nurbs) will be meshed into triangles
- **However, this simplification must be made carefully**
  - This solar array structural element is made of about ***more than 80 elementary shapes*** (quadrangles and cylinders)
- **Without simplification, a new family of huge thermal models will appear**
  - Difficult management for thermal software
  - Difficult analysis of results for users



Import of CAD geometries
CONCLUSION

- **Import of CAD geometry is now possible in Thermica**
- **The methodology built within EADS Astrium has supported our approach, it will now benefit to all users**
- **The CAD import module is well suited to this methodology**
- **It will be improved according to the user feed-back**
- **Available in Thermica v3.2.20 (October 2004)**

Temperature Solver
Emergence of needs

- **In a long-term perspective, Thermica needs to be a more and more <u>complete software package</u> for space thermal analysis**
  - Agressive competition of mature software from outside Europe
- **User survey (internal & external users) : need to be compatible with the European standard language Esatan**
  - To allow the computation of previous models
  - To keep the existing process
  - To consolidate the user experience
  - To **<u>preserve harmonization</u>** in Europe

Temperature Solver
Main characteristics

- **Compatibility with the Esatan language**
  - Internal data structure has also been made compatible
  - Other languages could also be introduced if necessary
- **Pre-processing**
  - Very fast, robust, user-friendly (clear error messages)
- **Temperature computation**
  - Standard algorithms have been implemented (Newton Raphson, Crank Nicholson) – *takes benefit of our experience in solvers within other space environment applications (Systema)*
  - Innovative new algorithms have been developed and integrated

Temperature Solver
Validation / Maturity

- **A intensive validation phase has occured in EADS Astrium : near 50 real test cases**
  - Coming from several space projects, different users, different cultures, different project phases, different size (small → very big)
  - MEX, Pleiades, Ariane5, Arabsat, VEX, Melfi, Intelsat10, Inmarsat4, HotBird8, Metop, Amazonas, Anik, W3A, ISS, Gaia, LHP…
- **Results :**
  - Compatibility with Esatan language : near 100%
  - Compatibility with user subroutines & libraries
  - Temperature results have been extensively validated

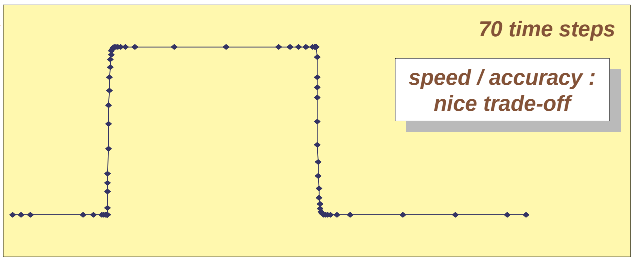
    (with standard methods : Newton Raphson & Crank Nicholson)

Innovation 1 : Automatic time-stepping
Main principle

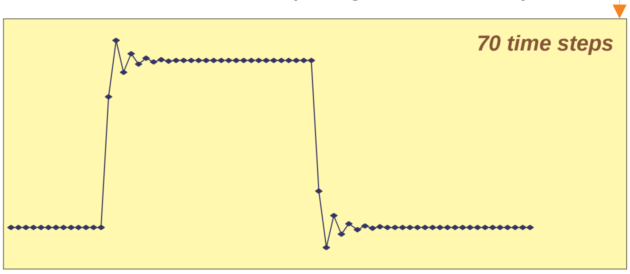
- **The user specifies the accuracy he wants to have on the temperatures**
- **During the computation, the error is estimated**
  - The error is not just only evaluated by ΔT but is given by a more complex mathematical development of the Crank Nicholson scheme (more accurate)
- **Then, the time step is automatically changed in order to obtain the desired accuracy**
- **This process is completely automatic…**
  - No need to program manual changes for eclipse entry/exit, instruments activation, …
- **…and managed by the only interesting criteria : <u>accuracy</u>**

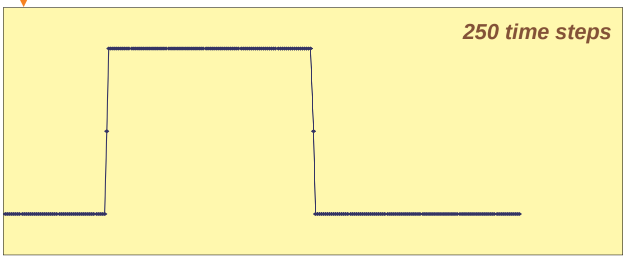
Innovation 1 : Automatic time-stepping
Application

- **Model = 1 diffusive node (C=10) + 1 boundary node which temperature switches between 0°C and 20°C, GL=10**
- **Automatic time stepping**
  - 70 time steps
  - Good accuracy



- **Constant time step**
  - 70 time steps : bad accuracy
  - 250 time steps : good accuracy



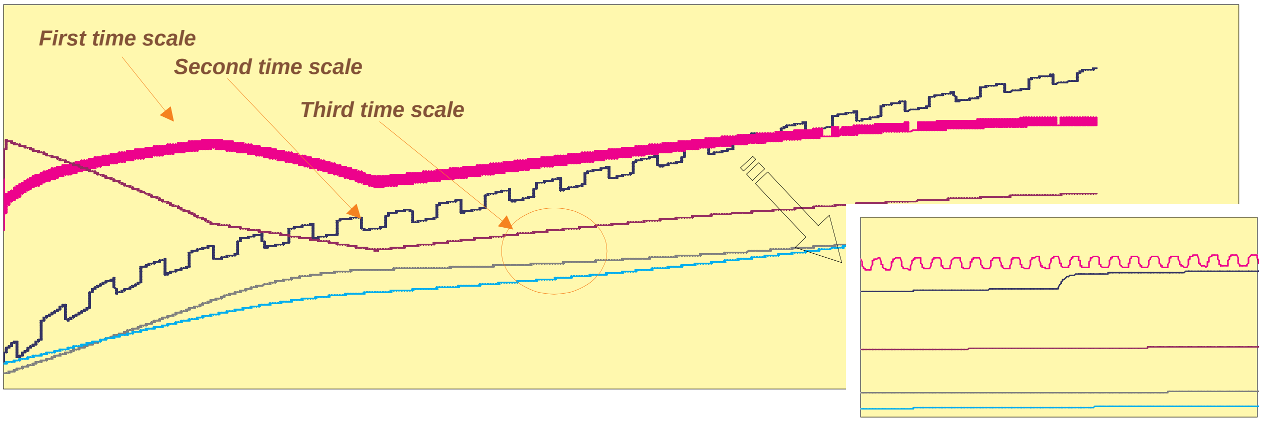


Innovation 2 : Parallel time-stepping
Main principle

- **In a large number of applications, all thermal nodes don't have the same time scales in their temperature variations**
  - satellite vs equipments
  - satellite vs external appendices
  - equipments vs fluid loops
- **During the computation, the nodes are automatically classified into several families**
  - One family per time scale
  - <u>Each family has its own time step</u>
- **<u>Mix of simultaneous different time steps</u>**
- **Optimization of CPU time without loss of accuracy**

Innovation 2 : Parallel time-stepping
Application

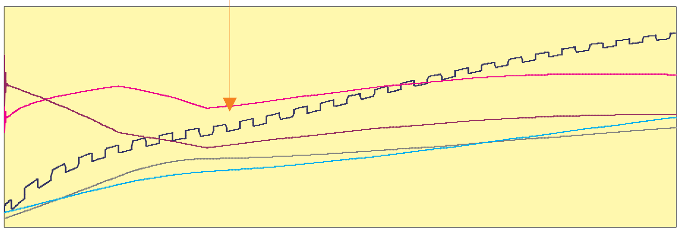
- **Model made of 200 nodes**
  - 1 node has temperature variations with a 1s period
  - 1 node has temperature variations with a 20s period
  - 198 nodes have variations with a large time scale (whole satellite)



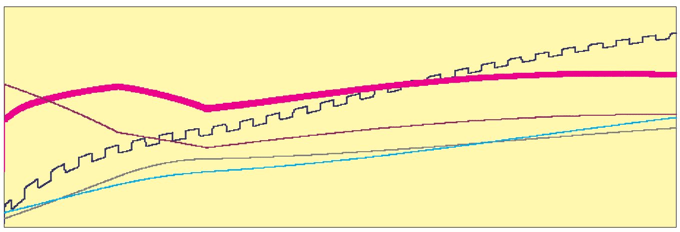
- **The parallel time-stepping gives <u>accurate results</u> with an <u>optimized CPU time</u> (mix between dt=50s, dt=2s and dt=0.1s)**

Innovation 2 : Comparison with standard methods
Classical methods are not suited to models with several time scales

- **A fix time step algorithm with dt=1s gives wrong results for the high frequency variations**



- **A fix time step algorithm with dt=0.1s has a correct accuracy (but dt=0.1s is <u>applied to all the nodes</u> !)**



- **For this kind of models, the classical methods can be 10 times slower than the parallel time-stepping algorithm**

Temperature Solver
CONCLUSION

- Thermica Solver is in line with the European standards
- The development has been driven by the user needs
- It has been successfully validated in many space projects
- It offers a reliable mastering of accuracy
- This solver comes with new approaches for the current & future needs with innovative algorithms
- Available in Thermica v3.2.20 (October 2004)

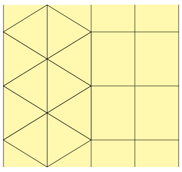
Accurate modelling of thermal conduction
Emergence of needs

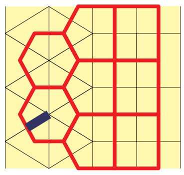
- **Classical approaches use geometrical considerations and apply classical λS/L-like formulas**
  - We have no idea of the validity in general cases
  - No idea of the accuracy
  - No idea of the limits
- **When accuracy is needed, a real numerical simulation is necessary : strict derivation of Fourier's law on the meshing**
- **Methods investigated : inspired from <u>Finite Volumes</u> and <u>Finite Elements</u>**
  - Need to apply these methods to standard Thermica geometries
  - Compatibility with the lumper parameter approach (nodal method) is requested : <u>conductive study = computation of couplings</u> (temperatures are solved later)

Accurate modelling of thermal conduction

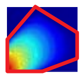
Two main theoretical approaches

- **Option 1 : inspired from a Finite Volume approach**
  - Construction of a dual meshing, temperature smooth interpolations in dual meshes and computation of fluxes crossing initial shapes



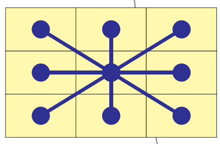


$$T(x,y) = \sum_k \alpha_k(x,y) T_k$$

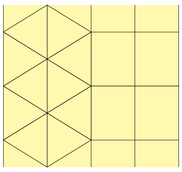


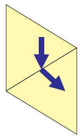
$$\Phi = -\int e\lambda \ \vec{\nabla} T \cdot \vec{n} \ d\sigma$$

$$= \cdots = \sum a_{pq} \left(T_q - T_p \right)$$



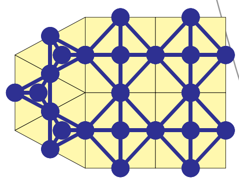
- **Option 2 : inspired from a Finite Element approach**
  - Linear temperature profile inside meshes, leading to couplings between centers and edges





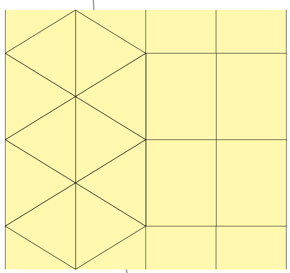
$$T(x,y) = a + b\,x + c\,y$$

$$\Phi = -\int e\lambda \ \vec{\nabla} T \cdot \vec{n} \ d\sigma$$



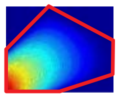
Option 1 : Simulation by Finite Volume method

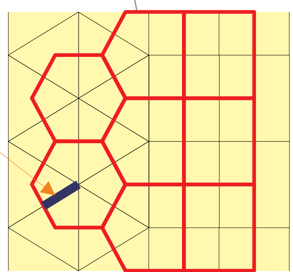
Description of the algorithm



- **The Finite Volume method creates a <u>dual meshing</u> based on the <u>center</u> of each shape *(global approach)***
- **In each dual mesh, the temperature is interpolated from the temperatures of initial user meshes :**

$$T(x,y) = \sum_k \alpha_k(x,y) T_k$$

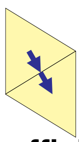




- **In each dual mesh, the flux crossing two shapes is :**

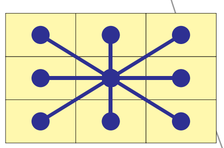
$$\Phi_\sigma = -\int_\sigma e\lambda \ \vec{\nabla} T \cdot \vec{n} \ d\sigma = \cdots = \sum a_{pq} \left(T_q - T_p \right)$$

- **This flux is a continuous function**



- **Then, a global assembly of the linear coefficients a_{pq} leads to a set of couplings between thermal nodes**

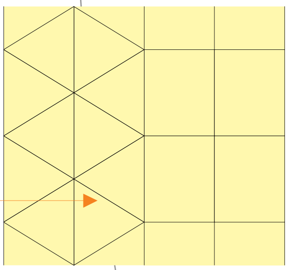
$$GF(i,j) = \sum_{p,q} a_{pq}$$



- **<u>Many couplings between neighbours</u>**

Option 2 : Simulation by Finite Element method
Description of the algorithm

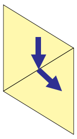
- The Finite Element method apply Fourier's law in each individual triangle *(local approach)*



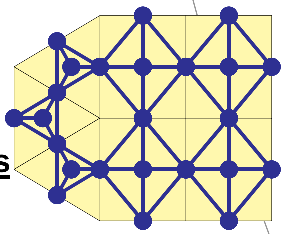
- A linear temperature profile is assumed in each triangle

$$T(x,y) = a + b\,x + c\,y \qquad \nabla T = (b,c)$$

- The flux crossing two nodes is not continuous



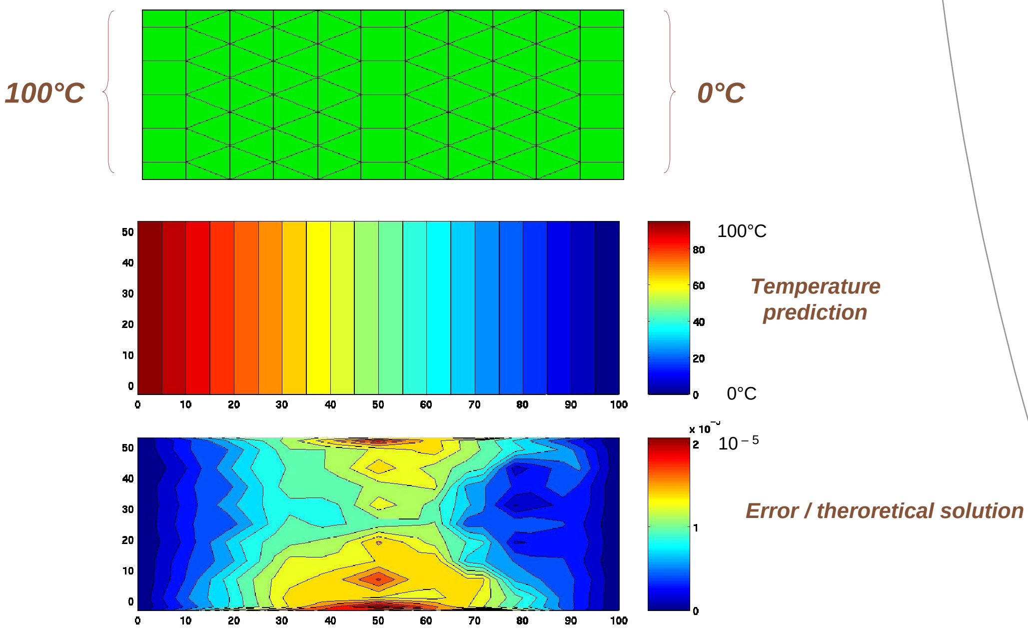
- A lot of additional thermal nodes are automatically created (edge centers)



- **Many couplings inside shapes, independant from neighbours**

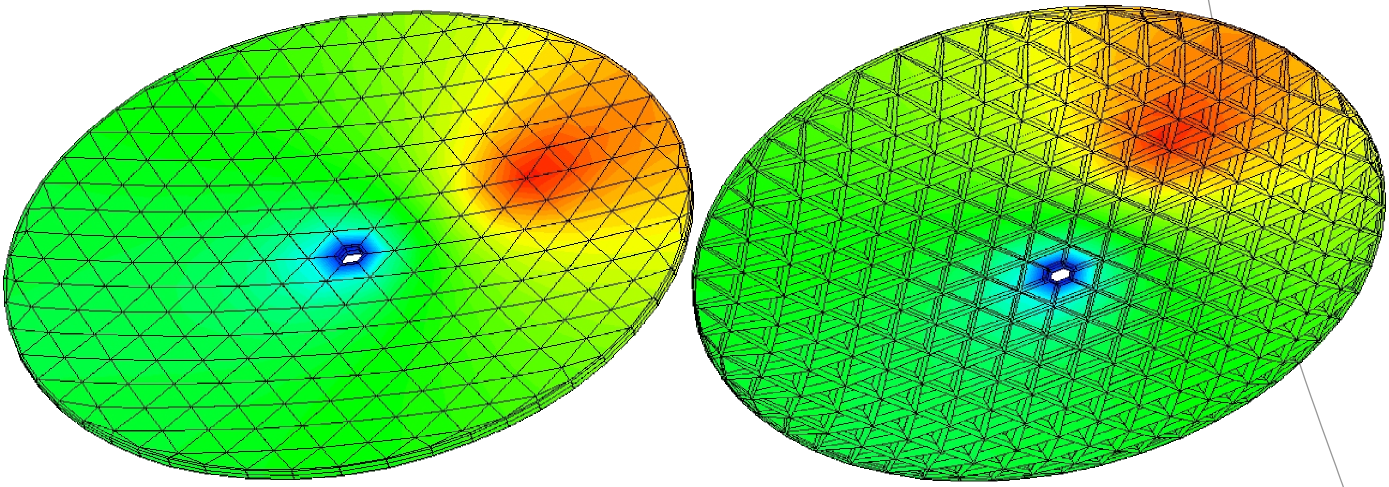
Validation of the two methods (1/2)
Academic tests

- Application to the classical rectangle with boudary temperatures on left & right (0°C and 100°C)
- Error / theoretical solution < 10^{-5} °C ! *(10^{-7} %)*



Validation of the two methods (2/2)
Application to an industrial project

- **Application to the mirror of an observation spacecraft**
  - Boundary temperature at the center
  - Solar flux on 2 meshes
- **These new algorithms are perfectly correlated with the operational method used on current projects**



Accurate modelling of thermal conduction
CONCLUSION

- **These new methods give very promising results**
  - High accuracy
  - Compatibility with classical Thermica geometries
- **Next step in the integration to Thermica : a trade-off will be made to select F.V. approach or F.E. approach**
  - Maybe both of them will be available
- **Schedule : at <u>beginning of 2005</u> the new conduction module will be fully integrated in the standard Thermica package**

CONCLUSION

- **Thermica : a more and more complete European software package for Space Thermal Analysis**
  - Framework : 3D modeler, interactive menus, post-processing
  - Mission : orbit & kinematics, standard & complex missions
  - Thermal radiation : accurate Monte Carlo Ray Tracing, complex planetary fluxes (Earth, Mars, Venus, Mercury, …)

    Current version v3.2.19
  - Thermal conduction (accurate FV and FE method) → *Beginning 2005*
  - Temperature solver → *v3.2.20 : October 2004*
  - Connexion with CAD → *v3.2.20 : October 2004*
  - New framework with high interactivity & new ergonomy → *v4.1 : June 2005*
- **We try to enlarge the offer with new modules and innovative solutions in accordance to the user needs**
- **These improvements are delivered with no price increase**

Appendix P: Thermal and Radiative Modelling

Thermal
and
Radiative
Modelling

J. Thomas
ALSTOM

Oct 2004

Radiative & Thermal Modelling

Julian Thomas

ALSTOM

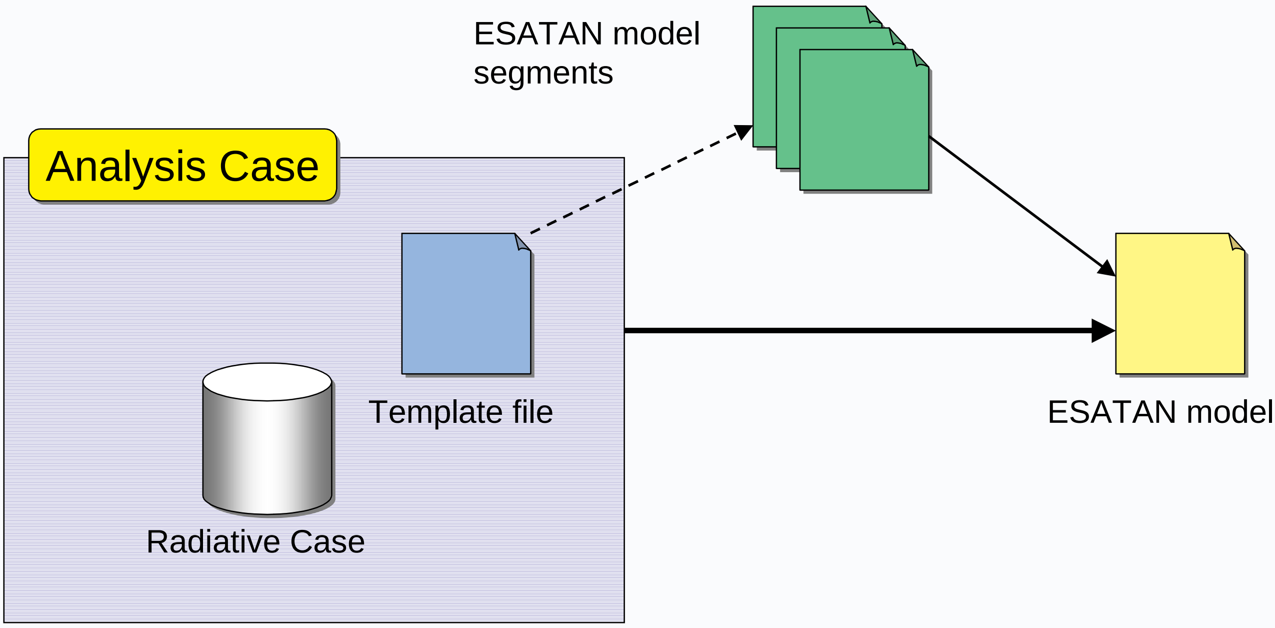
Contents

ALSTOM

- Review of Analysis Case concept
- Step by step:
  - Statement of problem
  - Layout of model
  - Radiative Cases
  - Analysis Cases

Case Management

ALSTOM



- Control & Manage Multiple Cases -

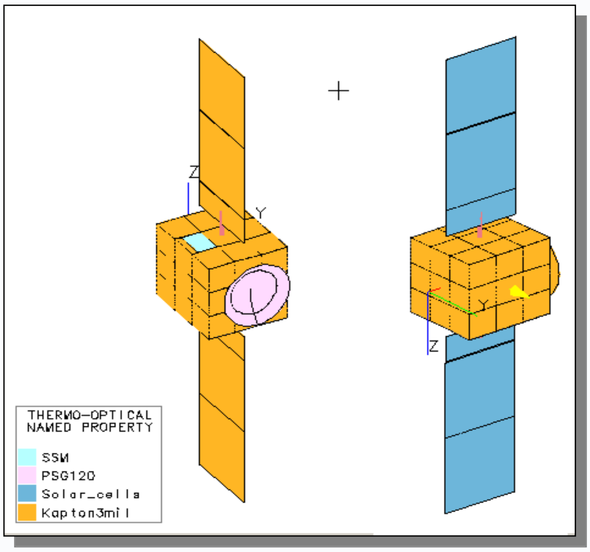
Simple Example

ALSTOM

Interactive Demo

Our Example “Problem”

GEO Sat

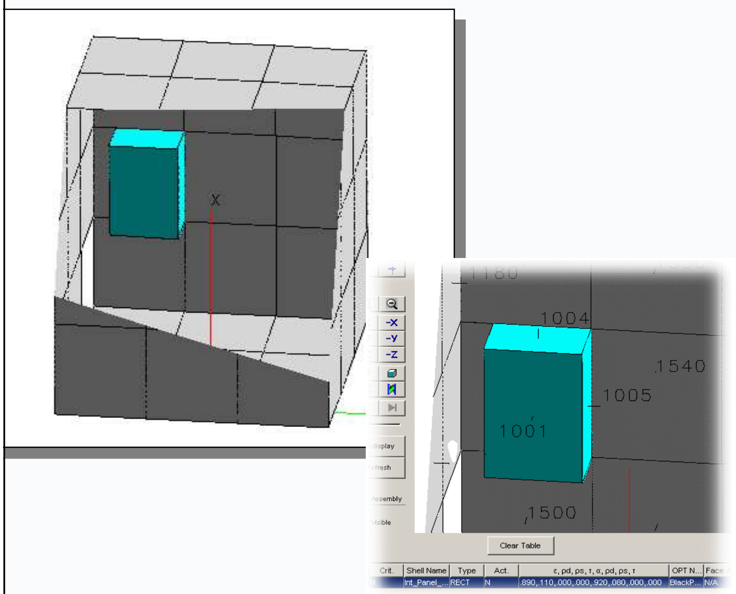


- 3 analysis conditions (cases) to consider:
  - Summer BOL Operating
  - Summer BOL Non-Op
  - Winter EOL Operating
- Unit mounted internally on the north panel, with an external radiator surface.

- External Geometry -

Our Example “Problem”

GEO Sat



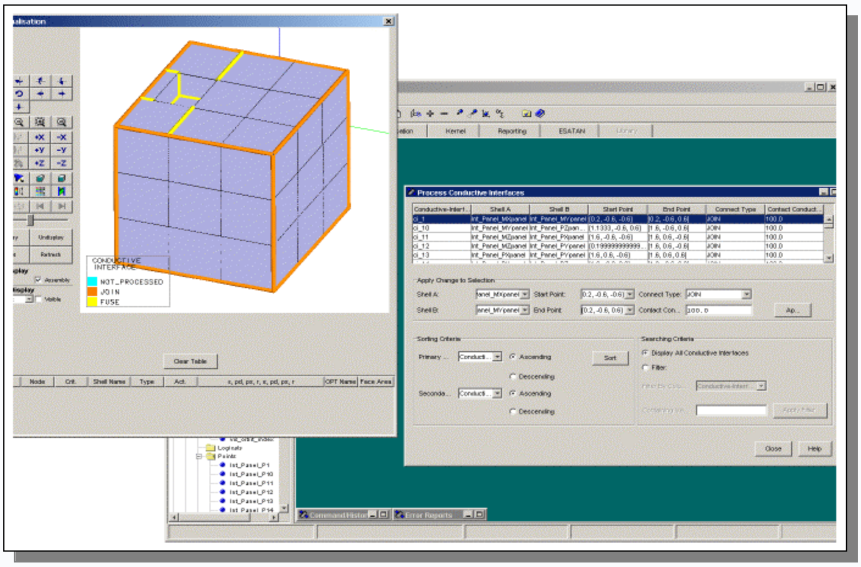
- 3 analysis conditions (cases) to consider:
  - Summer BOL Operating
  - Summer BOL Non-Op
  - Winter EOL Operating
- Unit mounted internally on the north panel, with an external radiator surface.

- Internal Geometry -

Our Example "Problem"

ALSTOM

GEO Sat

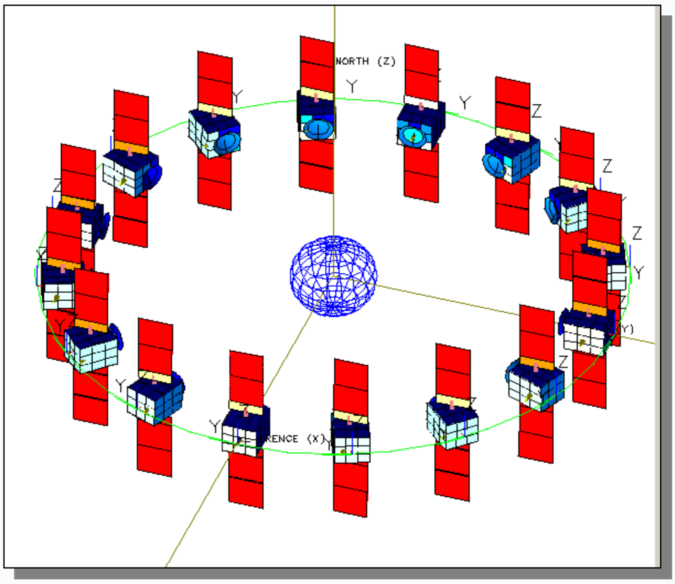


- ACG used to find and calculate links.
  - New general ACG solver to be released in 2005.

- Conductor Generation -

Radiative Cases

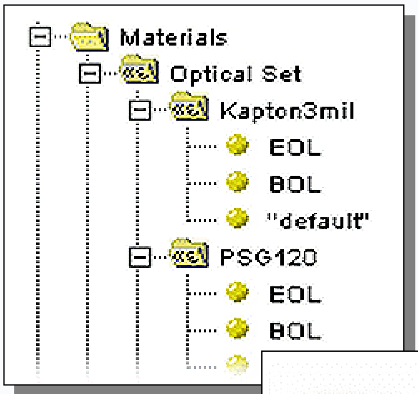
ALSTOM



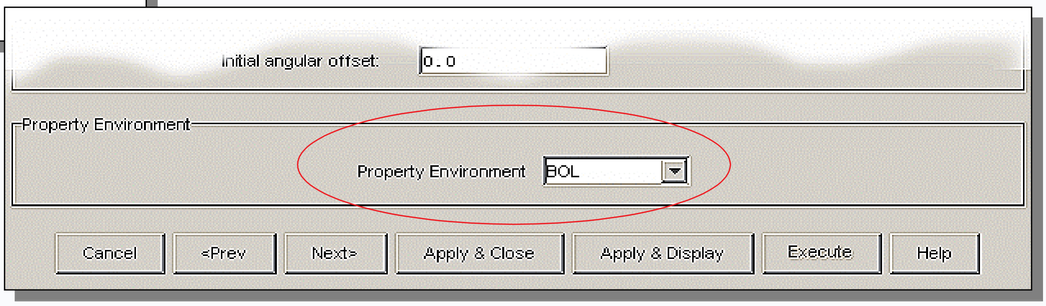
- Need to consider 2 Radiative Cases:
  - Summer BOL
  - Winter EOL
- Vary:
  - Earth-Sun distance
  - Solar Declination
  - Optical Properties

Optical Property Environment

ALSTOM



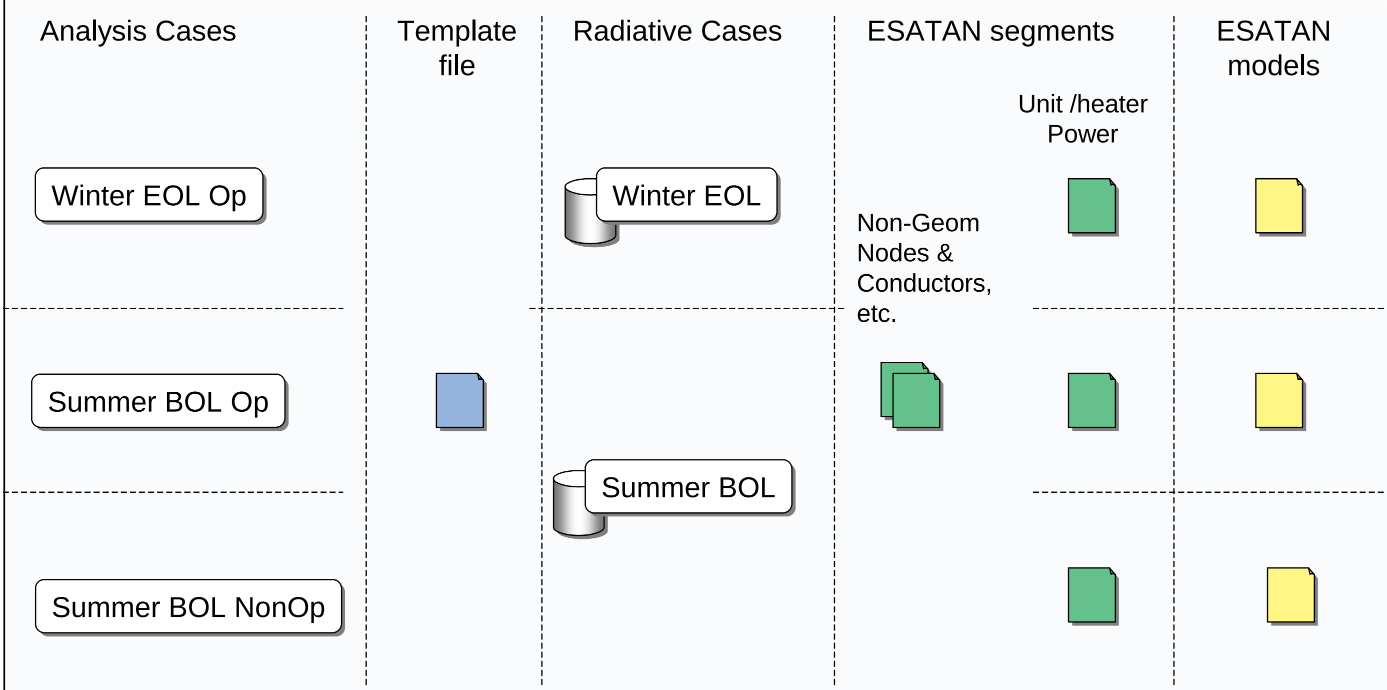
Selected in Radiative Case:



- Introduced with v5.6 -

Case Management

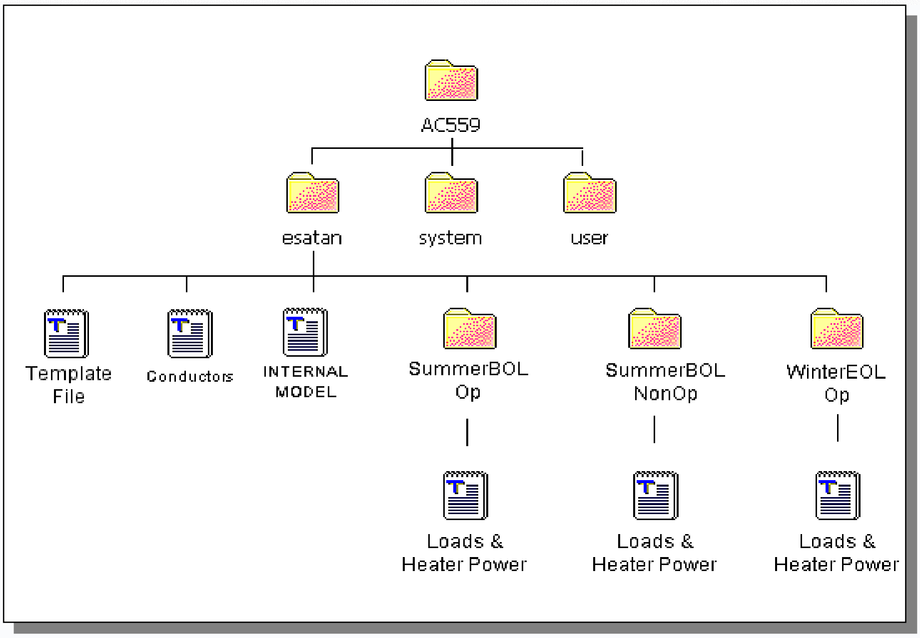
ALSTOM



- Control & Manage Multiple Cases -

File Organisation

ALSTOM



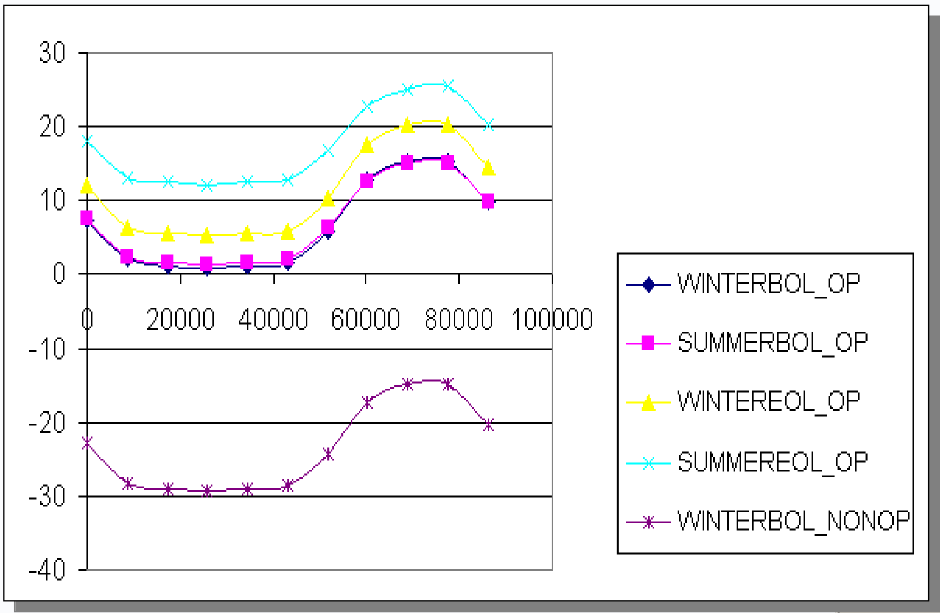
Demo

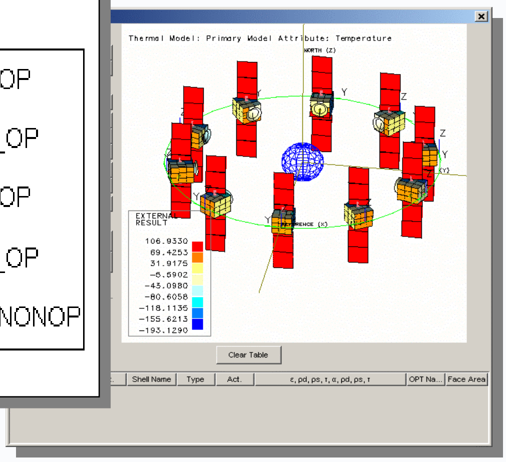
ALSTOM

Interactive Demo

And the Results...

ALSTOM





ALSTOM

www.alstom.com

Appendix Q: Thermal Network Viewer

Thermal
Network
Viewer

H. Brouquet
ALSTOM

October 2004

Thermal Network Viewer

ThermNV

Henri Brouquet

ALSTOM

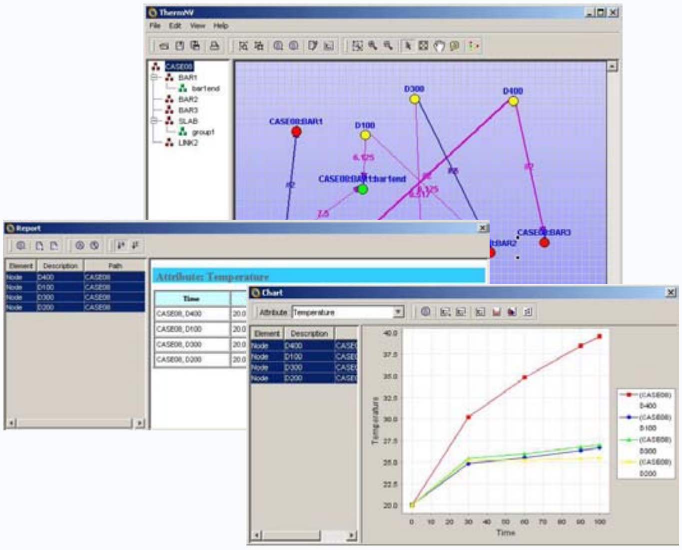
What is ThermNV for ?

ALSTOM

ThermNV provides an environment for the visualisation and inspection of thermal networks in a schematic form

Model validation (nodes, sub-models, conductors)

Post-processing (heat flow inspection, charting)



Key Features (1)

ALSTOM

ThermNV enables to:

Import GFF network file as generated by ESATAN & ThermXL v4

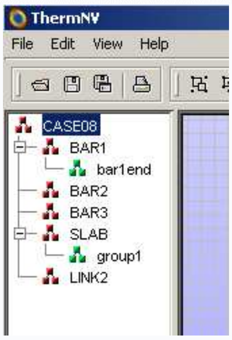
Visualise network schematic (nodes and conductors)

Layout schematics and save for import to similar networks

Key Features (2)

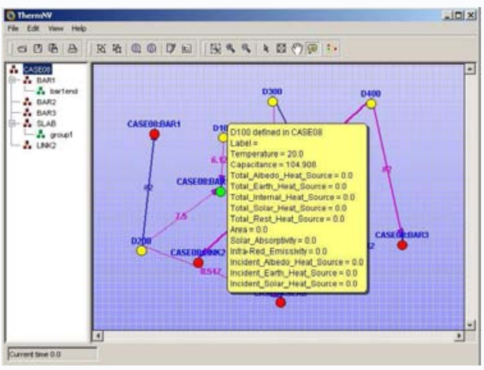
ALSTOM

ThermNV enables to:



Browse model by sub-model

Create virtual sub-models (group of nodes)



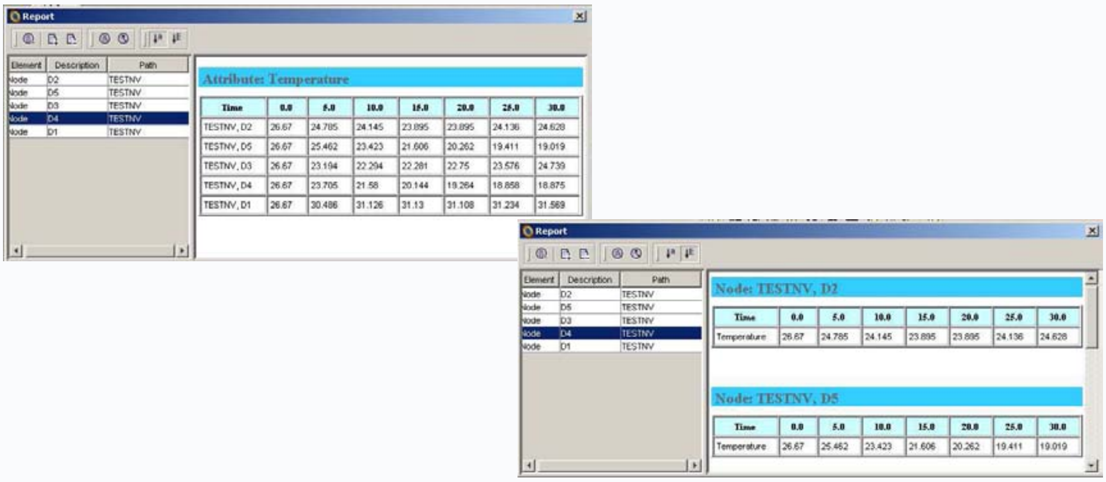
Select the ‘hover’ data on nodes, conductors and sub-models for a rapid model inspection

Key Features (3)

ThermNV enables to:

Inspect heat flows directly on schematic

Report on any model result data



Key Features (4)

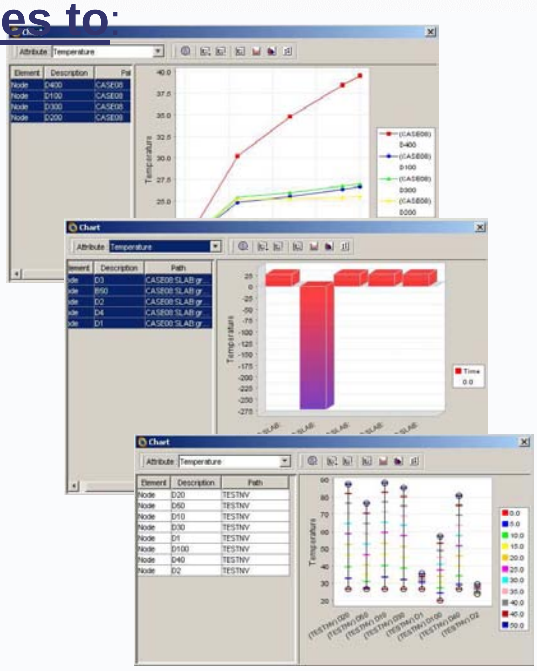
ThermNV enables to:

Chart results

line charts for time dependant model data

Bar charts for distribution data

Min/Max charts for limit inspection



Conclusion

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ThermNV is a major enhancement to the product suite

model understanding

model validation

reporting

charting

post-processing on heat fluxes, including visualisation

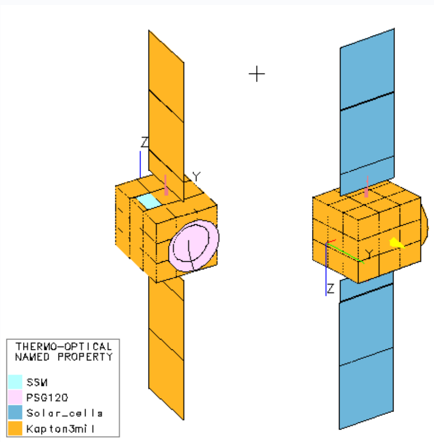
Pre-release version ThermNV 0.1 available

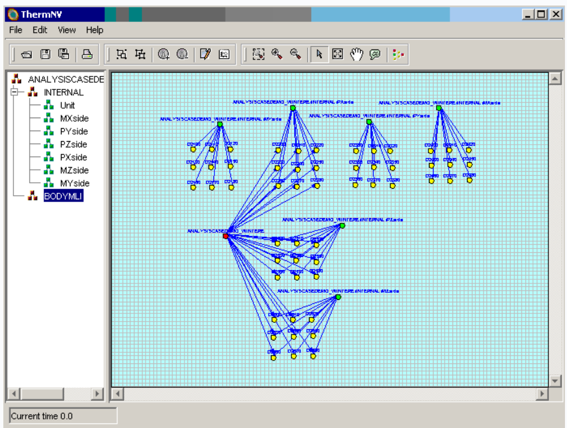
full release planned before Christmas

Live Demo

ALSTOM

Go for a live demo of ThermNV





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Appendix R: Modelling the Martian Surface Thermal Environment with ESATAN and ESARAD

Modelling the
Martian Surface Thermal Environment
with
ESATAN and ESARAD

B. Shaughnessy
Rutherford Appleton Laboratory

CCLRC Rutherford Appleton Laboratory

Modelling the Martian Surface Thermal Environment with ESATAN and ESARAD

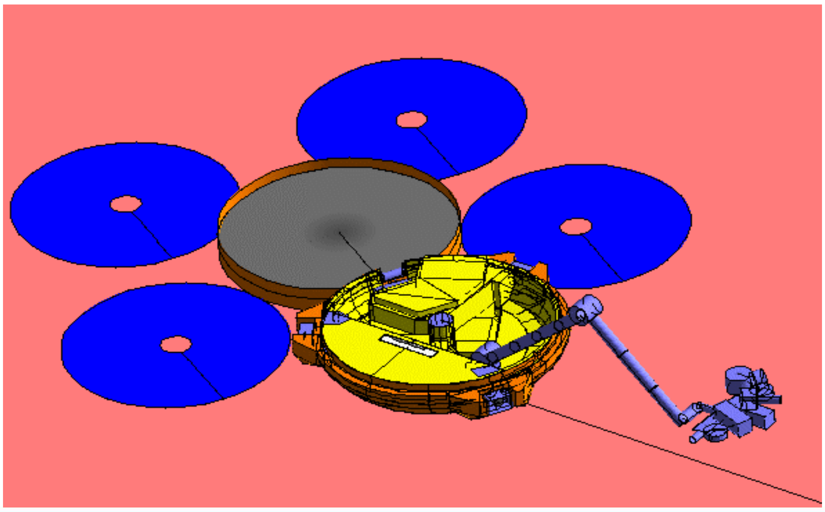
Dr Bryan Shaughnessy

Space Science and Technology Department

Rutherford Appleton Laboratory (RAL)

Contents

- Environmental overview.
- Environmental modelling approach.
- Suggested improvements to ESATAN and ESARAD.



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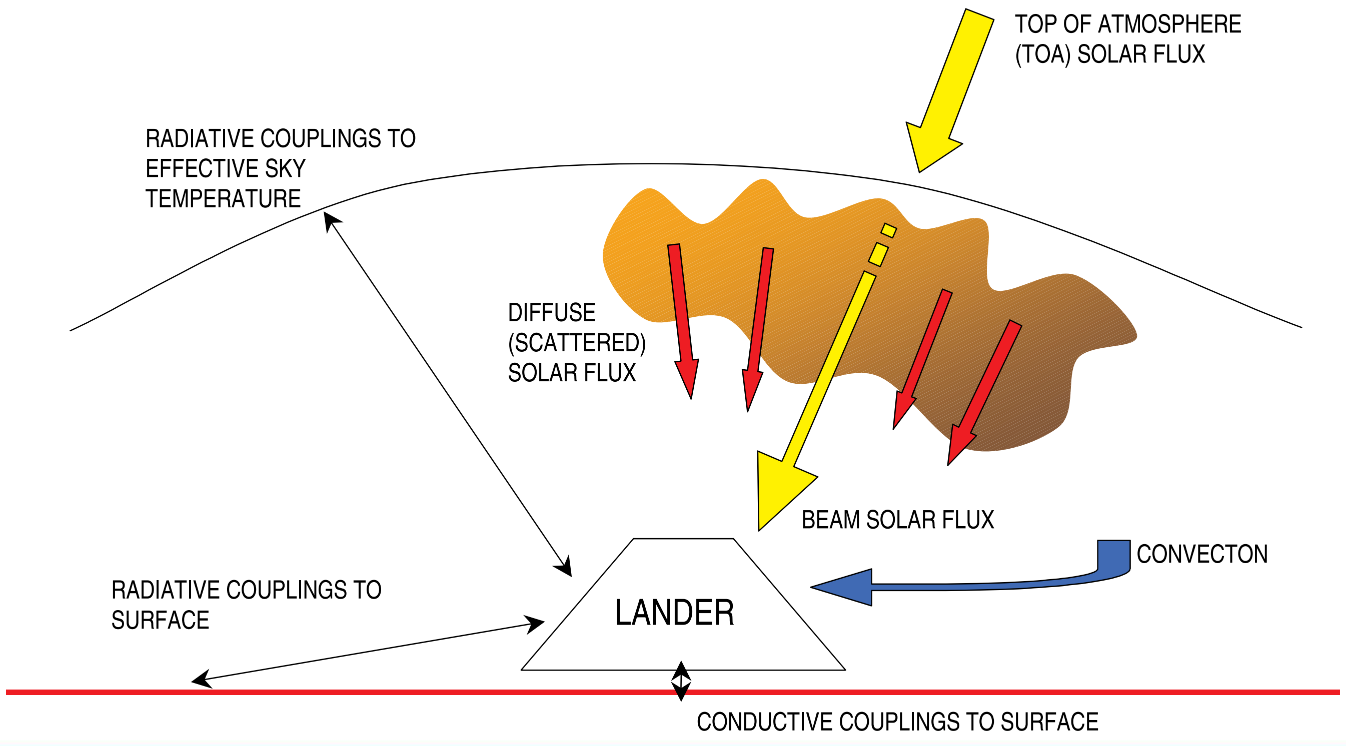
Lander Environmental Boundary Conditions



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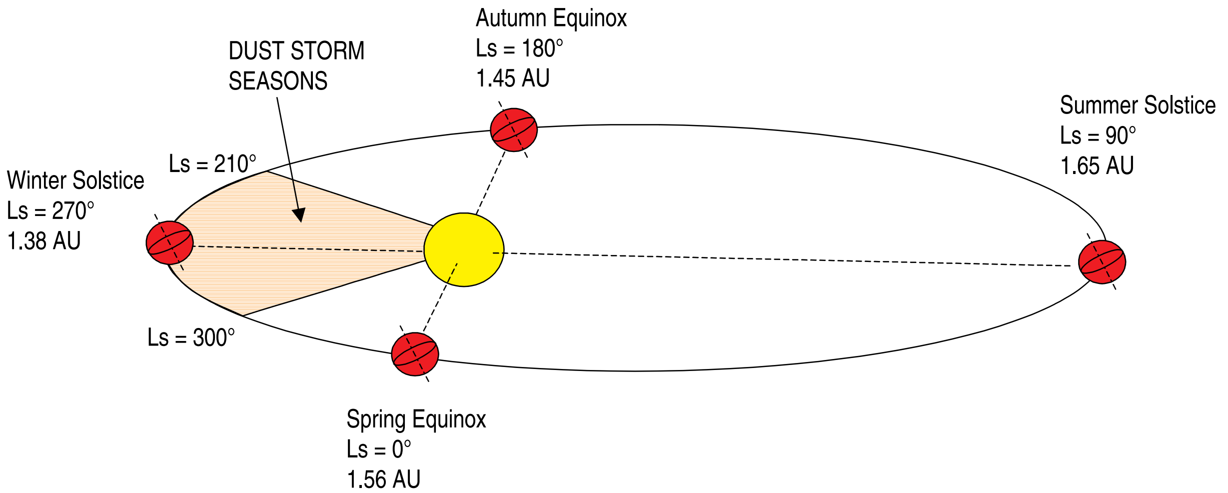
Orbit and Seasons of Mars



Northern Hemisphere Seasons

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Environmental Overview

Lander boundary conditions are a strong function of optical depth:

- Attenuation and scattering of TOA flux.
- Effective sky temperature.
- Surface and air temperatures.
- Dust settling / contamination of surface finishes.
  - 0.3% area coverage per Sol recorded by Sojourner MAE experiment.

Optical depth varies with Season:

- Optical depths up to ~ 3.0 recorded by Viking Landers during dust storms.
- Optical depth can exceed 5.0 (the Sun would hardly be visible from the surface).
- Optical depth decreases to < 0.5 outside of dust storm seasons.

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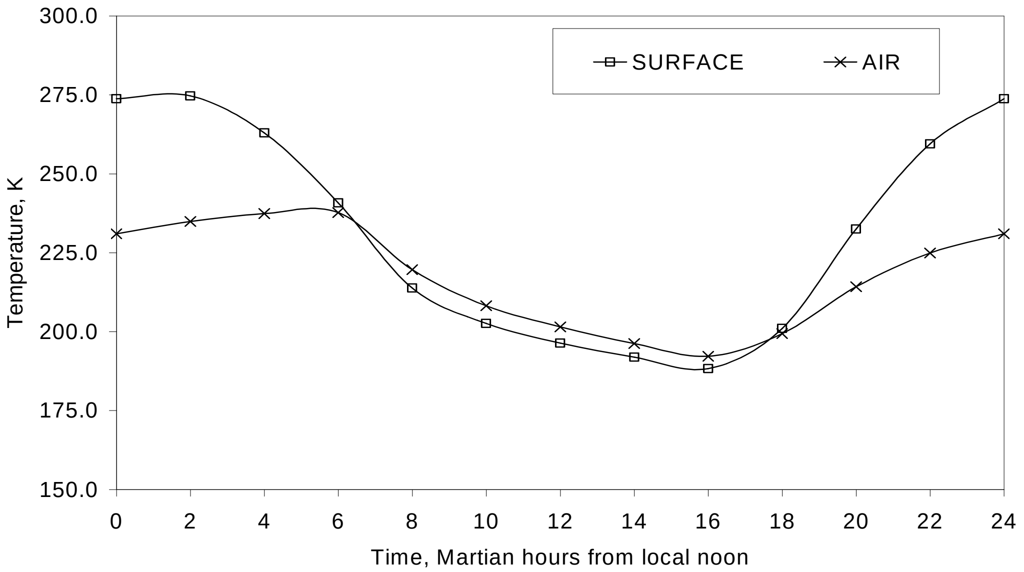
Environmental Overview



Typical surface and air temperature profiles

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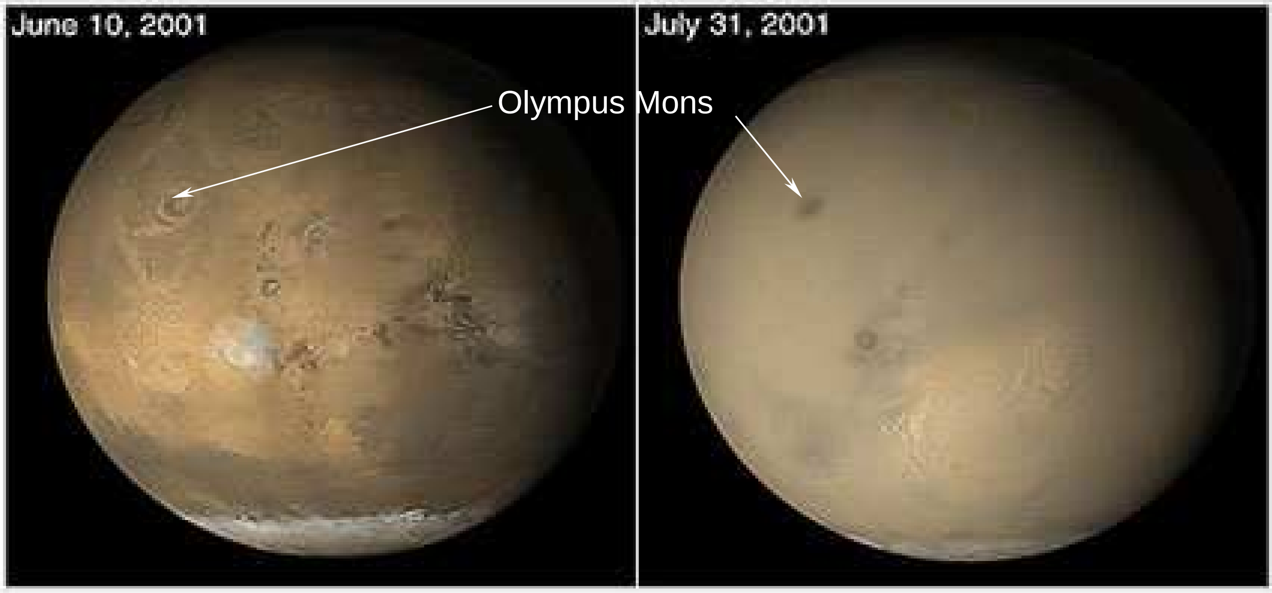
Dust Storms – Mars Global Surveyor Images



NASA/JPL/Malin Space Science Systems

End of Martian winter to early spring

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Modelling Boundary Conditions

TOA Flux: function of Mars orbital parameters.

Beam Flux: function of TOA flux, optical depth, and zenith angle.

$$S_b = S \exp\left(\frac{-\tau}{\cos(\theta_z)}\right)$$

Diffuse Flux: from atmospheric modelling. Array interpolation as function of optical depth and zenith angle.

Surface and air temperatures: from atmospheric modelling (Mars Climate Database). Array interpolation as function of time.

Effective sky temperature: from atmospheric modelling. Array interpolation as function of optical depth and time.

Other Thermal Modelling Considerations

Convection: heat transfer coefficients can be estimated from standard correlations (need to account for gravity and atmospheric density/pressure)

Gas conduction: gas nodes may be required. Shape factors required for gas conduction between surfaces and gas nodes.

Time: conversion between Mars and Earth time systems.

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Implementation in ESARAD

Beam solar loads calculated, as a function of time, to nodes for a nominal TOA flux and no attenuation. A kernel has been written to do this as a function of landing site location and orbital characteristics.

Radiative couplings in solar wavelengths from all nodes to the sky (for calculation of diffuse solar loads).

Radiative couplings in thermal infrared wavelengths.

Implementation in ESATAN

Determines local solar times, zenith angles, and sunset/sunrise events as function of landing site location and Ls.

Calculates the actual beam solar loads by scaling ESARAD calculated loads (as function of TOA flux, zenith angle, and optical depth).

Calculates the actual diffuse solar loads by scaling the TOA flux with the nominal diffuse flux datasets and the ESARAD calculated solar wavelength radiative couplings.

Interpolates surface, air, and sky temperatures datasets.

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Suggested Improvements

ESARAD:

- Include radiative/analysis case for planet surface calculations.
- Allow solar-wavelength radiative couplings to be readily exported (at present having to use ‘report’ and manually edit file).
- Generation of surface to surface shape factors for gas conduction links.
- Management of surface properties for various cases (e.g., BOL, EOL). Prefer not to have separate geometry files for each case.
- Allow output file of ALP (and other) parameters and values (to be used as input files for solar load calculations).

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Suggested Improvements

ESATAN:

- Include routines to convert between Universal Coordinated Time (UTC) and Mars Local True Solar Time (mission planning, correlation with on-surface measurements)

Appendix S: Data Exchange between CFD and ESATAN in the case of Natural Convection

Data Exchange
between
CFD and ESATAN
in the case of
Natural Convection

C. Wendt
EADS Space Transportation

Competence Centre

18th Thermal and ECLS Software Workshop, Oct. 2004

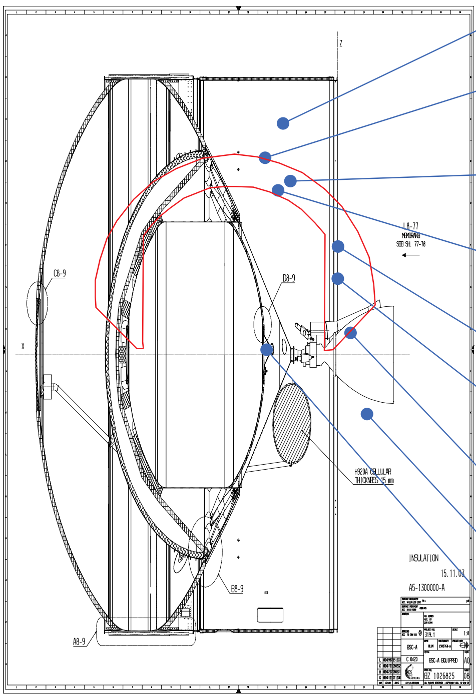
Data Exchange between CFD and ESATAN in Case of Natural Convection

by Christian Wendt EADS ST, Bremen

- A5 ESC-A Intertank-Cavity
- Order of Magnitude & Simplifications
- CFD Model
- CFD Results
- Data Exchange between CFD and ESATAN
- Discussion
- Summary

Competence Centre

A5 ESC-A Intertank-Cavity



LH2-tank, liquid @ 20 K

Dacron w. Liner-Insulation:
Inner Dome Insulation

Intertank-Cavity: Chinese Hat Cavity (CC)
He-venting: 0.45 g/s

Intertank-Cavity: Upper Cavity w. Spacer (UC)
He-venting: 0.5 g/s

MLI/Dacron-Insulation: Chinese Hat

Intertank-Cavity: Side Cavity (SC)
He-venting: 0.5 g/s

MLI/Dacron-Insulation: Intertank-Membrane

Gas in Interstage-Cavity @ 244 K ... 274 K

LOX-tank, liquid @ 90 K

Order of Magnitude & Simplifications

Order of Convection in Cavity L = 80 ... 800mm

Gas: He @ 1atm, $\overline{T}^{gas} \approx 100K$

Wall: $\overline{T}^{wall} \approx 80K$

$\Delta T = 10 \ldots 50$ K

Rayleigh-Number: $Ra = Gr*Pr = g L^3 \beta \Delta T / \nu^2 * \nu / a = 10^6 \ldots 10^{10}$

with $Ra < 10^8$: laminar

⇒ laminar / turbulent flow

Simplifications

- axisymmetric model
- spacers in UC have been neglected
- venting gas (0.5 ... 1 g/s) is assumed to enter and to leave the cavities homogeneously distributed with the temperature of the leaving gas at the mean temperature of the cavity
  ⇒ ventilation is solely considered as an energy source,
  the same approach has been used in the ESATAN stage model (SM)

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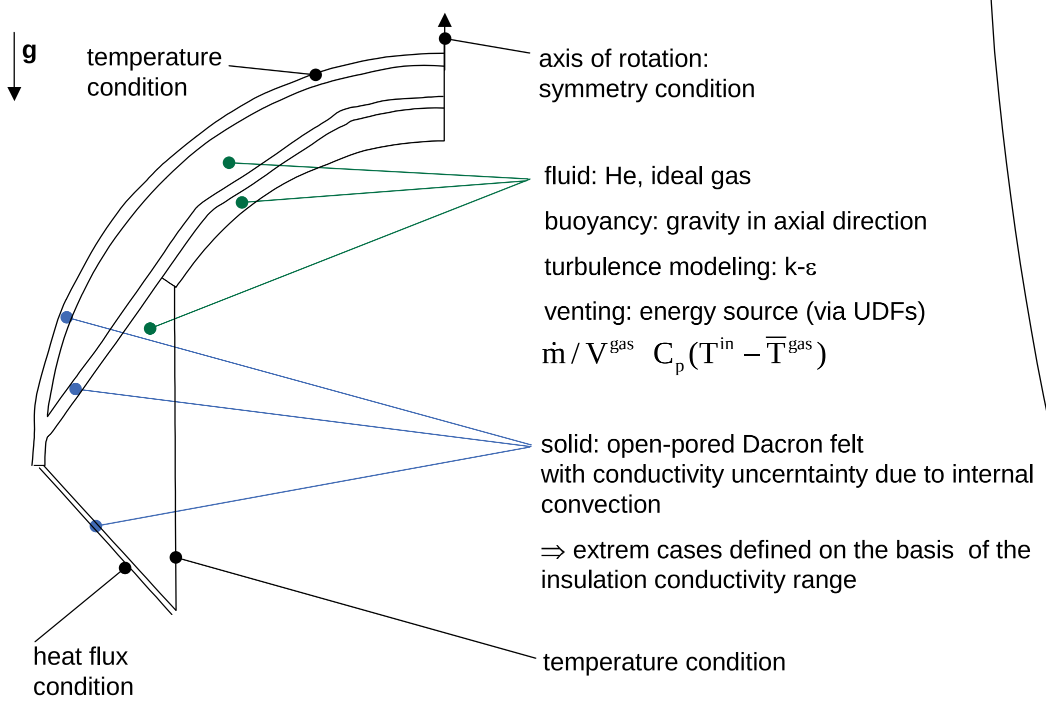
CFD-Model (FLUENT): stationary case just before lift-off



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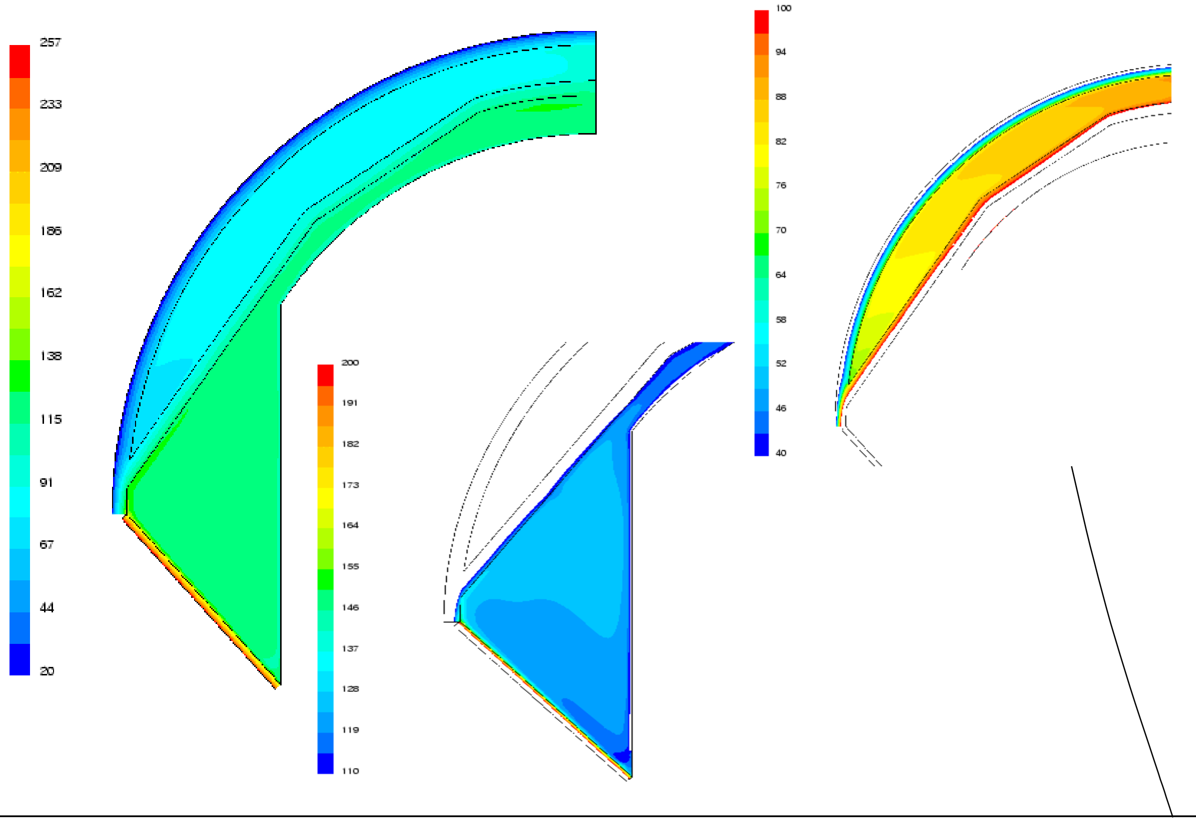
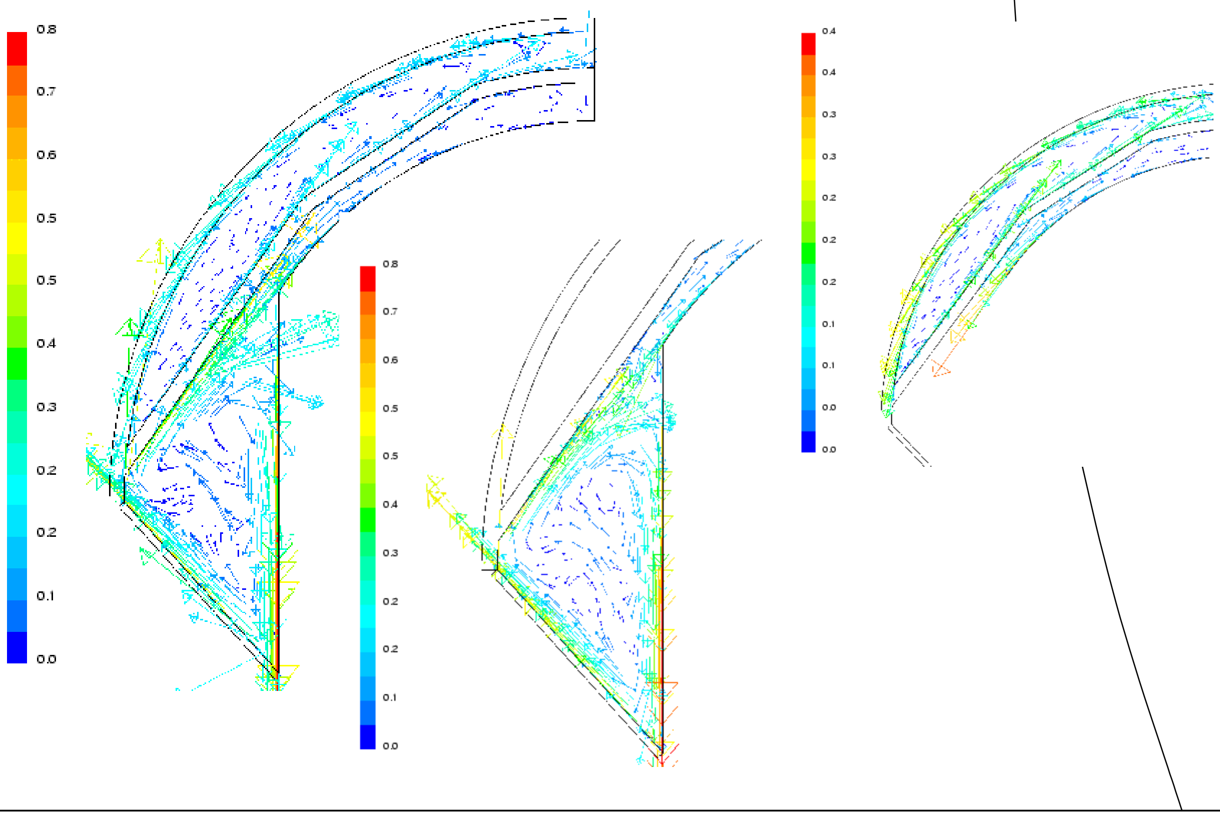
CFD-Results: Temperature-Contours [K]



Competence Centre

CFD-Results: Velocity Vectors [m/s]



Competence Centre

Data Exchange between CFD and ESATAN

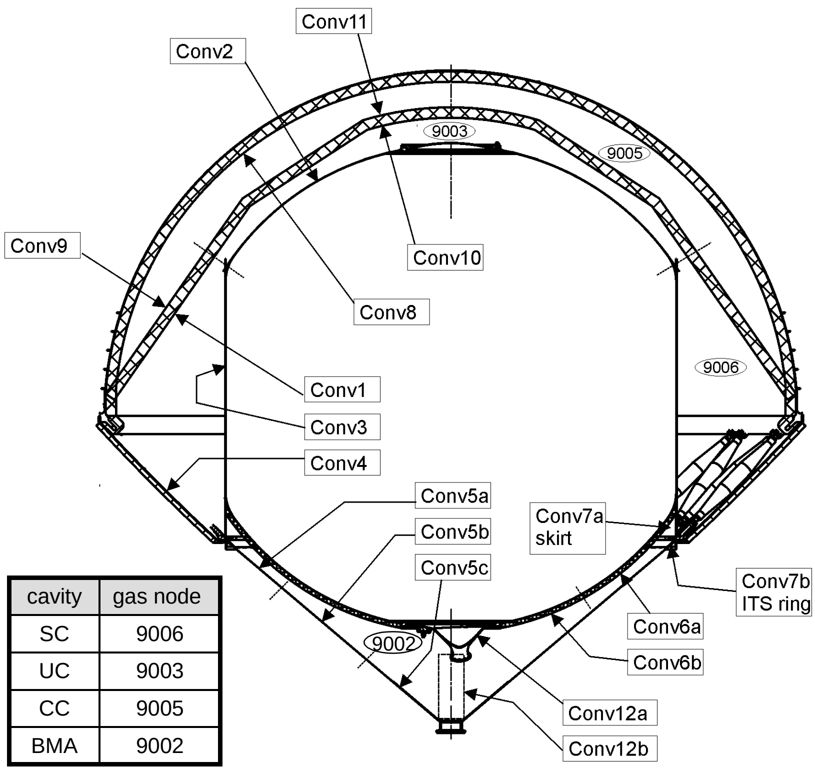
CFD-Results		ESATAN
volume-averaged temperature $\overline{T}^{gas}$ of cavity	$\hat{=}$	gas-node D^{gas} temperature of cavity
area-averaged temperature $\overline{T}^{wall}$ of certain wall section	$\hat{=}$	certain-wall node D^{wall} temperature
area-averaged convective wall heat flux $\overline{Q}^{conv}$ of certain wall section with area A^{wall}	$\overset{!}{=}$	convective heat flux of certain wall node D^{wall}
energy transport Q^{flow} between two cavities with volume-averaged temperatures $\overline{T}^{gas}_{1,2}$	$\overset{!}{=}$	energy transport between two gas nodes $D^{gas}_{1,2}$

wall conv. heat transfer coeff.
$h^{wall} = \overline{Q}^{conv} / A^{wall} / (\overline{T}^{gas} - \overline{T}^{wall})$ → $GL(D^{wall}, D^{gas}) = h^{wall} * A^{wall}$

inter gas conductance
$H^{flow} = Q^{flow} / (\overline{T}^{gas}_1 - \overline{T}^{gas}_2)$ → $GL(D^{gas}_1, D^{gas}_2) = H^{flow}$

Competence Centre

Data Exchange between CFD and ESATAN (cont‘d)



cavity	gas node
SC	9006
UC	9003
CC	9005
BMA	9002

Coefficient	[W/(m²K)]
CONV1	59.97
CONV2	9.97
CONV3	9.21
CONV4	13.79
CONV5A	14.41
CONV5B	11.39
CONV5C	19.66
CONV6A	10.30
CONV6B	15.31
CONV7A	2.62
CONV7B	4.07
CONV8	9.33
CONV9	77.03
CONV10	8.64
CONV11	6.06
CONV12A	6.25
CONV12B	0.48
Gas Conductance	[W/K]
9003 <-> 9006	162.73

Discussion

- because the h^{wall} refer to the average gas temp., unfamiliar high values may result in cases, where the wall temp. is near the average gas temp., e.g.

section	wall area A^{wall} [m²]	wall temp. $\overline{T}^{wall}$ [K]	conv. heat flux $\overline{Q}^{conv}$ [W]	average gas temp. $\overline{T}^{gas}$ [K]	conv. heat transfer coeff. $h^{wall} = \overline{Q}^{conv} / A^{wall} / (\overline{T}^{gas} - \overline{T}^{wall})$ [W/(m²K)]
conv1	11.52	121.2	1292	123.07	59.97
conv9	8.86	84.0	-732	82.9	77.03

- as long as the difference of the local gas temp. and the wall temp. has the same sign as the difference of the average gas temp. and the wall temp. the CFD derived h^{wall} lead to the correct ESATAN corresponding node temp. and heat fluxes, otherwise the gas cavity has to be subdevided and additional gas nodes have to be introduced in CFD and ESATAN, respectively

- if a cavity is subdevided into subdomains, for implementation of gas conductances in ESATAN the borderline between the subdomains should be set in a way, that heat is transferred from the subdomain with a higher average gas temp. to the subdomain with a lower average gas temp.

Summary

- natural convection is of great importance for the the thermal performance of cryogenic vehicles, as shown for A5 ESC-A Intertank-Cavity (IC): due to great temp. gradients the flow is locally turbulent in the IC

- an axisymmteric CFD model has been established using the commercial code FLUENT

- the ventilation has been implemented in the CFD model, where the same approach has been considered as used for ESATAN stage model (SM)

- from the CFD results convective heat transfer coefficients and conductances between gas nodes have been derived, which are now used in the SM

- unfamiliar high convective heat transfer coefficients may result, which can be lead back to the difference between the local and the average gas temperature

- in case of a cavity subdivision the borderline of the subdomains should respect the direction of heat transfer for solids

Appendix T: Development of an Interface Software for Patran/Thermal and ESARAD

Development of an
Interface Software for
Patran/Thermal
and
ESARAD

C. Heller
EADS Astrium

Development of an I/F Software for Patran/Thermal and ESARAD

18th European Workshop an Thermal and ECLS Software

Dr. Cosmas Heller

EADS ASTRIUM GmbH, Friedrichshafen - Germany

All the space you need

Contents

Problem Definition

The Structural Analysis "World":

- Use of FEM meshes - edge nodes
- Thermo-elastic distortion analysis from thermal input
- Lack of ray tracing (no specular reflection)
- No orbital analysis capability

The Thermal Analysis "World":

- Use of FDM - surface centered nodes
- Ray tracing and orbital load analysis implemented

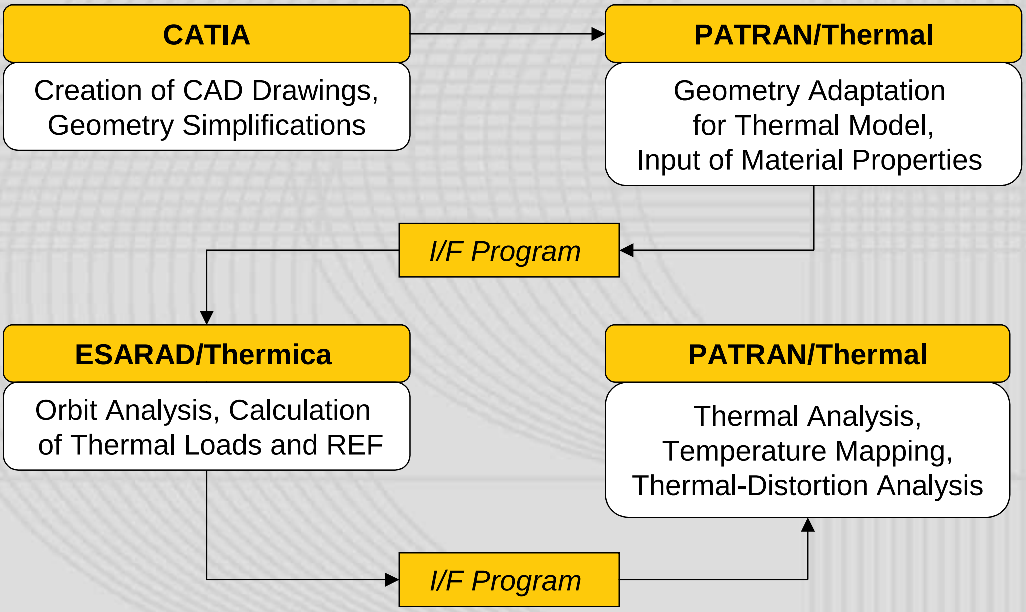
Current Drawbacks:

→ Mainly manual temperature mapping from FDM to FEM mesh

→ Separate effort for thermal and structural model creation

Interface Approach

Analysis Work Flow:



Interface Approach

Structural Analysis
PATRAN/NASTRAN

Thermal Analysis

PATRAN/Thermal:

- Geometry creation
- Thermal mesh creation (edge nodes used)
- Calculation of linear conductors
- Definition of thermo-optical properties
- Definition of internal heat loads

ESARAD/Thermica:

- Calculation of REF
- Orbit Analysis

- Temperature calculation

Advantages

- Exchange of geometry data according to project needs
- No duplication of geometry
- Makes best use of capabilities of both “worlds”:
  - Pre- and post-processing capability of PATRAN
  - PATRAN/Thermal functions to calculate linear conductors
  - Orbit analysis tools and ray-tracing in ESARAD/Thermica
- Capable of generating automated temperature mapping of structural model for thermal distortion analysis without extrapolation

→ Addition of functionality and saving of time

I. Problem Definition

II. Interface Approach

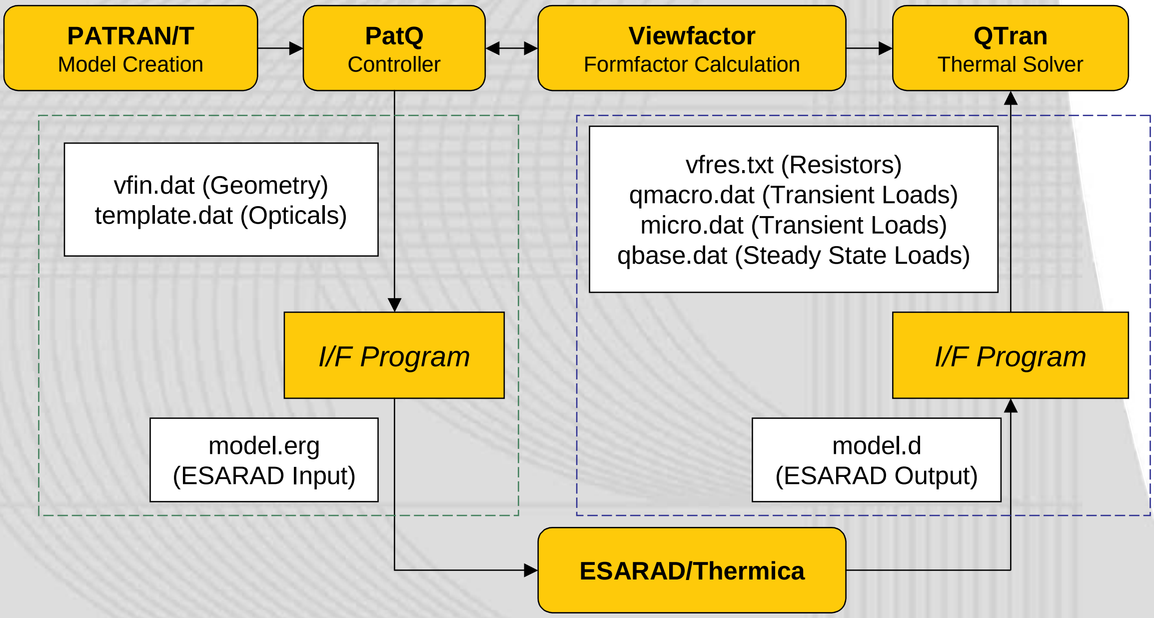
III. Data Transfer

IV. Interface Handling

V. Verification and Test

VI. Summary

Data Transfer



I. Problem Definition

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VI. Summary

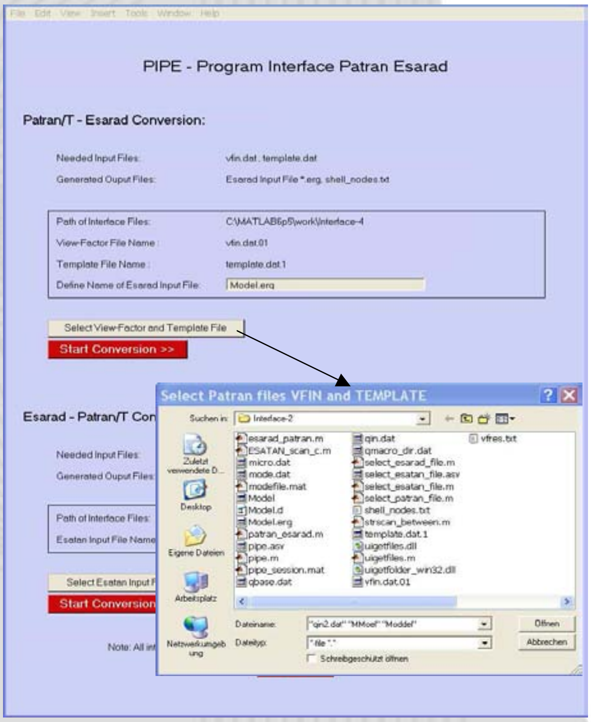
Interface Patran/T to ESARAD

- Define Esarad geometry file: **.erg*
- Select the view factor input file: *vfin.dat*
- Select thermo-optical property data: *template.dat*

→ Automated transfer to Esarad geometry file:

Opticals, points, triangles, rectangles and groups

(one model hierarchy level can be defined via media node)



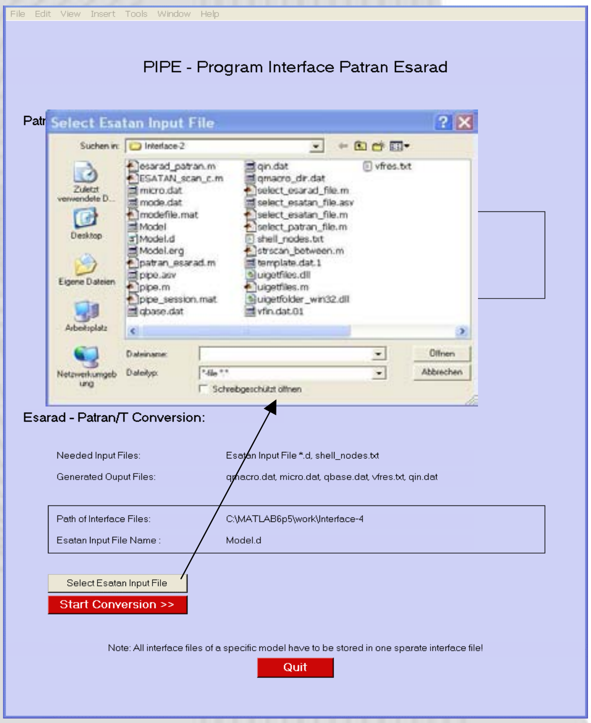
Interface ESARAD to Patran/T

- Select the Esatan input file: **.d*

→ Automated definition of thermal loads in *qmacro.dat, qbase.dat*, *micro.dat*

→ Creation of *vfres.txt* containing radiative couplings for edge nodes in Patran/Thermal

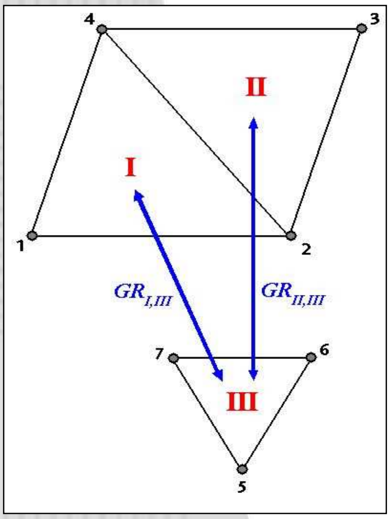
→ Adaptation of *qin.dat* to read ASCII file *vfres.txt* before solving



Verification of Radiative Approach

Radiative Model:

- Three triangles of same size with same normal vector
- Surface Indices: $p, q = I, II, II$ Edge Indices: $i, j = 1, 2, \ldots 6$
- Number of edges: $n_I = 3, \quad n_{II} = 3, \quad n_{III} = 3$
- REF of triangles: $GR_{I,III} = GR_{II,III}, \quad GR_{I,II} = 0$



HF calculated in ESARAD:

$$\dot{Q}_{TOT,ESARAD} = \dot{Q}_{I,III} + \dot{Q}_{II,III} = \sigma \cdot \left[GR_{I,III} \cdot \left(T_I^4 - T_{III}^4 \right) + GR_{II,III} \cdot \left(T_{II}^4 - T_{III}^4 \right) \right]$$

HF calculated in PATRAN:

$$\dot{Q}_{TOT,PATRAN} = \sigma \cdot \left[\begin{array}{l} \frac{\left(T_1^4 - T_7^4\right)}{R_{1,5}} + \frac{\left(T_1^4 - T_6^4\right)}{R_{1,6}} + \frac{\left(T_1^4 - T_5^4\right)}{R_{1,7}} + \frac{\left(T_2^4 - T_5^4\right)}{R_{2,5}} + \frac{\left(T_2^4 - T_6^4\right)}{R_{2,6}} + \frac{\left(T_2^4 - T_7^4\right)}{R_{2,7}} \\ + \frac{\left(T_3^4 - T_5^4\right)}{R_{3,5}} + \frac{\left(T_3^4 - T_6^4\right)}{R_{3,6}} + \frac{\left(T_3^4 - T_7^4\right)}{R_{3,7}} + \frac{\left(T_4^4 - T_5^4\right)}{R_{4,5}} + \frac{\left(T_4^4 - T_6^4\right)}{R_{4,6}} + \frac{\left(T_4^4 - T_7^4\right)}{R_{4,7}} \end{array} \right]$$

→ HF values are identical for: $R_{i,j} = \sum_{p,q} \frac{n_p \cdot n_q}{GR_{p,q}}$

Test Examples

Model Comparison

- First a satellite model is built in ESARAD
- Temperature calculations are performed with ESATAN using ESARAD nodes

- A second similar satellite model is built in PATRAN
- Temperature calculations are performed with PATRAN/Thermal using edge nodes

→ Verification of correct geometry transfer from PATRAN to ESARAD

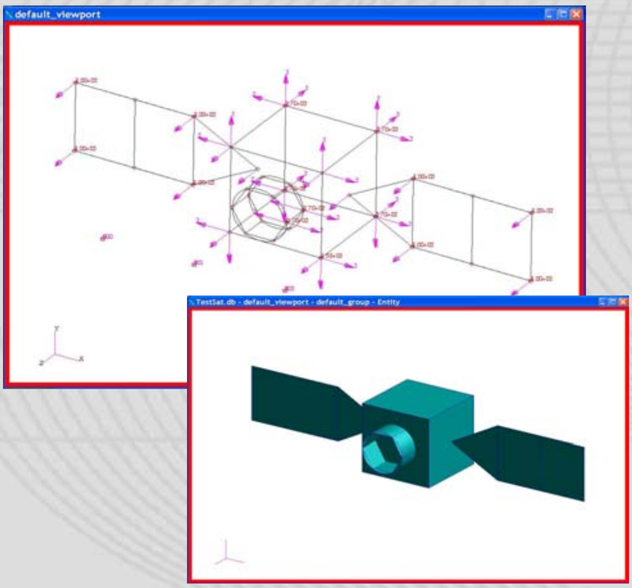
→ Verification of correct transfer of thermo-optical properties

→ Verification of correct calculation of external loads for both geometries

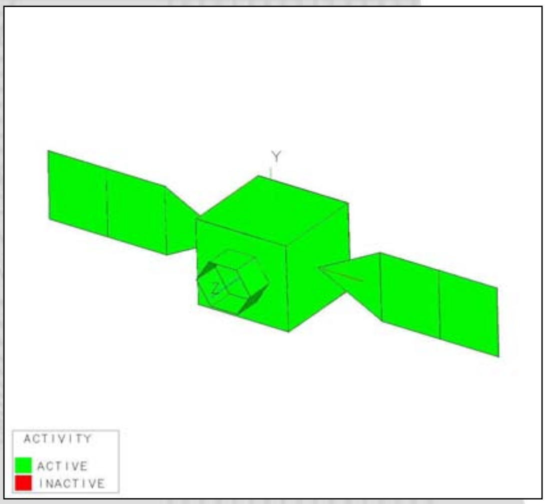
Test Examples

Geometry Transfer

Geometry build in PATRAN/Thermal:



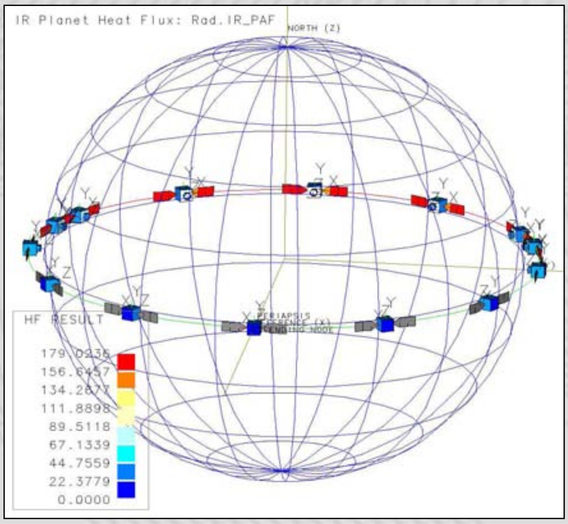
After Transfer to ESARAD:



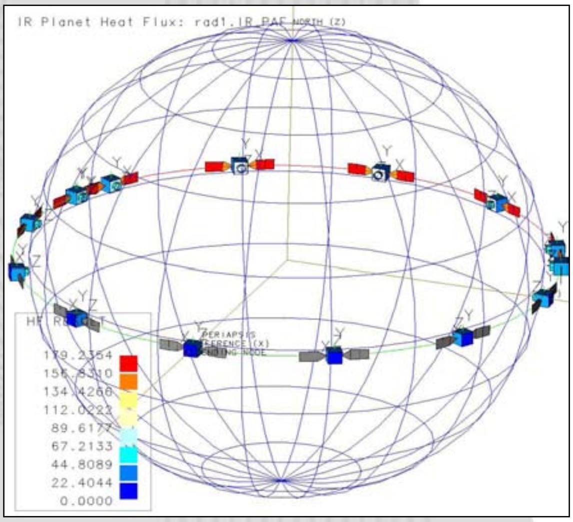
Test Examples

Planet Heat Flux Results

Geometry converted from PATRAN:



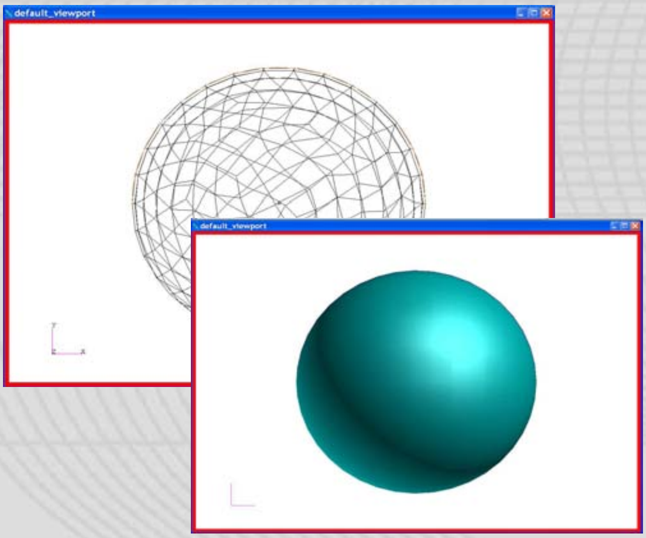
Geometry created in ESARAD :



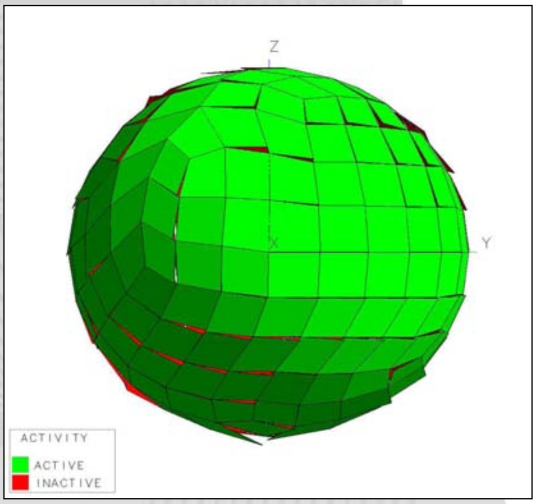
Test Examples

Ball Model

Build and meshed in PATRAN/Thermal:



… and what arrived in ESARAD:



→ There is still a significant amount of work ahead !

I. Problem Definition

II. Interface Approach

III. Data Transfer

IV. Interface Handling

V. Verification and Test

VI. Summary

Summary

- I/F software has been implemented to link ESARAD and PATRAN for analysis of thermal distortion problems.
- An algorithm has been developed to assign the REF from ESARAD to PATRAN/Thermal.
- Triangular and rectangular surfaces are supported
- I/F software is coded in Matlab
- Future activities:
  Creation of I/F to Thermica,
  Verification of temperature calculation,
  Software test in real project environment

Appendix U: New version of BAGHERA STEP viewer based on open standard technologies

New version of
BAGHERA STEP viewer
based on
open standard technologies

E. Lebegue
CSTB/GRAITEC

New version of BAGHERA STEP Viewer based on Open Standard technologies

18th European Thermal & ECLS Software Workshop
ESA/ESTEC
Noordwijk
5-6 October 2004

Eric Lebègue (CSTB / GRAITEC – eric.lebegue@cstb.fr)
Thierry Warrot (CNES – thierry.warrot@cnes.fr)

CSTB le futur en construction
cnes CENTRE NATIONAL D'ETUDES SPATIALES

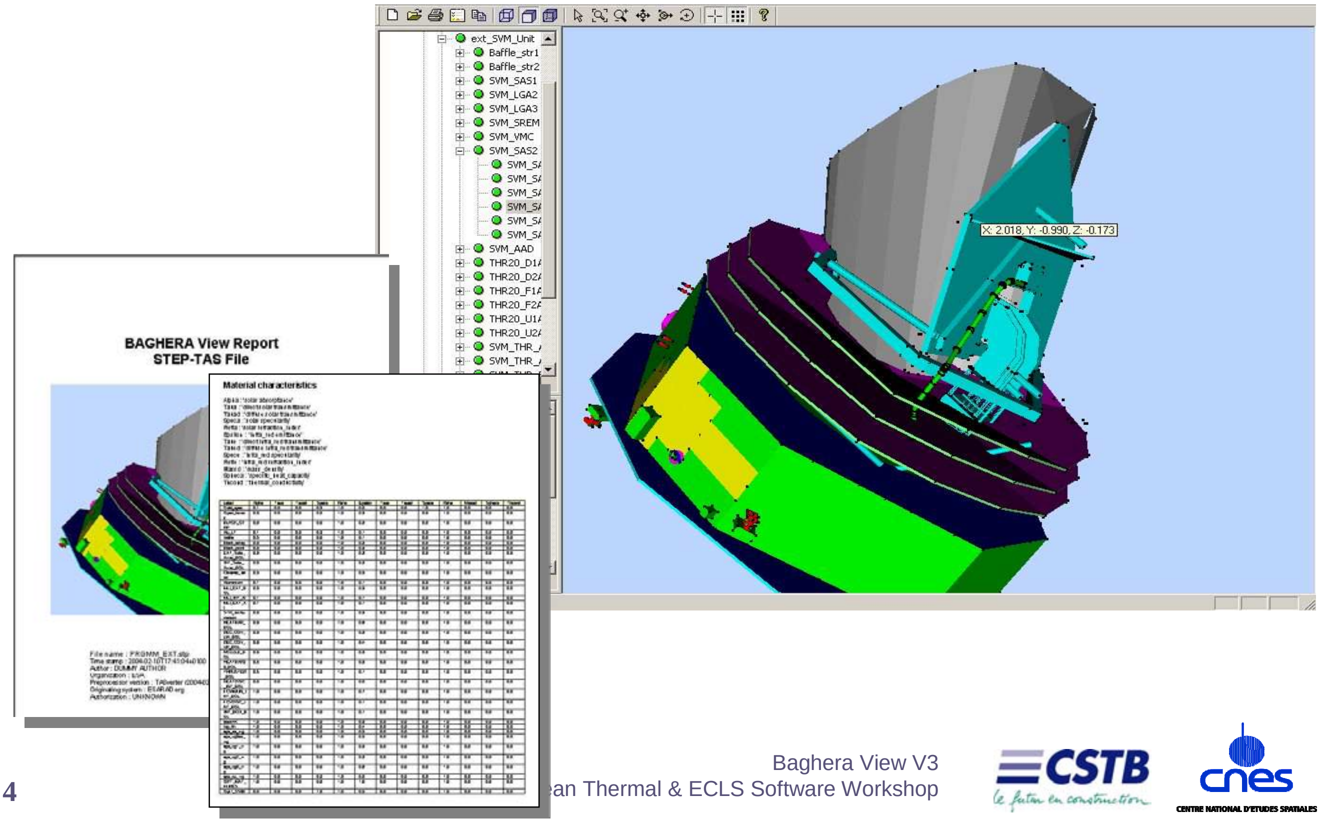
Context : STEP standards available

- STEP standards are now available and becoming stable for exchange and archiving of technical data for space engineering domain
  - AP203/214 : for general CAD
    - Available with CATIA and most of standard general CAD tools
  - STEP-TAS : radiative thermal analysis
    - Industrial level available within main European radiative thermal tools, thanks to TAS-Verter:
      - ESARAD, THERMICA, CORATHERM

Intermediate checking tool required

- Now, in data exchange phase, between engineers using different tools, it is important to propose a « common reference » checking viewer :
  - To be used by sender and receiver of the data, for :
    - Checking 3D geometry
    - Checking assemblies and properties
    - Reporting the exchanged data
- This is the goal of BAGHERA View

Demonstration



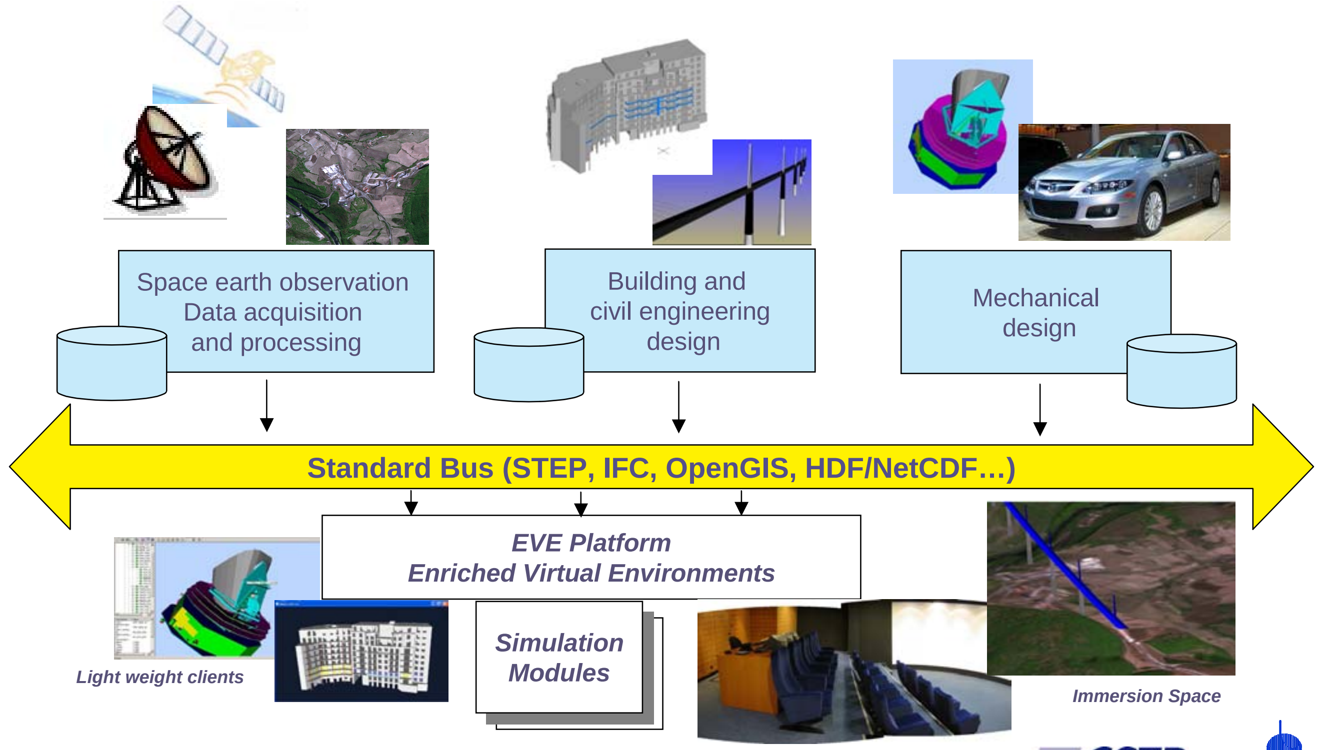
New version of BAGHERA View

- STEP-TAS loading with PyEXPRESS/C++ library
- Direct translation of STEP-TAS objects into OpenGL/VTK representation
- AP203/214 loading with OpenCascade 5
- Report generation in Word/RTF format
- Windows GUI (MFC)

Characteristics

- Installation (STEP-TAS) :
  - ZIP < 4 MB
  - unzip < 15MB
  - no particular graphic cards required
  - => easy to distribute
- Intuitive GUI => no training
- Loading METOP model (>17000 instances) in few seconds !

Development context : CSTB EVE Platform



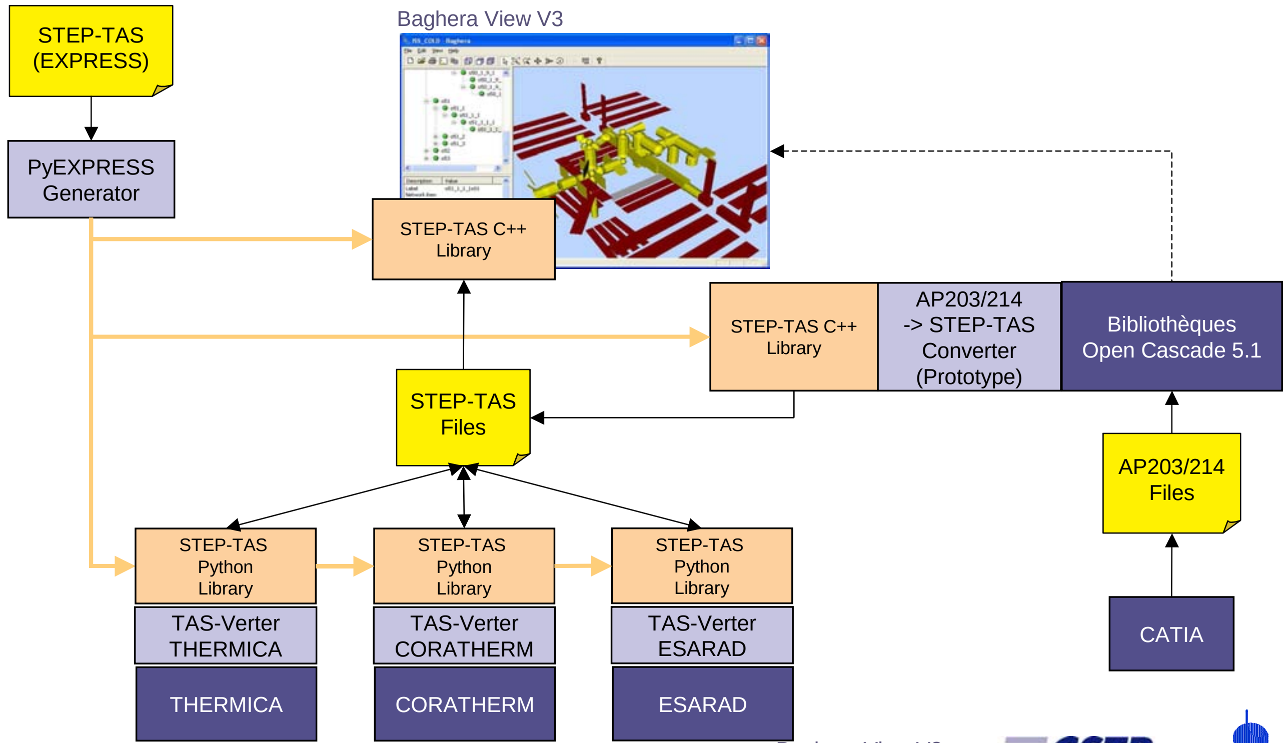
Current status

- Current version : 3.0.beta
  - Compliant with TASverter r2004-02-11
    - See : http://www.estec.esa.int/thermal/tools/tasverter.html
  - Beta testing in progress with CNES, ESA, Astrium and Alcatel Space
- First OP version : 3.1
  - Planned : November 2004
  - CNES is willing a free distribution
    - Contact : Thierry Warrot : thierry.warrot@cnes.fr

AP203 / 214

- AP203/214 to STEP-TAS converter prototype
  - OpenCascade 5 for loading AP203/214
  - PyEXPRESS/C++ for writing STEP-TAS
  - Compliant with TAS Verter
  - Generates triangles and hierarchy
  - Can be loaded into Baghera View 3.1
- In work
  - Direct loading of AP203/214 into Baghera View
    - Optional plug-in
    - Planned V 3.2, end 2004 (beta)

Summary : A new Architecture



Proposed extensions (1/2)

- Comparison of models
  - For checking incremental exchanges
- Filtering of report generation
  - For getting more compact documents
- Detailed STEP files analysis (rules checking…)
  - Required for files not generated by TAS Verter
- Various extension of GUI (table of colours, extended properties window…)
  - Portable GUI : UNIX, Linux…
- Upgrade to be compliant with future TAS Verters
  - Orbitography, kinematic, missions related data…

Proposed extensions (2/2)

- Extension and industrialisation of AP203/214 to STEP-TAS converter prototype
  - Semi-Automatic filtering
  - Shapes recognition
- New loadings :
  - STEP-NRF (results of analysis, ESATAN…)
  - STEP-SPE (ESABASE…)
  - AP209 (structural)
- Other ideas ?

Thank you for your attention

- Contacts :
  - Thierry Warrot : thierry.warrot@cnes.fr

Appendix V: Interface between STEP-TAS format and Alcatel Space's CIGAL2 application

Interface between
STEP-TAS format
and
Alcatel Space's
CIGAL2 application

C. Caillet
Open Cascade

STEP-TAS Activities

Christian CAILLET - Thierry BASSET

c-caillet@opencascade.com
thierry.basset@space.alcatel.fr

October 2004

Open CASCADE

- A member of Principia R & D
  - A group involved in Scientific Engineering, basically specialized in Numerical Simulation ..
  - .. Integrating Open CASCADE to address Software Engineering and CAD-CAE link
  - We support the Open Cascade and SALOME Technology Platforms
  - We provide Customer Solutions based on it
- Development Platforms for 3D software
  - For industrial, scientific, trade specific applications
  - Open Source approach : LGPL-compatible license
  - Runs on Linux, Windows, Unix

Open CASCADE and STEP

- Adhesion to STEP, a standard for exchanges

  a key factor for collaborative work in heterogeneous environment
- Commitment and skills in STEP exchanges
- Open Source Platform for 3D Integration
  - Allows STEP exchanges of CAD data, healing, upgrading, etc..
  - Extensible in a modular and flexible way
- Dedicated tools for STEP
  - General Purpose (like STEP Viewer) ..
  - Or customized to specific user needs
- Integration in proprietary applications

  to reach the customer's need for collaborative work

OPENCASCADE

ALCATEL SPACE

Benefits of Open CASCADE : the Open Source approach

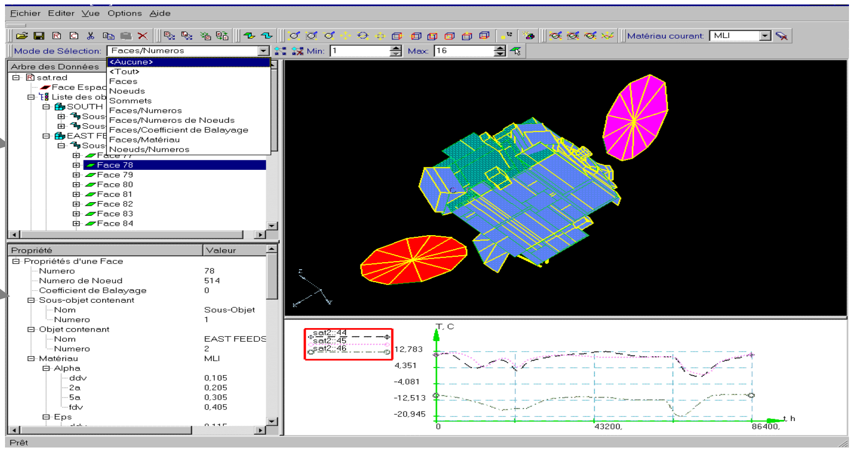
- Open Source : a way to address a common concern
  - Open CASCADE; SALOME; ...
- Open Source : WHY
  - A basis for sharing efforts on mutual concerns
  - Easy Dissemination of the results
  - Open Control on Development Strategy and Evolution
- Open Source : HOW
  - Common project (consortium ..) or company initiative
  - Results as sources, libraries, ready-to-use executable ..
  - Involvement of partners all along the project
  - Open Source and Service Approach (no run-time fee)

OPENCASCADE

ALCATEL SPACE

Alcatel Space's Tools and Strategy : the calculus chain

- Alcatel Space uses an in-house tool : CORATHERM (complete calculus chain)
- With its Modeller and Post-Processor : CIGAL2, developed by Open Cascade for Alcatel Space



Alcatel Space's Tools and Strategy : exchanges with other tools

- Alcatel Space needs to exchange data (especially for the scientific programs) between CORATHERM and other tools of the market place (ESARAD, THERMICA)
- Open Cascade develops interfaces for Alcatel Space CIGAL2-CORATHERM <==> STEP-TAS
  - In accordance with the harmonisation of T&SE analysis software and interfaces leaded by ESA

STEP-TAS exchanges with Alcatel's CIGAL2 / CORATHERM

- Development in 3 steps
  - First step (achieved) : basic exchanges on geometrical radiative models
  - Second step (in progress) : exchanges of CIGAL2 primitives
  - Next step (to come in the frame of ARTES-8) : exchanges of surfacic geometrical conductive models
- Based on ESA's TASverter technology (Python)
- To read and write STEP Part21 files
  - as a neutral, transportable support for data exchanges

OPENCASCADE

ALCATEL SPACE

Main Features of radiative models of CIGAL2 / CORATHERM

- Material description
  - Library of materials, each is defined by a set of properties, each property is acknowledged for a set of life cycle stages
  - Computation modes : Total (for a specular and diffuse radiation)
    Hypothesis : refraction ratio = 1

Input Quantities of **Coratherm**		**Thermica**		**Esarad**
Alpha-*		Alpha-Vis-Total		Alpha-Vis-Total
Eps-*		Eps-IR-Total		Eps-IR-Total
Tau-Vis-*		Tau-Vis-Diff		Tau-Vis-Total
Tau-IR-*	⟷	Tau-IR-Diff	⟷	Tau-IR-Total
Rho-Vis-Spec		Specularity ratio in IR		Rho-Vis-Diffus
Rho-IR-Spec		Specularity ratio in Vis.		Rho-IR-Diffus
Tau-Vis-Spec		Tau-Vis-Spec		Rho-Vis-Total
Tau-IR-Spec		Tau-IR-Spec		Rho-IR-Total

  - or Diffuse (for a diffuse radiation) : Alpha-Vis-Diffus, Eps-IR-Diffus, Tau-Vis-Diff, Tau-IR-Diff (same definition in Cigal2-CORATHERM, ESARAD, THERMICA)
  - Space Environment : described as a Material

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ALCATEL SPACE

Main Features of radiative models of CIGAL2 / CORATHERM

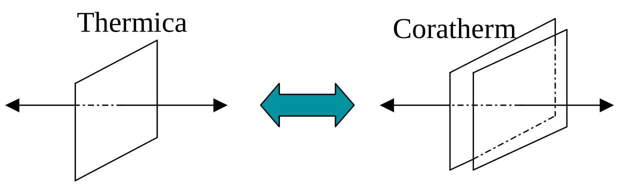
- Geometry and structure
  - 3-level structure : objects, sub-objects, Facets
  - Sub-objects can be :
    - Free Form Sets of Facets (triangles or quadrangles)
    - Simple Primitives (as DISK, Open CYLINDER ..)
    - Complex Primitives (as BOX, Full CYLINDER, ..)
  - All sub-objects, including the primitives, have Facets
  - Physical attributes, Node, Material are assigned to Facets

OPENCASCADE

ALCATEL SPACE

Main Features of radiative models of CIGAL2 / CORATHERM

- Particular treatments
  - Double face



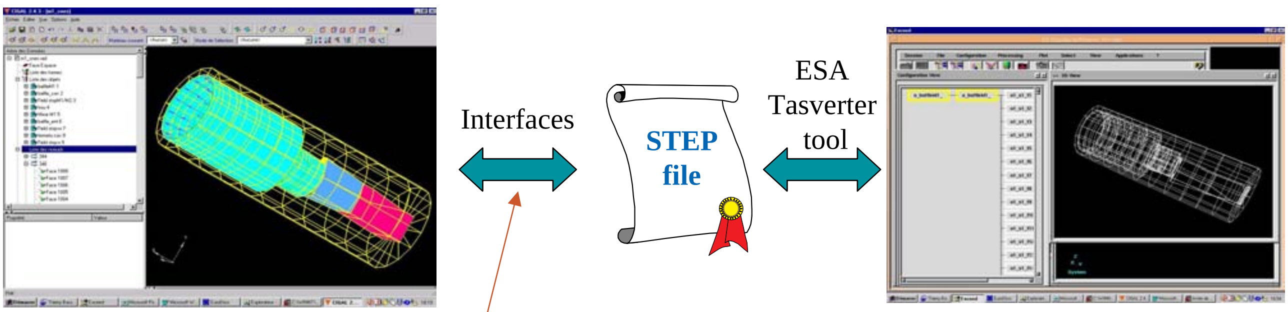
  - Inactive face which absorbs all the radiation
    - In Coratherm, declaration of geometrical face called “mask face” is made with an negative numerical coefficient
  - Possibility to change node indices with a connection file
  - Possibility to change labels of materials with a connection file

OPENCASCADE

ALCATEL SPACE

Application : exchanging radiative models by using STEP-TAS

- Interfaces used on the the Corot, GSTB, Koreasat ... programs in export and export modes
- Using of Tasverter tool available on the ESA website
- Example : M1 Mirror Corot




```
TASverter completed succesfully.
Elapsed time is      81.2 seconds
```

THERMICA :
.SYSBAS, .SYSMAT

CIGAL2 / STEP-TAS : First step basic exchanges of radiative models

- Now achieved (from April 2004)
  integration of TASverter (using Python) in CIGAL2 application
  with support from ESA for this first use
- Exchange is based on Facets only
  Facets : Triangles, Quadrangles
  - on export : sets of facets (description of primitive ignored)
  - on import : facets are computed from STEP-TAS primitive
- Full support of CIGAL2 Material description
  - including stages of life cycle (transmitted in STEP-TAS)
  - computation modes : Total or Diffuse
  - additional data : provided by preference file
    (example : space temperature for export)

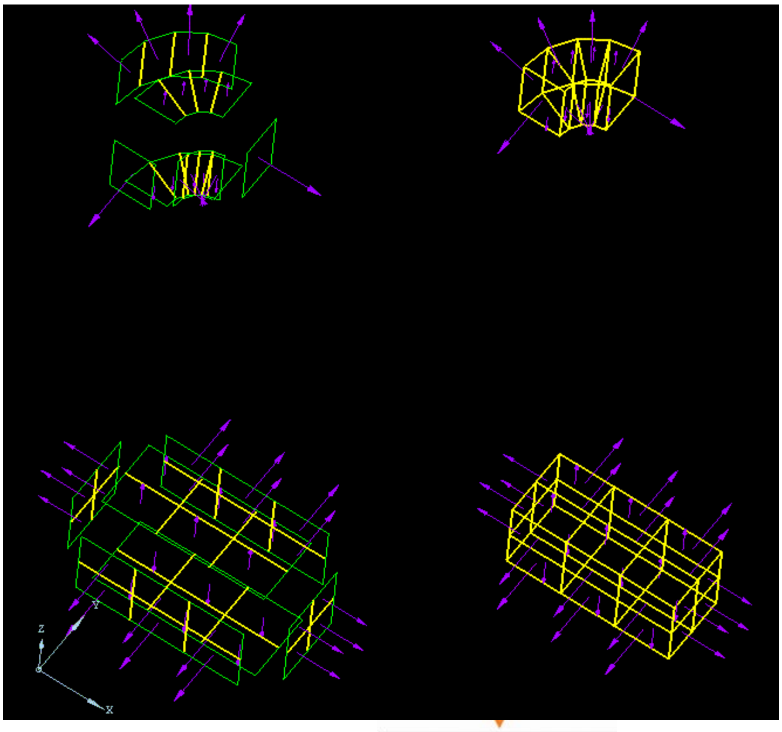
CIGAL2 / STEP-TAS : Second step exchanges of CIGAL2 primitives

- In progress (to be delivered)
- Export
  - checks relevant primitives : same material for all facets
  - a simple primitive : directly exported to STEP-TAS as it is
  - a complex primitive : to a compound of STEP-TAS which lists its sub-parts (components), each one as a STEP-TAS primitive
- Import
  - recognizes a combination of primitives in a compound as describing a complex primitive of CIGAL2
  - by checking adequacy of : geometries, orientations, meshings
  - other primitives : directly mapped to simple primitives of CIGAL2

An example of complex primitive

Up-right : cylinder
(angle 90 deg, inner hole, full)
Up-left : its break-down

Down-left : box
Down-right : its break-down



Next step (in the frame of ARTES-8) : surfacic conductive models

- Thermal analysis software pre-development philosophy
  - To insure compatibility and input data exchange solutions for already existing conductive modules (GENASSIST for EADS Astrium and "PLATEAU-EQUIVALE" for ALCATEL SPACE)
- Definition of standard data exchange
  - Panel, Units on structure, External and embedded heatpipes, Heat sink, Hole, Interface nodes, 2nd level elements of the model
- Development of standard data exchange format interfaces for conductive modules that will automate panel data exchange
- STEP-TAS format based on the TASverter tool

OPENCASCADE

ALCATEL SPACE

In conclusion

- Open CASCADE and Alcatel Space are now jointly committed in working with STEP-TAS and TASverter
- STEP-TAS : a common way to exchange thermal data
- STEP-TAS Part21 file format
  - provides a neutral, transportable, easy to check, data support
  - allows embedded interfaces in each software
- Interest in having embedded interfaces in thermal softwares (as now done in CIGAL2)
- A concern : impact of coming evolutions of STEP-TAS and TASverter
  - to be integrated in the actually used interfaces
  - to assume compatibility (or notify needs for adaptation)

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Thank you for your attention!

Appendix W: STEP-TAS and TASverter from the user's point of view

STEP-TAS and TASverter
from the
user's point of view

D. Alsina Orra
ESA/ESTEC

STEP-TAS & TASverter from the user's point of view

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tasverter@thermal.esa.int
ESA/ESTEC Thermal Analysis and Verification Section
(D/TEC-MCV)
18th European Workshop on Thermal and ECLS Software
ESA/ESTEC, Noordwijk (ZH), The Netherlands
5-6 October 2004

Topics

- What is STEP-TAS?
- What is TASverter?
  - Overview
  - Running TASverter
- Understanding TASverter
- Additional Features of TASverter
- TASverter cases
- Current status
- How to get it?

What is STEP-TAS?

STEP Thermal Analysis for Space

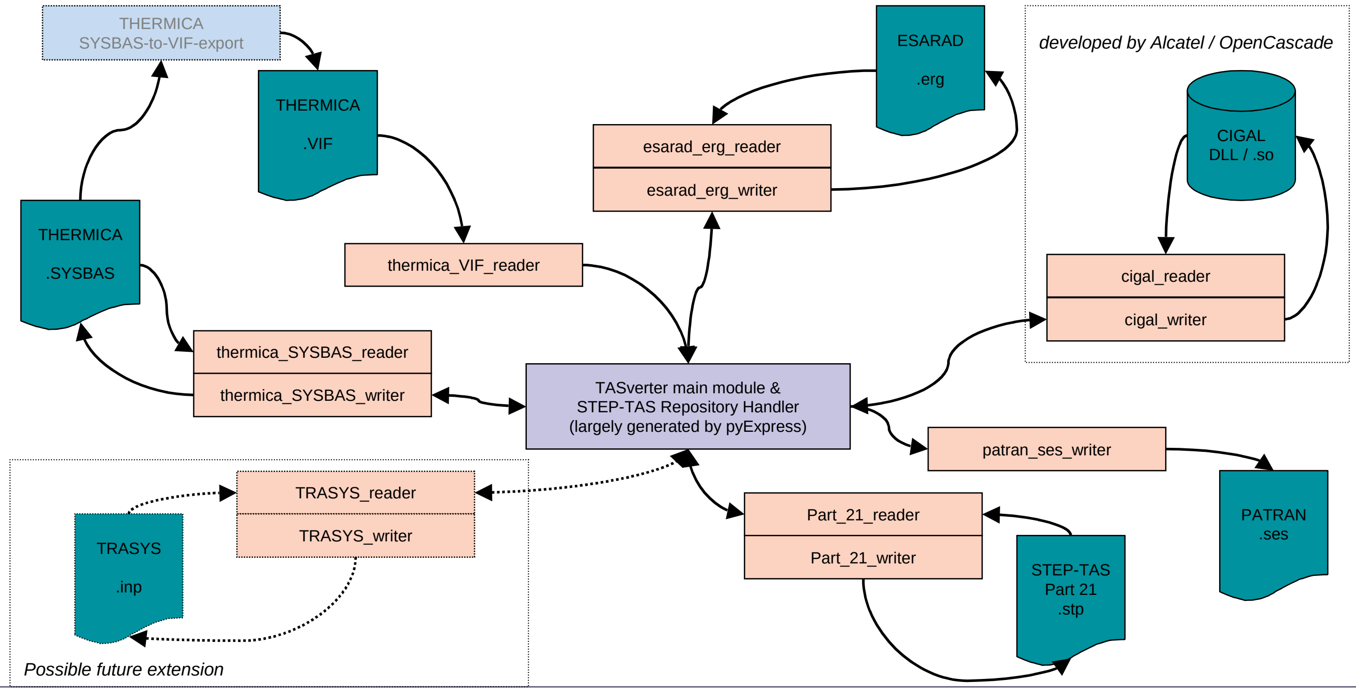
- Based on STEP standards for the exchange of Product model data
- Provides a tool neutral format for data exchange and archiving of Thermal Analysis models and results
  - Every thermal analysis model entity can be represented by a STEP-TAS entity

What is TASverter? Overview (1)

TASverter is a general converter for Thermal Analysis for Space models

- The only operational and official ESA tool for STEP-TAS based model data exchange between European thermal analysis tools (ESARAD, Thermica, Cigal2)
- Currently supporting geometrical model information
- Using STEP-TAS as neutral intermediate representation format
- Fully implemented in Python language following previous positive experience
- Running on multiple platforms: Linux, Windows NT4/2000/XP, UNIX (SUN Solaris, Irix SGI)

What is TASverter? Overview (2)



What is TASverter? Running TASverter (1)

- Interfacing with TASverter is done via command-line
- Options are passed to TASverter to specify the source and destination formats

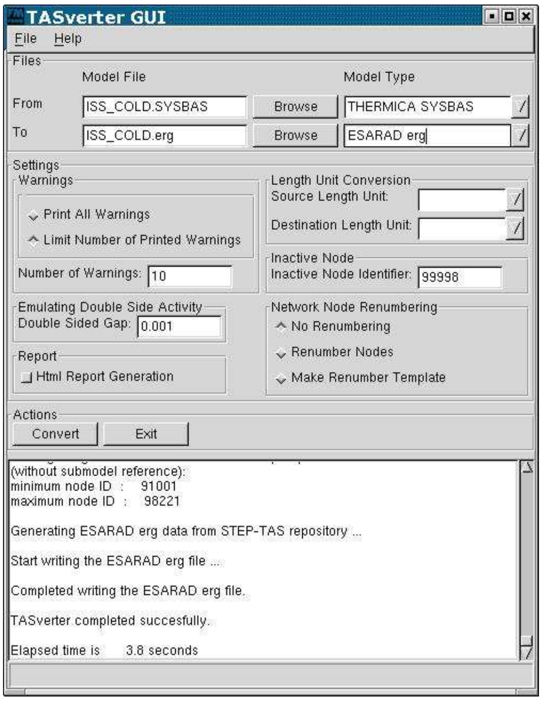
```
TASverter --from_FORMAT=in_file.XXX --to_FORMAT=out_file.YYY
```

--from_SYSBAS	--to_SYSBAS
--from_VIF	--to_erg
--from_erg	--to_PAT
--from_TAS	--to_TAS

- Other options can be passed to TASverter to refine its behaviour
- Usage information is printed when invoking TASverter without arguments

What is TASverter? Running TASverter (2)

- Following request from users a Beta version of a TASverter GUI has been developed and it will be soon available
- The TASverter GUI translates user options to command line arguments
- Messages generated by TASverter are printed in the GUI
- Runs on multiple platforms (use of wxPython based on wxWidgets)



Understanding TASverter (1)

Readers: Python programs able to read models in the source tool format

- Parse the model definition based on:
  - Information in user manual of tool
  - Reverse engineering of undocumented features (many test cases)
- Check validity and consistency of model data
  - Many checks are done, but source file correctness is assumed
- Translate tool entities to equivalent STEP-TAS entities (e.g. Surfaces, material properties, …)
  - The original model hierarchy is converted fully to STEP-TAS

NB: Tool developers do not need to parse the file. They can just export to STEP-TAS from its own data models (e.g Cigal)

Understanding TASverter (2)

Writers: Python programs able to write STEP-TAS models to the destination tool format

- Translate STEP-TAS entities to equivalent tool entities
  - Not all tools support the same features
    - TASverter warns the user when a feature is not supported by a tool
      - E.g. Cutting operations are not supported by all tools
    - TASverter provides alternative solutions in some cases
      - E.g. Renumbering may be helpful for tools not supporting thermal submodels
    - User intervention may be required
- Create a model file in the destination tool format

Understanding TASverter (3)

- TASverter output
  - Information messages for the user reports:
    - Source & destination files and options passed to TASverter
    - Operations being performed by TASverter (reading, converting, writing)
  - Reporting abnormal situations
    - Warnings:
      - Situations that do not prevent TASverter from converting the model but may affect the result (e.g. non-supported features, value corrections)
    - Errors:
      - Situations that prevent TASverter from converting the model. The execution is halted.
  - The amount of reported warnings of a certain type may be controlled (options `--max_warnings_number` and `--all_warnings`)
  - All the messages are also stored in a log file.

    `input_file_name.FROMFORMAT_to_TOFORMAT_log`

Additional Features of TASverter (1)

TASverter is not only limited to model conversion. It may also:

- Generate a report of a model contents in Html format (`--report`)
- Node Renumbering (`--make_renumber_template / --renumber`)
- Length unit conversion (`--source_length_unit / --destination_length_unit`)
- Emulating different thermal nodes at two sides of a surface (`--double_sided_gap`)
- Inactive Node number specification (`--inactive_node`)

Additional Features of TASverter (2)

- Generate a report of a model contents in Html format containing:
  - Model summary
    - Number of Face Sets, total active and inactive surface area, number of thermal nodes meshed…
  - Model Hierarchy: Geometrical models and submodels, face sets description…
  - Network Model: Description of each node in the model
  - Option `--report`

Additional Features of TASverter (3)

- Node Renumbering Feature:
  - There are some steps required to renumber thermal nodes for a model:
    1. Run TASverter using the option `--make_renumber_template` to obtain a template for the renumber file
    2. Modify the template file to specify the thermal nodes to be renumbered and rename it to `SOURCE_FILE.renumber`
    3. Re-run TASverter using the option `--renumber`
  - Renumbering can be used e.g. for:
    - Work around whenever the node numbers in the source model are outside the supported range of the destination format
    - Unsupported submodels in the destination format may cause duplication of node Ids

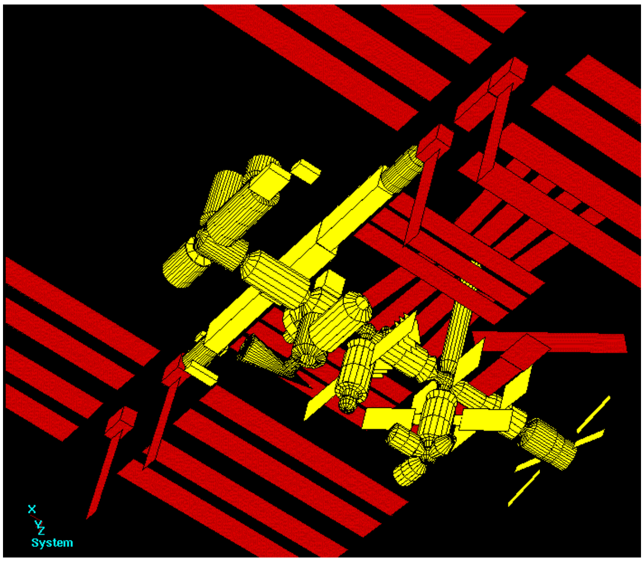
Additional Features of TASverter (4)

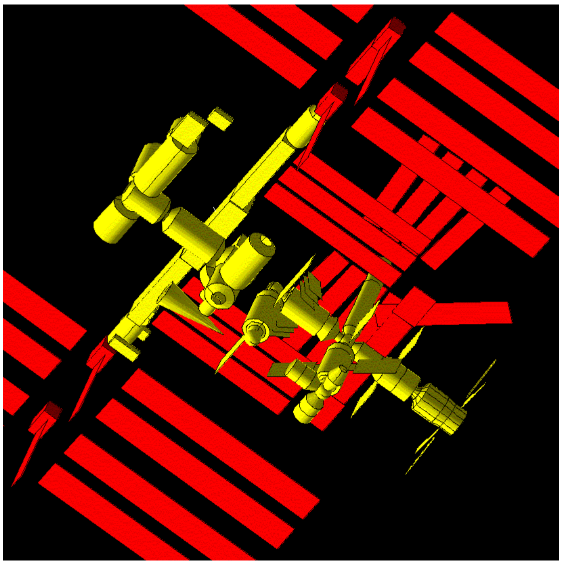
- Length unit conversion for source and destination model
  - Conversion will be automatically made by TASverter
  - Length units accepted are metre, centimetre, millimetre, inch and foot
  - Options `--source_length_unit` and `--destination_length_unit` allow the specification of the length units
- Emulating different thermal nodes at two sides of a surface
  - Some tools do not allow different thermal nodes at the two sides of a surface
  - TASverter solves this by defining two surfaces separated by a (small) gap
  - The size of this gap may be specified using the option `--double_sided_gap`

Additional Features of TASverter (5)

- Inactive Node number specification
  - Source model contains radiation blocking surfaces
    - E.g. the radiation blocking surfaces in THERMICA models (nrays=0)
  - Convert to STEP-TAS: active_side_type = NONE
  - When destination model does not support radiation blocking surfaces:
    - E.g ESARAD:
      - double sided active surface is created
      - solar absorptance = infra-red emittance = 1.0
      - Inactive node is assigned to faces of the surface
  - Option `--inactive_node`

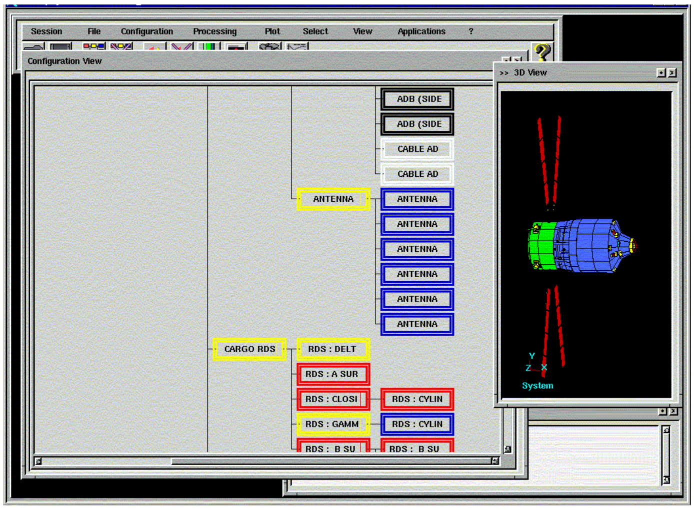
TASverter Cases (1)
THERMICA to ESARAD

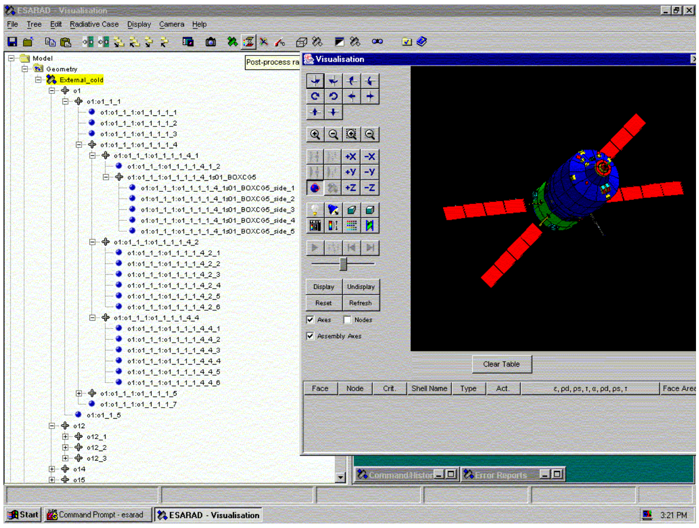




711 thermal-radiative surfaces converted.

TASverter Cases (2)
THERMICA to ESARAD





1700 thermal-radiative surfaces converted.

Model hierarchy and coordinate transformations fully retained.

TASverter Cases (3)
THERMICA to ESARAD

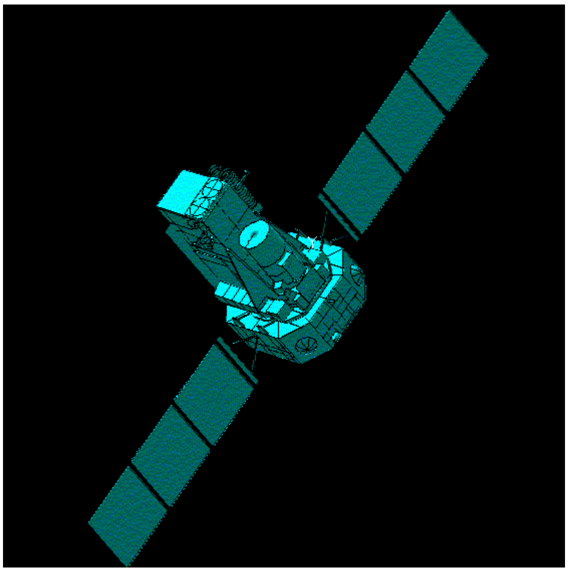
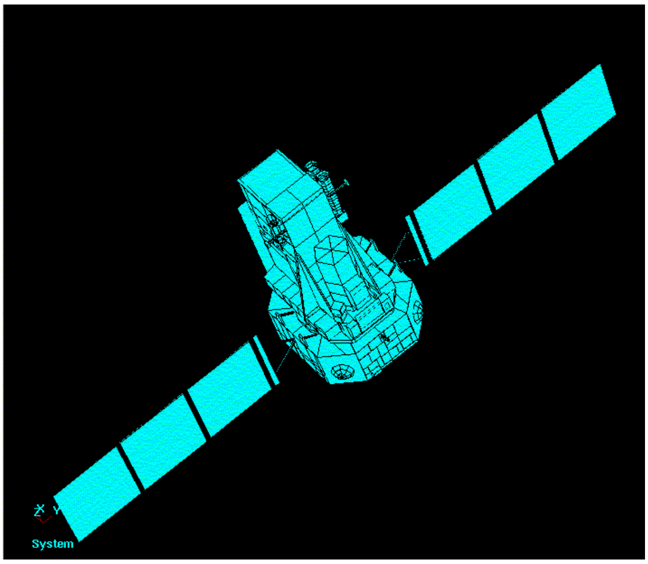
```
<1,1,1,1,4,4,2>     ANTENNA LAT MAIN BODY
$INFO       COLOUR=BLUE
$C_PROPERTY
        C_COATING=PSG_120_FD_cold
$TSHAPE     CYLINDER P1=(        .0,        .0,    -4.380) &
                     P2=(        .0,        .0,    -4.400) &
                     P3=(    0.155,         .0,    -4.380) &
                     DIAM=0.154
            MESH     NODE=(1,1) ELEM=(1,1) SIDE=POS
$THERM      NAME=(9966)
$AXIS       TRAX=0.04   TRAY=-0.333

<1,1,1,1,4,4,3>     ANTENNA UPP MAIN BODY
$INFO       COLOUR=BLUE
$C_PROPERTY
        C_COATING=PSG_120_FD_cold
$TSHAPE     DISC     P1=(        .0,        .0,    -4.400) &
                     P2=(        .0,        .0,    -4.480) &
                     P3=(    0.155,         .0,    -4.400) &
                     DIAM1=0.154  DIAM2=0.045
            MESH     NODE=(1,1) ELEM=(1,1) SIDE=POS
$THERM      NAME=(9965)
$AXIS       TRAX=0.04   TRAY=-0.333
```

Original THERMICA .SYSBAS

```
SHELL o1_1_1_1_4_4_2s01;
o1_1_1_1_4_4_2s01 = SHELL_SCS_CYLINDER(
    label   = "ANTENNA LAT MAIN BODY <1,1,1,1,4,4,2>",
    radius  =  7.70000000000000e-002,
    hmax    =  2.00000000000005e-002,
    hmin    =  0.00000000000000e+000,
    angmax  =  3.60000000000000e+002,
    angmin  =  0.00000000000000e+000,
    side1   = "ACTIVE",
    side2   = "INACTIVE",
    opt1    = PSG_120_FD_cold,
    nbase1  = 9966,
    ndelta1 = 1,
    colour1 = "BLUE",
    colour2 = "BLUE",
    nodes1  = 1,
    nodes2  = 1,
    ratio1  = 1.000000,
    ratio2  = 1.000000,
    thick   = 0.0);

o1_1_1_1_4_4_2s01 =
    ROTATE (object_name = o1_1_1_1_4_4_2s01,
            x_ang =  1.80000000000000e+002,
            y_ang =  0.00000000000000e+000,
            z_ang =  0.00000000000000e+000);

o1_1_1_1_4_4_2s01 =
    TRANSLATE (object_name = o1_1_1_1_4_4_2s01,
               x_dist =  0.00000000000000e+000,
               y_dist =  0.00000000000000e+000,
               z_dist = -4.38000000000000e+000);

SHELL o1_1_1_1_4_4_2;
o1_1_1_1_4_4_2 =
         (o1_1_1_1_4_4_2s01);

o1_1_1_1_4_4_2 =
    TRANSLATE (object_name = o1_1_1_1_4_4_2,
               x_dist =  4.00000000000000e-002,
               y_dist =  0.00000000000000e+000
```

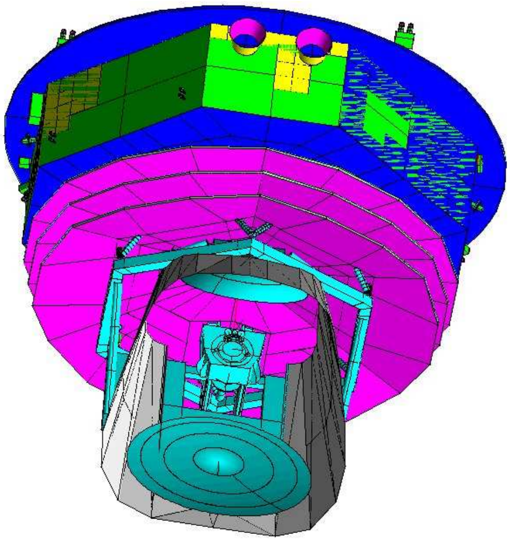
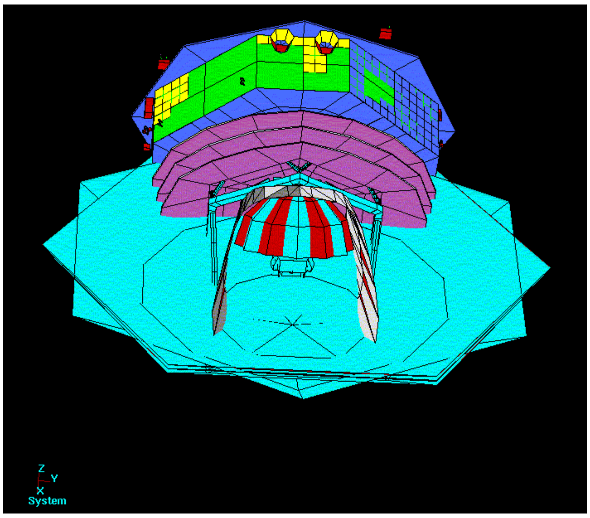
Generated ESARAD .erg

TASverter Cases (4)
ESARAD to THERMICA

828 thermal-radiative surfaces converted.

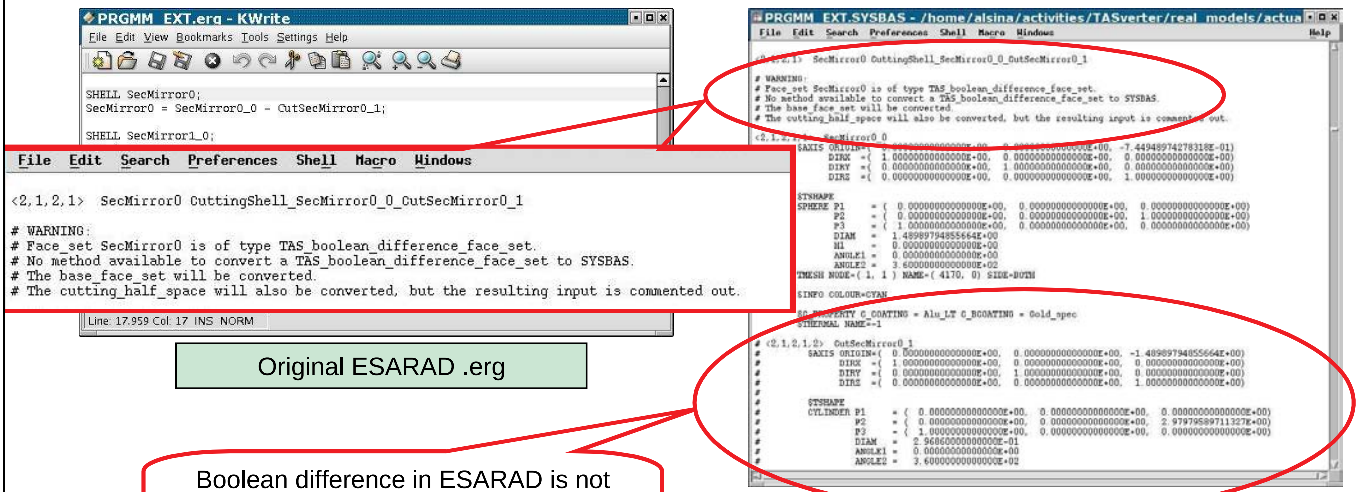
TASverter Cases (5)
ESARAD to THERMICA

Cutting operations are not supported in THERMICA

TASverter converts the base surfaces and leaves out the cutting surfaces

TASverter Cases (6)
ESARAD to THERMICA



Original ESARAD .erg

Generated THERMICA .SYSBAS

Boolean difference in ESARAD is not translated to Thermica but the cutting surface is added as comment

Current status

- Finalising STEP-TAS protocol
- Reviewing, updating and documenting TASverter software

- To be started next year:
  - Conversion of kinematics and analysis case definitions

How to get it?

Executables for Windows NT/2000/XP, SUN Solaris, SGI Irix and Linux can be freely downloaded from:

http://www.estec.esa.int/thermal/tools/tasverter.html

Please provide us with feedback

E-mail: tasverter@thermal.esa.int

Any comments and suggestions are welcome

Appendix X: STEP-TAS and TASverter from the software developer's point of view

STEP-TAS and TASverter
from the
software developer's
point of view

HP. de Koning
ESA/ESTEC

STEP-TAS & TASverter from the software developer's point of view

Hans Peter de Koning

(ESA/ESTEC D/TEC-MCV)

Topics

- Why open data exchange standards?
- Overview of general data exchange standardisation for space industry
- Short history of STEP-TAS development
- Main elements of the STEP-TAS standard and implementation software
- Supporting implementation software: pyExpress and TASverter
- Further development and formal standardisation schedule

Why open data exchange standards? (1)

Reliable and easy-to-use product data exchange is essential

in order to achieve efficient and cost-effective industrial product development processes

- Prescription of single CAx tools (per discipline) in space projects is not effective
  - Project teams involve many partners and are often multi-national
  - Each organization should have the possibility to optimize its own processes
  - Support for multiple tools within one organization is costly – licenses, training
  - Competition between tool developers is healthy, yields better tools, promotes innovation

Why open data exchange standards? (2)

- Direct conversion between tools may provide a short term solution
  - But not sustainable over longer term: maintenance cost and reliability problems
  - Converter developer controls and masters only one side of interface
  - N tools require N*(N-1) converters for complete exchange capability
  - Large duplication of effort
- Data exchange via open standards is the rational long-term solution
  - Stability of open standard can be guaranteed by independent international body
  - Both sides of interface are fully visible to converter developer
  - N tools require 2N converters for complete exchange capability
  - However places very severe requirements on the quality and completeness of the standard and its supporting implementation software
  - Drawback is that open standard has to address lowest common denominator, therefore loss of information after transfer can not always be prevented

Requirements on open data exchange standards and implementation technology

- Shall be reliable
- Shall be easy to use and understand by end-users
  - Absolute minimum number of transfer parameter settings
- Shall be rigorously verifiable
- Shall be complete and self-contained – yet as simple as possible
- Shall be designed for extension with full backwards compatibility
- Shall be portable – no computer platform dependencies
- Shall avoid dependence on third party proprietary software
- Shall be designed for low cost implementation and maintenance
  - Shall minimize required investments from tool/converter developers

Additional uses of open data exchange standards

- Long term archiving of models and results
- Well-controlled migration path from existing tools to next generation tools
  - Enlarges possibilities for end-users – stimulates competition between developers
  - Major benefits for rigorous verification of new software tool
- Tool-independent definitions of benchmark problems
- Developments sponsored from public funding (e.g. ESA) could be done against open standard's programming interface
  - Enables sharing of R&D results between different tool developers
- Custom utilities could be created efficiently using the open standard's programming interface

Open data exchange standards relevant for aerospace (1/2)

ISO 10303 (STEP = *Standard for the Exchange of Product model data*)
- ✓ Part 11: EXPRESS data modelling language
- ✓ Part 21: Physical file
- ✓ Parts 22,23,24,26: C, C++, Java Programming I/Fs
- ✓ Part 28: Link with XML and XMI data transfer ⬅
- ✓ Parts 4x: Generic Resources: product structure, geometry, topology, …
- ✓ Parts 5x: Basic blocks engineering analysis: mathematical spaces, functions, structured/unstructured meshings, properties, results data, …
- ✓ PDM schema
- ✓ AP203: PDM + 3D explicit shapes ⬅
- ✓ AP209: FE analysis
- ✓ AP210: Electronic assemblies (avionics, PCBs, …)
- ✓ AP212: Electro-technical (harnesses, …)
- ✓ AP214: Automotive (AP203 + CSG, kinematics, …)
- ✓ AP221: Process plant (registries, STEPLib, multi-language)
- ✓ AP232: Technical data packages
- ✓ AP233: Systems engineering ⬅
- ✓ AP237: CFD data

Basic ISO standards
- ✓ ISO 31 & 1000: Quantities and units, SI
- ✓ ISO 8879 SGML: Standard Generalized Markup Language

ISO 13584 / PLIB
- ✓ STEP-compatible parts libraries ⬅

STEP-based standards (*developed by ESA*)
- ✓ STEP-TAS: Thermal Analysis for Space
- ✓ STEP-NRF: Network-model Results Format ⬅

Open data exchange standards relevant for aerospace (1/2)

W3C standards
- ✓ HTTP and URI/URL
- ✓ HTML & XHTML
- ✓ XML: eXtensible Markup Language ⬅
- ✓ MathML: Mathematical Markup Language ⬅
- ✓ XSL & XSLT & XPath: eXtensible Stylesheet Language and XSL Transformations & Path
- ✓ XML-Schema ⬅
- ✓ RDF: Resource Description Framework ⬅ "Semantic Web"
- ✓ OWL: Web Ontology Language ⬅
- ✓ DOM: Domain Object Model
- ✓ SOAP: Simple Object Access Protocol ⬅ "Web Services" based on HTTP and XML
- ✓ PNG: Portable Network Graphics
- ✓ SVG: Scalable Vector Graphics

IETF
- ✓ LDAP: Lightweight Directory Access Protocol ⬅

OMG standards
- ✓ UML: Information System Modelling ⬅
- ✓ OCL: Object Constraint Language ⬅
- ✓ SysML: System Engineering ⬅
- ✓ CORBA: OO Distributed Processing
- ✓ MDA: Model Driven Architecture ⬅
- ✓ XMI: XML Metadata Interchange ⬅
- ✓ MDTF: Manufacturing Domain Task Force

Web 3D Consortium
- ✓ VRML: Virtual Reality Modeling Language ISO/IEC 14772

Public domain standards
- ✓ HDF5: Hierarchical Data Format (NCSA) ⬅
- ✓ NetCDF: Network Common Data Form (UCAR)

ECSS E-10 Part 7 "Product data exchange"

- ECSS E-10 Part 7 "Product data exchange" in final stage of publication
  - Available October 2004 from http://www.ecss.nl
  - 'Umbrella' standard providing a central point of reference for all product data exchange standards applicable to space projects – a tailorable list of references to standards to exchange data from a discipline A to a discipline B
  - Will be updated on a regular basis (probably once a year)
- ECSS E-10 Part 9 Engineering Database (in progress)
- ECSS E-10 Part 13 Modelling & Simulation (in progress)

Example clause ECSS E-10 Part 7

The specific requirements are given as subclauses under subclause 4.3, and written in a structured way. For each discipline listed in Table 1 there is a level 3 subclause (4.3.x) which designates the source discipline. Each source discipline subclause contains a collection of applicable destination disciplines, referenced as 4.3.x.y. The body of all specific requirement subclauses adheres to the following template:

Table (example)

Reference	Source representation	Destination representation	Product data to be transferred	Standard reference to apply
4.3.x.y				

Layers in different standard families

Standard family	ISO 10303 (STEP)	W3C XML	W3C Semantic Web	W3C Ontology	OMG UML/MDA
Origin	Mechanical engineering	Structured web data	Structured web data with meaning	Structured web data capturing knowledge	Software engineering
Data structure definition	ISO 10303-11 EXPRESS	DTD XML Schema	RDF Schema (uses XML Schema datatypes)	OWL (Lite/DL/Full) (builds on top of RDF Schema)	UML OCL XMI
File exchange	ISO 10303-21 clear text encoding ("STEP file") ISO 10303-28 XML encoding ISO 10303 Binary (in progress, possibly HDF5)	XML Unicode encoding (e.g. UTF8) XML/Binary (in progress)	RDF-XML	OWL-XML	-
Data access API	ISO 10303-22 SDAI ISO 10303-23 C++ ISO 10303-24 C ISO 10303-27 Java	DOM SAX	RDF library (various open source)	OWL library (various open source e.g. Jena)	Generated from UML model

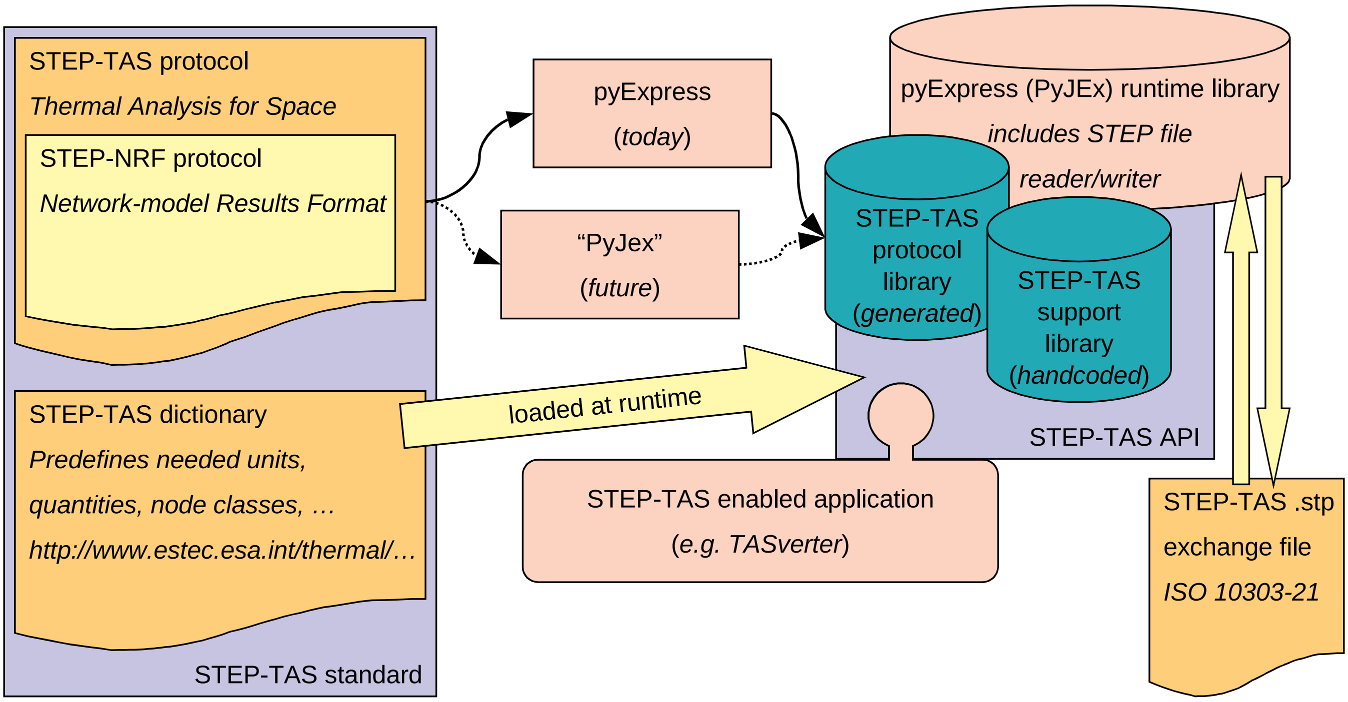
Short history of STEP-TAS development (1)

- In 1995 ESA selected ISO 10303 (STEP) as the basis for the *Thermal Analysis for Space* data exchange standard
  – Nowadays one would possibly select an XML based approach, but in 1995 XML was not yet around and even now XML and XML/Schema still lack some of the more advanced features of the STEP architecture – in addition STEP and XML are being consolidated: ISO 10303-28 (released in 2002) defines how to map STEP to XML and back
- The STEP-TAS standard consists of 3 parts:
  – The NRF (Network-model Results Format) protocol (with EXPRESS schema)
    - Defines a generic network model and results representation and many basic discipline independent data structures – may contain lumped parameter as well as FE, FV definitions
    - Can be used for analysis, test and operation models
  – The TAS (Thermal Analysis for Space) protocol (with EXPRESS schema)
    - Adds specific data structures for space thermal analysis
  – The runtime-loaded TAS Dictionary
    - Defines a large set of standard NRF and TAS instances (units, quantity types, node classes, …)
    - Can be extended in a backwards compatible way without affecting the NRF or TAS protocol or already implemented software

Short history of STEP-TAS development (2)

1991-1993	Precursor: French SET-ATS standard – Some limited implementation in THERMICA and ESARAD
1994	Initial ideas for STEP standard for exchange of thermal models (from ESA ICETAS study)
1995-1997	Development of STEP-NRF and STEP-TAS version 1 Software library by Simulog (France) on top of ST-Developer toolkit by STEP Tools Inc. (USA)
1998	Prototype implementations of STEP-TAS v1 in Europe and US
1999	Implementation of STEP-TAS v1 in industrial releases of ESARAD, THERMICA and Thermal Desktop Not successful: very slow, excessive memory usage and problems with larger models
End 2002-now	Significant simplification of STEP-NRF and STEP-TAS at ESTEC leading to version 2 Development of pyExpress compiler/code generator to remove dependency on COTS toolkits Development of TASverter in Python programming language using library generated by pyExpress Readers & writers for ESARAD, THERMICA and Coratherm – successfully used in industry from August 2003 Start of STEP-SPE (Space Environment analysis model exchange) extension of STEP-TAS Start of formal ECSS and ISO standardisation (preparation of paperwork) Start of full open source STEP development toolkit by University of Manchester (nickname “PyJex”)

STEP-TAS data exchange infrastructure



Main characteristics STEP-TAS (1) "Thermal Analysis for Space"

- “STEP-TAS” is the standard that end-users need be aware of
  - STEP-TAS includes STEP-NRF which is a discipline independent building block
    - NRF provides the general features to enable multi-discipline data exchange
    - NRF enables proper modular software engineering
- Supports three kinds of models:
  - Thermal geometric models represented by bounded surfaces
    - Thin shells with oriented faces, mesh and notional thickness
  - Thermal lumped parameter network models
    - With all typical ESATAN or SINDA like data
  - Thermal test (or flight) models with sensor identification and possible location
    - Represents test article with thermo-couples, thermistors, data acquisition channels, …
    - Can be used in conjunction with corresponding STEP AP203/AP214 CAD model

Main characteristics STEP-TAS (2) "Thermal Analysis for Space"

- Geometric and mathematical submodels – no limitation on depth
- Separate specification of model and (load/analysis/test) case definition
  - Supports multiple case definitions per model
- Arbitrary number and depth of coordinate system transformations
  - Retains human-understandable rotations – sequence of rotations w.r.t. the major axes
- Mesh definitions on geometric faces
- Mapping from geometric faces to thermal mathematical model nodes
- Rigid body kinematics with on-orbit pointing for articulated parts

Main characteristics STEP-TAS (3) "Thermal Analysis for Space"

- Space trajectory, attitude and orientation
  - Keplerian or general ephemeris orbit arc definition
  - Support for definition of discrete events, sequencing of cases, parameterized attitude, etc.
- Named materials with their thermo-optical and physical properties
  - Supports multiple sets of properties with material property environment (e.g. BOL, EOL)
- Analysis, test or operation results with complete run-execution information
  - Date & time stamp of execution start and end, tool/facility name and version, etc.
- Supports choice of SI or other unit systems (but requires one consistent set)
  - Conversion factors and offsets w.r.t. SI reference units are explicitly defined
  - STEP-TAS dictionary fully defines all Imperial units used in US projects

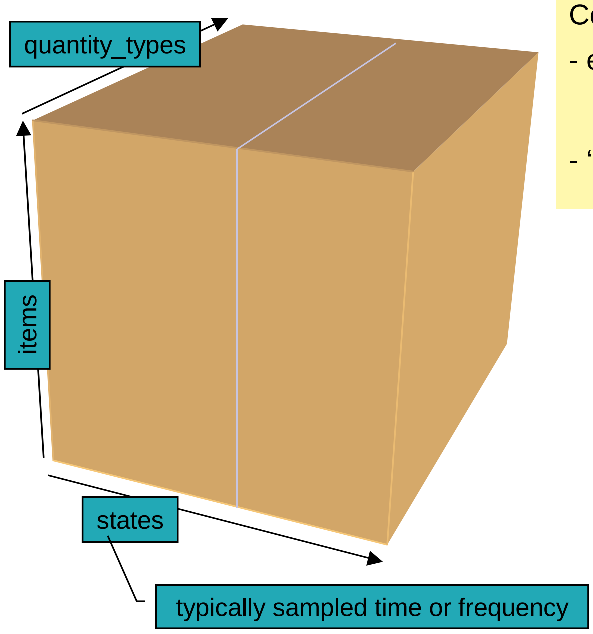
Main characteristics STEP-TAS (4) "Thermal Analysis for Space"

- A 'Conformance Class' is a consistent subset of a STEP protocol
  - A STEP-compliant import/export interface is required to implement complete Conformance Classes
- STEP-TAS Conformance Classes:
  - CC-1: Thermal radiation and conduction model defined by shell geometry
  - CC-2: CC-1 plus kinematic model
  - CC-3: CC-1 plus constructive geometry
  - CC-4: CC-3 plus kinematic model
  - CC-5: CC-1 plus space mission aspects
  - CC-6: CC-4 plus space mission aspects
  - CC-7: Thermal lumped parameter model
  - CC-8: CC-7 plus results
  - CC-9: Thermal test or operation model with results

Main characteristics STEP-NRF (1) "Network-model Results Format"

- Generic, discipline-independent protocol to exchange models, cases & results
  - Model definition, using a discrete network representation
    - Supports model/submodel hierarchy (no limitation on depth)
  - Results data, produced in analysis, test or operation
  - Meta-data, which records details of actual analysis, test or operation performed
  - Provides common basis for a suite of multi-discipline exchange standards
- Discipline-dependent data is defined in a runtime-loaded dictionary
- Supports discrete observations: Sampled results at discrete locations for discrete states
  - No support for continuous fields, etc.
- Any quantity has explicit an quantity type and unit – no 'loose' numerical values
  - e.g. quantity type = temperature / unit = kelvin
- Data model designed to cope efficiently with large amounts of results data
  - Built-in support for scalar, vector, matrix, tensor data structures
  - Designed to map well onto existing scientific data storage standards like HDF5

Main characteristics STEP-NRF (2) "Network-model Results Format"



Central NRF data structure is the 'datacube'

- each element of the cube is a scalar, vector or tensor property for a specific combination of (item, quantity_type, state)
- 'literal' and 'prescription' SUBTYPEs, for literal and generalised functionally prescribed values

```
ENTITY nrf_datacube
  ABSTRACT SUPERTYPE OF( ONEOF(
    nrf_literal_datacube,
    nrf_prescription_datacube ) );
  name              : nrf_label;
  security_class    : OPTIONAL nrf_security_classification_level;
  value_order       : nrf_datacube_order_type;
  quantity_basis    : nrf_quantity_type_list;
  item_basis        : nrf_observable_item_list;
  state_basis       : nrf_state_value_list;
  real_values       : LIST OF REAL;
  integer_values    : LIST OF INTEGER;
WHERE
  wr1: SIZEOF(real_values) = quantity_basis.number_of_real_values
      * SIZEOF(item_basis.items) * SIZEOF(state_basis.state_values);
  wr2: SIZEOF(integer_values) = quantity_basis.number_of_integer_values
      * SIZEOF(item_basis.items) * SIZEOF(state_basis.state_values);
  wr3: nrf_valid_values_in_datacube(SELF);
END_ENTITY;
```


Excerpts from the STEP-TAS dictionary (Example of an NRF dictionary)

ISO 10303-21 version (STEP file)

```
ISO-10303-21;
HEADER;
/* This STEP / ISO 10303-21 file was produced using the pyExpress toolkit */
/* The pyExpress toolkit is developed by the European Space Agency (ESA) */
...
#31=NRF_DIMENSIONAL_EXPONENTS(2.0,1.0,-2.0,0.0,0.0,0.0,0.0);
#32=NRF_DIMENSIONAL_EXPONENTS(-1.0,1.0,-2.0,0.0,0.0,0.0,0.0);
#33=NRF_DIMENSIONAL_EXPONENTS(2.0,0.0,-2.0,0.0,0.0,0.0,0.0);
#34=NRF_DIMENSIONAL_EXPONENTS(0.0,1.0,-1.0,0.0,0.0,0.0,0.0);
#35=NRF_DIMENSIONAL_EXPONENTS(3.0,0.0,-1.0,0.0,0.0,0.0,0.0);
#36=NRF_DIMENSIONAL_EXPONENTS(1.0,-1.0,2.0,0.0,0.0,0.0,0.0);
#37=NRF_SI_UNIT(*,*,*,'','metre',*);
#38=NRF_SI_UNIT(*,*,*,'kilo','gram',*);
#39=NRF_SI_UNIT(*,*,*,'','second',*);
#40=NRF_SI_UNIT(*,*,*,'','ampere',*);
#41=NRF_SI_UNIT(*,*,*,'','kelvin',*);
#42=NRF_SI_UNIT(*,*,*,'','radian',*);
#43=NRF_SI_UNIT(*,*,*,'','degree_Celsius',*);
#44=NRF_SI_UNIT(*,*,*,'','newton',*);
#45=NRF_SI_UNIT(*,*,*,'','joule',*);
#46=NRF_SI_UNIT(*,*,*,'','watt',*);
#47=NRF_SI_UNIT(*,*,*,'milli','metre',*);
#48=NRF_SI_UNIT(*,*,*,'centi','metre',*);
#49=NRF_CONVERSION_BASED_UNIT('degree','deg',*,#42,1.74532925199
#50=NRF_DERIVED_UNIT_ELEMENT(#49,1.0);
#51=NRF_DERIVED_UNIT_ELEMENT(#39,-1.0);
#52=NRF_DERIVED_UNIT('degree per second',*,#20,(#50,#51));
#53=NRF_CONTEXT_DEPENDENT_UNIT('dimensionless','-',#19);
#54=NRF_DERIVED_UNIT_ELEMENT(#37,1.0);
#55=NRF_DERIVED_UNIT_ELEMENT(#39,-1.0);
#56=NRF_DERIVED_UNIT('metre per second',*,#24,(#54,#55));
...
#121=NRF_BASIC_QUANTITY_TYPE('t','time','Time',#12);
#122=NRF_BASIC_QUANTITY_TYPE('T','temperature','Temperature',#14
#123=NRF_BASIC_QUANTITY_TYPE('rho','mass_density','Unit mass per
#124=NRF_BASIC_QUANTITY_TYPE('C','specific_heat_capacity','Unit
#125=NRF_QUANTITY_TYPE_QUALIFIER('p','constant_pressure','At con
...
END-ISO-10303-21;
```

HTML version

tas_arm_dictionary - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Search Favorites Media

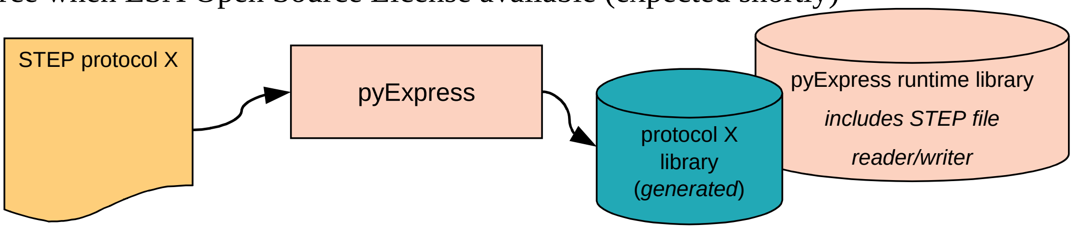
Address C:\Documents and Settings\hanspeter\My Documents\0-sandbox\step-tas\tas_arm_dictionary.html

Dictionary quantityTypesSi: SI-based real quantity types (Nrf_real_quantity_type)

key/qualified name	symbol	base quantity	qualifiers	unit	lowerbound	upperbound
absorbed_albedo power	Q_A	power	absorbed_albedo (A)	watt	NA	NA
absorbed_internal power	Q_I	power	absorbed_internal (I)	watt	NA	NA
absorbed_planet_infra_red power	Q_E	power	absorbed_planet_infra_red (E)	watt	NA	NA
absorbed_rest power	Q_R	power	absorbed_rest (R)	watt	NA	NA
absorbed_solar power	Q_S	power	absorbed_solar (S)	watt	NA	NA
area	A	area	NA	square metre	>=0.0	NA
constant_pressure heat_capacity	mC_p	heat_capacity	constant_pressure (p)	joule per kelvin	>=0.0	NA
constant_pressure specific_heat_capacity	C_p	specific_heat_capacity	constant_pressure (p)	joule per kilogram kelvin	>=0.0	NA
cross_sectional_flow area	A_cf	area	cross_sectional_flow (cf)	square metre	>=0.0	NA
fluid_conductor	GP	fluid_conductor	NA	joule per pascal	>=0.0	NA
hydraulic diameter	D_F	diameter	hydraulic (F)	metre	>=0.0	NA
hydraulic length	L_F	length	hydraulic (F)	metre	>=0.0	NA
incident_albedo power	Q_AI	power	incident_albedo (AI)	watt	NA	NA
incident_planet_infra_red power	Q_EI	power	incident_planet_infra_red (EI)	watt	NA	NA
incident_solar power	Q_SI	power	incident_solar (SI)	watt	NA	NA
infra_red diffuse transmittance	tau_ir_dif	transmittance	infra_red (ir) diffuse (dif)	dimensionless	>=0.0	<=1.0

Implementation software - pyExpress

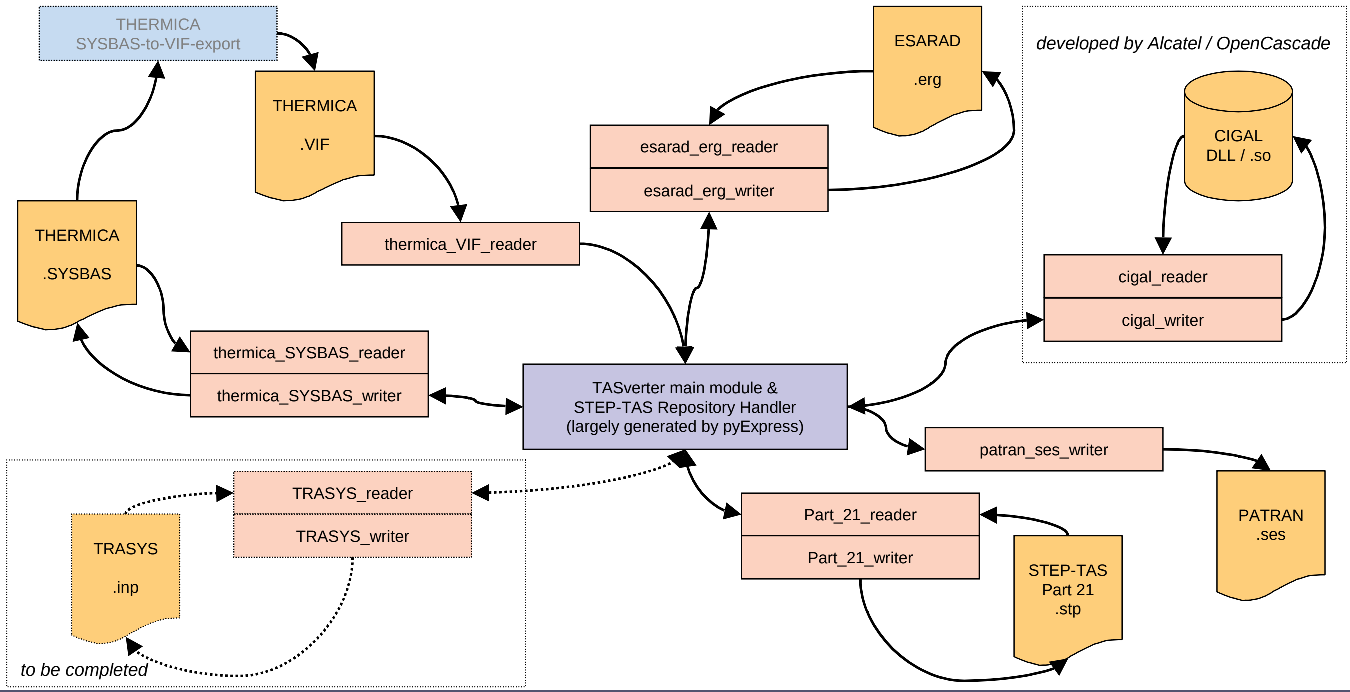
- pyExpress is an EXPRESS compiler / code generator / runtime environment
  - EXPRESS is the STEP data model definition language (ISO 10303-11)
  - Developed by ESA/ESTEC in Python programming/scripting language
    - Python is a freely available, open source, object-oriented language (www.python.org)
    - Very powerful, short development cycle, good performance
    - Very good interfacing with C/C++
      - Use SWIG to generate Python layer on existing C/C++ library (www.swig.org)
    - Provided as open source to ESA contractors – will be made available as global open source when ESA Open Source License available (expected shortly)



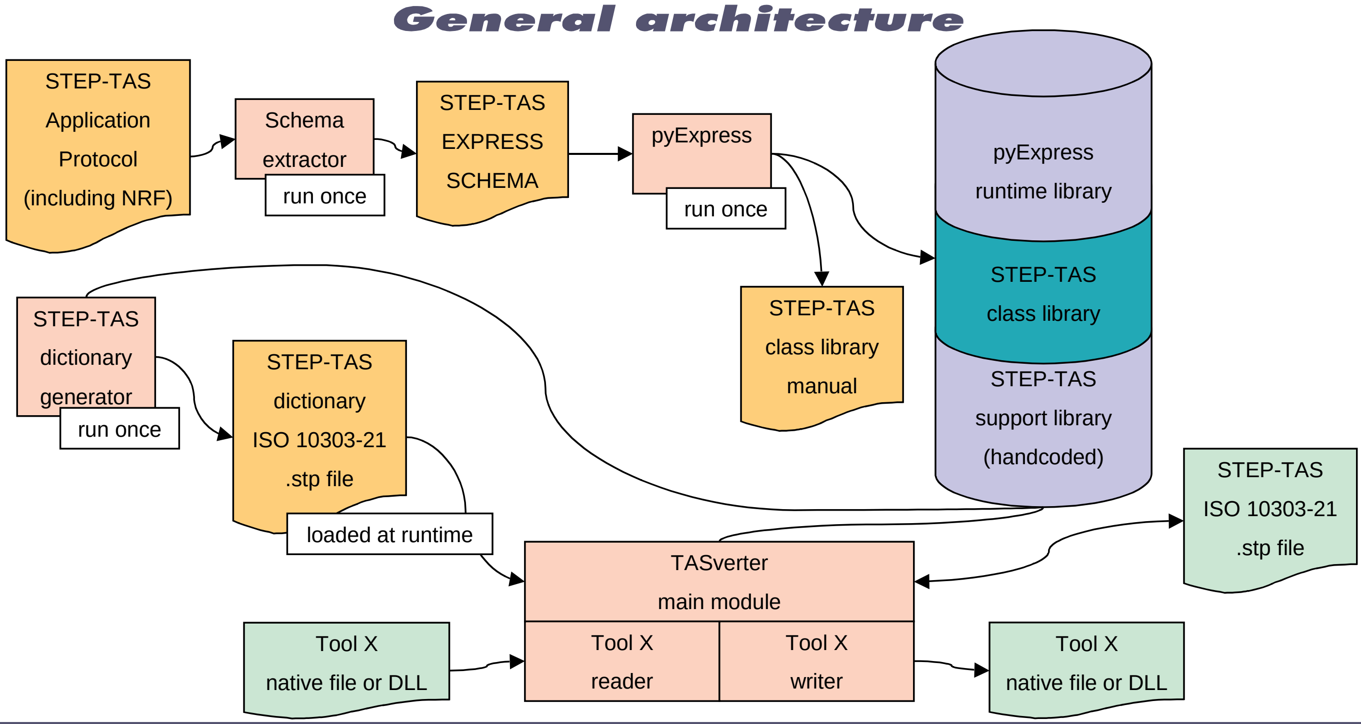
Implementation software – TASverter (1)

- TASverter is a STEP-TAS model conversion tool
- Developed by ESA/ESTEC in Python since January 2003
- Objectives
  - Offer end-users finally a properly working solution for exchange of thermal models
    - First between major European analysis tools ESARAD and THERMICA
  - Produce a fully functional open source framework for STEP-TAS
    - Including extensive validation and verification
  - Create maintainable and cost-effective implementation alternative
    - Can be used by converter developer with minimal STEP knowledge
  - Ensure long term availability, i.e. no dependence on any proprietary software

Implementation software – TASverter (2)



Implementation software – TASverter (3)
General architecture



Implementation software Verification Test Suite

- More than 200 unit tests (CC-1 and CC-3)
  - Documented as a website
    - with naming convention for subdirectories per testcase
    - actual and reference results for regression testing
  - Fully scripted to run and be diff-ed automatically
- Real model tests, e.g.:
  - ATV (Automated Transfer Vehicle) model
  - METOP C/D full spacecraft model
  - NASA's ISS thermal interface model
  - Herschel-Planck full spacecraft model
  - Integral full spacecraft model
- All unit tests and most real models (some cannot be made public) will be made available to STEP-TAS interface developers

Schedule (1)

- Freeze of STEP-NRF and STEP-TAS protocols in Nov 2004
- Update of TASverter to support final STEP-TAS standard
  - Release expected Jan 2005 (CC-1 and CC-3)
- Transfer THERMICA reader/writer modules to Astrium SAS for further maintenance
- Prepare and submit NRF and TAS to ECSS and ISO TC 184 / SC 4 for formal standardisation
  - ECSS = European Cooperation for Space Standardization
- Publish standards and software as open source
  - pyExpress and TASverter
  - on ESA website with full configuration control
  - STEP-TAS and STEP-NRF schemas, Python libraries
  - Pending on completion of formal ESA Open Source License (expected 2004-Q3)
- ESATAN model and results writer being developed by ESTEC in frame of ESATAP project
  - First delivery took place 1 Oct 2004 – validated protocol to support ESATAN/SINDA type models
- Upgraded BagheraView – independent STEP-TAS viewer/reporter
  - Development ongoing under CNES contract

Schedule (2)

- ESA funded development of STEP-SPE (Space Environmental Analysis)
  - Start October 2003 – Scheduled for completion in 2005
  - Extends STEP-TAS for micro-meteorites/debris, contamination, atomic oxygen, high energy particle radiation, plume impingement, etc.
- Full open source EXPRESS software development toolkit – nickname ‘PyJex’
  - ESA contract to Computer Science group in University of Manchester
  - Development ongoing and progressing well since April 2004
  - Provide full EXPRESS compiler with open backend / code generators for C/C++, Java and Python
  - Python API will be backward compatible with pyExpress generated API
  - Public release scheduled for April 2005
- Add conformance classes to existing readers / writers:
  - Kinematics and mission aspects (release expected 2005 Q2)
- Promote implementation of STEP-TAS in US and Canadian tools
  - TMG, Thermal Desktop, TSS, ...

Schedule (3)

- New readers and writers
  - Transform existing TRASYS/ESARAD converter to TRASYS/TAS reader/writer
  - Transform existing SINDA85/ESATAN converter to SINDA85/TAS reader
  - Add STEP AP203 reader/writer, with primitive shape recognition capability
    - Can be derived from existing AP203/ESARAD converter plus old TAS version 1 mapping and facetting of remaining NURBS surfaces
  - Mapping to HDF5 in stead of ISO 10303-21 for efficient handling of large datasets

Closing statements

- ESA is fully committed to making STEP-TAS a success
  - Funding and maintaining robust open data exchange standards and software is fully in line with the Agency's mandate
  - It's a key element in Thermal and Space Environment Analysis Software Harmonisation
- The user community as a whole will benefit from reliable STEP-TAS middleware
  - Both end-users and developers
  - Our hope is that it will create a higher level playing field with healthy competition between the analysis tools while still safeguarding the long term interests of end-users

Acknowledgements

- Simon Appel, David Alsina, Duncan Gibson (ESA/ESTEC)
- Olivier Pailles, Arnaud Klinger (Incka, previously Simulog, France)
- Eric Lebègue and co-workers (CSTB/GRAITEC, France)
- Julian Thomas, David Scurrah, John Hurdle (ALSTOM Power, UK)
- Marc Jacquiau (Astrium SAS, France)
- Thierry Basset (Alcatel Space, France)
- Christian Caillet (OpenCascade, France)
- Georg Siebes (NASA-JPL, US)

References

- ISO 10303 (STEP) standards
  http://www.tc184-sc4.org
- STEP-TAS
  http://www.estec.esa.int/thermal/tools/standards.html
- TASverter
  http://www.estec.esa.int/thermal/tools/tasverter.html
- Annual NASA-ESA workshop on product data exchange
  6th edition, 2004 April 20-23, at EADS/Astrium, Friedrichshafen, Germany
  http://www.estec.esa.int/conferences or http://step.jpl.nasa.gov
- Hierarchical Data Format (version 5) – HDF5
  http://hdf.nsca.uiuc.edu
- European Cooperation for Space Standardization
  http://www.ecss.nl
- Python (freely available open source scripting language)
  http://www.python.org
- SWIG (freely available open source programming language interface generator)
  http://www.swig.org

Appendix Y: List of Participants

List of Participants

18th European Workshop on
Thermal and ECLS Software

5-6 October 2004
ESTEC, Noordwijk, Netherlands

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