TMG: New Technologies and Modeling Approaches

Sixteenth European Thermal & ECLS Software Workshop

22-23 October 2002

Introduction to TMG

Comprehensive thermal simulation software package

Integrated with I-DEAS and FEMAP

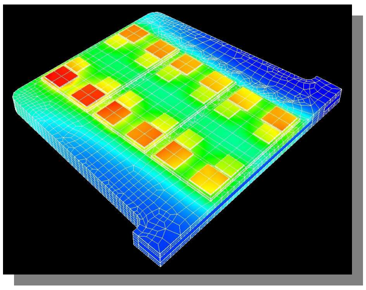
- advanced FE modeling packages

Finite volume method

- accurate, efficient

Complete, integrated radiation simulation

- radiosity, ray-tracing, orbital heating



Fluid flow simulation

- comprehensive CFD, duct flow capabilities
- free and forced convection

State-of-the-art solvers

- powerful iterative solver (bi-conjugate gradient stabilized technique)
- implicit, explicit transient integration scheme

Open, modular architecture

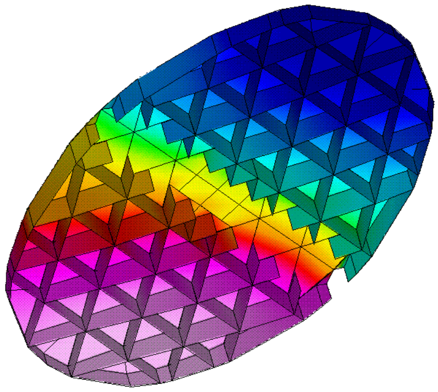
- fully documented
- user subroutines

Modeling technologies

Geometry-based modeling
- consistent mesh for conduction, radiation
- extensive CAD abstraction tools
- associativity, assemblies

Meshing
- free, mapped, manual

Conduction
- finite volume method
- accurately handles arbitrary element shapes
- orthotropic materials, multilayer shells
- compatible with finite difference solvers (SINDA / ESATAN



Thermal couplings
- modeling assemblies
- enables geometry abstraction
- sliding contact

Graphical post-processing, results visualization
- model validation and correlation

Conduction formulation

Finite volume formulation
- elements used directly as control volumes
- local, global conservation of energy
- yields accurate conductive conductances for arbitrary element shapes
- retains “physicality” of finite difference approach

Calculation points (network “nodes”) established at the boundaries of the element and the centroid

Capacitance, surface heat transfer (radiation, convection) “lumped” at the centroidal point

Efficient handling of temperature-dependent thermal conductivity
- all terms are associated with a single element

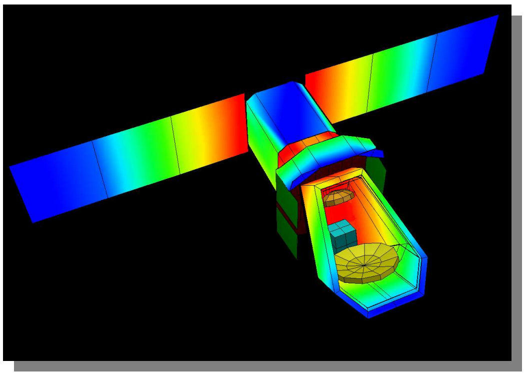
Compatible with SINDA / ESATAN
- TMG’s solution matrix can be solved using SINDA / ESATAN

Supports direct entry or modification of conductances and capacitances
- “non-geometric” modeling

Radiation

TMG radiation simulation:

- full modeling of radiative interchange
- orbital environmental heating
- arbitrary radiative sources
- diffuse/specular/transmissive surfaces
- articulating, spinning assemblies
- angle-dependent specularity, transmissivity
- temperature-dependent emissivity
- refraction



Solution technology:

view factors using hemicube or analytical methods
deterministic ray-tracing for specular reflections (two-pass method)
iterative correction of view factors to extinguish residual
radiosity methods for radiative interchange calculations
conjugate gradient solver technology to handle very large models

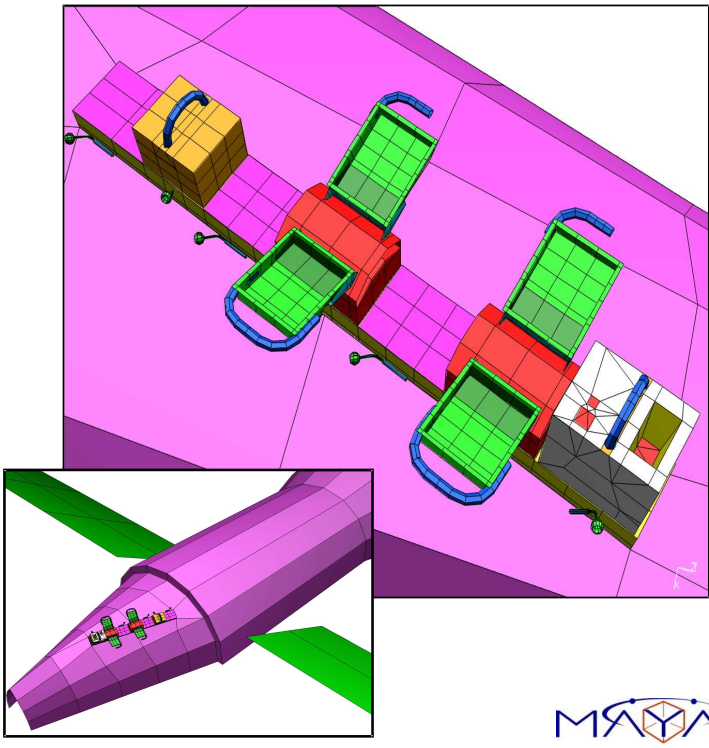
View factor calculation

Hemi-cube algorithm

- uses graphics hardware
- implementation based on OGL
- very fast, especially for large models
- error detection and correction

Analytical algorithm

- exact contour integral technique for unshadowed surface pairs
- Nusselt sphere method for obstructed views
- control over subdivision, including error-based scheme
- shadowing surface algorithm minimizes shadowing checks



Ray tracing

Two-pass method:
- specular reflections and transmissions are ray traced
- view factor matrix is adjusted

Ray distribution is deterministic
- based on view factors to specular, transmissive elements
- elements are subdivided, rays launched between sub-elements
- user controls subdivision level (ray density)
- ray density can be proportional to view factor magnitude
- rays traced until extinguished

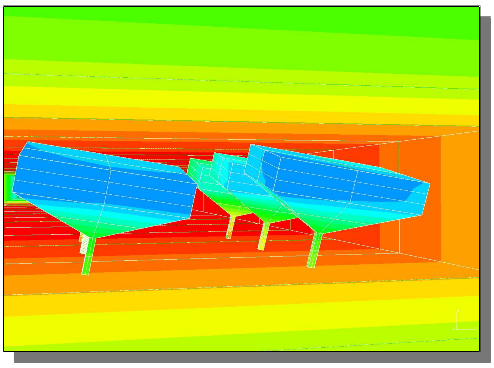
Accurate and efficient solution of large models
- generally much less sensitive to ray density, sampling issues than Monte Carlo
- exploits efficient solution of radiosity equations using iterative solvers

Supports curved surfaces
- parabolic elements capture surface curvature
- enables accurate modeling of focussing effects (e.g. parabolic reflectors)

Directional surface properties
- specular reflectivity, transmissivity versus angle, direction of incidence

Radiative exchange matrix

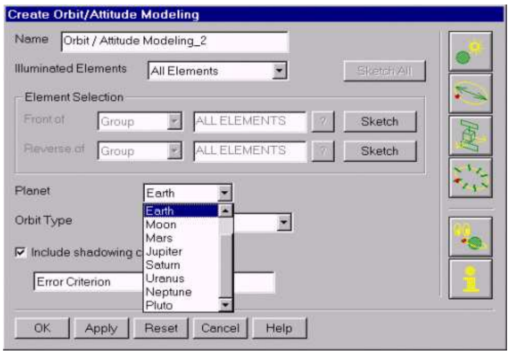
Iterative adjustment algorithm to extinguish residual view factors
- handles internal or external enclosures
- preferentially corrects shadowed view factors
- effective correction of view factors to space

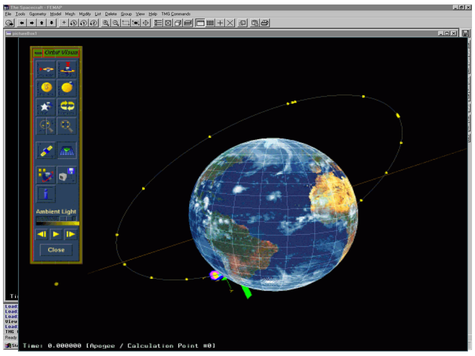


Gebhardt's formulation
- yields element-to-element conductance matrix
- inefficient for large models

Oppenheim's method (radiosity)
- exploits advanced iterative solver
- bypasses matrix inversion
- generally yields smaller radiation matrix
- handles temperature-dependent emissivities accurately, efficiently
- have observed order-of-magnitude reductions in solution time versus Gebhardt's
- very efficient for articulating models

Orbit and attitude modeling





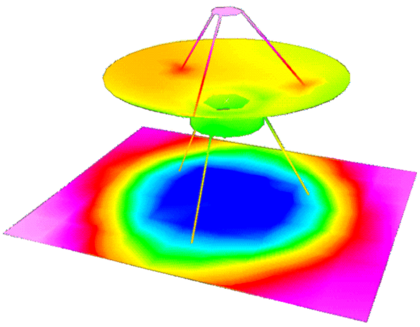
Orbital modeling/heating for spacecraft

- select planet, orbit type
- planet and sun data is pre-loaded
- solar flux calculated from date
- vector-based attitude modeling
- arbitrary rotations, maneuvers
- control over orbital calculation points
- option to enter sun, earth vectors
- orbit chaining

Orbit Visualizer

- Animated view of model in orbit
- Dynamically rotate while animating
- Viewer updates dynamically with parameter changes in forms

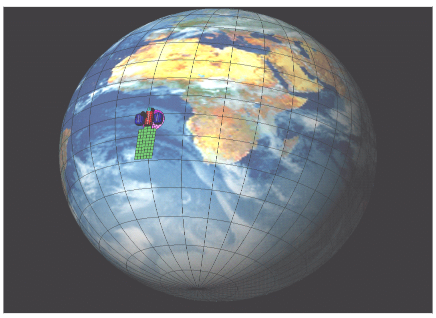
Orbital heating



Computes orbital environmental heat loads

- direct solar, albedo, planet IR
- computes view factors to environmental sources
- eclipses modeled automatically
- ray tracing of specular reflections, transmissions of collimated solar
- radiosity formulation of radiative exchange equations (extended Oppenheim's method)
- efficient solution using iterative conjugate gradient solver

Heat loads automatically loaded for solver



Articulating spacecraft

- efficient algorithms to recompute view factors
- visualize results on displaced geometry

Spinning spacecraft

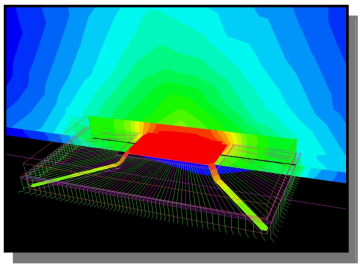
- heat flux averaging

Orbital averaged heat loads

Thermal solver technology

Steady state: conjugate gradient solver

- powerful iterative solver (bi-conjugate gradient stabilized technique)
- pre-conditioning matrix (ILU factorization)
- Newton-Raphson method for non-linear terms
- very high performance for large, ill-conditioned systems
- handles negative terms



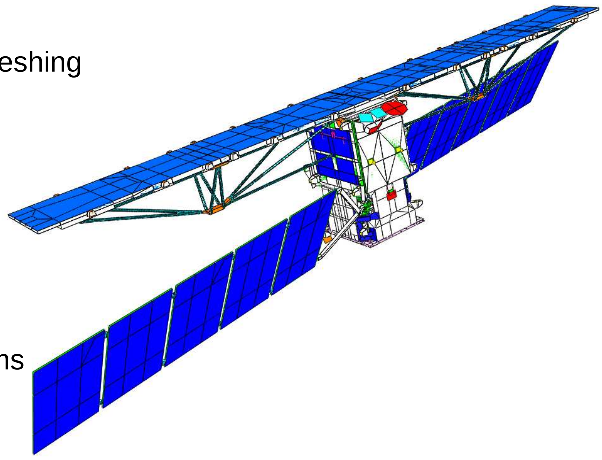
Transient solver

- explicit schemes: forward, exponential forward
- implicit methods: arbitrary degree of implicitness
- also exploit CG solver

Radiation for large models

Strong trend towards larger models for spacecraft thermal analysis

- modern finite element modeling tools enable meshing of complex systems
- greater processing power available
- geometric fidelity
- minimize discretization errors



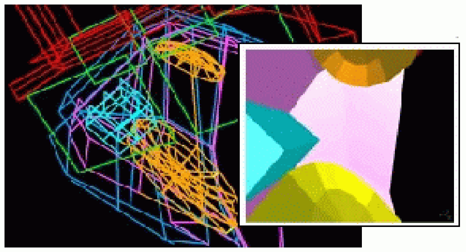
Challenges:

- computing the radiative exchange terms
- storing, manipulating the terms
- solving the model
- post-processing and diagnostics

Radiation for large models

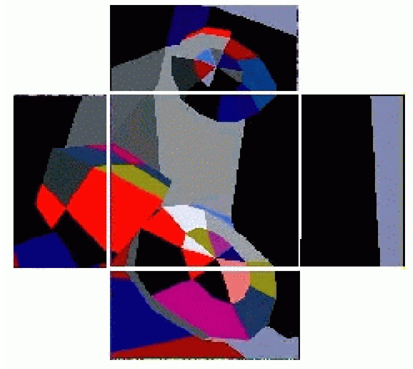
Hemicube method for view factor calculation

- enabling technology for large FE-based radiation models
- calculation time nearly linear with element count
- uses OGL-based rendering - exploits high performance graphics hardware



How it works:

- pixelized half-cube constructed around radiating element
- all other radiating elements are graphically projects onto the faces of the cube, using OGL
- each pixel is associated with a precomputed view factor
- Algorithm collects rendering data, and computes view factors



Accuracy:

- view factor resolution limited by pixel size: user controlled tradeoff between accuracy and calculation time
- algorithm detects closely-spaced elements, and performs multiple renderings from distributed positions on the emitter
- excellent overall accuracy observed for all classes of models

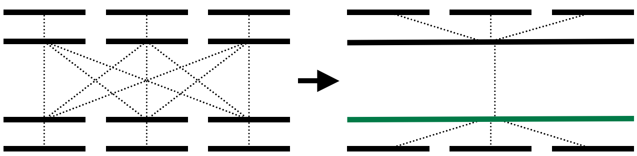
Radiation for large models

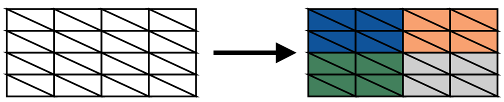
"Patching" algorithm

- densely meshed models can yield a very large number of radiative terms (up to n^2)
- conjugate gradient solver technology can effectively handle very large models, but:
  - memory requirements and disk space can become a problem
  - transient model solve time can still be an issue
- A new algorithm was developed in TMG to which exploits the radiosity formulation to condense the radiative exchange matrix

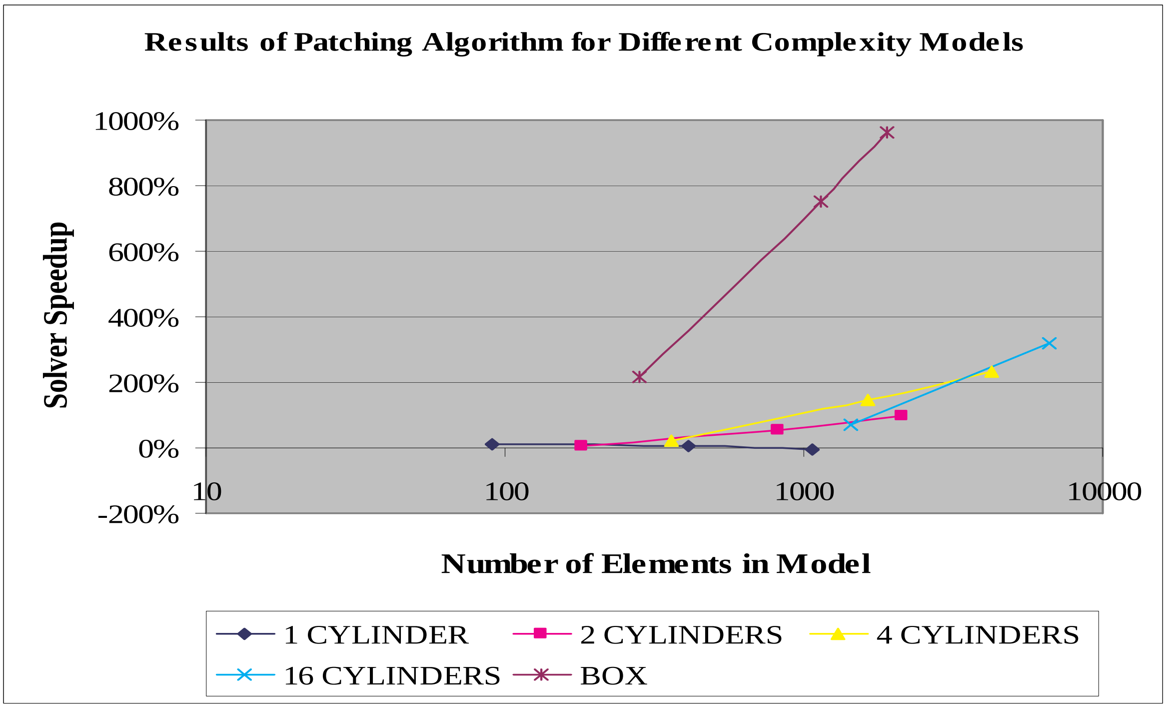
How it works:

- automatically identifies "patches" - sets of adjacent elements with identical thermo-optical properties
- merges the Oppenheim nodes (radiosity potential) for all elements in a patch
- includes new terms to correct for false diffusion between the patch elements
- with the default settings, generally reduces the radiation matrix by an order of magnitude



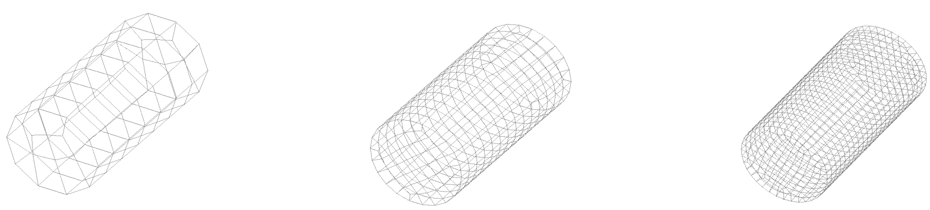


Patching algorithm



Patching algorithm

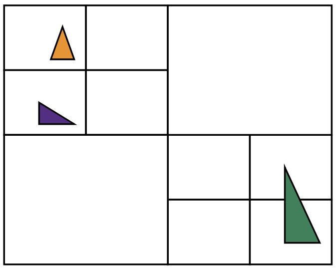
Model	# elements	patched ?	Max. Temp. Error (deg.C)
1 cylinder	1064	no	reference
1 cylinder	1064	yes	0.007
1 cylinder	412	no	1.44
1 cylinder	412	yes	1.49
1 cylinder	90	no	5.780
1 cylinder	90	yes	5.88

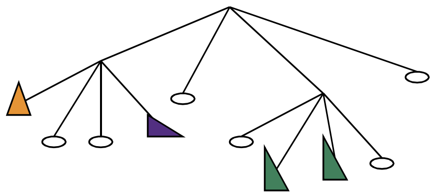


Radiation for large models

Advanced data structures

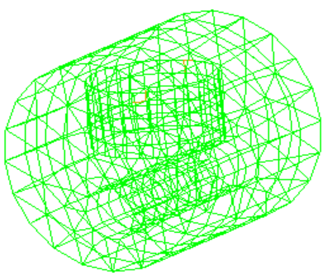
- designed to accelerate ray tracing procedure for large models
- Octree data structure for spatial sorting and searching
- Pluecker coordinates:
  - six dimensional coordinates for representing line segments in space
  - test of ray-polygon intersection requires only a few operations with Pluecker coordinates
- View factor storage/retrieval data structure
  - efficient scheme for tallying up the view factors as the ray tracing proceeds

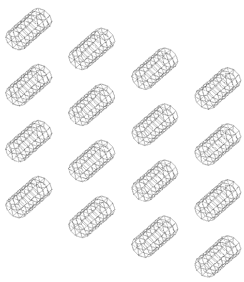


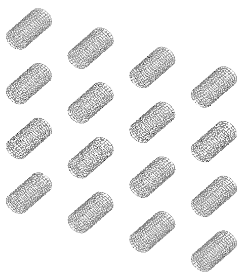


Advanced data structures

New ray-tracing engine designed based on these data structures







Model	# of Elements	Time without advanced data structures	Time with advanced data structures	Speedup
3 Cylinders	834	29.6 minutes	17.6 minutes	1.68
16 Cylinders	1446	2.06 hours	15 minutes	8.24
16 Cylinders	6598	17.2 hours	8.3 hours	2.07

Thermal model reduction

Computing heat flow between groups

- it is impractical to directly incorporate large, high-fidelity thermal models into a system-level model - model reduction technology is necessary (like Craig-Bampton method for structures)
- to provide engineering insight into large thermal models, it is necessary to enable users to evaluate heat flows between model segments (not just elements)
- Both of these requirements are addressed in TMG using an algorithm to compute heat flows between arbitrary groups of elements

How it works

- For radiative heat flows:
  - Set temperature of all secondary elements to 0K (i.e. no emission)
  - solve the full matrix to compute net heat radiative flow to all elements (exploits CG solver).
  - collect results for secondary group
- conductive heat flows extracted directly
- net conductances between groups computed from heat flows and temperatures
- For thermal model reduction, model is simply partitioned into non-overlapping groups.

Thermal Optical Mechanical Testbed

Proposed designs for space-based interferometers require optical element stability at picometer level

- corresponds to temperature disturbances at mK level
- thermally induced deformations are typically the major barrier to diffraction-limited performance

Verification by ground test of end-to-end optical performance is not practical

- analysis will play a major role in instrument validation

Project undertaken by Lockheed Martin ATC in collaboration with JPL:

- validate specific design requirements of the NASA/JPL Space Interferometry Mission (SIM)
- validate thermal-optical-mechanical models at disturbance levels for which thermally-induced wavefront errors are estimated to be significant for the SIM instrument: temporal changes in through-thickness gradient to the order of $\pm$ 1 mK

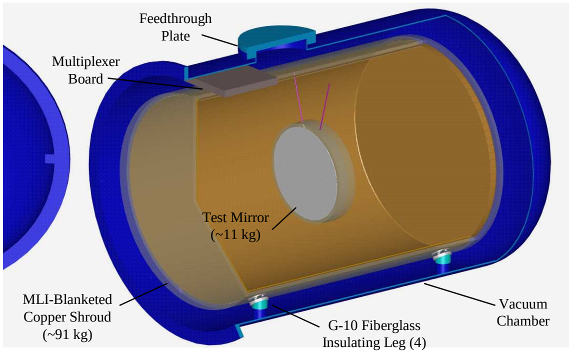
Test configuration

Cylindrical copper shroud mounted on four fiberglass supports inside the vacuum chamber

Shroud covered with 20 layer blanket, painted black on interior

Calibrated miniature Platinum Resistance Thermometers used for measurement

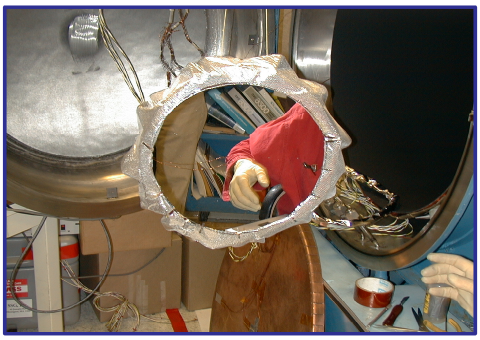
- high accuracy readout system: ± 1 mK relative accuracy following calibration

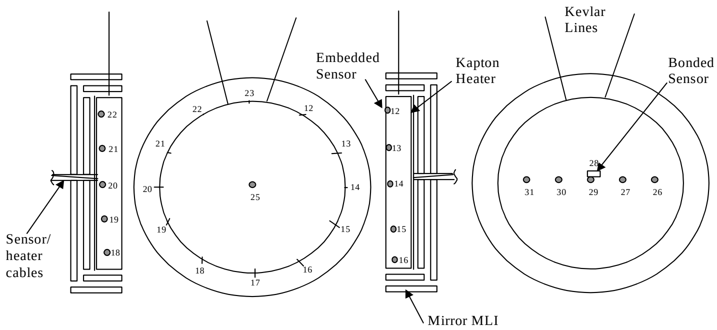


Test article

Test Article was pyrex plano mirror:

- 33.5 cm by 5 cm thick
- suspended in shroud via kevlar twine
- kapton heater bonded on back surface
- offset aluminum heater plate for radiative heating
- 40 layer MLI on sides and back
- instrumented with 18 PRT's



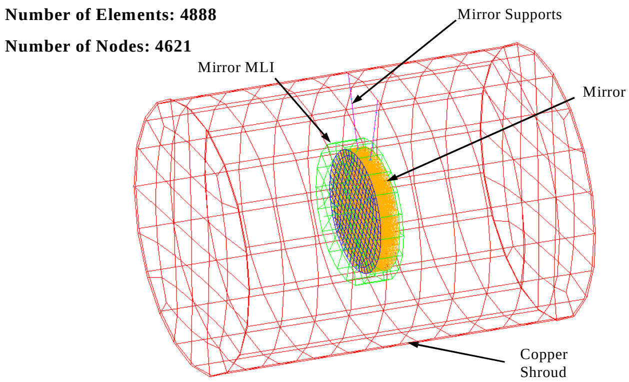


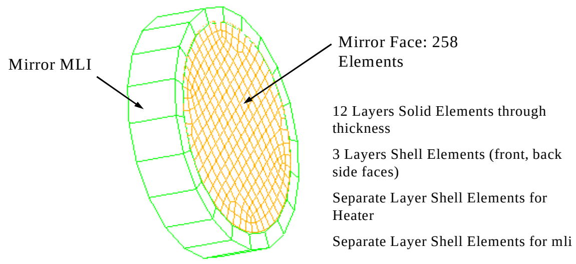
Thermal model

Numerical thermal model constructed using I-DEAS TMG

Boundary conditions:

- Fixed, constant shroud temperature
- Fixed temperature at Kevlar line ends (same as shroud)
- Fixed temperature at cable bundle end (same as shroud)
- Fixed heat load on heater or heater plate



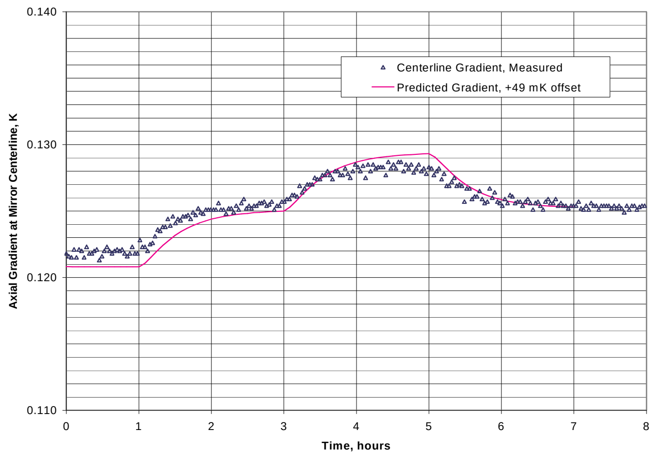


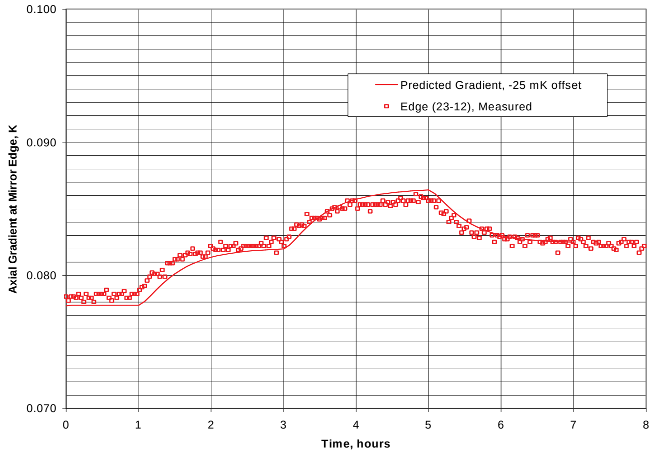
Results comparison

Transient behaviour of the predicted gradients was found to match the measured values very well

- agreement of approximately ±1 mK

Absolute gradients matched to within 25-50 mK

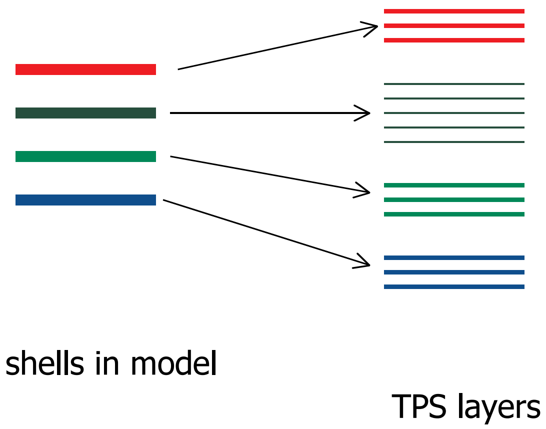




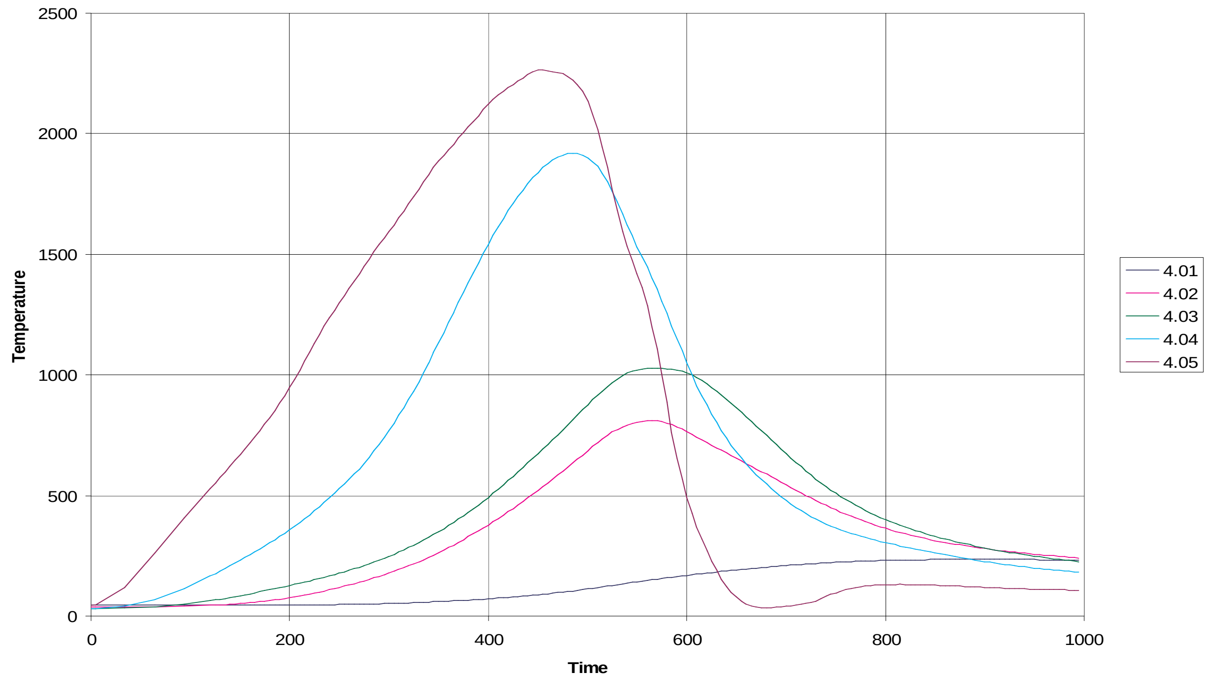
TPS modeling

Multilayer shell elements

- multiple layers of TPS represented by single shell element
- user specifies number of layers; TMG subdivides the element at solve time
- conductive couplings are automatically computed between layers, based on thickness and conductivity
- Thermal Couplings connected to top or bottom layer according to geometry
- supports orthotropic and temperature dependent material properties
- post-processing of layer results



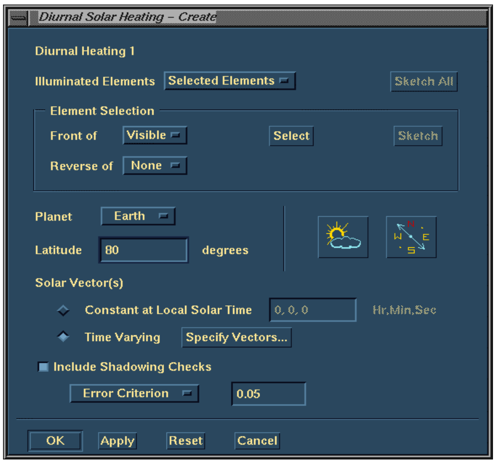
Temperature Profile Through TPS



Other new TMG technology

Diurnal Solar Heating

- computes solar radiative heating on planet surface
- accounts for atmospheric attenuation
- computes solar flux from time/date and planet location, ground surface reflectance, diffuse sky radiation and cloud cover and altitude
- solar vectors can be fixed or time varying



Sliding Contact

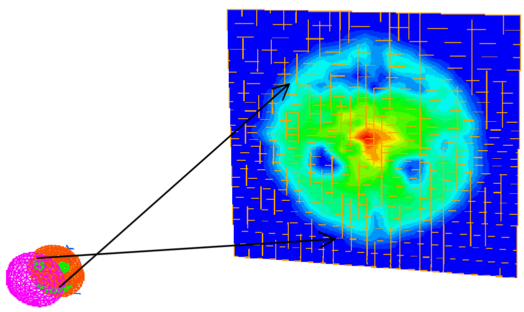
- TMG's Thermal Couplings feature now supports articulation
- time-dependent conductances will be computed based on the translation or rotation of the elements with respect to each other

Other new TMG technology

TMG now supports modeling of refraction through transparent materials

Explicit earth model

- option to use a meshed model of the planet for computing orbital fluxes
- provides more accurate calculation of planetary heat fluxes through narrow apertures
- element density under user control
- element distribution on the planet is optimised



Binary files

- Option to store view factors, conductances in binary format
- Reduces disk space, solution time (up to 2X)
- Utility proved to convert back to ascii

Primitives-based Modeling

Complementary modeling system based on shape primitives
- ESARAD/THERMICA approach
- creates element-based models for TMG
- can be exported as true primitives
- enables the import of primitives-based models

Parameter and point methods
- Distances and points can be picked from graphics or keyed in

Properties: color, material, thickness

HTML online help
- Detailed bitmap image

GUI is driven from ASCII file
- can easily be modified by user to support new type of primitives

Tools to move and rotate primitives

Primitives-based Modeling

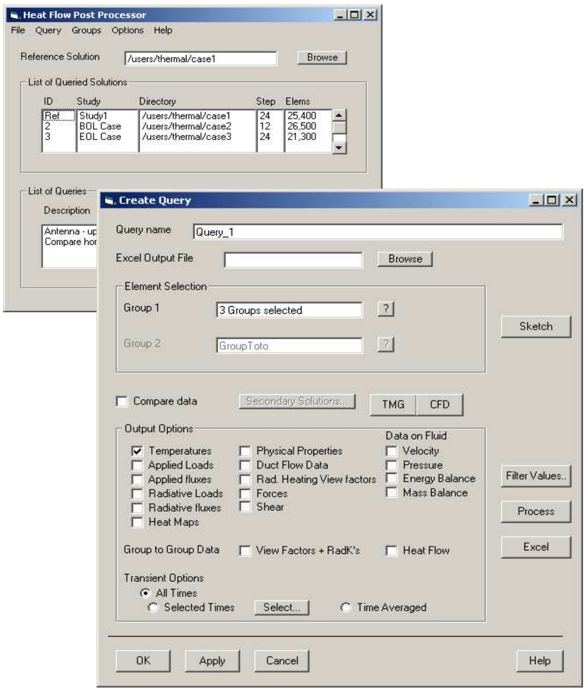
Import / Export
- **Tss**
- **Esarad**
- **Thermica**

Includes all material properties

Testing:
- **Component and large (7,000 primitives) system models have been imported / exported.**

Thermal results reporter

New capability, under development



Will let users query the solution results for detailed data

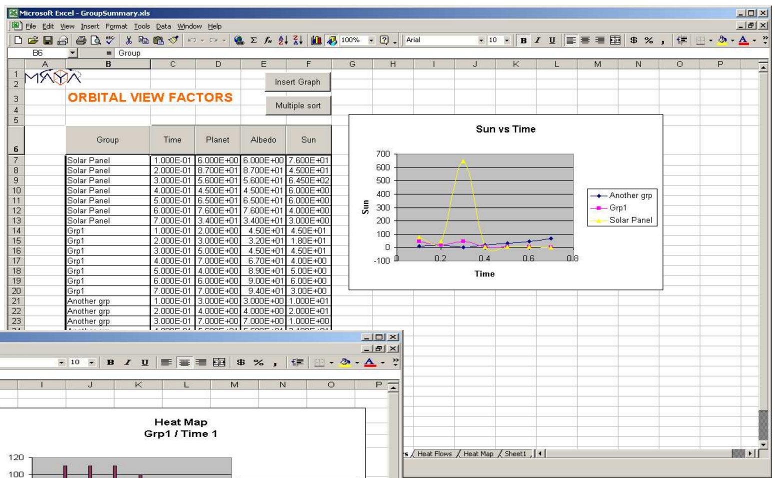
- steady state
- transient
- compare solutions
- time history
- orbital fluxes and view factors
- group to group heat flows
- heat maps

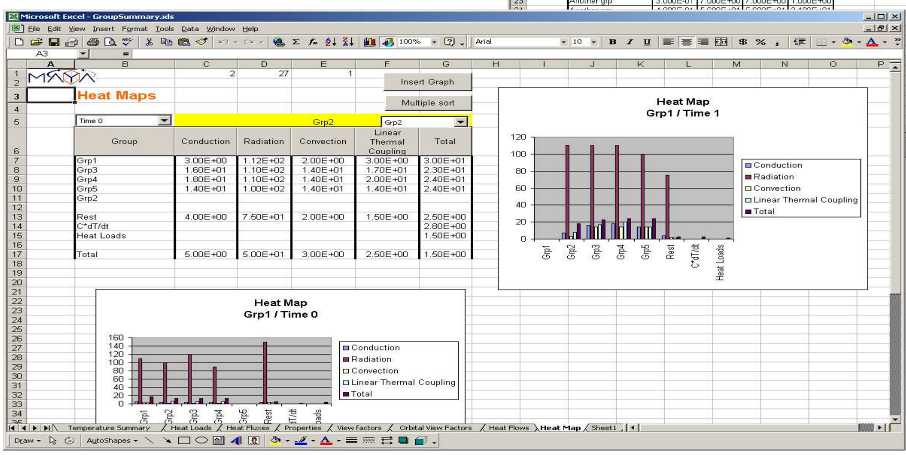
Data is automatically loaded into Excel spreadsheets

- macros to plot and sort

Thermal results reporter

Excel-based reports:





MAYA