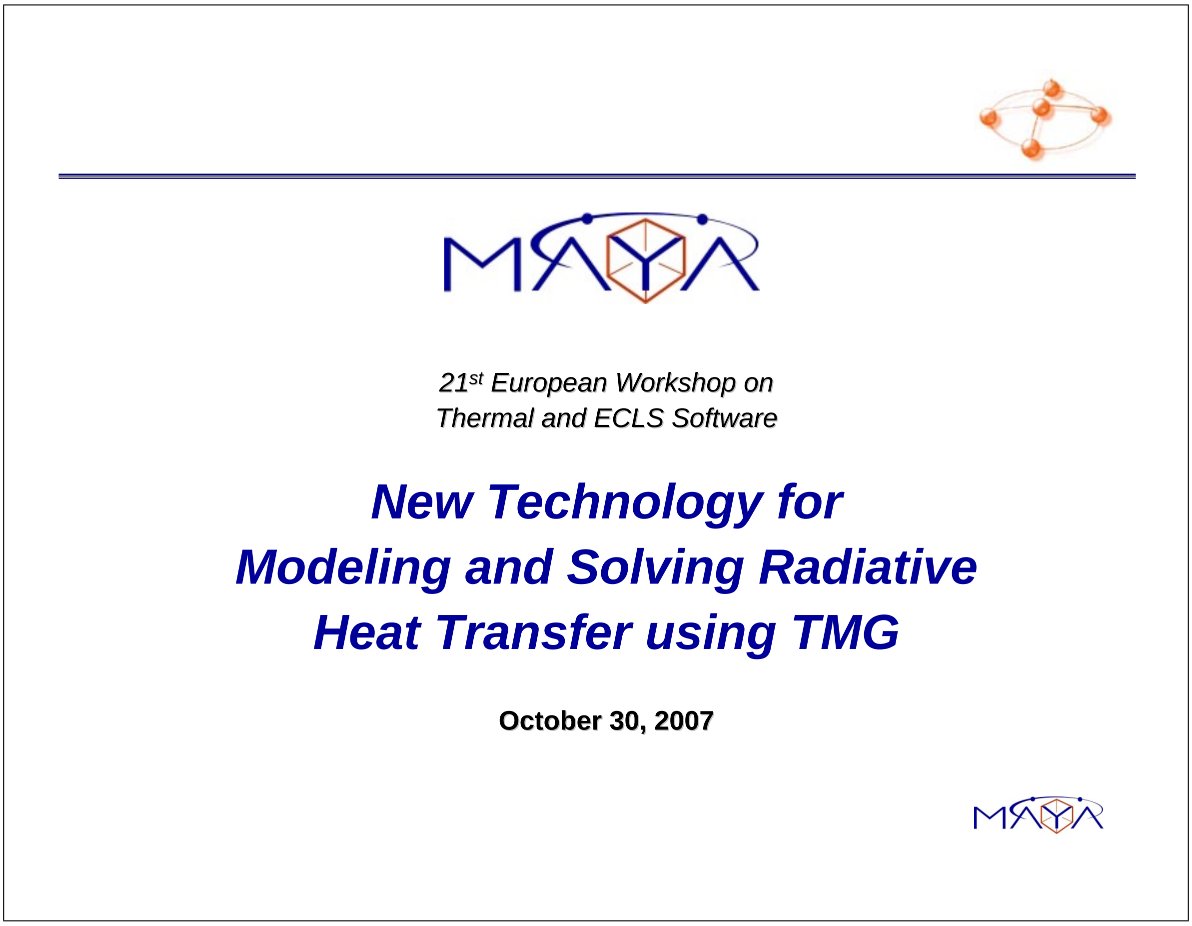
Appendix C

New technology for modelling and solving radiative heat transfer using TMG

Kevin Duffy
(MAYA, Canada)



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New Technology for Modeling and Solving Radiative Heat Transfer using TMG

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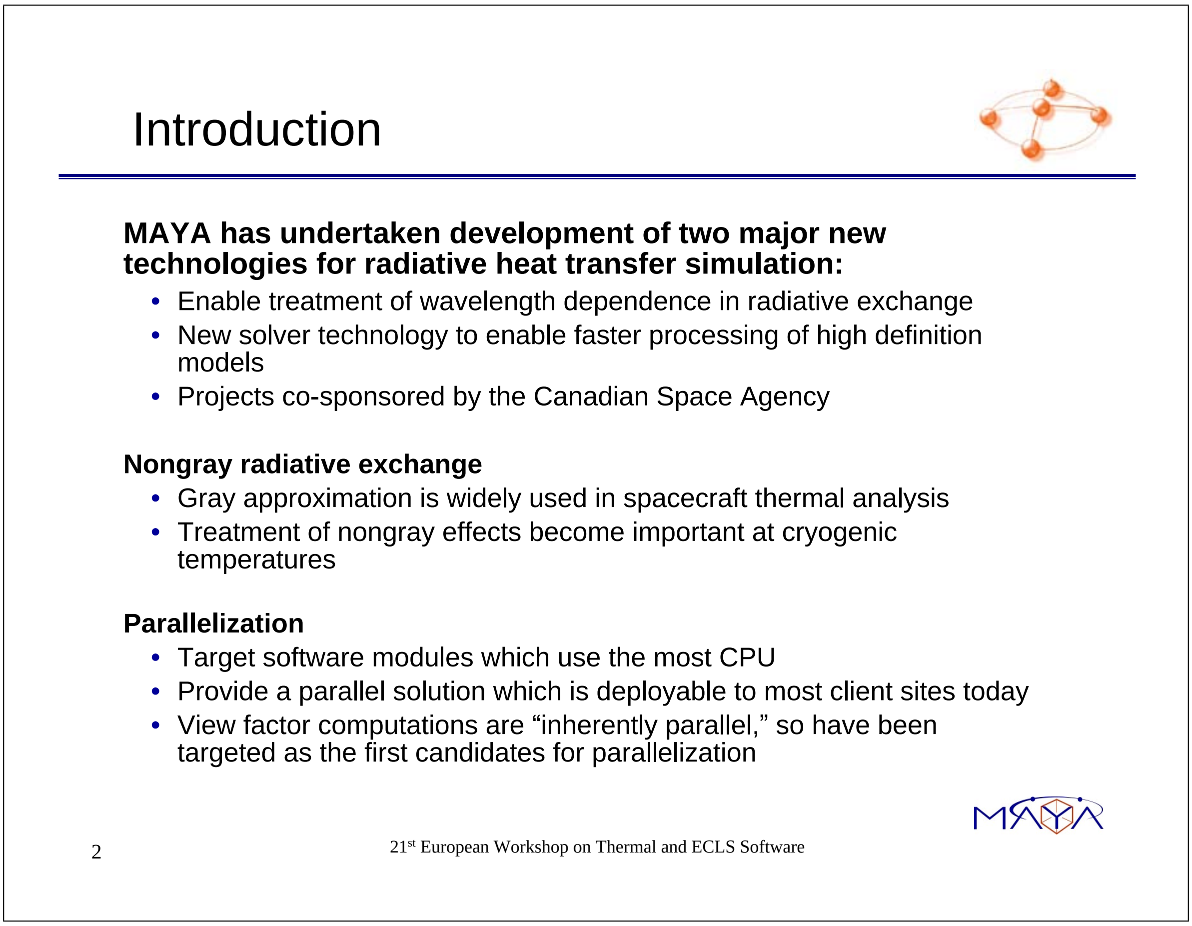


Introduction

MAYA has undertaken development of two major new technologies for radiative heat transfer simulation:

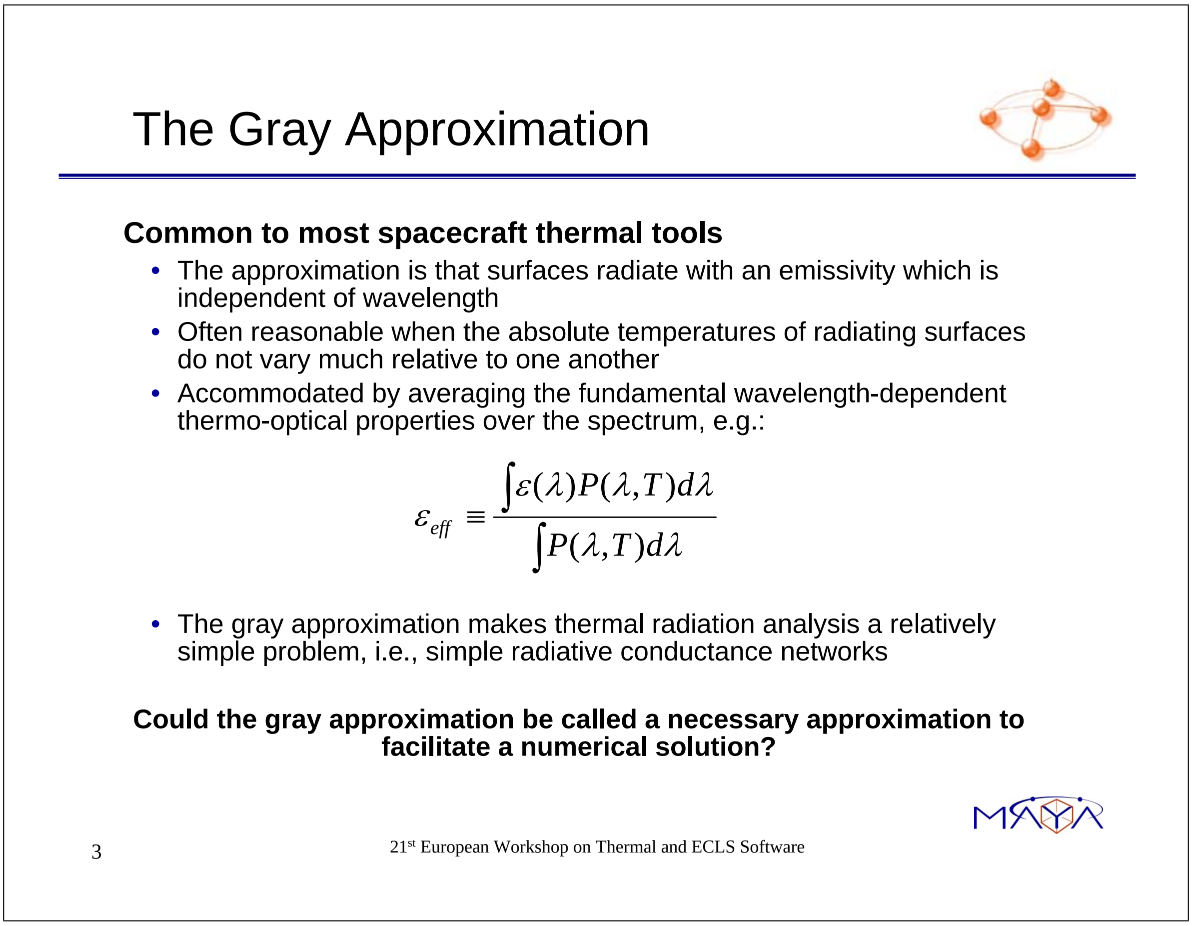
- Enable treatment of wavelength dependence in radiative exchange
- New solver technology to enable faster processing of high definition models
- Projects co-sponsored by the Canadian Space Agency

Nongray radiative exchange

- Gray approximation is widely used in spacecraft thermal analysis
- Treatment of nongray effects become important at cryogenic temperatures

Parallelization

- Target software modules which use the most CPU
- Provide a parallel solution which is deployable to most client sites today
- View factor computations are “inherently parallel,” so have been targeted as the first candidates for parallelization



The Gray Approximation

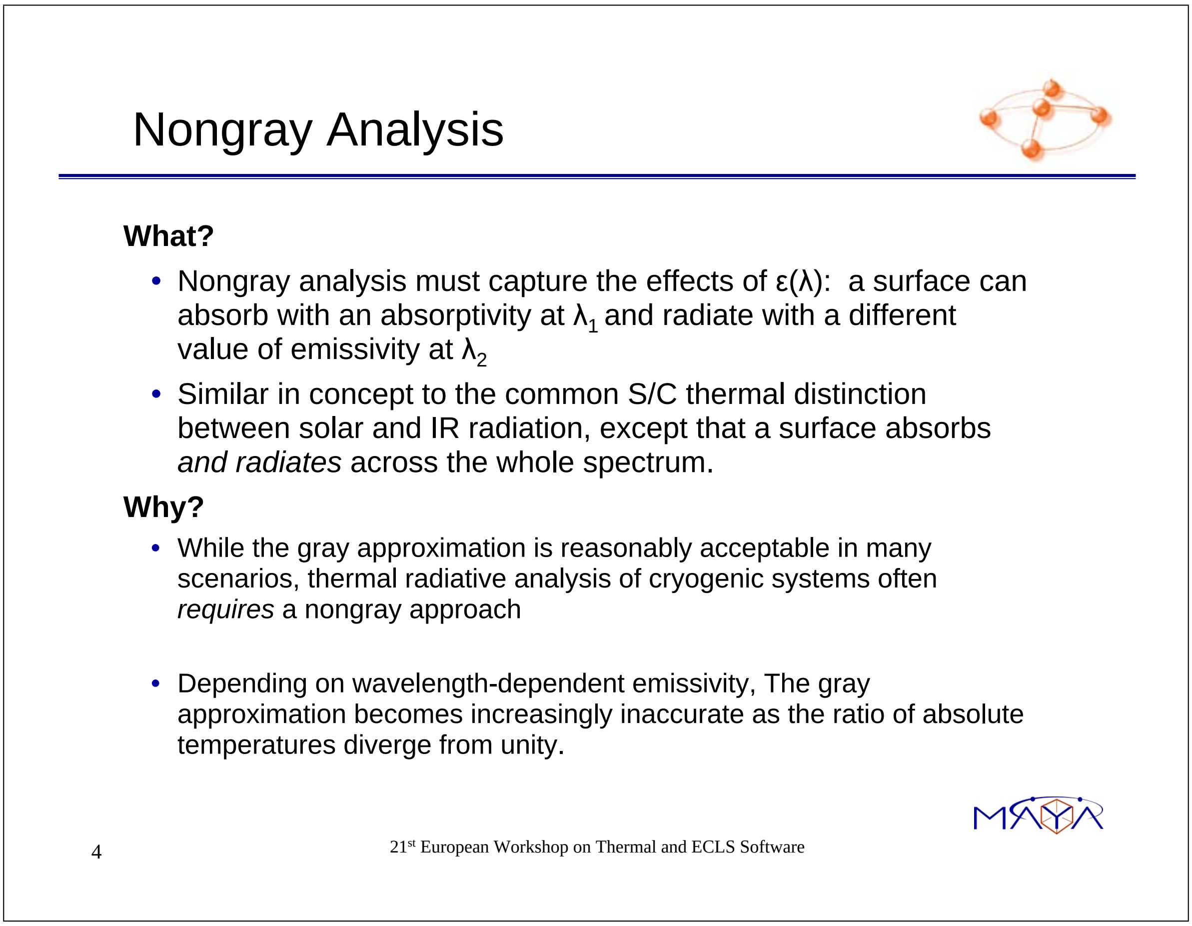
Common to most spacecraft thermal tools

- The approximation is that surfaces radiate with an emissivity which is independent of wavelength
- Often reasonable when the absolute temperatures of radiating surfaces do not vary much relative to one another
- Accommodated by averaging the fundamental wavelength-dependent thermo-optical properties over the spectrum, e.g.:

$$\varepsilon_{eff} \equiv \frac{\int \varepsilon(\lambda) P(\lambda,T)\, d\lambda}{\int P(\lambda,T)\, d\lambda}$$

- The gray approximation makes thermal radiation analysis a relatively simple problem, i.e., simple radiative conductance networks

Could the gray approximation be called a necessary approximation to facilitate a numerical solution?



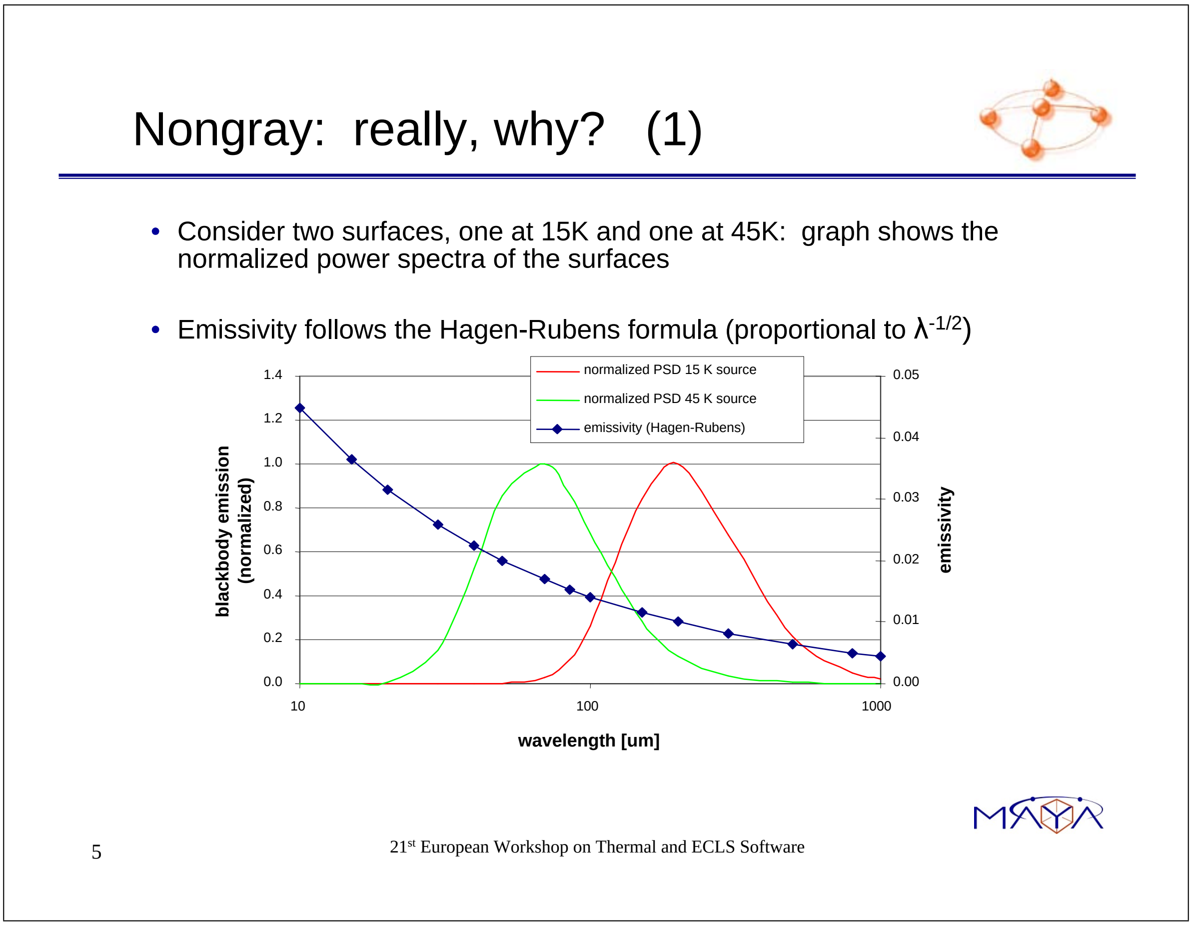
Nongray Analysis

What?

- Nongray analysis must capture the effects of $\varepsilon(\lambda)$: a surface can absorb with an absorptivity at λ_1 and radiate with a different value of emissivity at λ_2
- Similar in concept to the common S/C thermal distinction between solar and IR radiation, except that a surface absorbs *and radiates* across the whole spectrum.

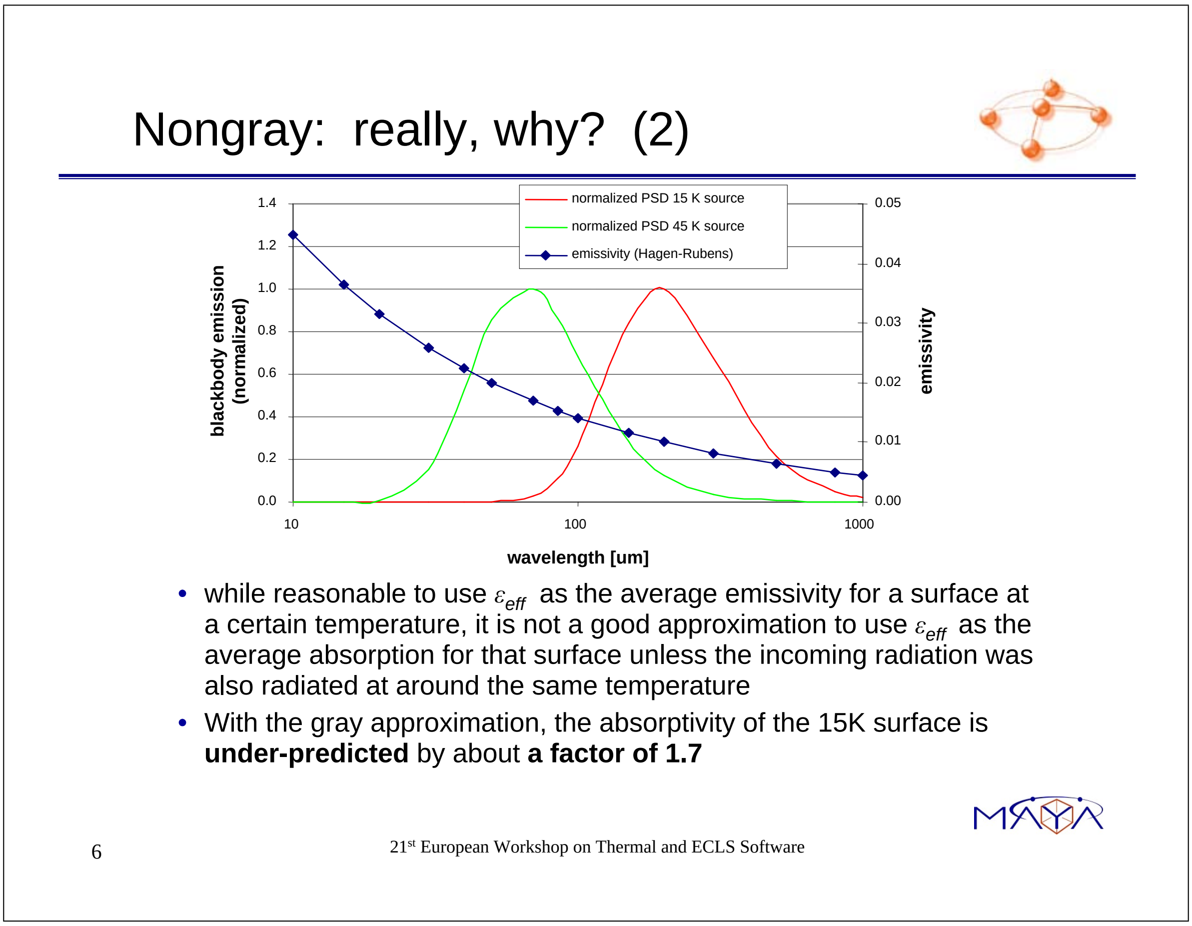
Why?

- While the gray approximation is reasonably acceptable in many scenarios, thermal radiative analysis of cryogenic systems often *requires* a nongray approach
- Depending on wavelength-dependent emissivity, The gray approximation becomes increasingly inaccurate as the ratio of absolute temperatures diverge from unity.



Nongray: really, why? (1)

- Consider two surfaces, one at 15K and one at 45K: graph shows the normalized power spectra of the surfaces
- Emissivity follows the Hagen-Rubens formula (proportional to $\lambda^{-1/2}$)



Nongray: really, why? (2)

- while reasonable to use ε_{eff} as the average emissivity for a surface at a certain temperature, it is not a good approximation to use ε_{eff} as the average absorption for that surface unless the incoming radiation was also radiated at around the same temperature
- With the gray approximation, the absorptivity of the 15K surface is **under-predicted** by about **a factor of 1.7**

Nongray Analysis in TMG

Discretization

- The fundamental equations for radiative exchange between surfaces are discretized in terms of wavelength
- The discretization takes the form of *N wavelength bands*
- Thermo-optical properties are now defined band-wise:

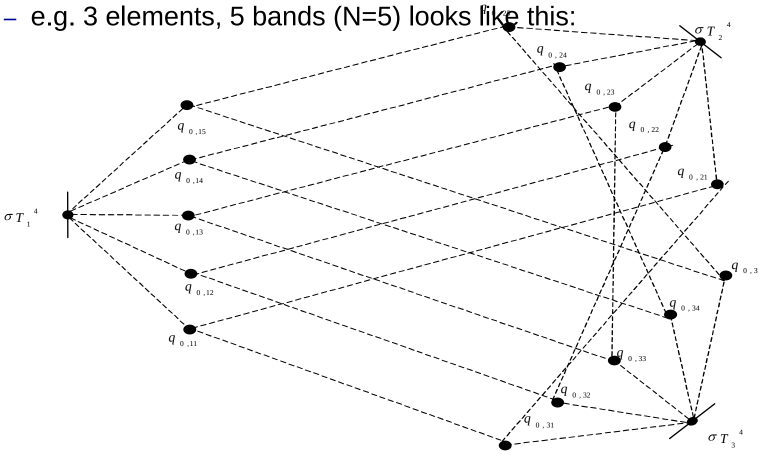
$$\varepsilon_{kg} \equiv \frac{\int_{\lambda_{g-1}}^{\lambda_g} \varepsilon(\lambda)P(\lambda,T)d\lambda}{\int_{\lambda_{g-1}}^{\lambda_g} P(\lambda,T)d\lambda} \approx \frac{\int_{\lambda_{g-1}}^{\lambda_g} \varepsilon(\lambda)d\lambda}{\int_{\lambda_{g-1}}^{\lambda_g} d\lambda} = \frac{1}{\Delta\lambda}\int_{\lambda_{g-1}}^{\lambda_g} \varepsilon(\lambda)d\lambda$$

- *g* is the band number
- number of bands and band spacing is user-input

Nongray Analysis in TMG

Multiband Radiosity Method

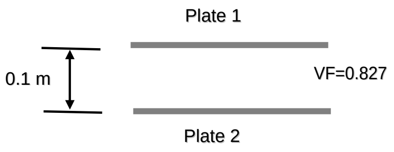
- The radiosity method has been rederived using the band structure
- Each radiating element takes N radiosity (‘Oppenheim’) elements
- A distinct radiative conductance network is created in each band
  - e.g. 3 elements, 5 bands (N=5) looks like this:



Nongray Validation

Two Plates in space

- Plate 1:
  area = 1 m^2, Sink @ T_1, ε_{1g}, g=1..N
- Plate 2:
  area = 1 m^2, ε_{2g}, g=1..N



- Total heat emitted and absorbed by plate 2 can be derived analytically:

$$Q_{2,emit} = \sum_{g=1}^{N} \varepsilon_{2,g}\, p_g(T_2) A \sigma T_2^4$$

$$Q_{2,abs} = \sigma \sum_{g=1}^{N} \left\{ \left[\varepsilon_{1g} A_1 p_g(T_1) T_1^4 VF_{12} \varepsilon_{2g} + (\varepsilon_{2g})^2 A_2 p_g(T_2) T_2^4 VF_{21} (1-\varepsilon_{1g}) VF_{12} \right] \times \left[\frac{1}{1 - VF_{12} VF_{21} (1-\varepsilon_{1g})(1-\varepsilon_{2g})} \right] \right\}$$

- 4 test cases varying T_1, N, ε_{1g} and ε_{2g}

Nongray Validation

Two Plates in Space: Test Matrix

Test Case	Number of Bands	Band limits (micrometers)					T_1 = Element 1 Temperature (sink)
		λ_0	λ_1	λ_2	λ_3	λ_4	
2.0	1	-	-	-	-	-	100 K
2.1	2	0	40.0	4.E3	-	-	100 K
2.2	2	0	40.0	4.E3	-		100 K
2.3	2	0	40	4.E3	6.E3		50 K
2.4	4	0	40.0	80.0	120.0	1.2E5	60 K

Test Case	Number of Bands	Band Emissivities (element 1)				Band Emissivities (element 2)			
		ε_1	ε_2	ε_3	ε_4	ε_1	ε_2	ε_3	ε_4
2.0	1	0.5	-	-	-	0.5	-	-	-
2.1	2	0.1	0.25	-	-	0.1	0.2	-	-
2.2	2	0.5	0.05	-	-	0.1	0.2	-	-
2.3	2	0.1	0.25	-	-	0.1	0.2	-	-
2.4	4	0.1	0.25	0.15	.05	0.3	0.25	0.2	0.18

Nongray Validation

Two Plates in Space: Results

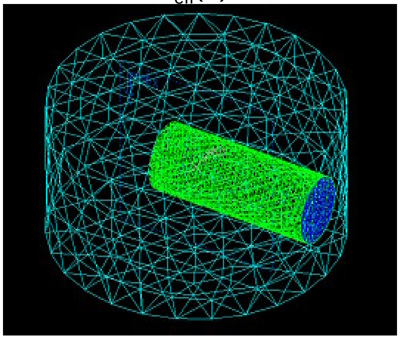
- T_2 is temperature computed with nongray method
- $Q_{2,abs}$ and $Q_{2,emit}$ are computed analytically from T2
- Method should yield $Q_{2,emit}=Q_{2,abs}$

Test Case	T_1 (input)	T_2 (result)	$Q_{2,emit}(T_2)$ (analytic)	$Q_{2,abs}(T_2)$ (analytic)	% error
2.0	100 K	77.95 K	0.419 W	0.415 W	0.9%
2.1	100 K	88.91 K	0.911 W	0.904 W	0.8 %
2.2	100 K	73.19 K	0.284 W	0.280 W	1.2%
2.3	50 K	40.05 K	0.0289 W	0.0286 W	0.8%
2.4	60 K	46.17 K	0.0559 W	0.0547 W	2.2%

Nongray: Sample Application

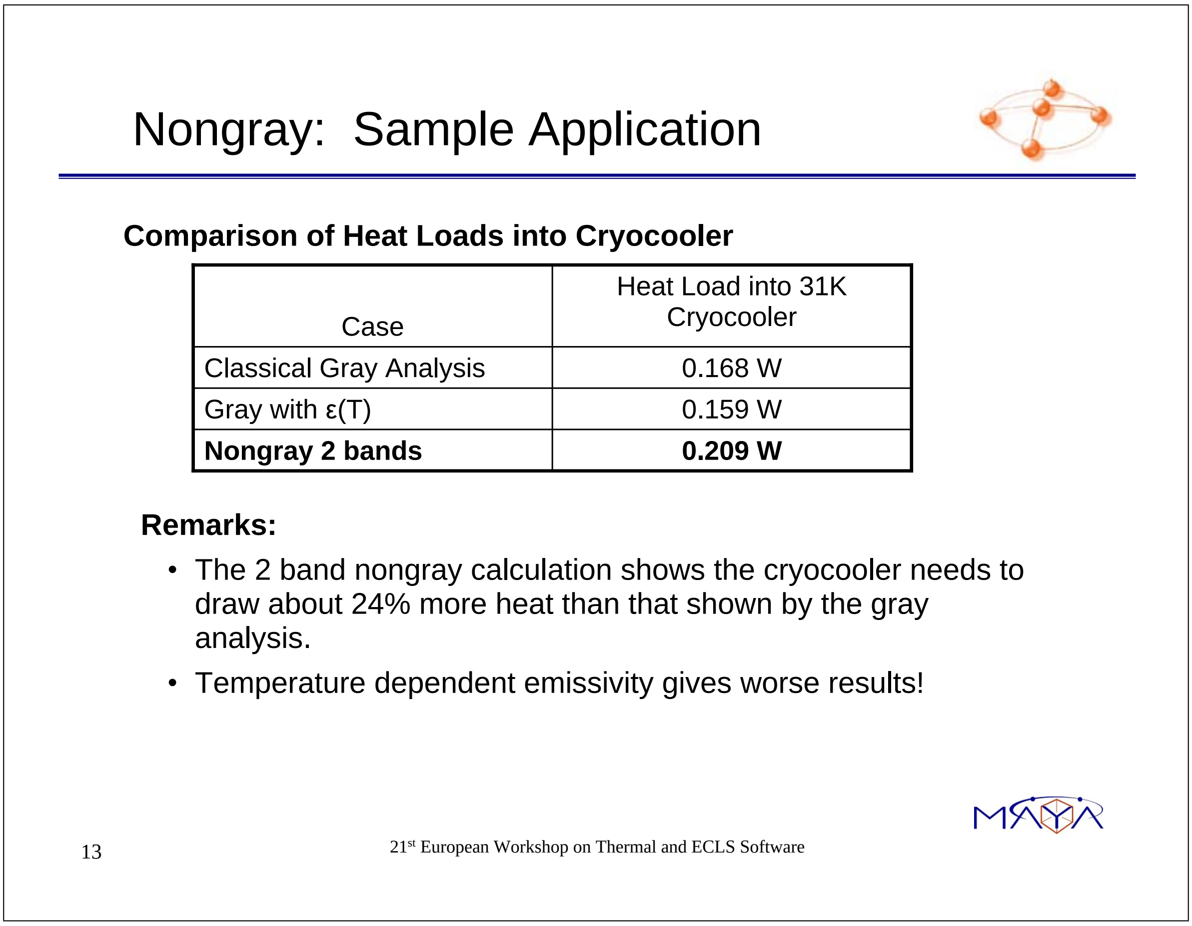
Simplified model of telescope instrument with cryogenic optics

- ε(λ) for the three materials in the model were used to determine emissivities for three separate analyses :
  - classical gray analysis with constant ε_{eff}
  - gray model with temperature dependent emissivities $\varepsilon_{eff}(T)$
  - two-band nongray model



- Cryocooler modeled as a 31 K nongeometric sink coupled to the end of the telescope

- Critical design issue is how much heat load goes into the cryocooler



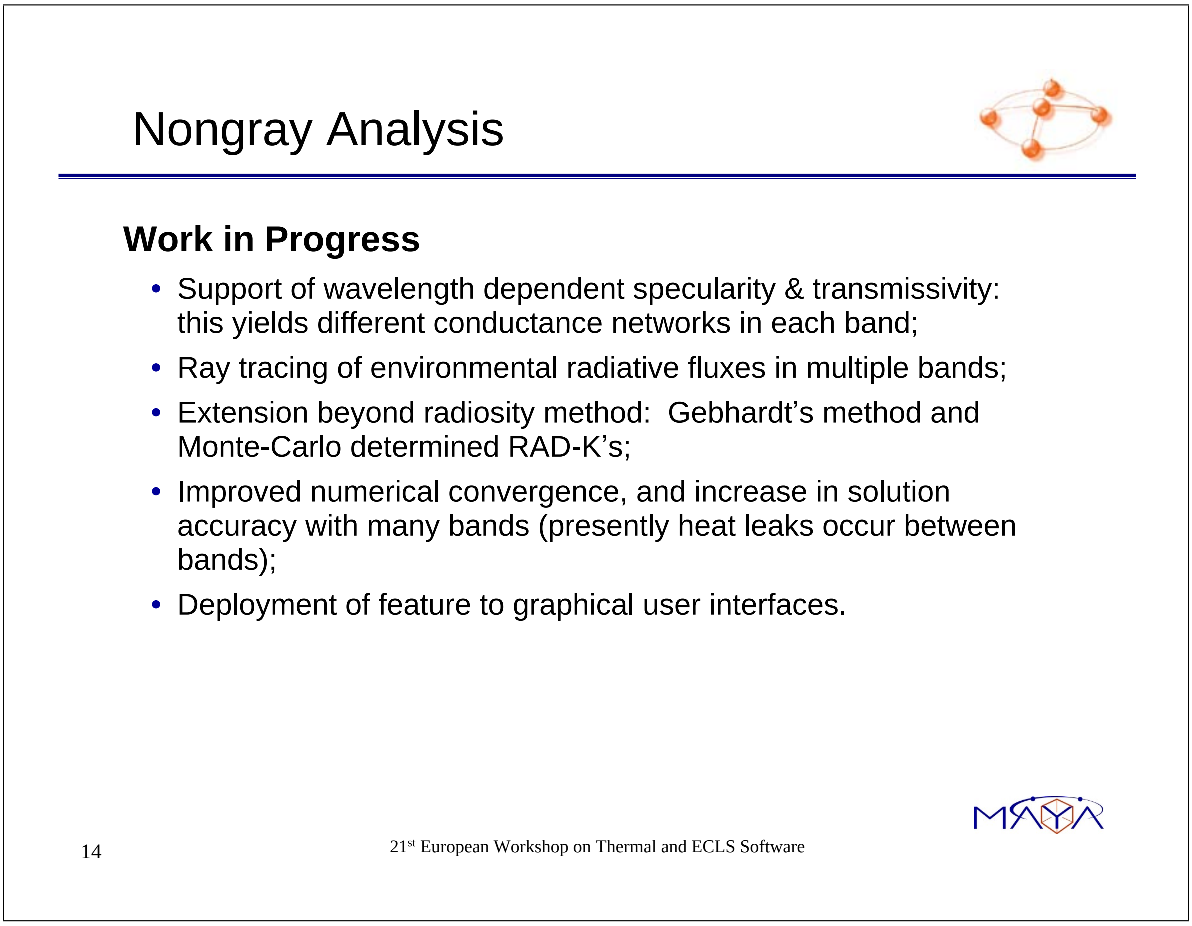
Nongray: Sample Application

Comparison of Heat Loads into Cryocooler

Case	Heat Load into 31K Cryocooler
Classical Gray Analysis	0.168 W
Gray with ε(T)	0.159 W
Nongray 2 bands	**0.209 W**

Remarks:

- The 2 band nongray calculation shows the cryocooler needs to draw about 24% more heat than that shown by the gray analysis.
- Temperature dependent emissivity gives worse results!



Nongray Analysis

Work in Progress

- Support of wavelength dependent specularity & transmissivity: this yields different conductance networks in each band;
- Ray tracing of environmental radiative fluxes in multiple bands;
- Extension beyond radiosity method: Gebhardt's method and Monte-Carlo determined RAD-K's;
- Improved numerical convergence, and increase in solution accuracy with many bands (presently heat leaks occur between bands);
- Deployment of feature to graphical user interfaces.

Parallel Computing

Motivation

- Analysts are consistently building bigger, higher fidelity models, and still want faster throughput
- Improvement in processor clock rates is becoming asymptotic
- Multi-core processors are becoming more predominant
- Many users wish to make use of networked computers and/or clusters

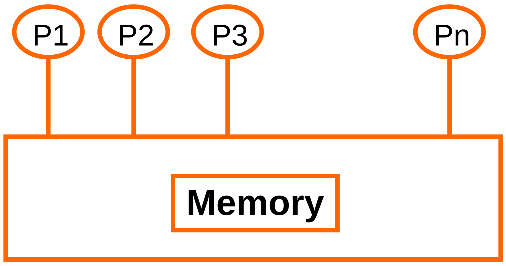
Possible Approaches

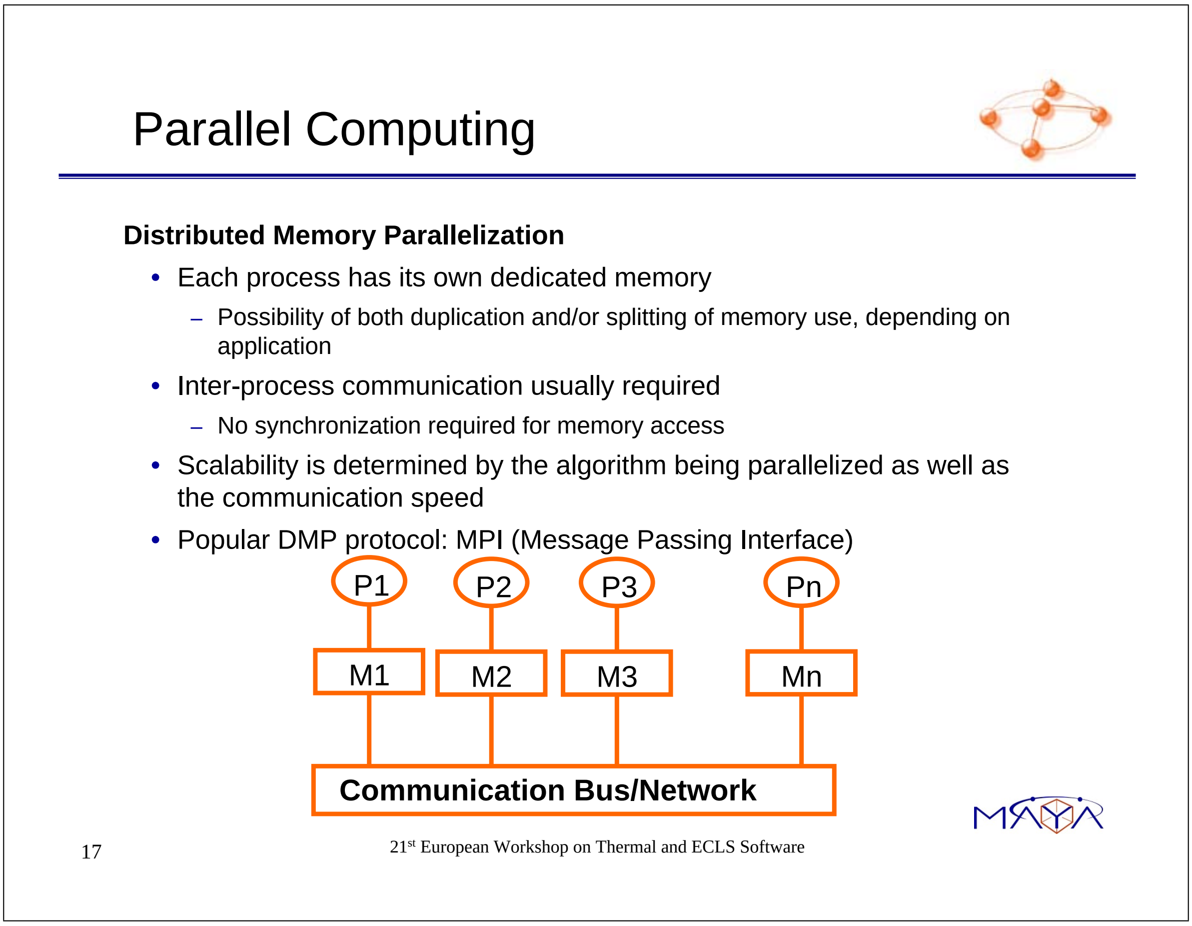
- Shared memory
  - Parallel processes or threads share same data space
- Distributed memory
  - Parallel processes each have dedicated memory and communicate via message passing.

Parallel Computing

Shared Memory Parallelization

- Same memory usage as the serial run
- Multiple processes use the same memory and I/O
  - Synchronization of tasks is the key for implementation
  - Deadlocks and memory overwrites must be avoided!
- Scalability is determined by the hardware
- Popular Open SMP protocol: OpenMP





Parallel Computing

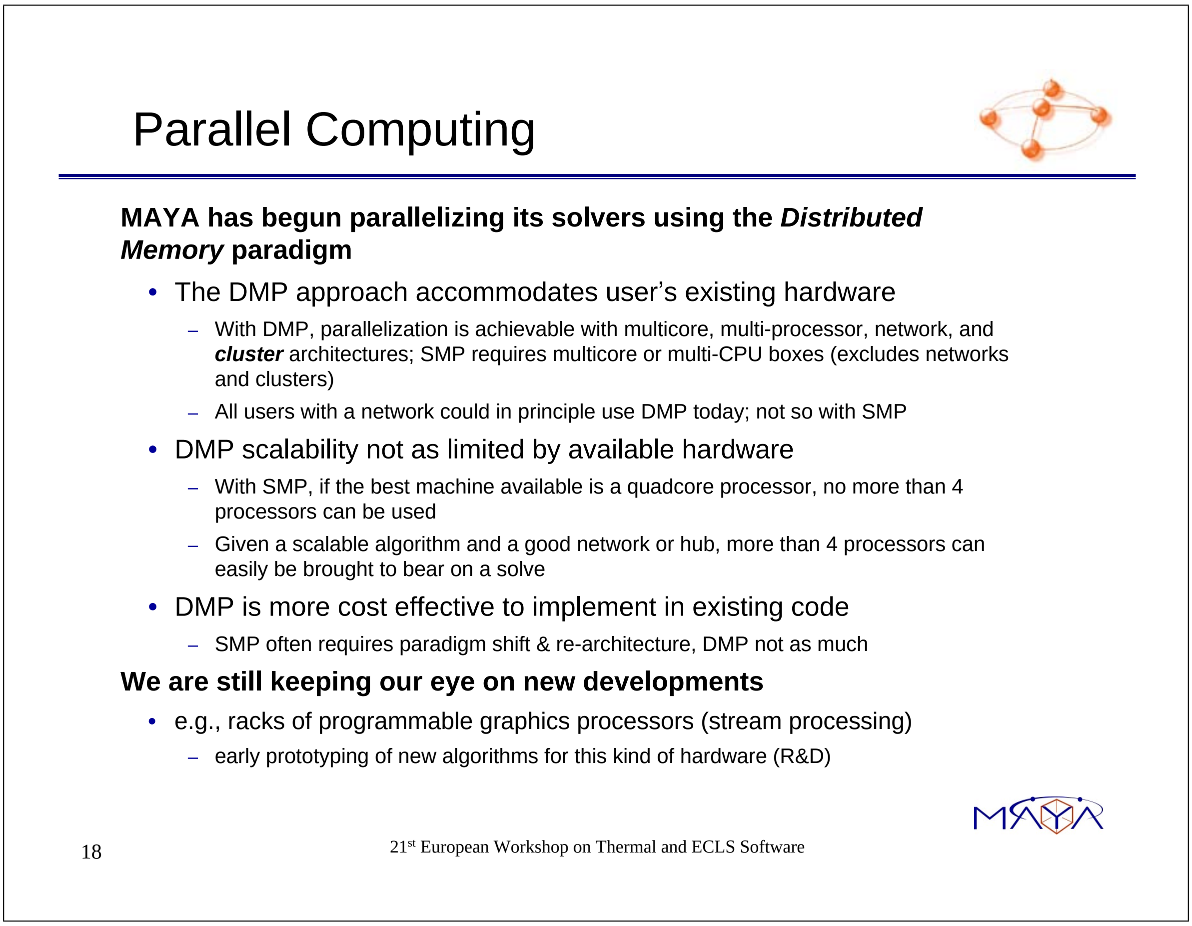
Distributed Memory Parallelization

- Each process has its own dedicated memory
  - Possibility of both duplication and/or splitting of memory use, depending on application
- Inter-process communication usually required
  - No synchronization required for memory access
- Scalability is determined by the algorithm being parallelized as well as the communication speed
- Popular DMP protocol: MPI (Message Passing Interface)

P1 P2 P3 Pn

M1 M2 M3 Mn

Communication Bus/Network



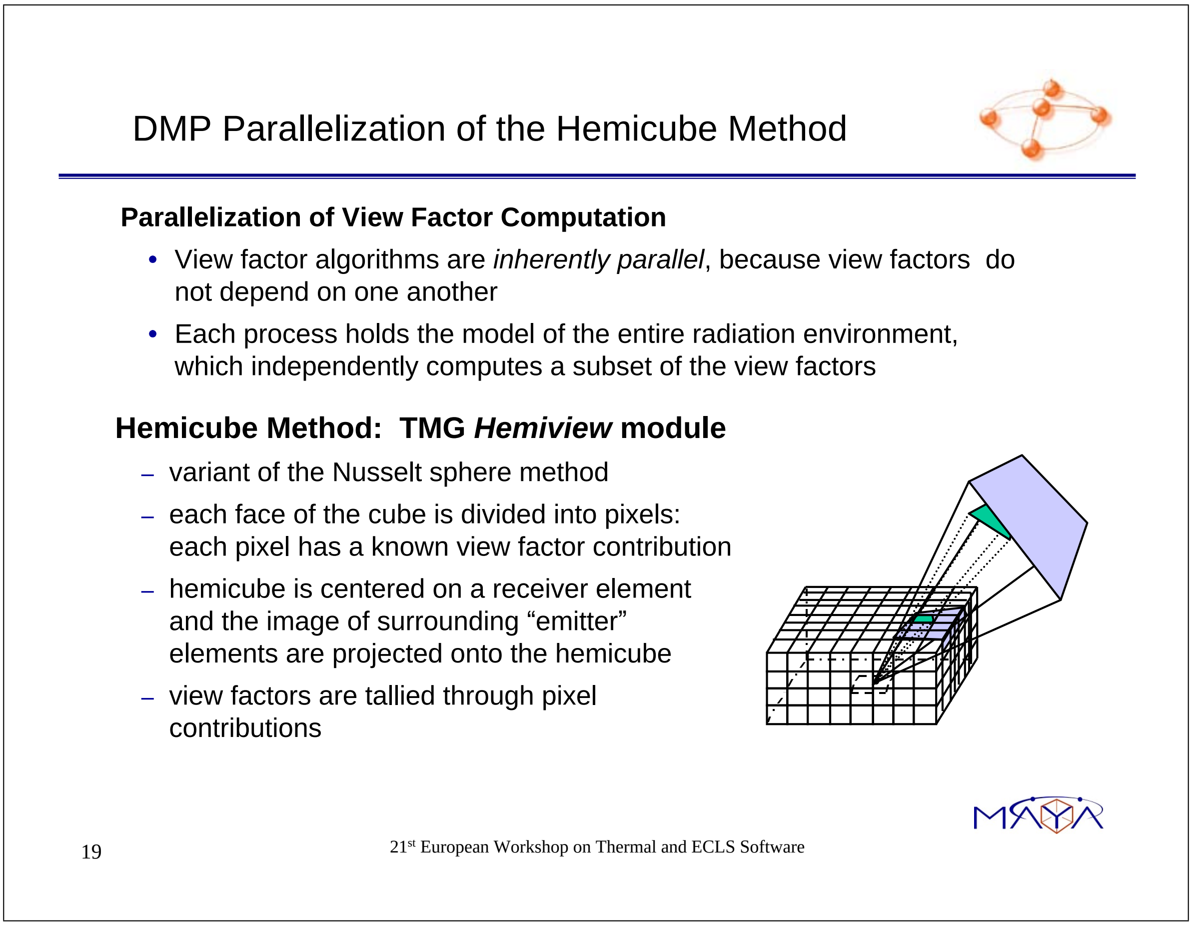
Parallel Computing

MAYA has begun parallelizing its solvers using the *Distributed Memory* paradigm

- The DMP approach accommodates user’s existing hardware
  - With DMP, parallelization is achievable with multicore, multi-processor, network, and ***cluster*** architectures; SMP requires multicore or multi-CPU boxes (excludes networks and clusters)
  - All users with a network could in principle use DMP today; not so with SMP
- DMP scalability not as limited by available hardware
  - With SMP, if the best machine available is a quadcore processor, no more than 4 processors can be used
  - Given a scalable algorithm and a good network or hub, more than 4 processors can easily be brought to bear on a solve
- DMP is more cost effective to implement in existing code
  - SMP often requires paradigm shift & re-architecture, DMP not as much

We are still keeping our eye on new developments

- e.g., racks of programmable graphics processors (stream processing)
  - early prototyping of new algorithms for this kind of hardware (R&D)



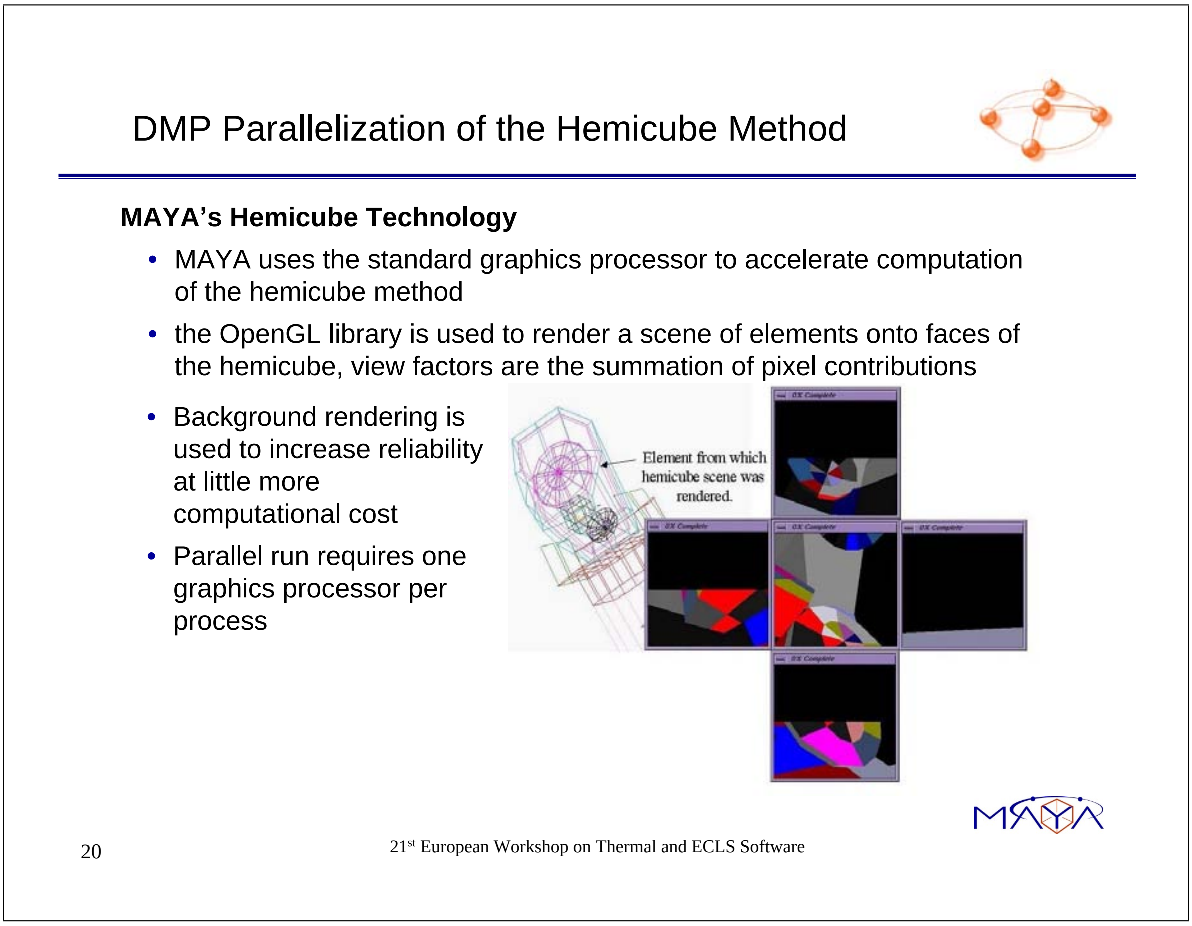
DMP Parallelization of the Hemicube Method

Parallelization of View Factor Computation

- View factor algorithms are *inherently parallel*, because view factors do not depend on one another
- Each process holds the model of the entire radiation environment, which independently computes a subset of the view factors

Hemicube Method: TMG *Hemiview* module

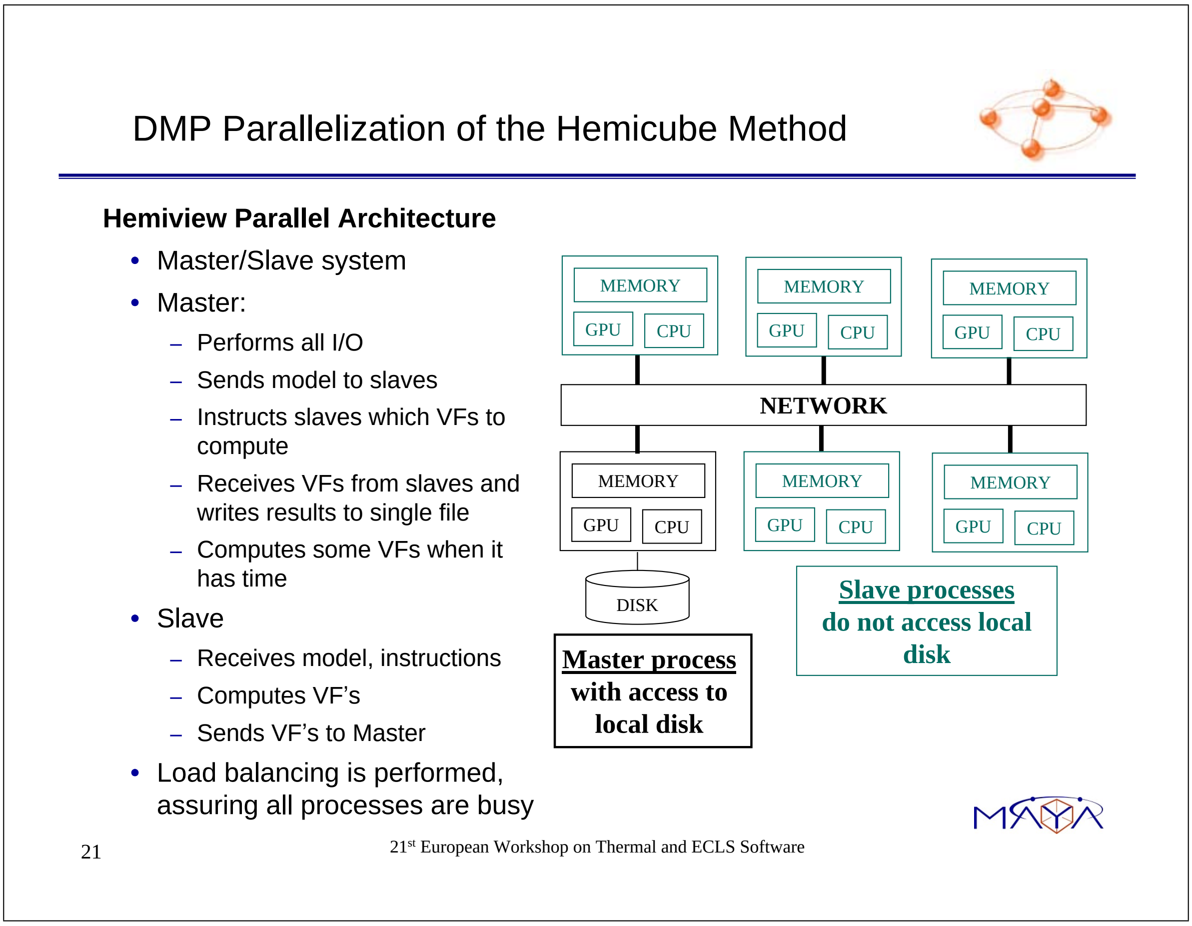
- variant of the Nusselt sphere method
- each face of the cube is divided into pixels: each pixel has a known view factor contribution
- hemicube is centered on a receiver element and the image of surrounding “emitter” elements are projected onto the hemicube
- view factors are tallied through pixel contributions



DMP Parallelization of the Hemicube Method

MAYA’s Hemicube Technology

- MAYA uses the standard graphics processor to accelerate computation of the hemicube method
- the OpenGL library is used to render a scene of elements onto faces of the hemicube, view factors are the summation of pixel contributions
- Background rendering is used to increase reliability at little more computational cost
- Parallel run requires one graphics processor per process



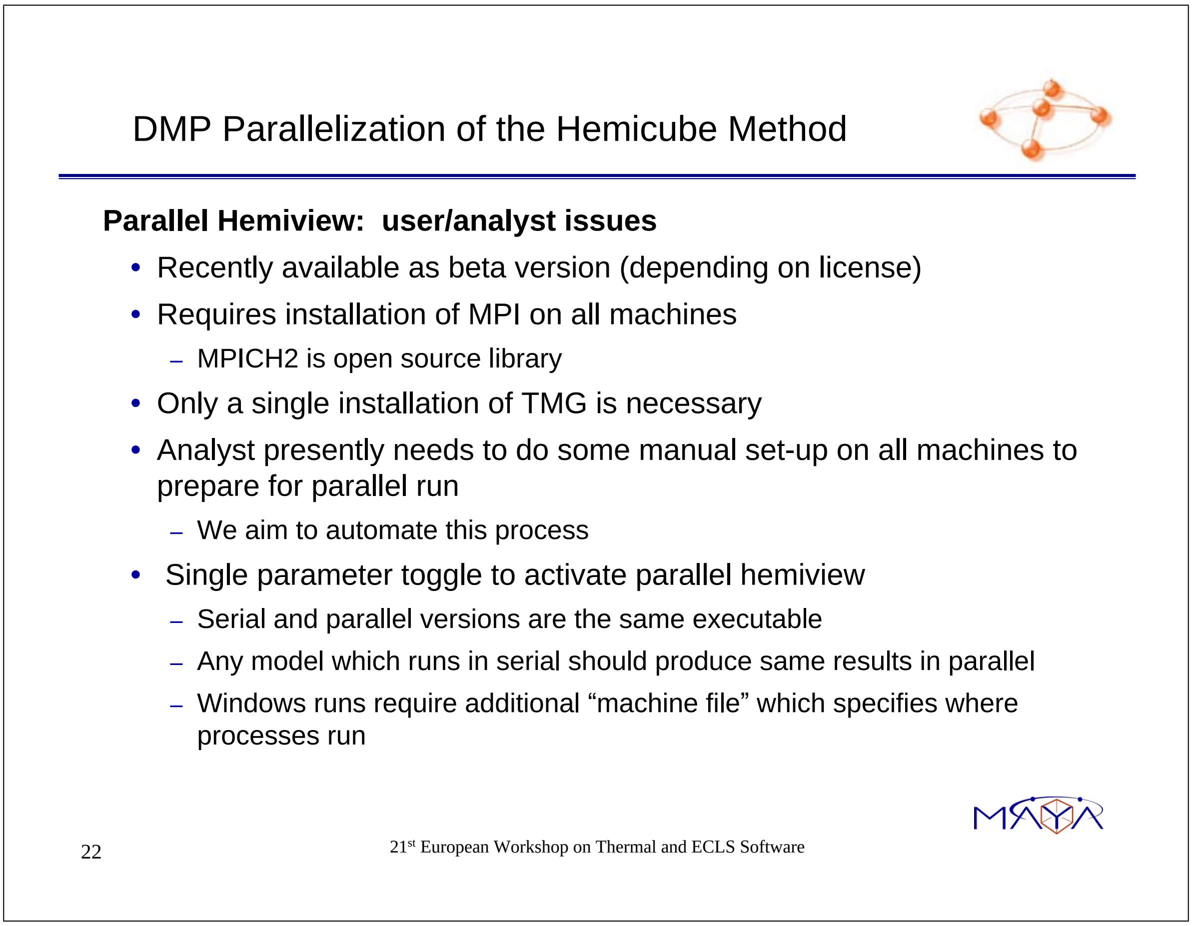
DMP Parallelization of the Hemicube Method

Hemiview Parallel Architecture

- Master/Slave system
- Master:
  - Performs all I/O
  - Sends model to slaves
  - Instructs slaves which VFs to compute
  - Receives VFs from slaves and writes results to single file
  - Computes some VFs when it has time
- Slave
  - Receives model, instructions
  - Computes VF’s
  - Sends VF’s to Master
- Load balancing is performed, assuring all processes are busy

Master process with access to local disk

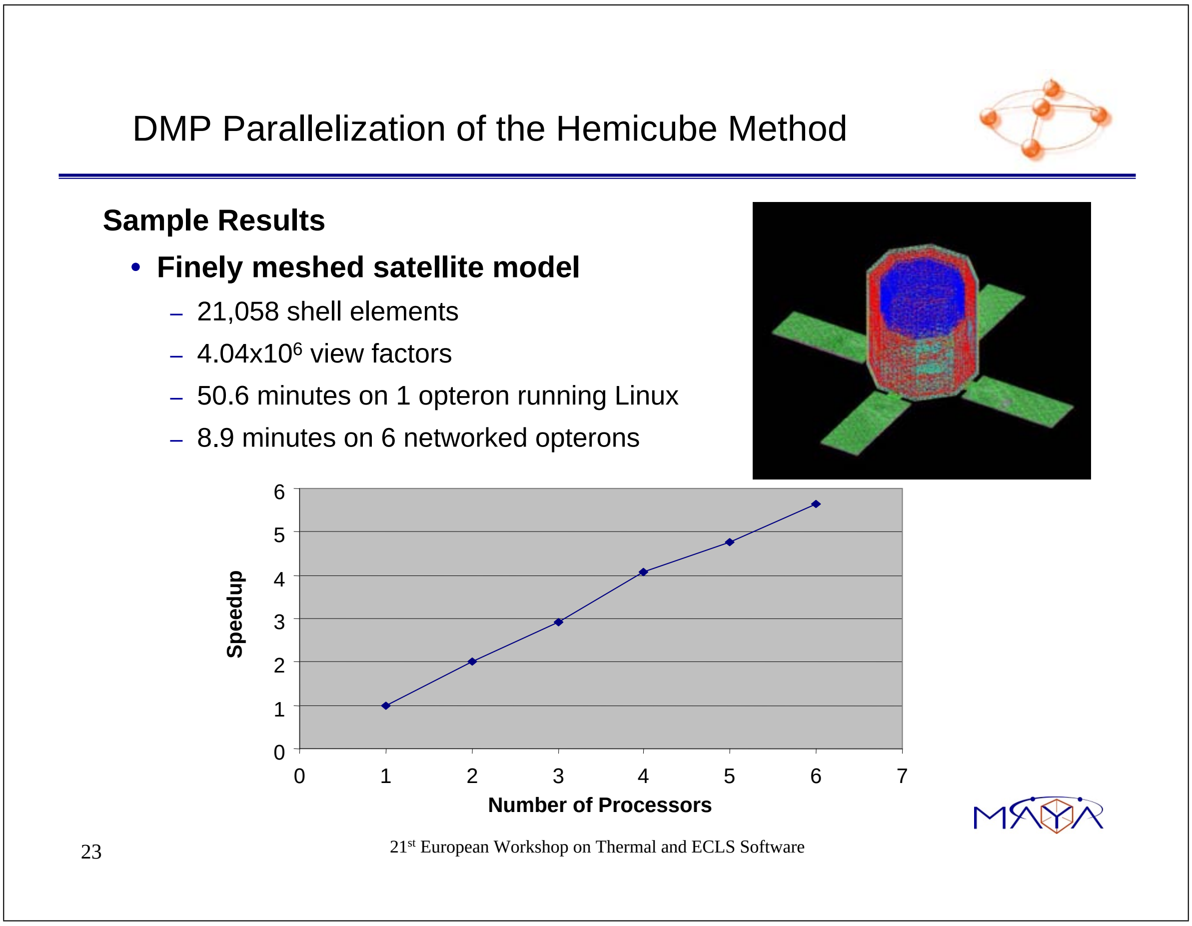
Slave processes do not access local disk



DMP Parallelization of the Hemicube Method

Parallel Hemiview: user/analyst issues

- Recently available as beta version (depending on license)
- Requires installation of MPI on all machines
  - MPICH2 is open source library
- Only a single installation of TMG is necessary
- Analyst presently needs to do some manual set-up on all machines to prepare for parallel run
  - We aim to automate this process
- Single parameter toggle to activate parallel hemiview
  - Serial and parallel versions are the same executable
  - Any model which runs in serial should produce same results in parallel
  - Windows runs require additional “machine file” which specifies where processes run



DMP Parallelization of the Hemicube Method

Sample Results

- **Finely meshed satellite model**
  - 21,058 shell elements
  - 4.04x10^6 view factors
  - 50.6 minutes on 1 opteron running Linux
  - 8.9 minutes on 6 networked opterons

More Parallelization

Work-in-progress and future work includes:

- Parallelization of linear conjugate gradient solver and matrix assembly (domain decomposition)
  - prototyping work indicates speedups of 2-3 on 4 processors for large models
  - ‘non-sparse’ radiation matrix complicates domain decomposition strategies
- Parallelization of ray-tracing and general view factor module (VUFAC)
- Parallelization of other key computational bottlenecks in the TMG solve
- Investigation of new hardware, especially programmable graphics processors


MAYA