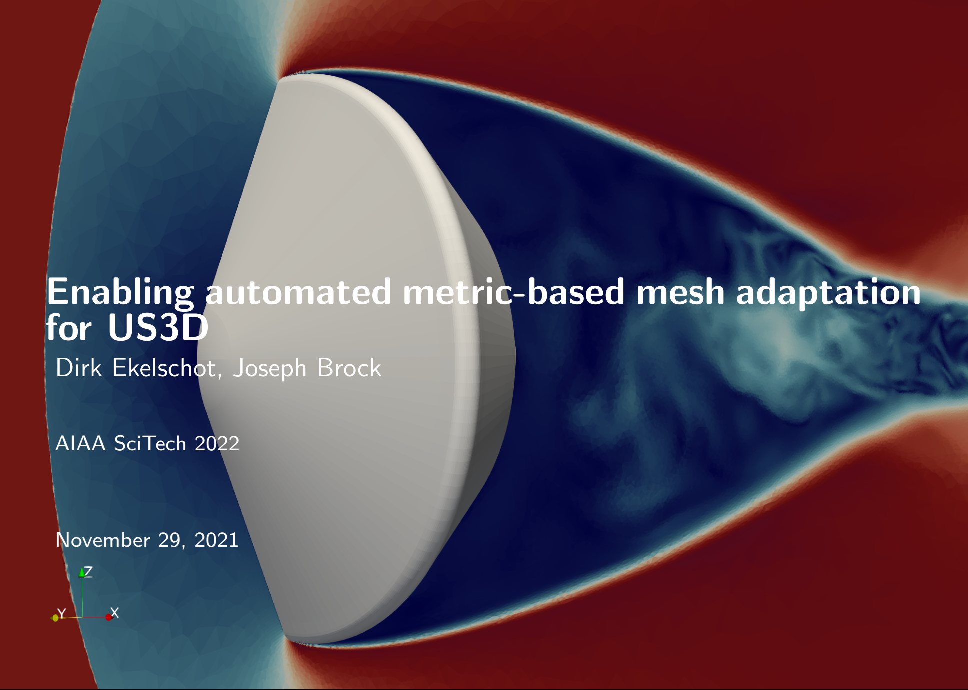

Enabling automated metric-based mesh adaptation for US3D

Dirk Ekelschot, Joseph Brock

AIAA SciTech 2022

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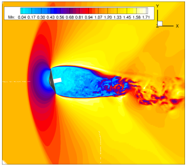
Table of Contents

Table of Contents

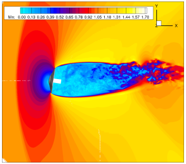
Why anisotropic mesh adaptation?

Goals

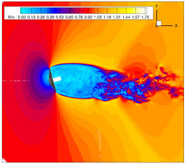
- **Simplify the mesh generation process for unsteady flows past complex geometries.**
- **Improve the resolution of free-flight CFD simulations of atmospheric entry vehicles using US3D.**



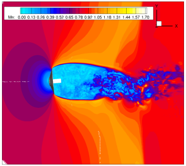
Mach at t≈ 0*s*



Mach at t≈ 2*s*

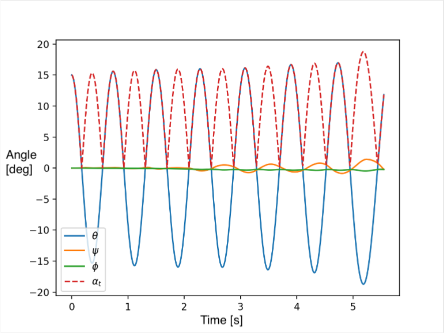


Mach at t≈ 4*s*



Mach at t≈ 5*s*

Mach solution for ADEPT at three different time instances.



Time history of the attitude for the ADEPT geometry.

Table of Contents

Serial implementation

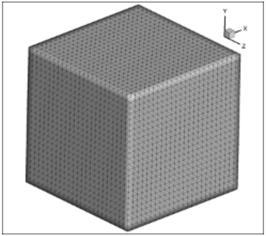
Required developments

- **Calculate metric data based on a US3D flow solution that can drive anisotropic mesh adaptation.**
- Implemented a prismatic boundary layer domain that is kept fixed.
- Linked US3D to MMG and demonstrated iterative adaptation in serial.

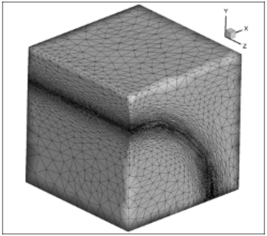
The aim of metric-based mesh adaptation is to control the local error by aligning the local size and directionality of the mesh edges/elements. Based on a given state/derived variable u we can calculate/reconstruct the metric tensor field that perscribes the **preferred direction** and **size** of the local edges/elements[a]:

$$M_{Lp} = D_{Lp} \left(\det \| H_u \| \right)^{\frac{-1}{2p+3}} \mathbf{R}_u^{-1} \| \Lambda \| \mathbf{R}_u \qquad (1)$$

Pass the metric tensor field to a adaptive capability that computes an aligned mesh.



Initial mesh that consists of 82000 tetrahedra.



Adapted mesh that consists of 72000 tetrahedra.

Serial implementation

Required developments

- Calculate metric data based on a US3D flow solution that can drive anisotropic mesh adaptation.
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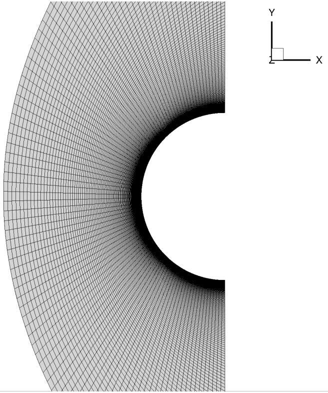
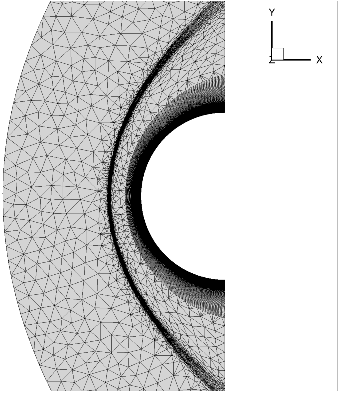
- Linked US3D to MMG and demonstrated iterative adaptation in serial.



Original hexahedral mesh.



Final hybrid (prisms+tetrahedra) mesh.

Serial implementation

Required developments

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- Implemented a prismatic boundary layer domain that is kept fixed.
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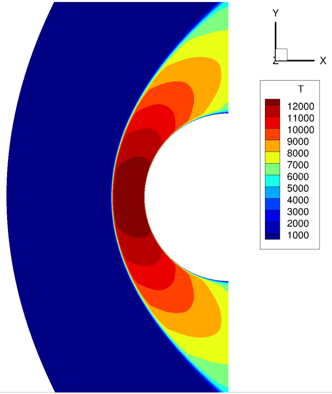
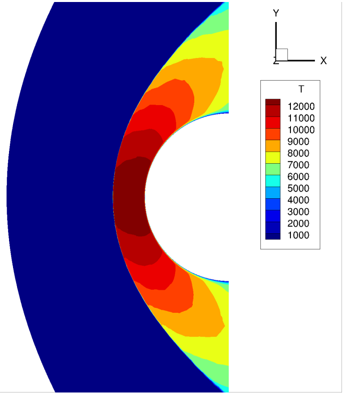


Temperature computed using original hexahedral mesh.



Temperature computed using the final hybrid mesh.

Serial implementation

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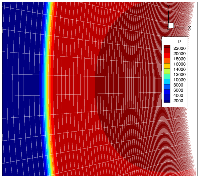
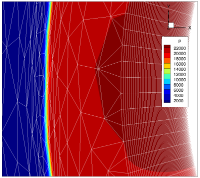
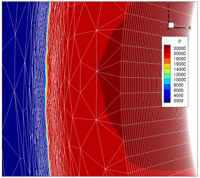


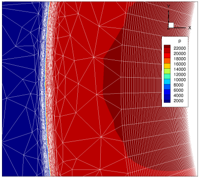
Mesh 1 (hexahedra)



Mesh 2 (prisms+tetrahedra)



Mesh 3 (prisms+tetrahedra)

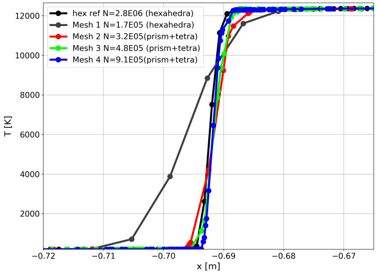


Mesh 4 (prisms+tetrahedra)

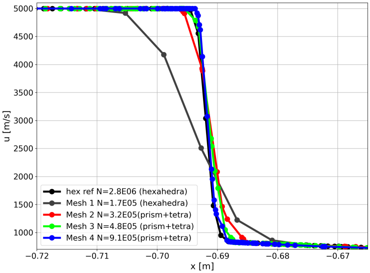
Recap

Required developments

- Calculate metric data based on a US3D flow solution that can drive anisotropic mesh adaptation.
- Implemented a prismatic boundary layer domain that is kept fixed.
- **Linked US3D to MMG and demonstrated iterative adaptation in serial.**



Temperature profile along the stagnation line.



u velocity along the stagnation line.

Serial implementation

Required developments

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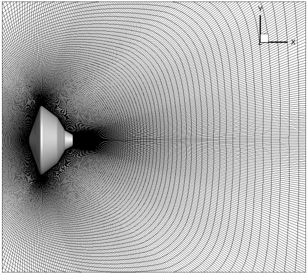
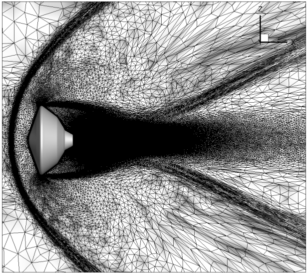


Initial mesh (hexahedra).



Adapted mesh (prisms+tetrahedra).

Serial implementation

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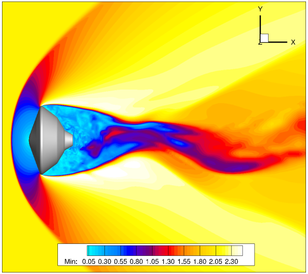
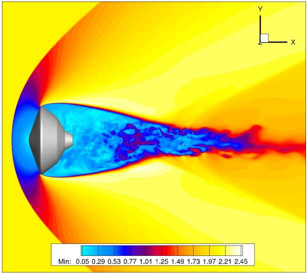


Initial mesh (hexahedra).



Adapted mesh (prisms+tetrahedra).

Limitations

- **Adapting a mesh that consists of approximately** 50×10^6 **elements takes about 1.5 hours in serial using MMG.**
- **Memory usage is limited being to able to just use one node.**

Table of Contents

Parallel implementation

Serial implementation

- Parallel reading from HDF5.
- Parallel reconstruction of the Hessian on a hybrid (prisms+tetrahedra) meshes and hexahedral meshes.
- Prism layer extraction from hexahedral meshes.
- Serial adaptation using MMG.
- Serial writing to HDF5 format compatible with US3D.

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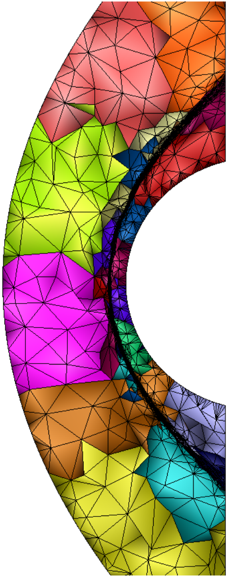
New features

- **Adapt the tetrahedra in parallel using ParMMG.**
  - **Repartition/redistribute the tetrahedra since ParMMG does not accept prisms.**
  - **Determine the correct shared interfaces between partitions.**
- Patch the adapted tetrahedra topology onto the fixed prismatic boundary layer topology.
- Apply wake refinement by letting the Turbulent Kinetic Energy (TKE) drive isotropic refinement.
- Output the distributed mesh into a single "grid.h5" file that is compatible with US3D.



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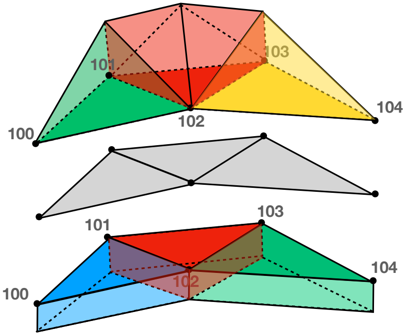

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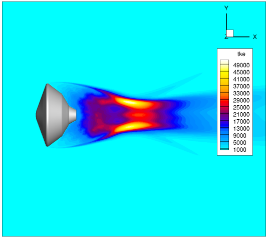
The anisotropic mesh refinement is driven by the metric term that relates the local mesh sizing and directionality to the local spatial linear interpolation error:

$$M_{Lp} = D_{Lp} \left(\det \|H_u\|\right)^{\frac{-1}{2p+3}} \mathbf{R}_u^{-1} \|\Lambda\| \mathbf{R}_u \tag{2}$$

The anisotropic mesh adaptation based on the Mach number is now combined with isotropic mesh adaptation based on the Turbulent Kinetic Energy (TKE).

$$M_t = (\xi - 1) M_{Lp} + \xi M_i \tag{3}$$

where the weights $\xi = f(k_t/k_{t,max})$ are determined linearly based on the TKE.



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$$M_{Lp} = D_{Lp} \left(\det \|H_u\|\right)^{\frac{-1}{2p+3}} \mathbf{R}_u^{-1} \|\Lambda\| \mathbf{R}_u \qquad (4)$$

The anisotropic mesh adaptation based on the Mach number is now combined with isotropic mesh adaptation based on the Turbulent Kinetic Energy (TKE).

$$M_t = (\xi - 1) M_{Lp} + \xi M_i \qquad (5)$$

where the weights $\xi = f(k_t/k_{t,max})$ are determined linearly based on the TKE.

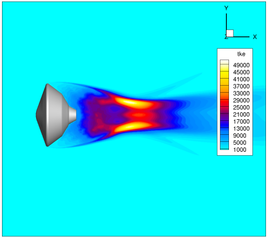
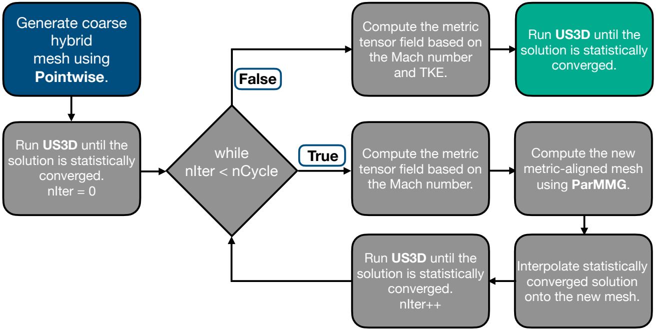
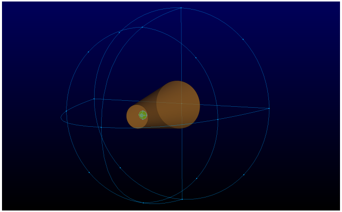


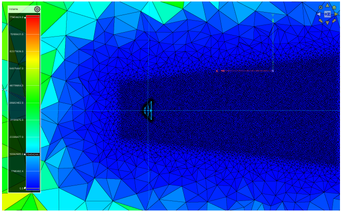
Table of Contents

Numerical examples





Initial mesh definition in Pointwise



A cut of the coarse initial volume mesh.

Numerical examples

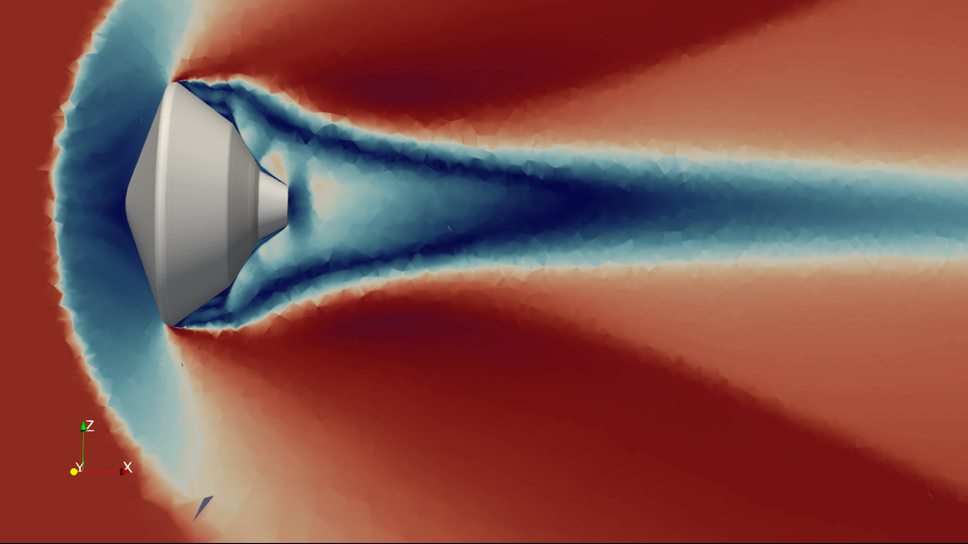
```
#PBS -S /bin/bash
#PBS -N eev_adaptionCycle
#PBS -q devel
#PBS -l select=100:ncpus=40:mpiprocs=40:model=sky_ele
#PBS -l walltime=2:00:00

export FOCUS=/modules/./test15

mkdir adaptCycle
cd adaptCycle
mkdir inputs
cd inputs
ln -s ../../grid.h5 grid.h5
ln -s ../../conn.h5 conn.h5
ln -s ../../data.h5 data.h5
cp -r ../../metric_new.inp metric.inp
cd ..
cp -r ../input.inp .

mpiexec -np 560 $FOCUS > adaption.log

mpiexec -np 40 us3d-prepar --grid=grid.h5 --conn=conn.h5 >
connBuild.log

mpiexec -np 1 us3d-interp --sdir=../ --ddir=../
adaptCycle_r2 --method=1 > interpolation.log

mv data.h5 data_restart.h5

mpiexec -np 4000 us3d --grid=grid.h5 --conn=conn.h5 --
restart=data_restart.h5 --data=data.h5 > wash.log
```

example .pbs file

Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

Ne = 8.1E06 (4.3E06 Prisms and 3.8E06 Tetrahedra)

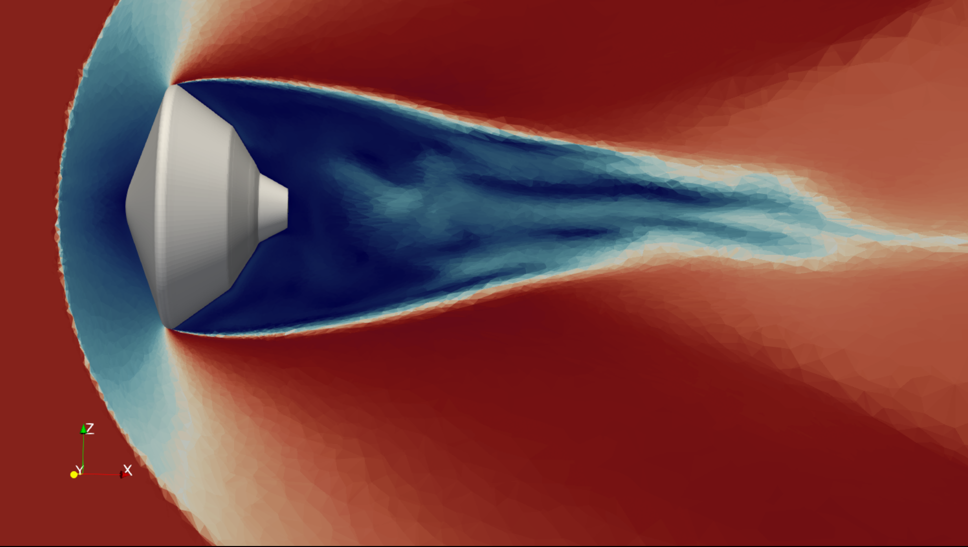
Nn = 2.7E06



Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

Ne = 6.2E06 (4.3E06 Prisms and 1.9E06 Tetrahedra)

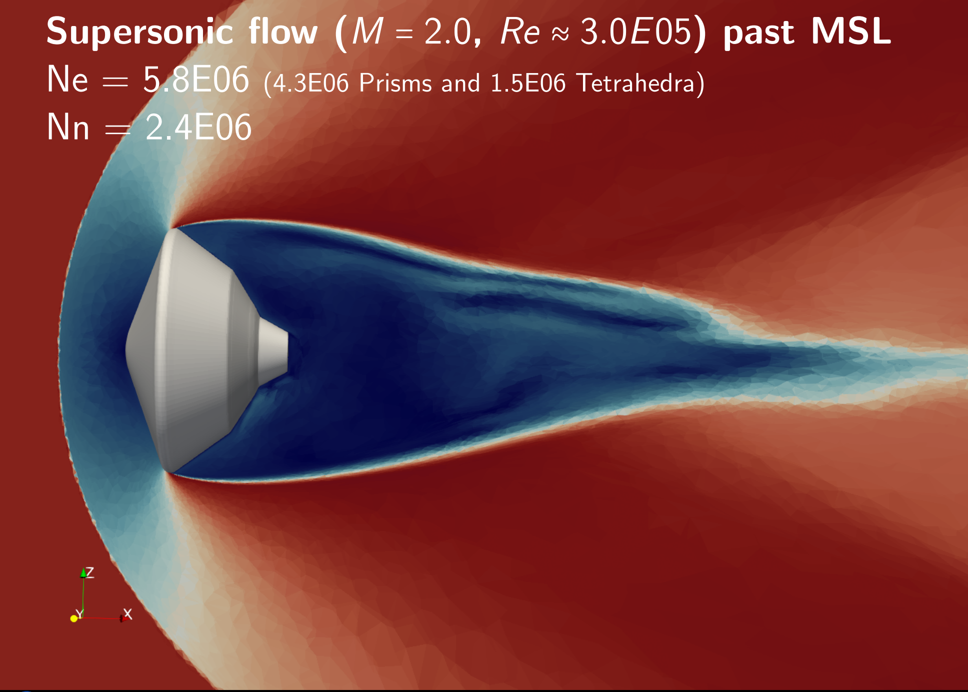
Nn = 2.4E06



Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

Ne = 5.8E06 (4.3E06 Prisms and 1.5E06 Tetrahedra)

Nn = 2.4E06



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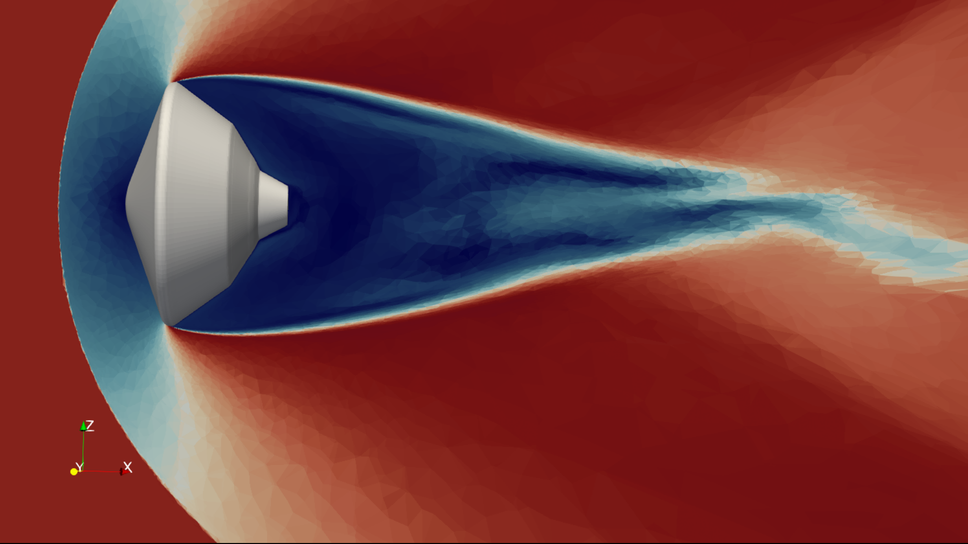
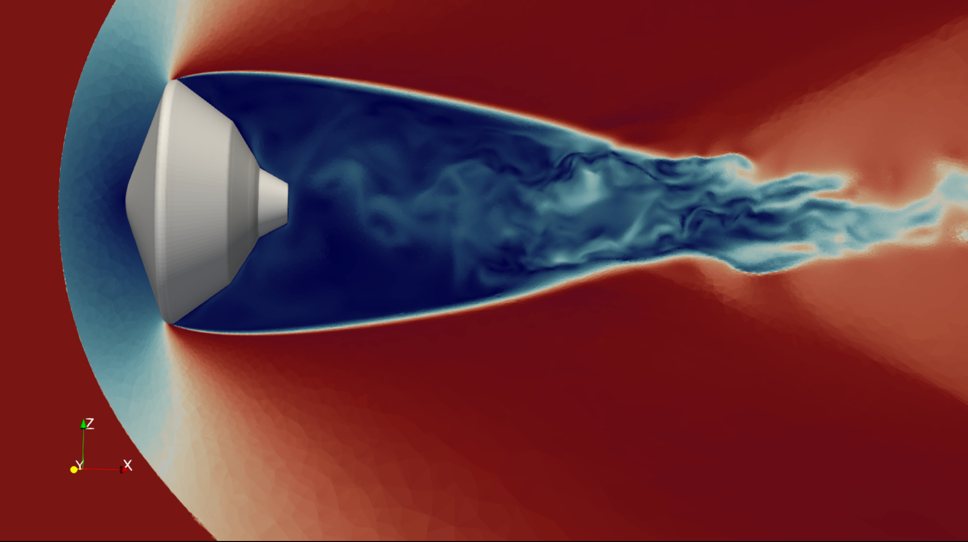


Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

Ne = 27.0E06 (4.3E06 Prisms and 22.5E06 Tetrahedra)

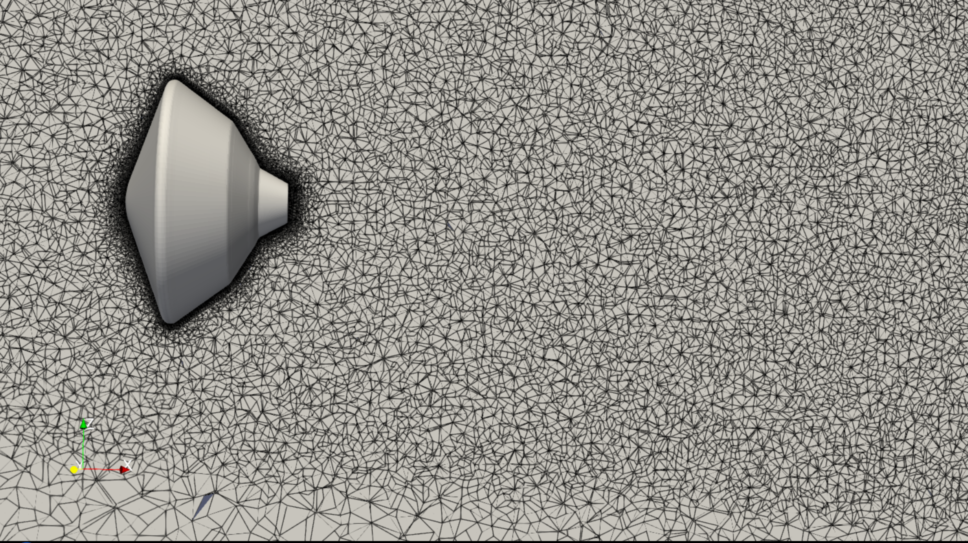
Nn = 5.9E06



Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

$\mathcal{T}_0$ has Ne = 8.1E06 (4.3E06 Prisms and 3.8E06 Tetrahedra)

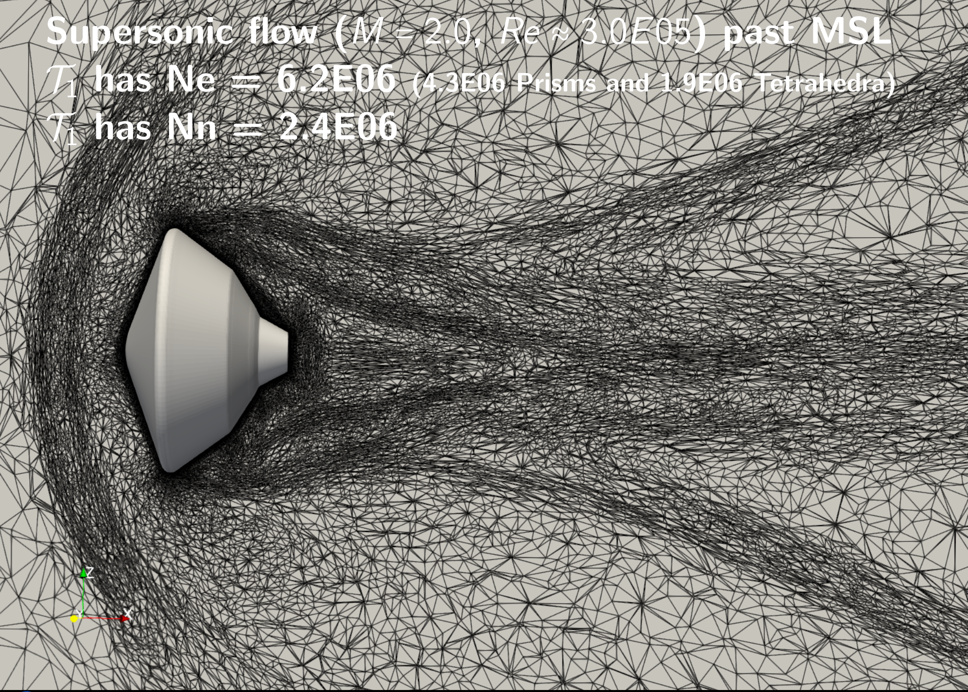
$\mathcal{T}_0$ has Nn = 2.7E06



Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

$\mathcal{T}_1$ **has Ne = 6.2E06** (4.3E06 Prisms and 1.9E06 Tetrahedra)

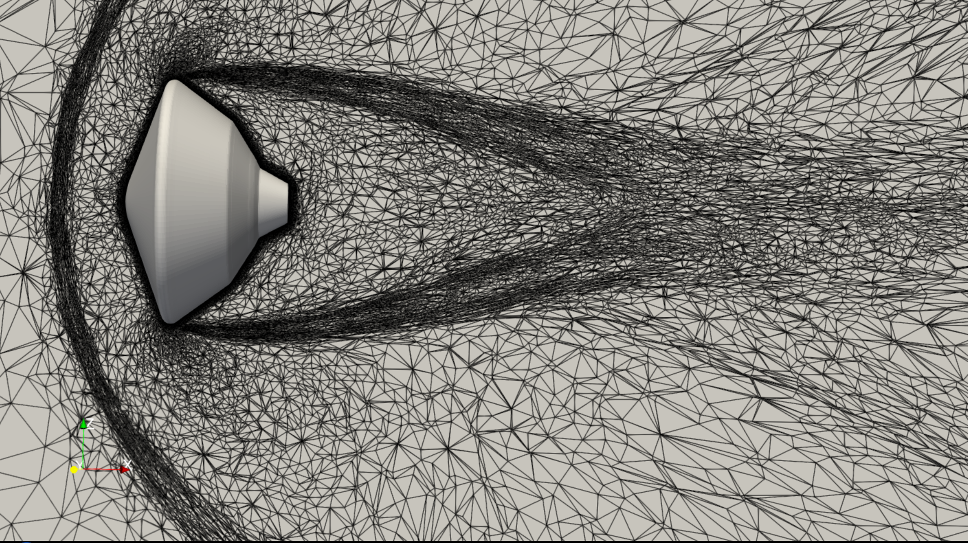
$\mathcal{T}_1$ **has Nn = 2.4E06**



Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

$\mathcal{T}_2$ has Ne = 5.8E06 (4.3E06 Prisms and 1.5E06 Tetrahedra)

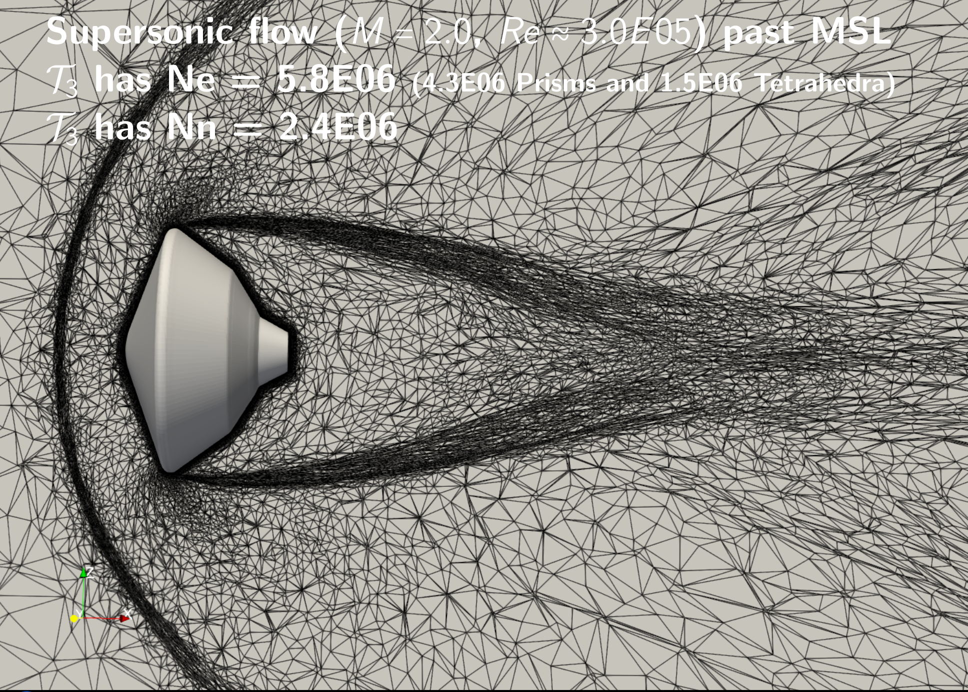
$\mathcal{T}_2$ has Nn = 2.4E06



Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

$\mathcal{T}_3$ has Ne = 5.8E06 (4.3E06 Prisms and 1.5E06 Tetrahedra)

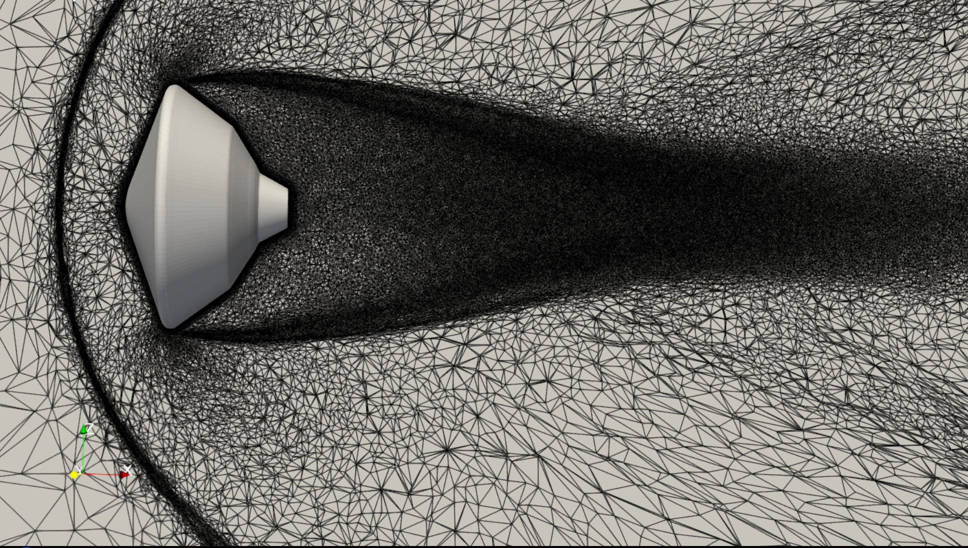
$\mathcal{T}_3$ has Nn = 2.4E06



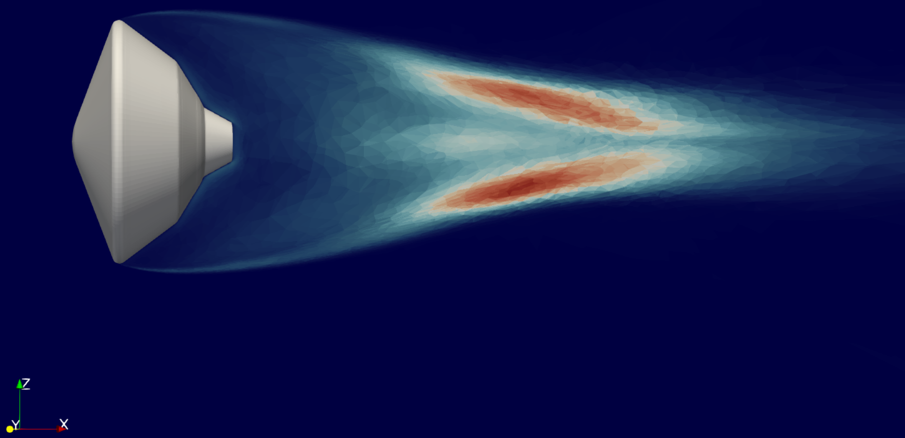
Supersonic flow ($M = 2.0$, $Re \approx 3.0E05$) past MSL

$\mathcal{T}_4$ has Ne = 27.0E06 (4.3E06 Prisms and 22.5E06 Tetrahedra)

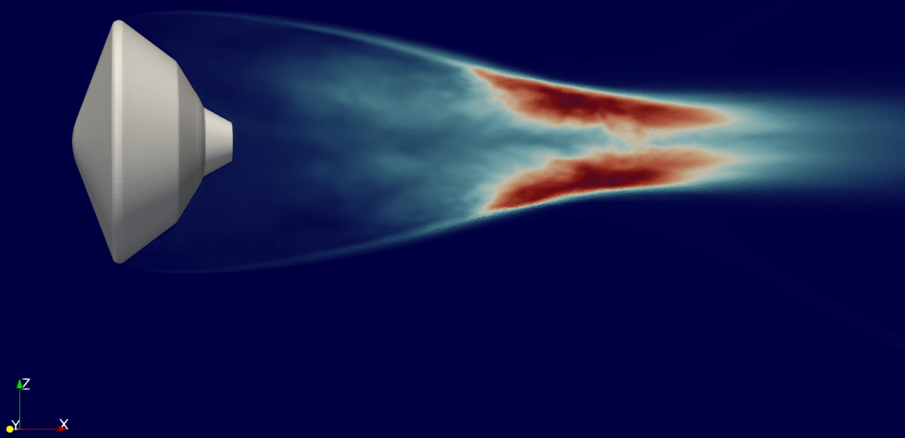
$\mathcal{T}_4$ has Nn = 5.9E06



TKE on $\mathcal{T}_3$



TKE on $\mathcal{T}_4$



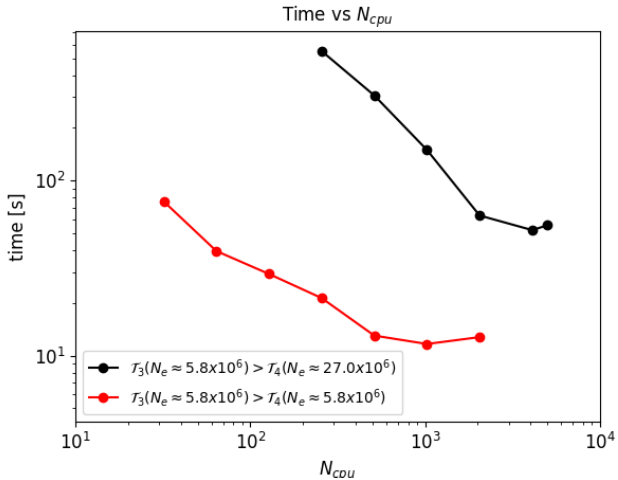
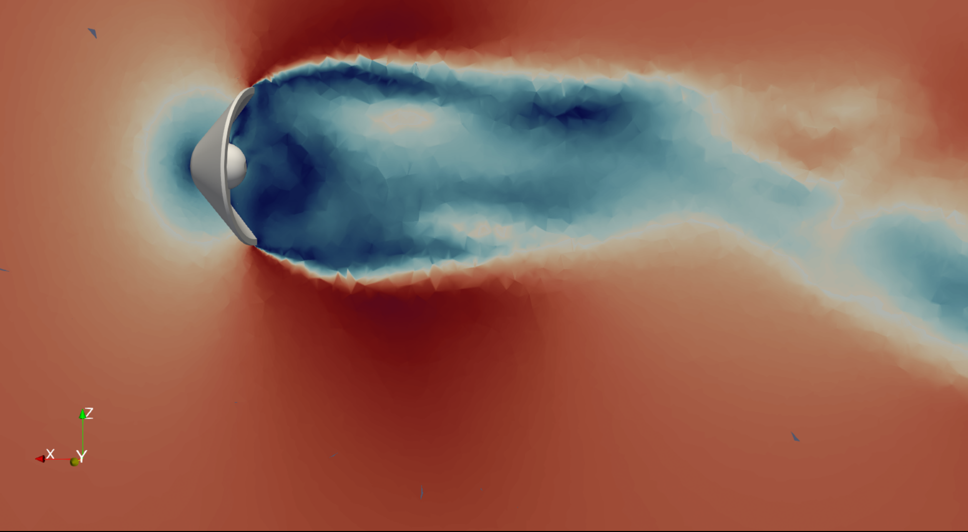


Figure: Time versus number of CPUs used to perform the adaptation for the last two adaptation iterations for supersonic flow past the MSL geometry.

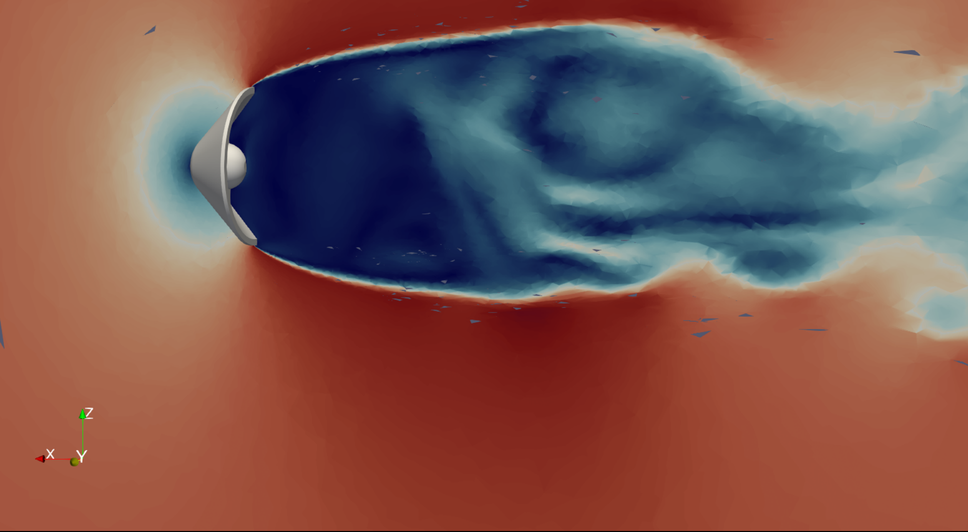
Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 42.7E06 (37.6E06 Prisms and 5.1E06 Tetrahedra)

Nn = 19.9E06



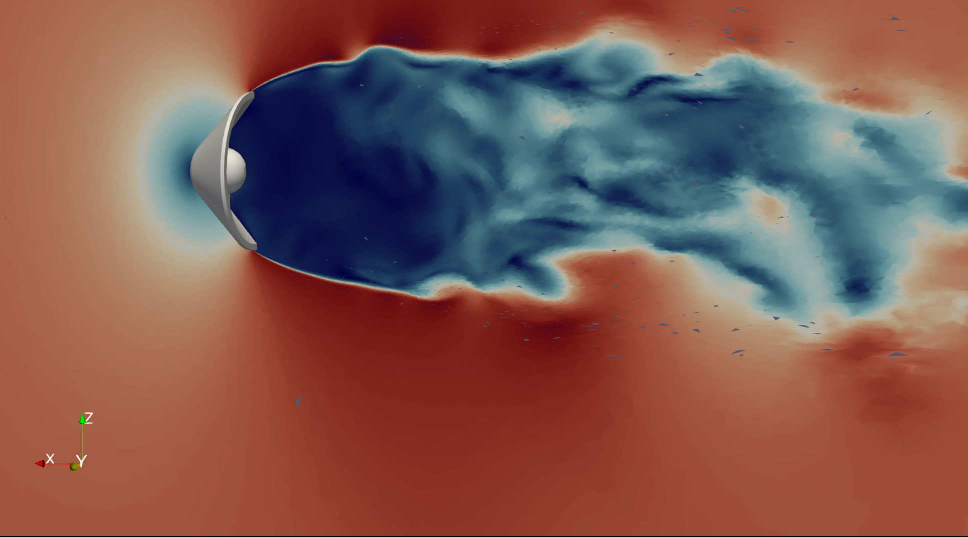
Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV
Ne = 42.1E06 (37.6E06 Prisms and 4.6E06 Tetrahedra)
Nn = 19.7E06



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 48.4E06 (37.6E06 Prisms and 10.8E06 Tetrahedra)

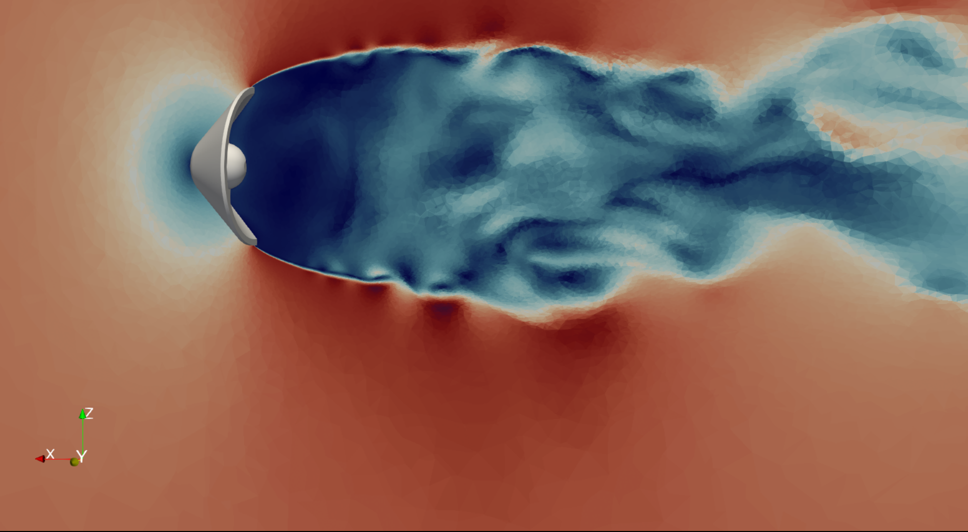
Nn = 20.7E06



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

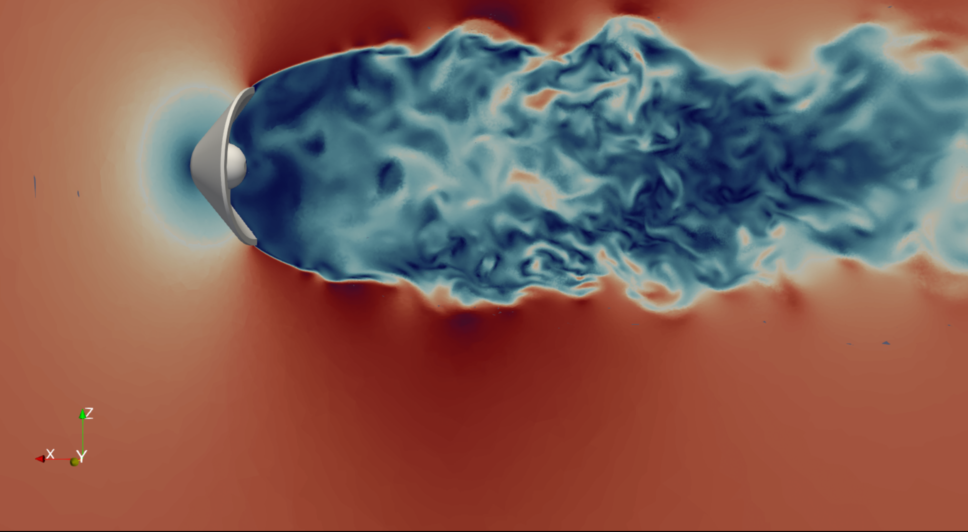
Ne = 47.5E06 (37.6E06 Prisms and 9.9E06 Tetrahedra)

Nn = 20.6E06



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 101.2E06 (37.6E06 Prisms and 63.6E06 Tetrahedra)
Nn = 29.6E06

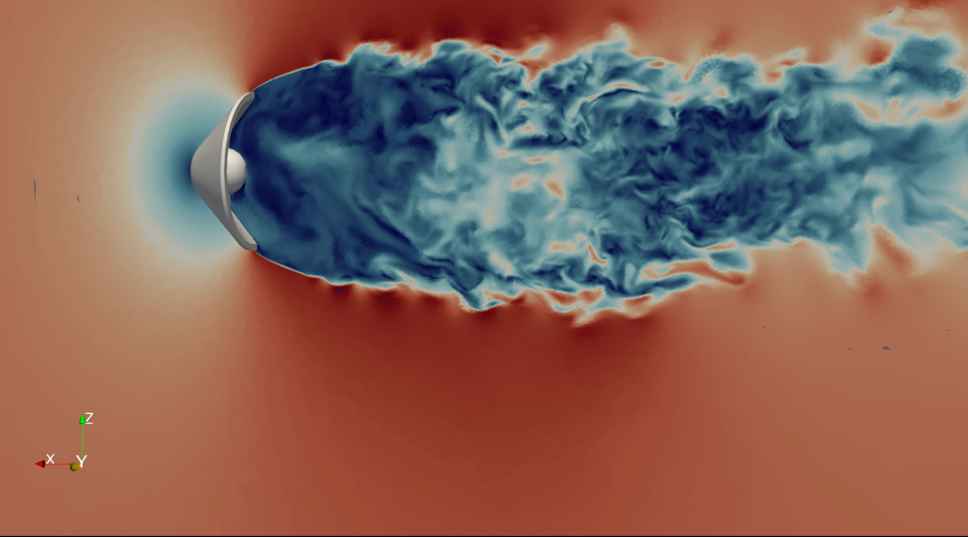


Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 101.2E06 (37.6E06 Prisms and 63.6E06 Tetrahedra)

Nn = 29.6E06

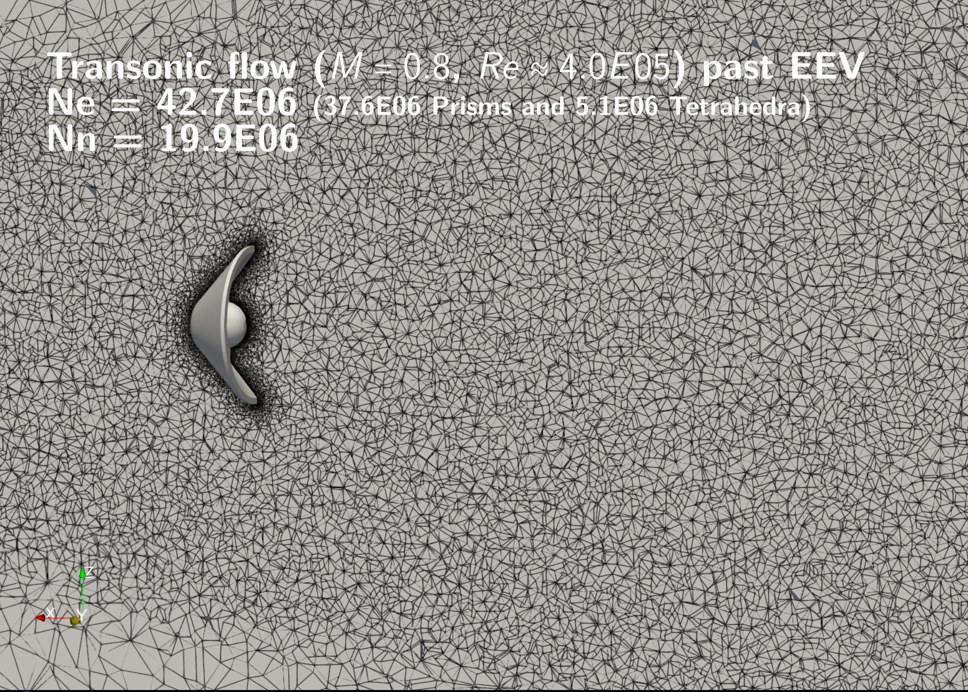
KEC flux



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 42.7E06 (37.6E06 Prisms and 5.1E06 Tetrahedra)

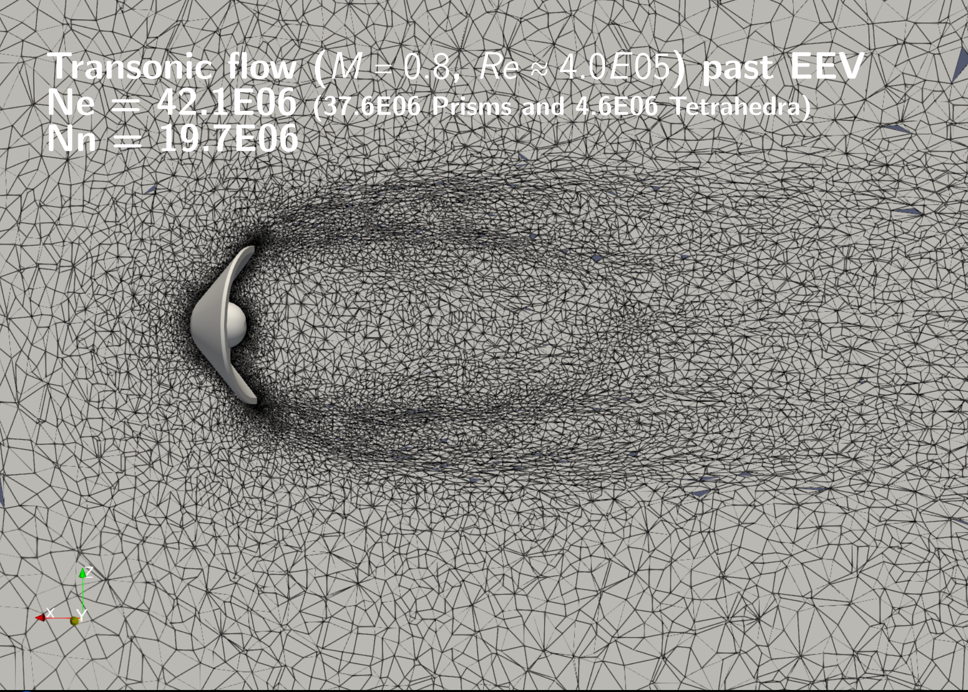
Nn = 19.9E06



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 42.1E06 (37.6E06 Prisms and 4.6E06 Tetrahedra)

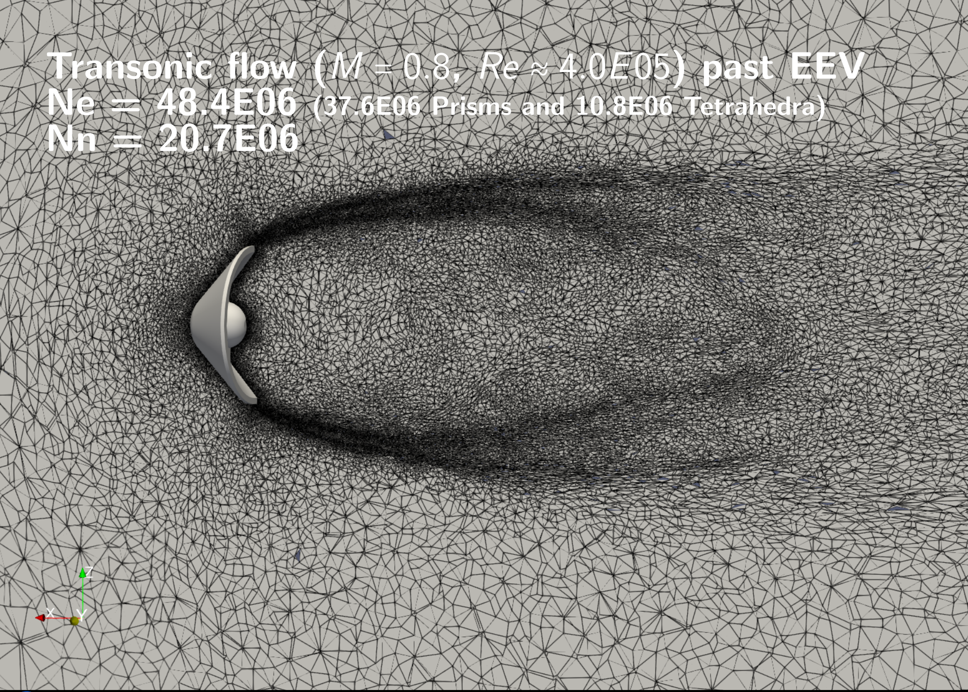
Nn = 19.7E06



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 48.4E06 (37.6E06 Prisms and 10.8E06 Tetrahedra)

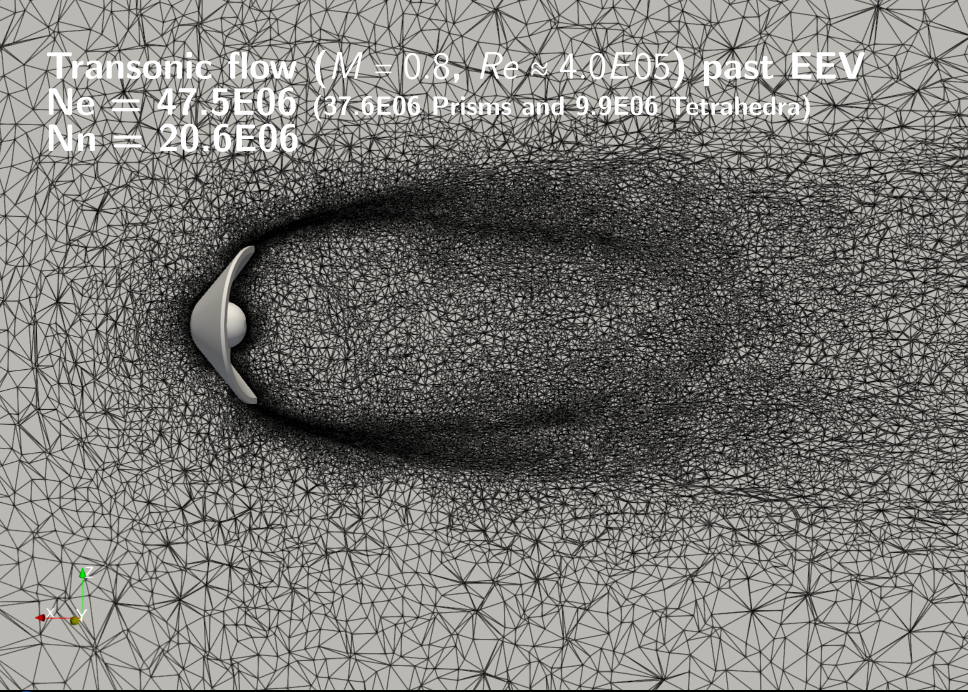
Nn = 20.7E06



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 47.5E06 (37.6E06 Prisms and 9.9E06 Tetrahedra)

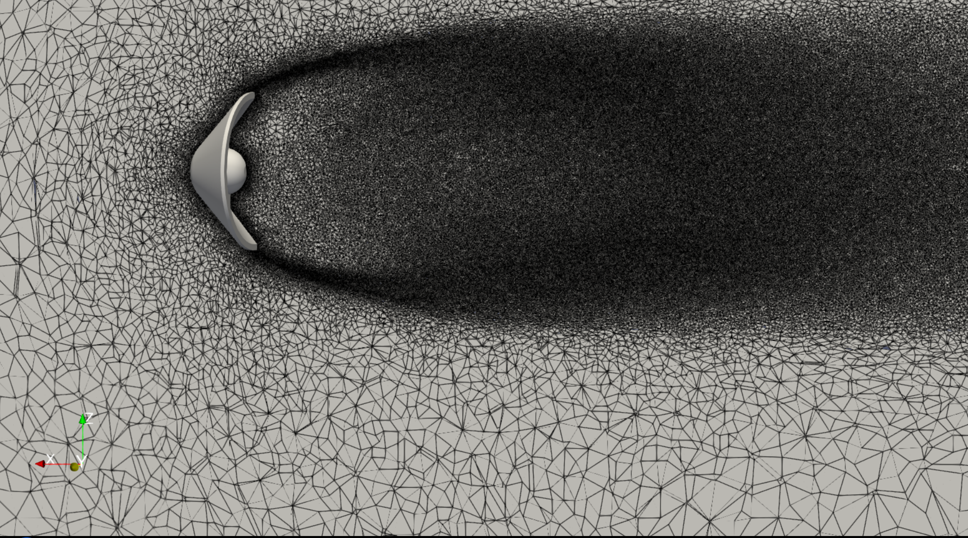
Nn = 20.6E06



Transonic flow ($M = 0.8$, $Re \approx 4.0E05$) past EEV

Ne = 101.2E06 (37.6E06 Prisms and 63.6E06 Tetrahedra)

Nn = 29.6E06



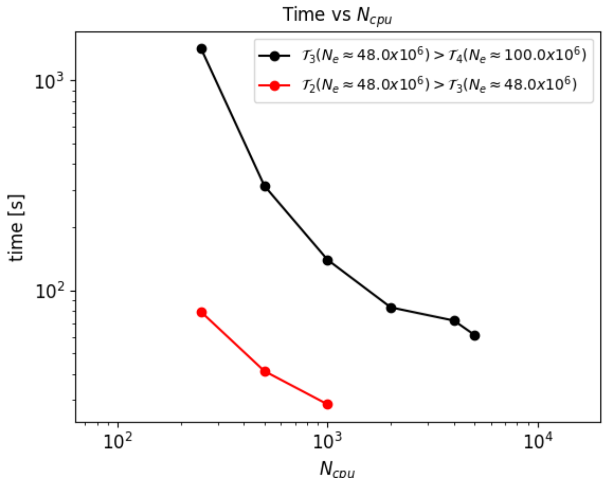


Figure: Time versus number of CPUs used to perform the adaptation for the last two adaptation iterations for supersonic flow past the EEV geometry.

Table of Contents

In summary...

Conclusions

- We currently have an anisotropic mesh adaptation utility that is compatible with US3D and is able to compute a solution-informed adapted mesh for realistic applications that are of interest to the EDL community.
- We have demonstrated a simplified simulation strategy that starts with a small and coarse mesh and applies iterative mesh adaptation to improve the resolution of the simulation while keeping the element count low.
- Currently we are able to generate a anisotropic adapted mesh of approximately 100×10^6 elements in 60 seconds.

Future work

- Streamline the workflow process of running the adaptive capability with US3D to improve usability of the tool.
- Improve the error estimation and include a temporal component to the metric tensor field computation.
- Potentially start employing anisotropic mesh refinement to the dynamic stability calculations for the Earth Entry Vehicle geometry.