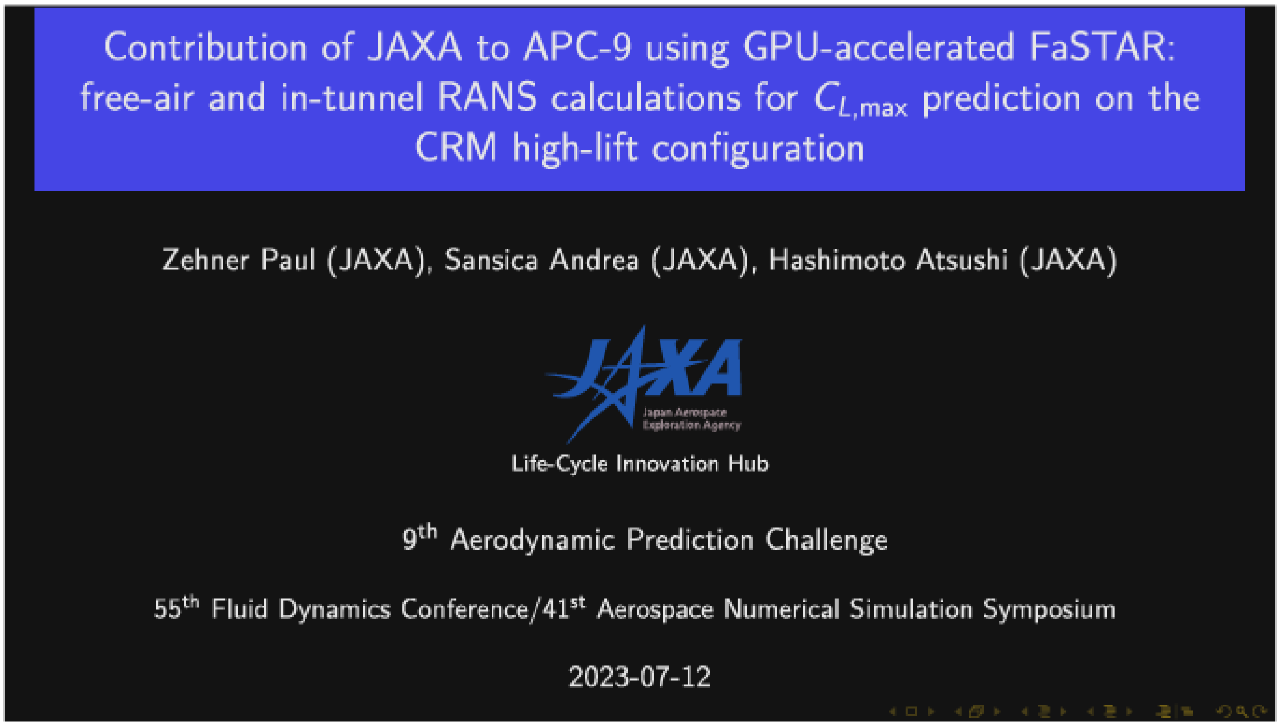
# Contribution of JAXA to APC-9 using GPU-accelerated FaSTAR: free-air and in-tunnel RANS calculations for CLmax prediction on the CRM high-lift configuration・Zehner Paul, Sansica Andrea, 橋本 敦 (JAXA)



## Contribution of JAXA to APC-9 using GPU-accelerated FaSTAR: free-air and in-tunnel RANS calculations for $C_{L,\max}$ prediction on the CRM high-lift configuration

Zehner Paul (JAXA), Sansica Andrea (JAXA), Hashimoto Atsushi (JAXA)

Life-Cycle Innovation Hub

9th Aerodynamic Prediction Challenge

55th Fluid Dynamics Conference/41st Aerospace Numerical Simulation Symposium

2023-07-12

## Outline

1. The FaSTAR solver
2. Performance metrics
3. Case 1 – Validation (RANS)
4. Case 2a – Free-air (RANS, APC-8)
5. Case 2b – In-tunnel (RANS)
6. Conclusion

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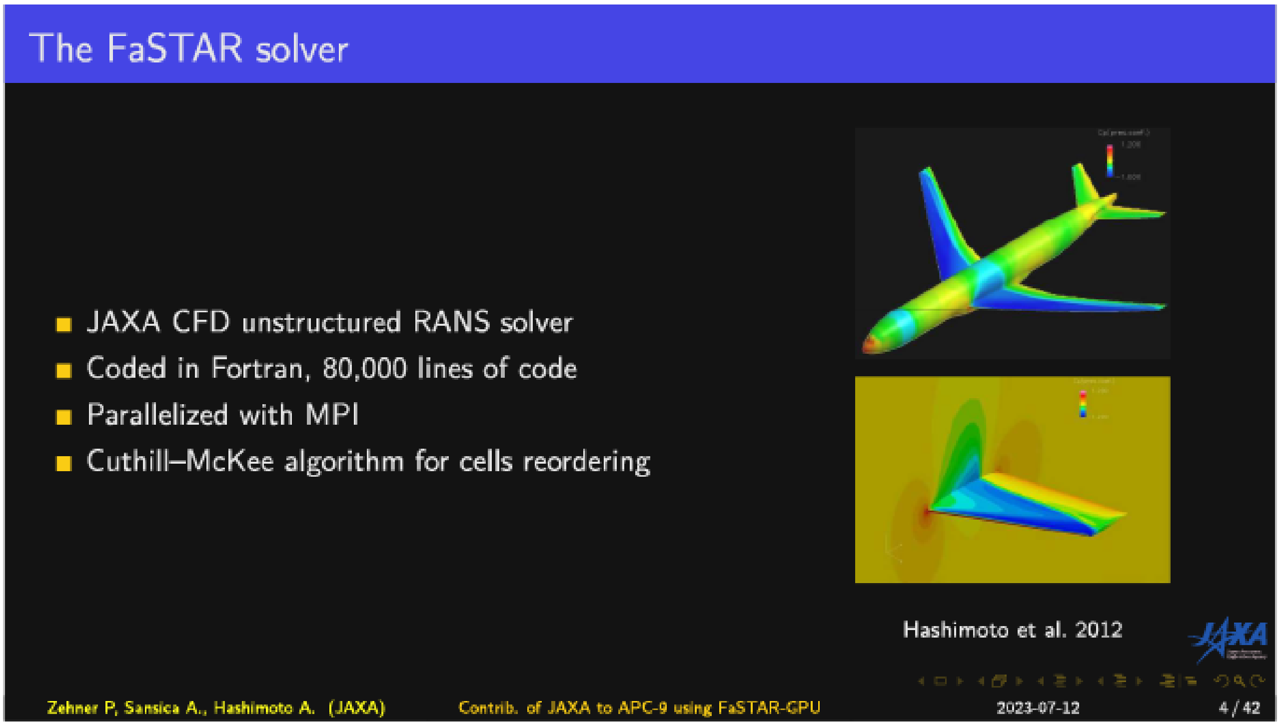
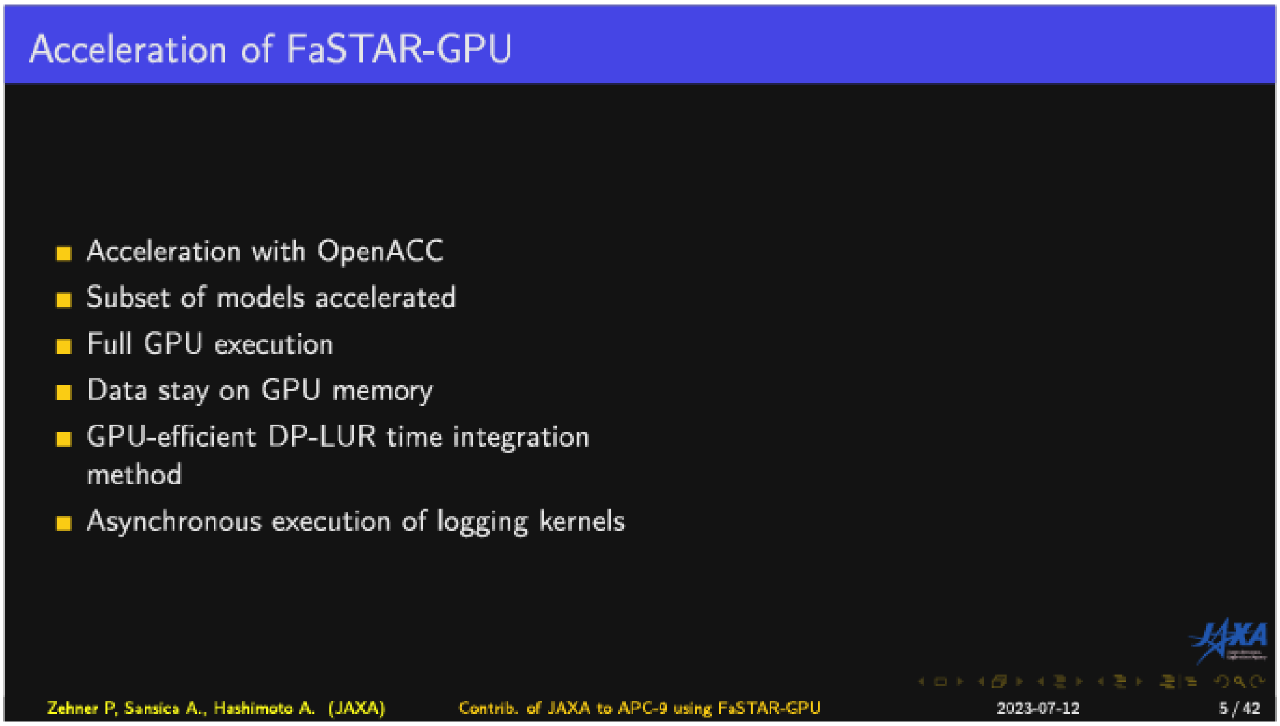


## The FaSTAR solver

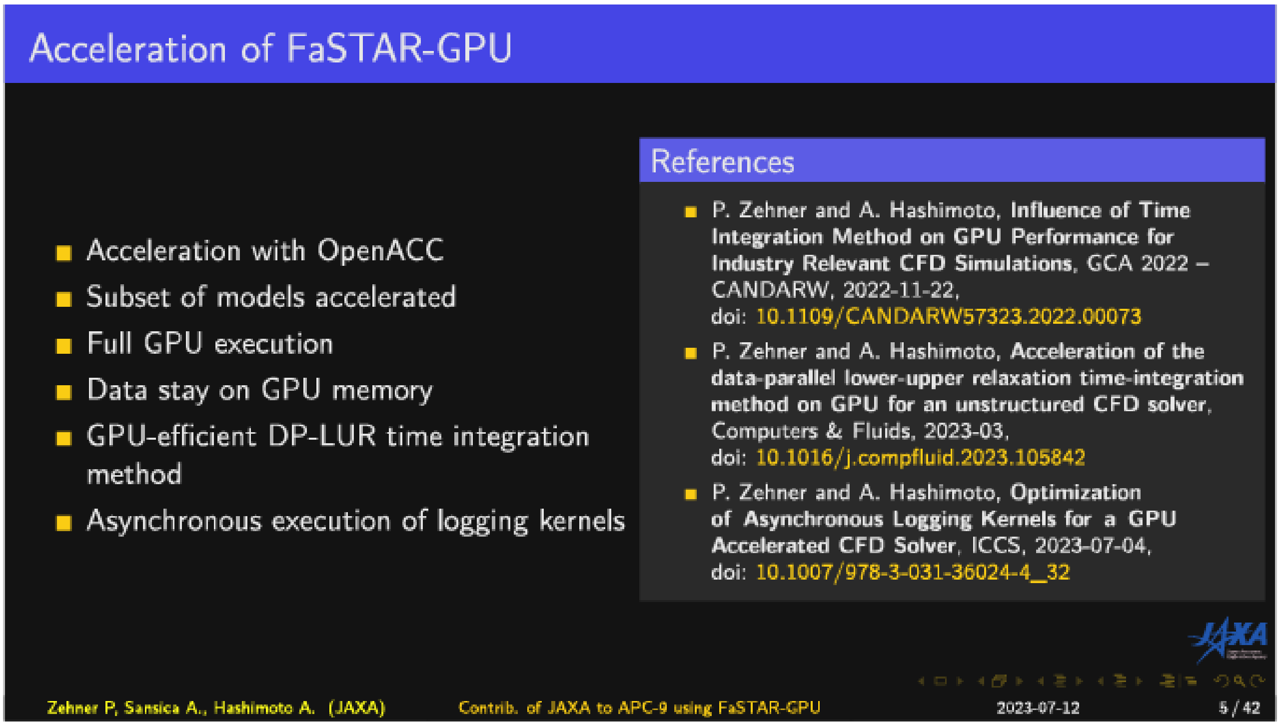
- JAXA CFD unstructured RANS solver
- Coded in Fortran, 80,000 lines of code
- Parallelized with MPI
- Cuthill–McKee algorithm for cells reordering

Hashimoto et al. 2012



## Acceleration of FaSTAR-GPU

- Acceleration with OpenACC
- Subset of models accelerated
- Full GPU execution
- Data stay on GPU memory
- GPU-efficient DP-LUR time integration method
- Asynchronous execution of logging kernels



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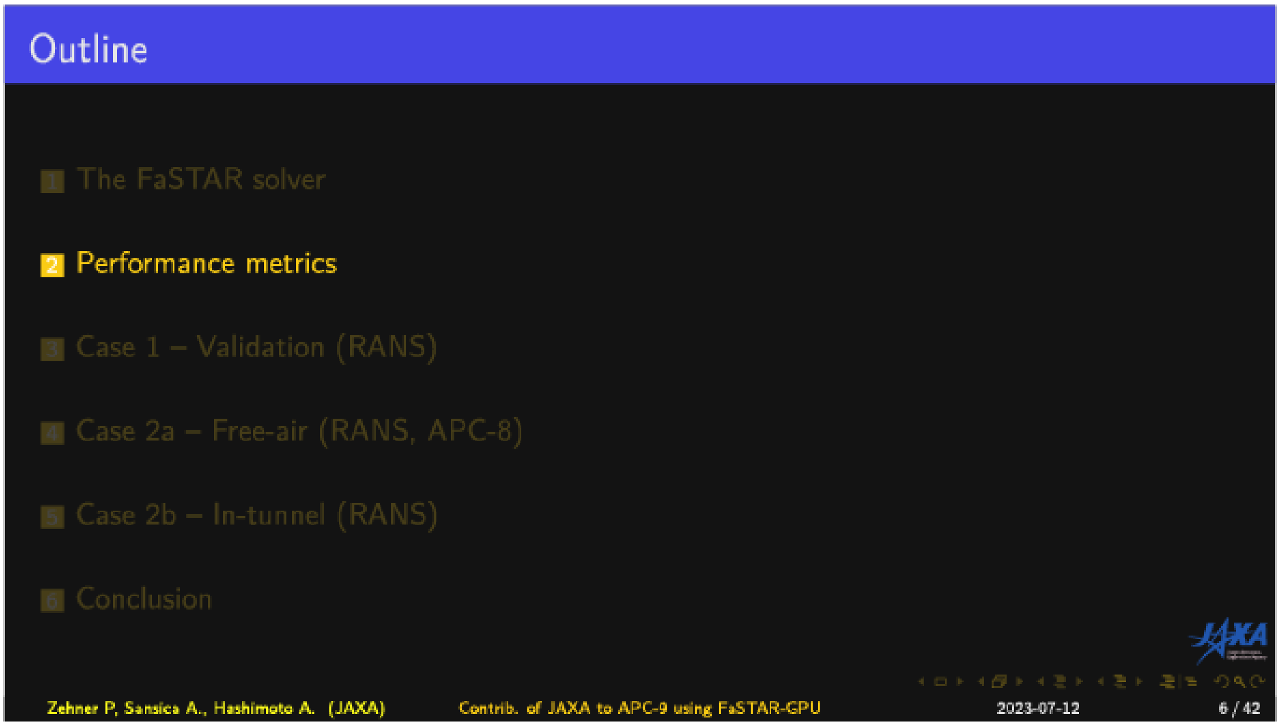
### References

- P. Zehner and A. Hashimoto, **Influence of Time Integration Method on GPU Performance for Industry Relevant CFD Simulations**, GCA 2022 – CANDARW, 2022-11-22, doi: 10.1109/CANDARW57323.2022.00073
- P. Zehner and A. Hashimoto, **Acceleration of the data-parallel lower-upper relaxation time-integration method on GPU for an unstructured CFD solver**, Computers & Fluids, 2023-03, doi: 10.1016/j.compfluid.2023.105842
- P. Zehner and A. Hashimoto, **Optimization of Asynchronous Logging Kernels for a GPU Accelerated CFD Solver**, ICCS, 2023-07-04, doi: 10.1007/978-3-031-36024-4_32



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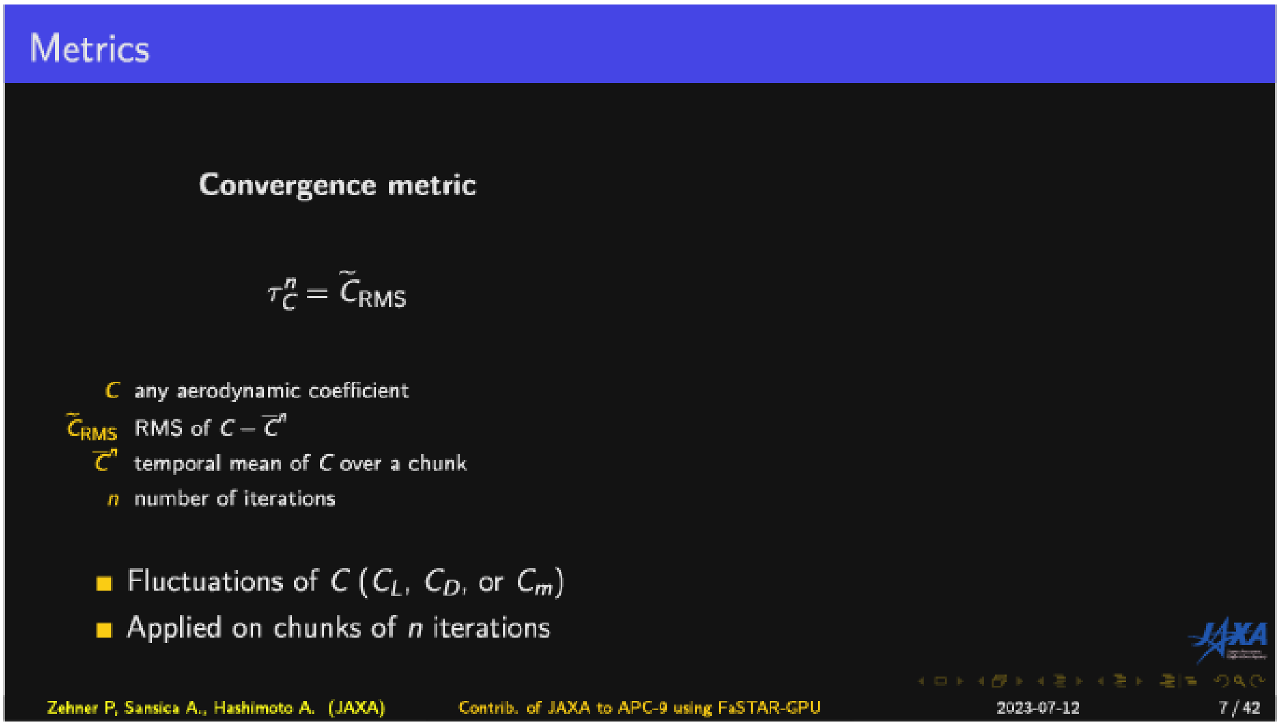


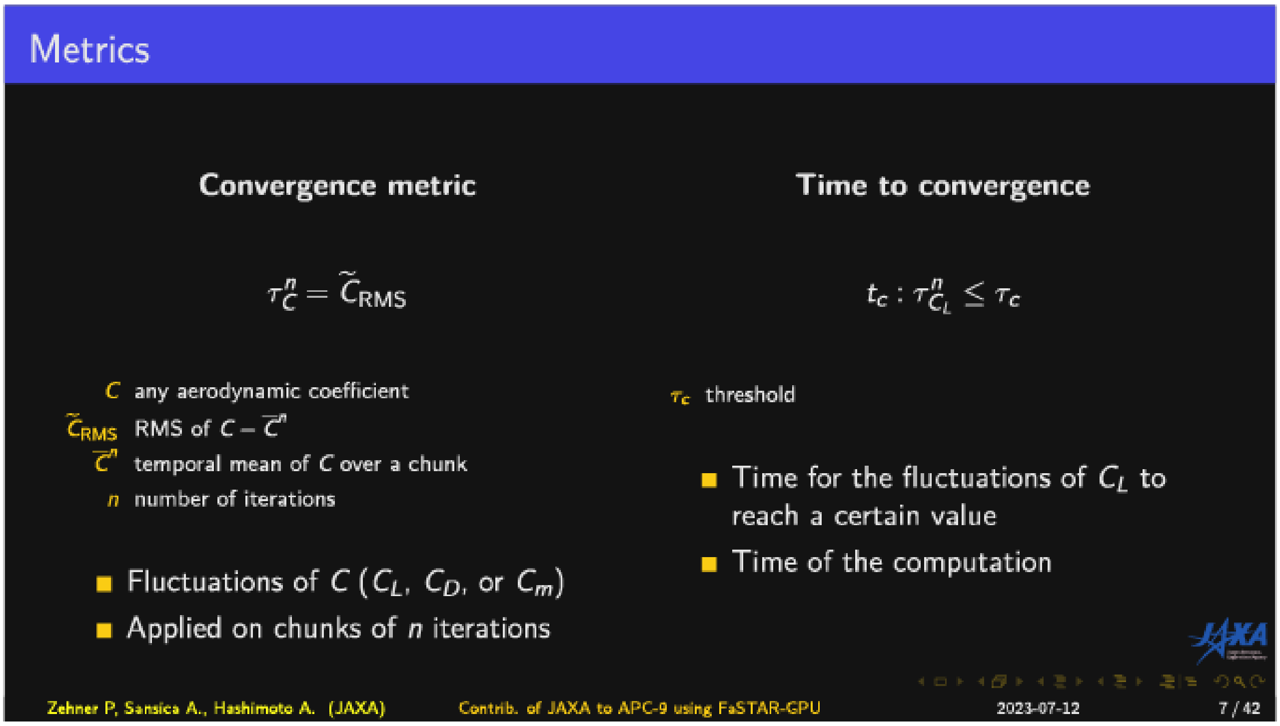
## Metrics

**Convergence metric**

$$\tau_C^n = \widetilde{C}_{\mathrm{RMS}}$$

| | |
|---|---|
| $C$ | any aerodynamic coefficient |
| $\widetilde{C}_{\mathrm{RMS}}$ | RMS of $C - \overline{C}^n$ |
| $\overline{C}^n$ | temporal mean of $C$ over a chunk |
| $n$ | number of iterations |

- Fluctuations of $C$ ($C_L$, $C_D$, or $C_m$)
- Applied on chunks of $n$ iterations



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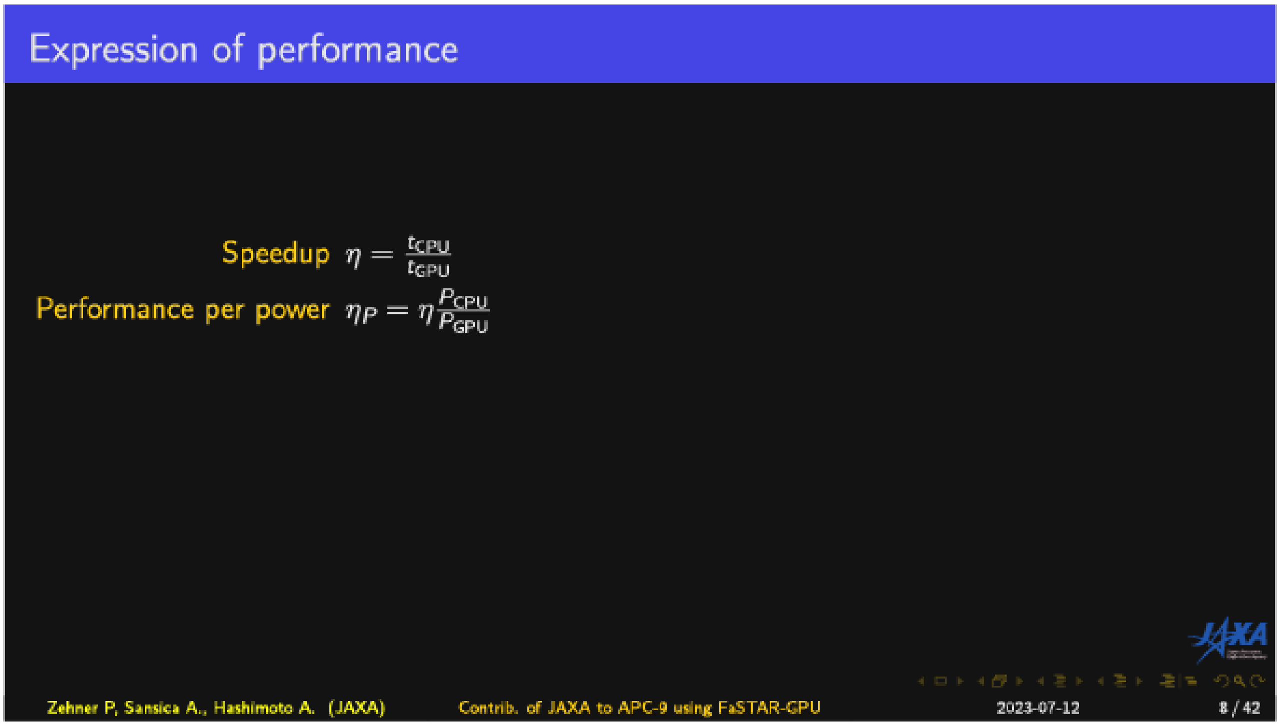
- Fluctuations of $C$ ($C_L$, $C_D$, or $C_m$)
- Applied on chunks of $n$ iterations

**Time to convergence**

$$t_c : \tau_{C_L}^n \leq \tau_c$$

$\tau_c$ threshold

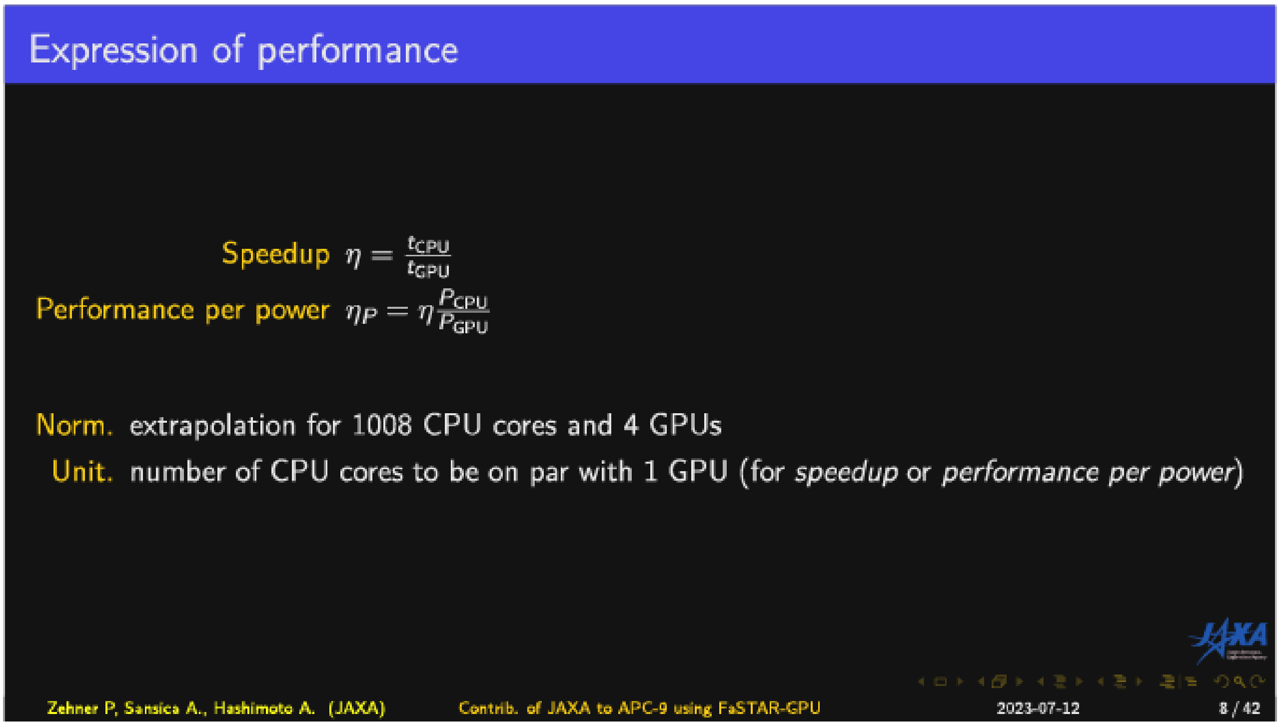
- Time for the fluctuations of $C_L$ to reach a certain value
- Time of the computation



## Expression of performance

Speedup $\eta = \frac{t_{\mathrm{CPU}}}{t_{\mathrm{GPU}}}$

Performance per power $\eta_P = \eta \frac{P_{\mathrm{CPU}}}{P_{\mathrm{GPU}}}$



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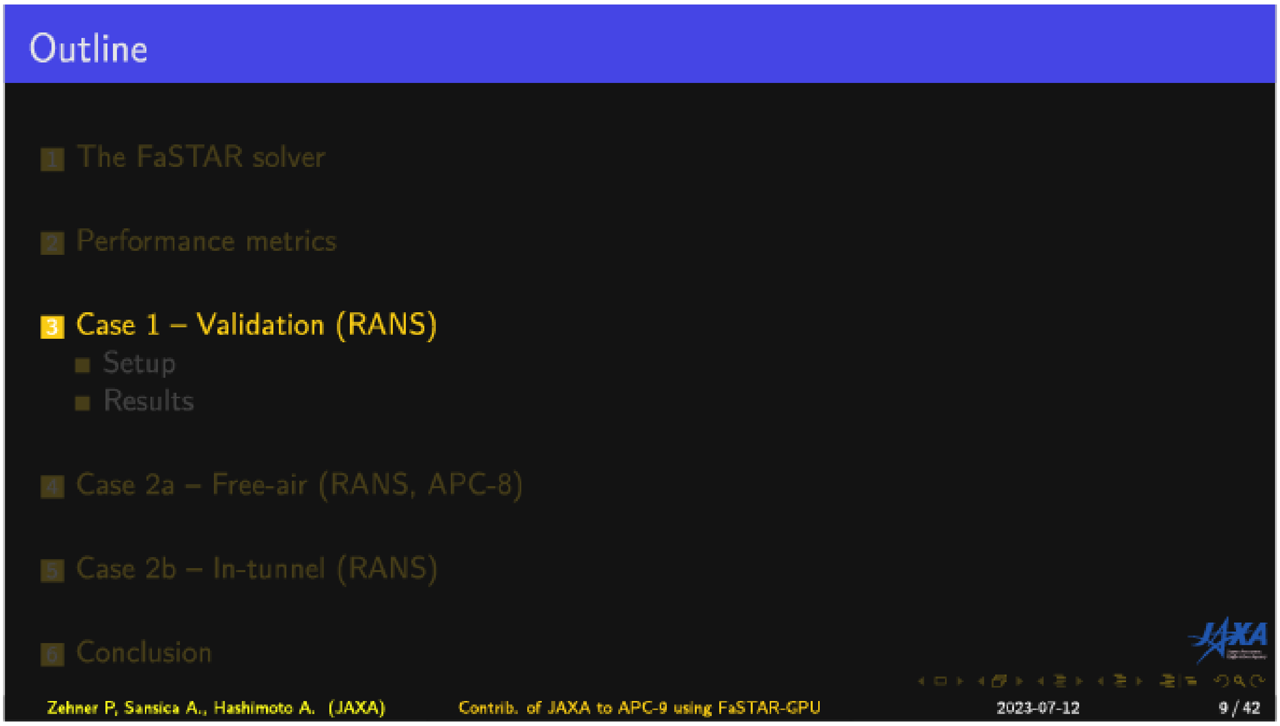
Speedup $\eta = \frac{t_{\mathrm{CPU}}}{t_{\mathrm{GPU}}}$

Performance per power $\eta_P = \eta \frac{P_{\mathrm{CPU}}}{P_{\mathrm{GPU}}}$

Norm. extrapolation for 1008 CPU cores and 4 GPUs

Unit. number of CPU cores to be on par with 1 GPU (for *speedup* or *performance per power*)



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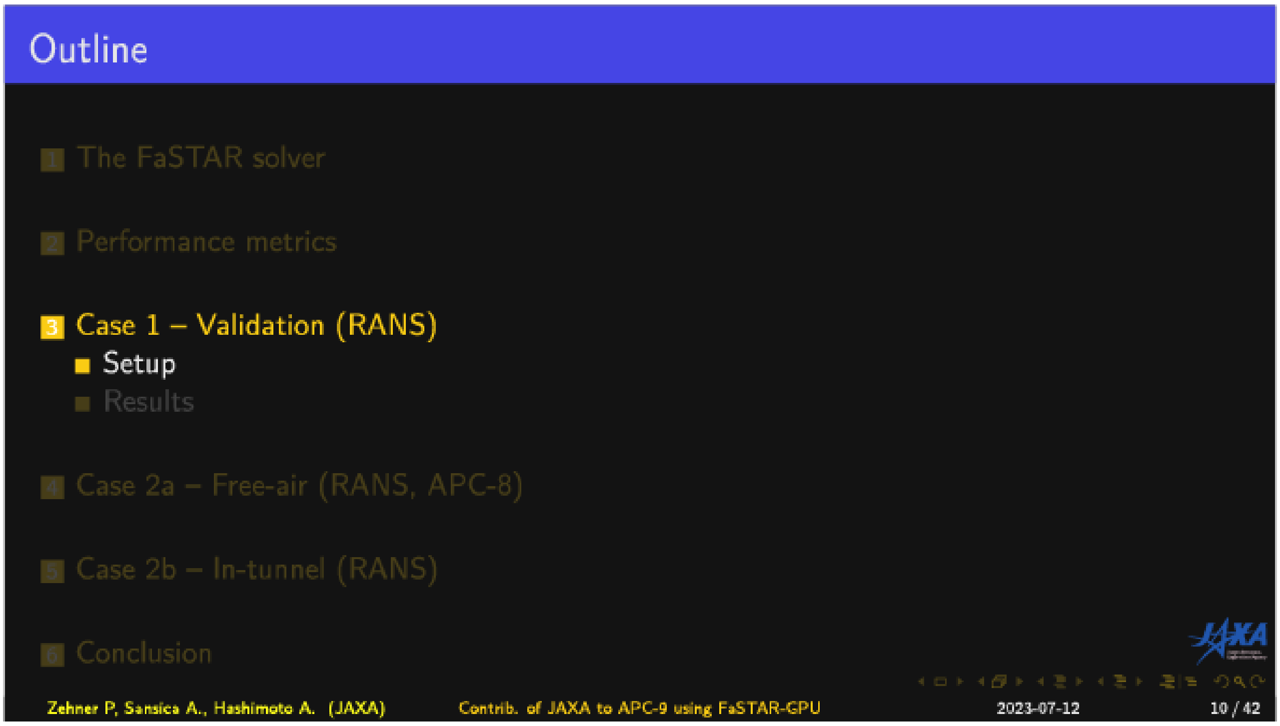

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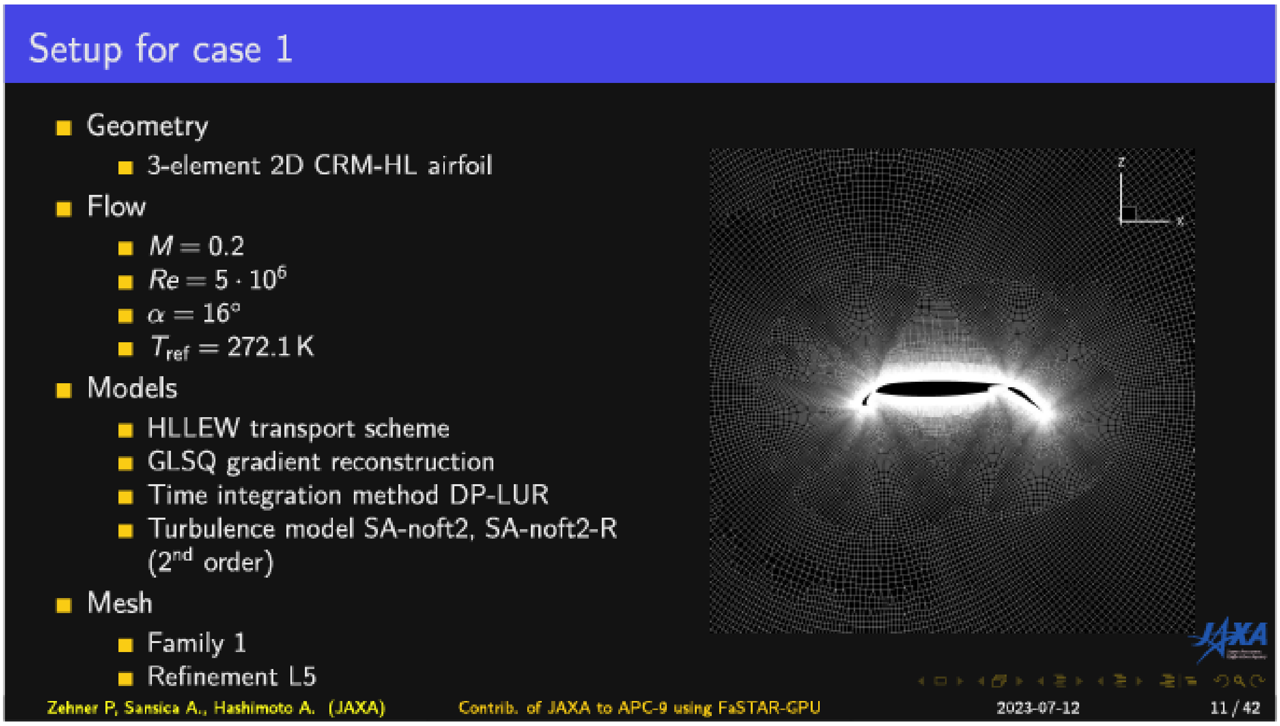
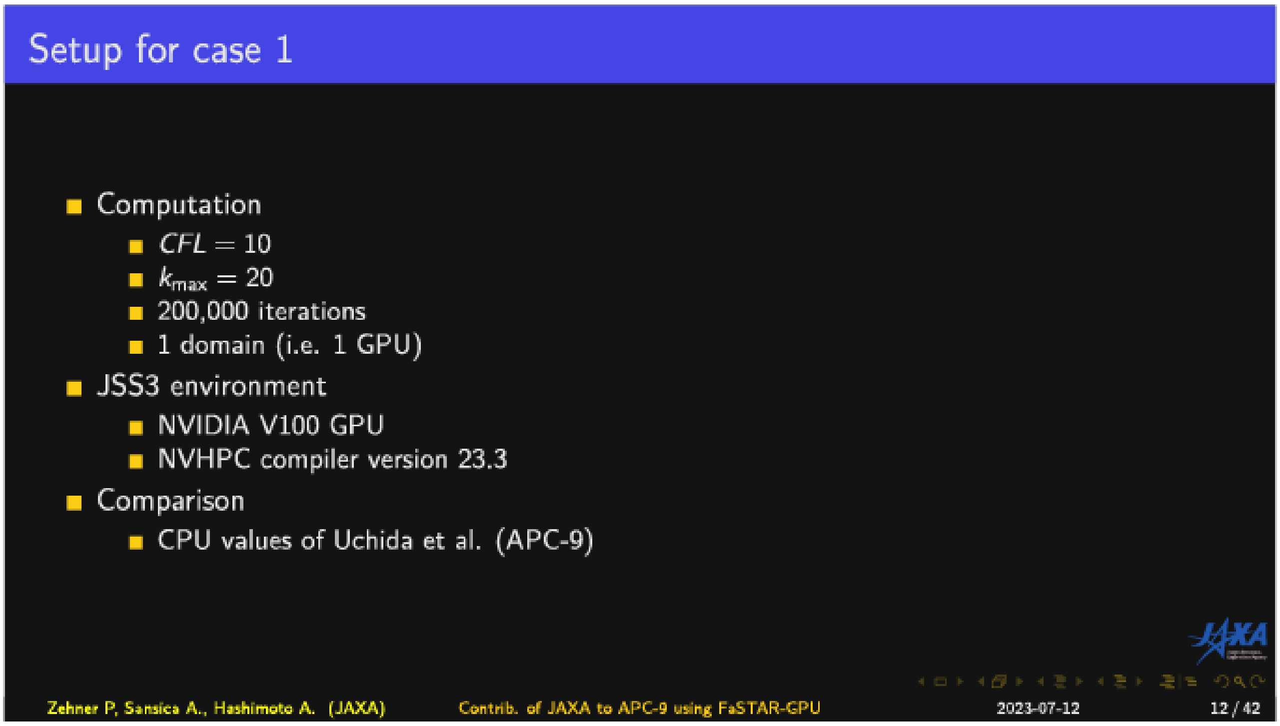


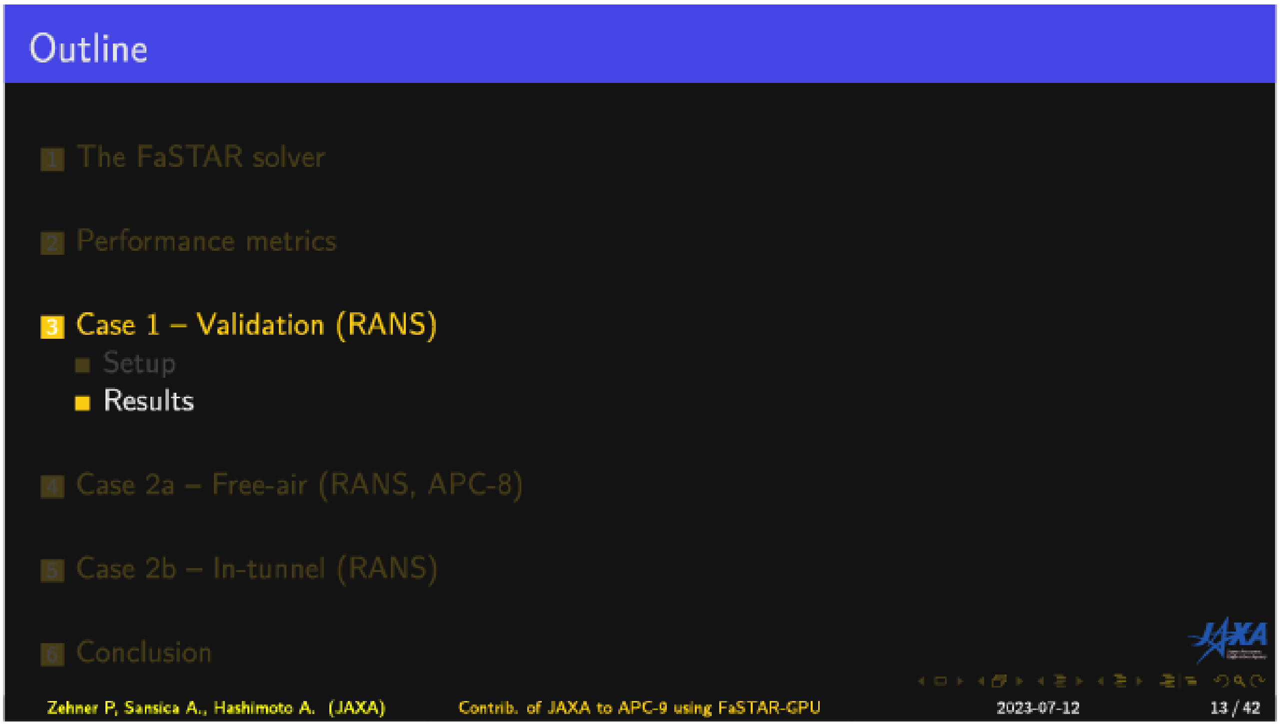
## Setup for case 1

- Geometry
  - 3-element 2D CRM-HL airfoil
- Flow
  - $M = 0.2$
  - $Re = 5 \cdot 10^6$
  - $\alpha = 16^\circ$
  - $T_{ref} = 272.1\,\mathrm{K}$
- Models
  - HLLEW transport scheme
  - GLSQ gradient reconstruction
  - Time integration method DP-LUR
  - Turbulence model SA-noft2, SA-noft2-R ($2^{nd}$ order)
- Mesh
  - Family 1
  - Refinement L5



## Setup for case 1

- Computation
  - $CFL = 10$
  - $k_{max} = 20$
  - 200,000 iterations
  - 1 domain (i.e. 1 GPU)
- JSS3 environment
  - NVIDIA V100 GPU
  - NVHPC compiler version 23.3
- Comparison
  - CPU values of Uchida et al. (APC-9)



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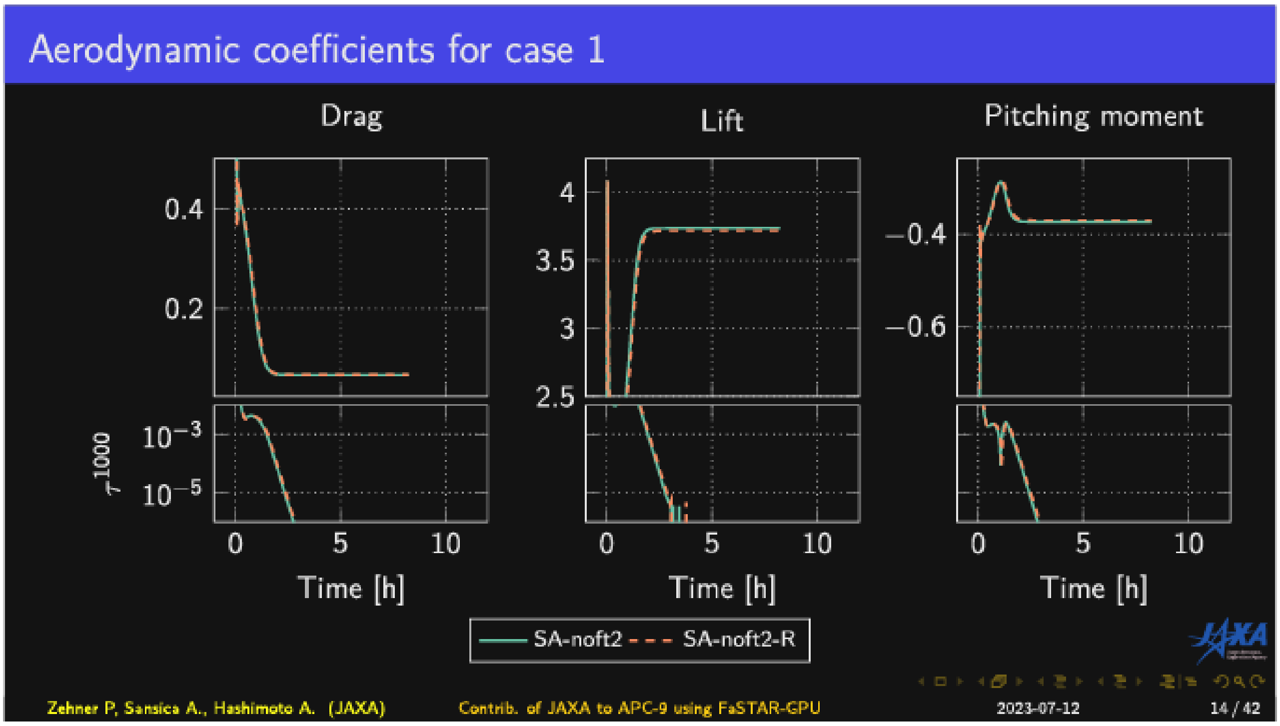
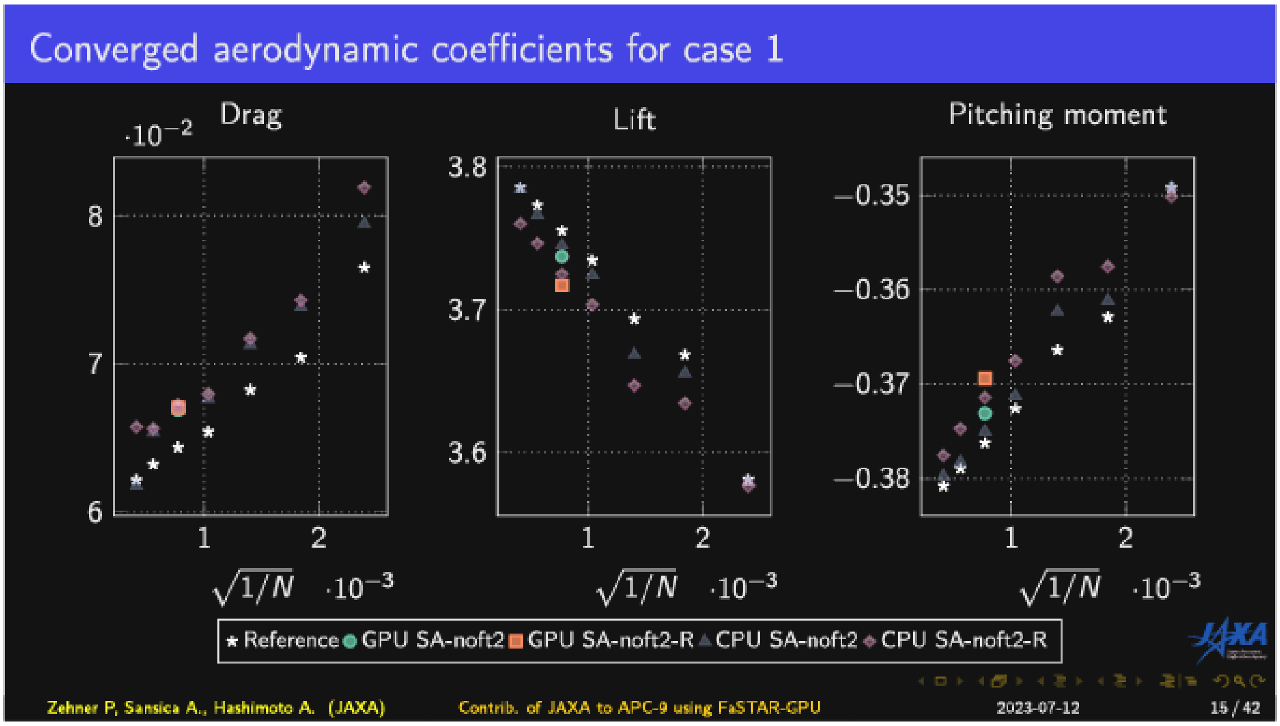


## Aerodynamic coefficients for case 1

Zehner P, Sansica A., Hashimoto A. (JAXA) Contrib. of JAXA to APC-9 using FaSTAR-GPU 2023-07-12 14 / 42



## Converged aerodynamic coefficients for case 1

Zehner P, Sansica A., Hashimoto A. (JAXA) Contrib. of JAXA to APC-9 using FaSTAR-GPU 2023-07-12 15 / 42

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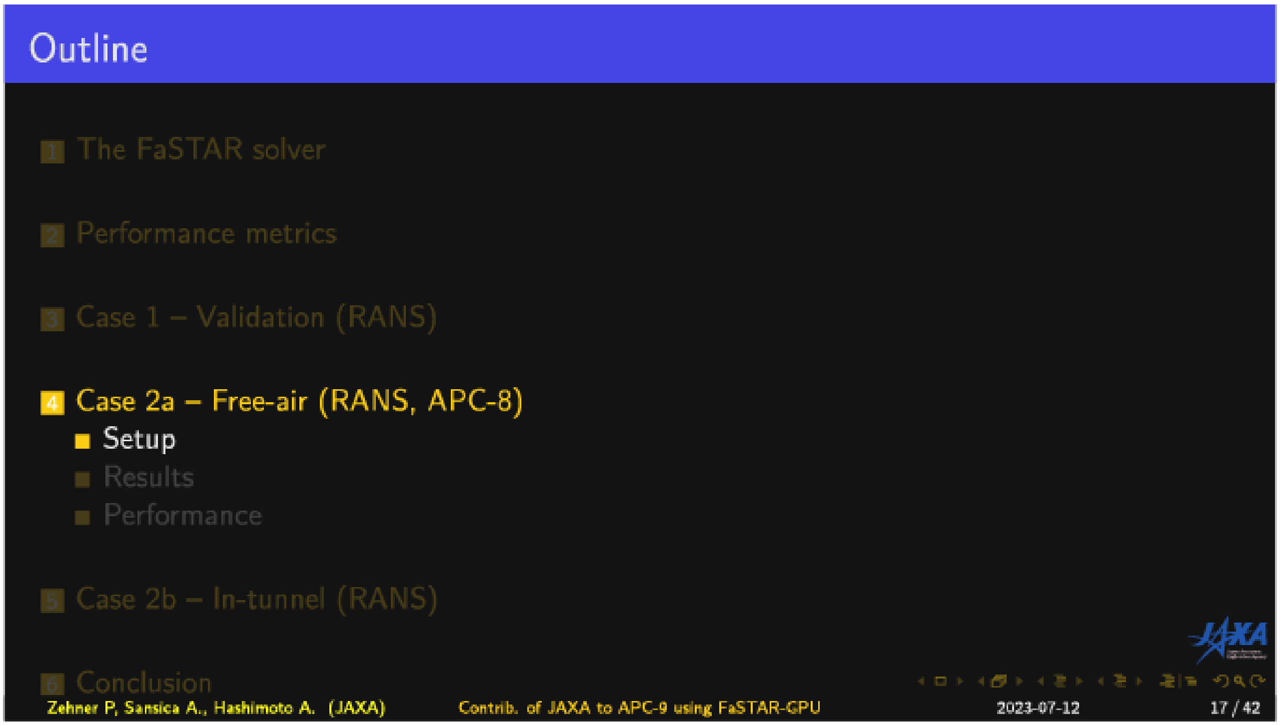

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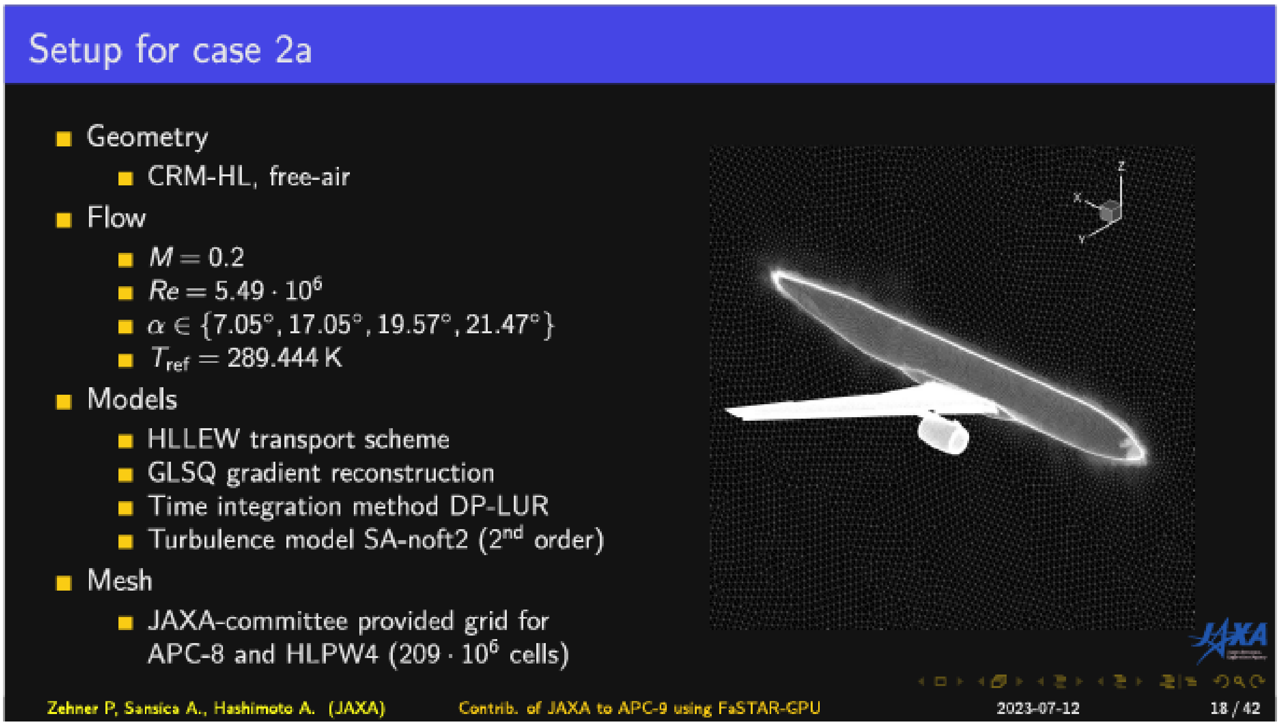
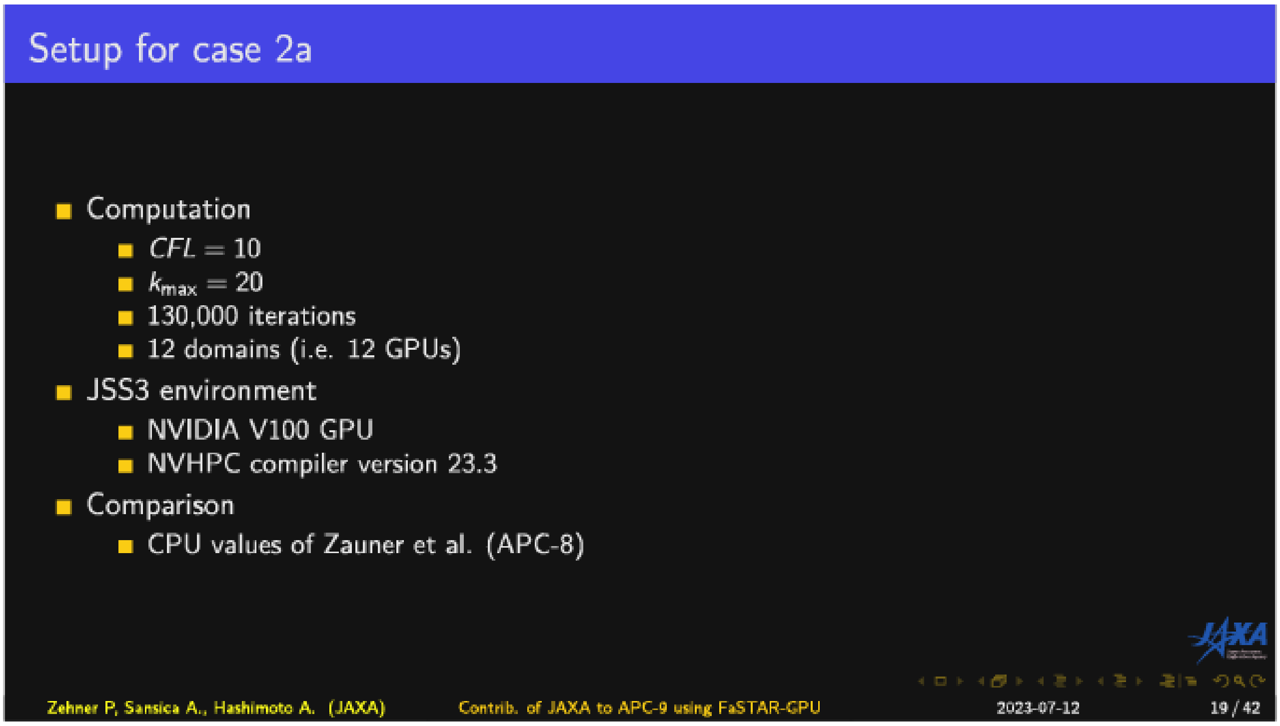


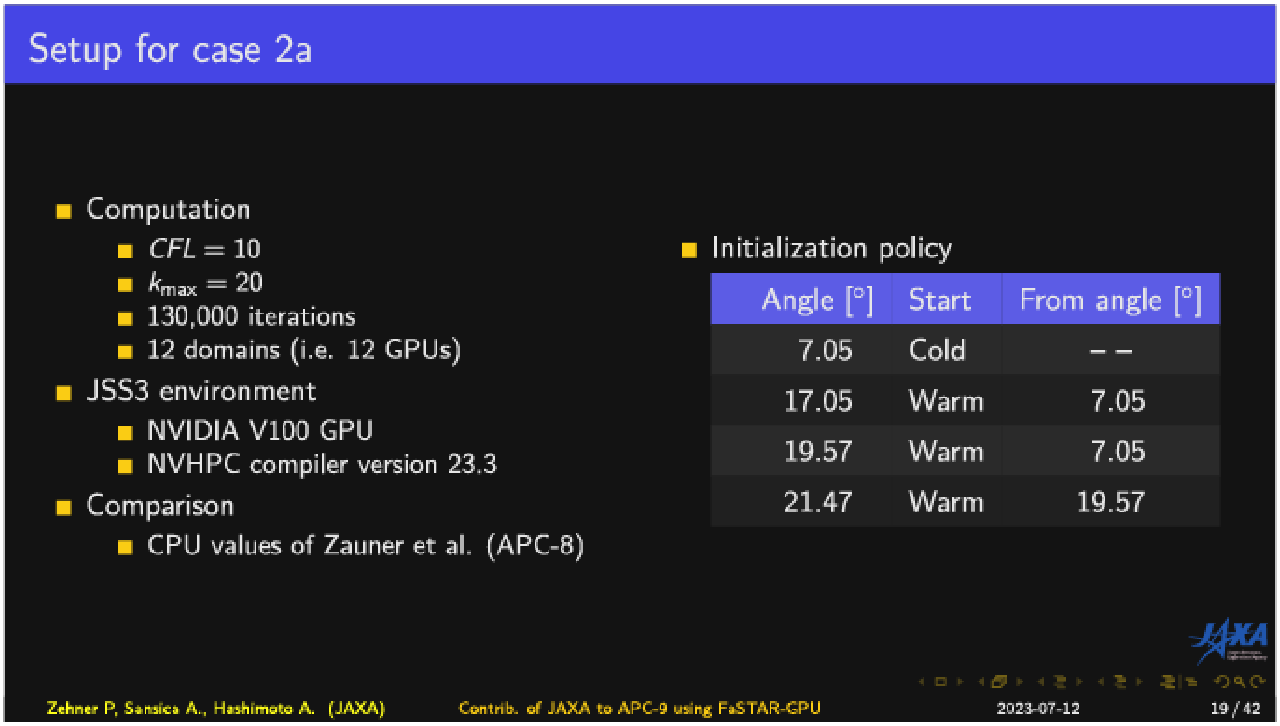
## Setup for case 2a

- Geometry
  - CRM-HL, free-air
- Flow
  - $M = 0.2$
  - $Re = 5.49 \cdot 10^6$
  - $\alpha \in \{7.05°, 17.05°, 19.57°, 21.47°\}$
  - $T_{\text{ref}} = 289.444\,\text{K}$
- Models
  - HLLEW transport scheme
  - GLSQ gradient reconstruction
  - Time integration method DP-LUR
  - Turbulence model SA-noft2 ($2^{\text{nd}}$ order)
- Mesh
  - JAXA-committee provided grid for APC-8 and HLPW4 ($209 \cdot 10^6$ cells)



## Setup for case 2a

- Computation
  - $CFL = 10$
  - $k_{\text{max}} = 20$
  - 130,000 iterations
  - 12 domains (i.e. 12 GPUs)
- JSS3 environment
  - NVIDIA V100 GPU
  - NVHPC compiler version 23.3
- Comparison
  - CPU values of Zauner et al. (APC-8)



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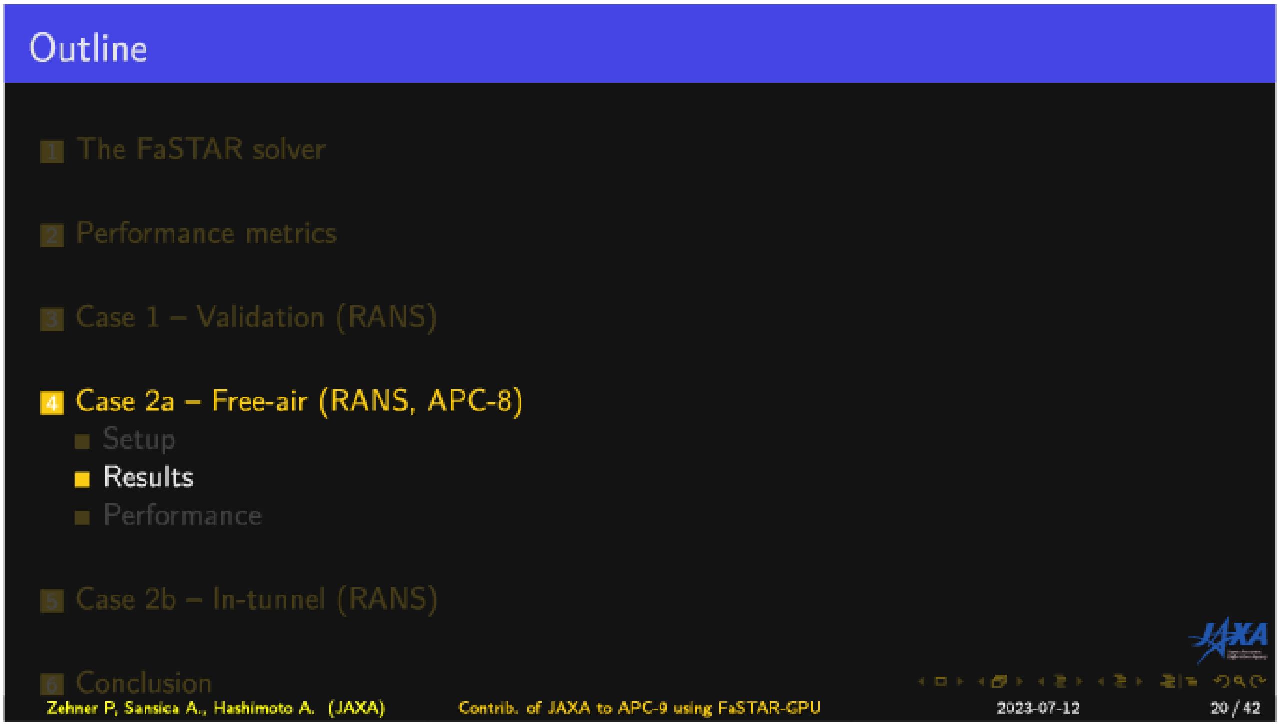
  - NVHPC compiler version 23.3
- Comparison
  - CPU values of Zauner et al. (APC-8)

- Initialization policy

| Angle [°] | Start | From angle [°] |
|---|---|---|
| 7.05 | Cold | – – |
| 17.05 | Warm | 7.05 |
| 19.57 | Warm | 7.05 |
| 21.47 | Warm | 19.57 |



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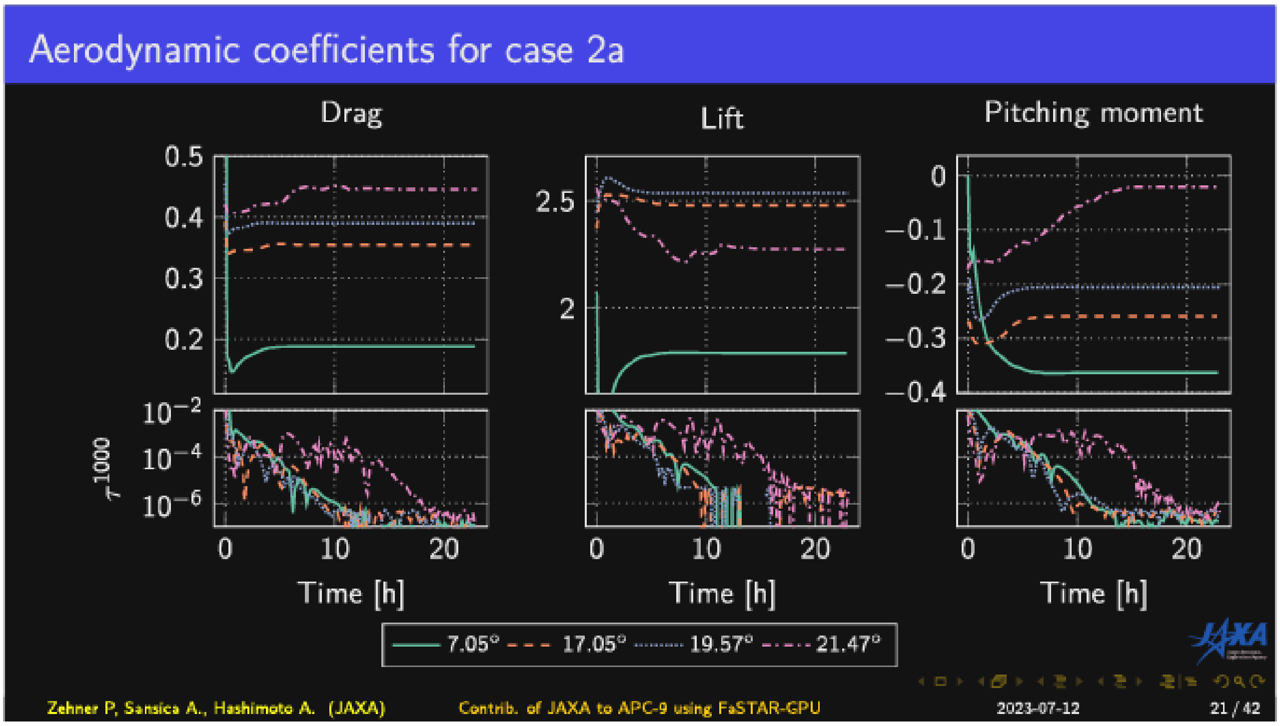
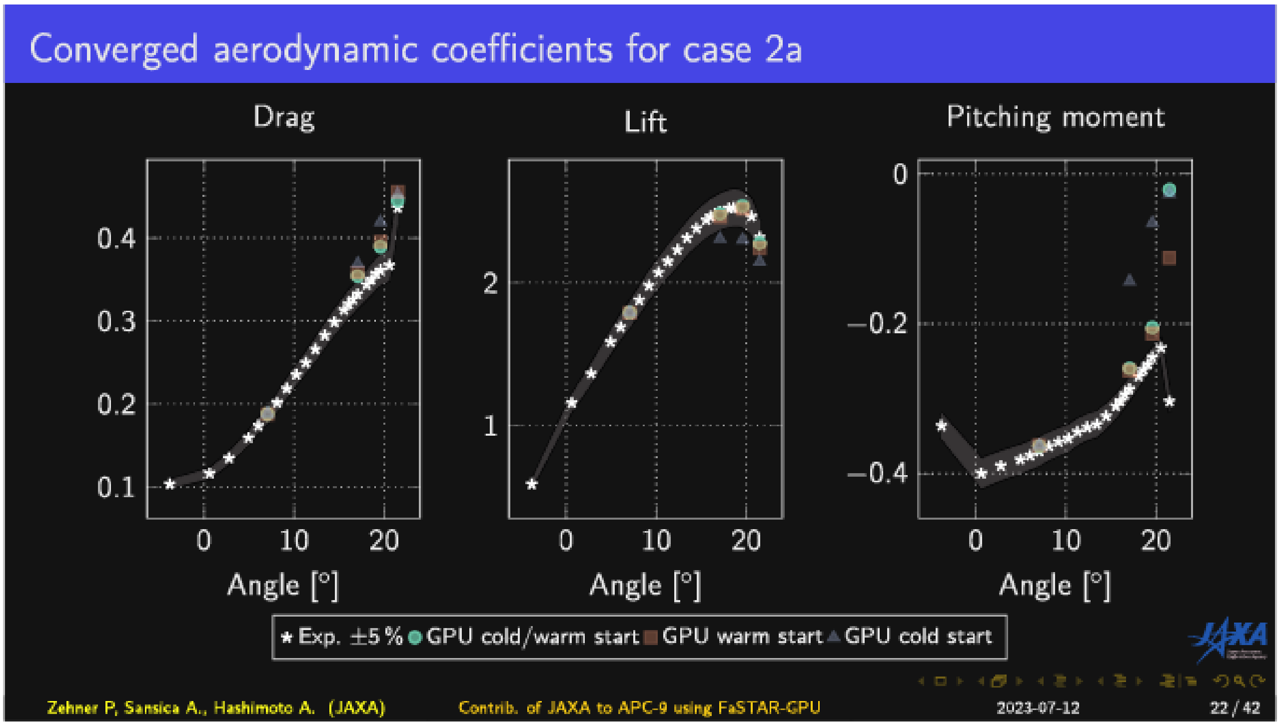


## Aerodynamic coefficients for case 2a

Zehner P, Sansica A., Hashimoto A. (JAXA)　Contrib. of JAXA to APC-9 using FaSTAR-GPU　2023-07-12　21 / 42



## Converged aerodynamic coefficients for case 2a

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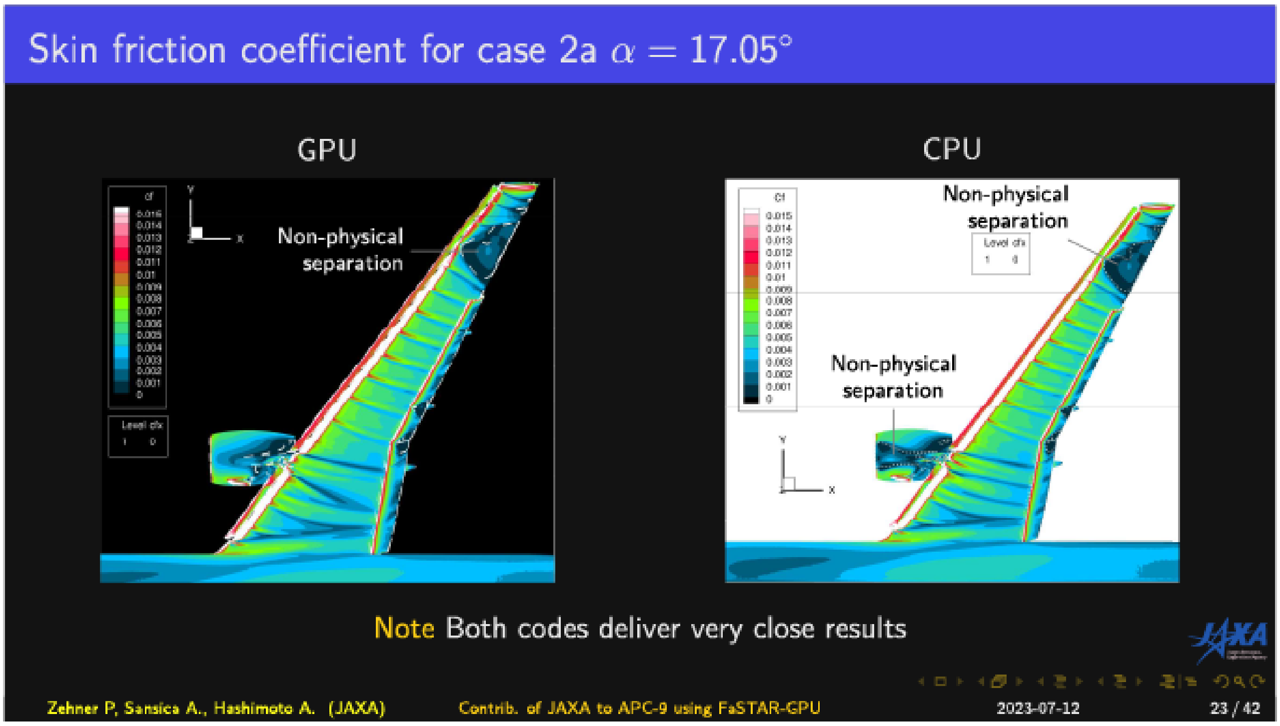
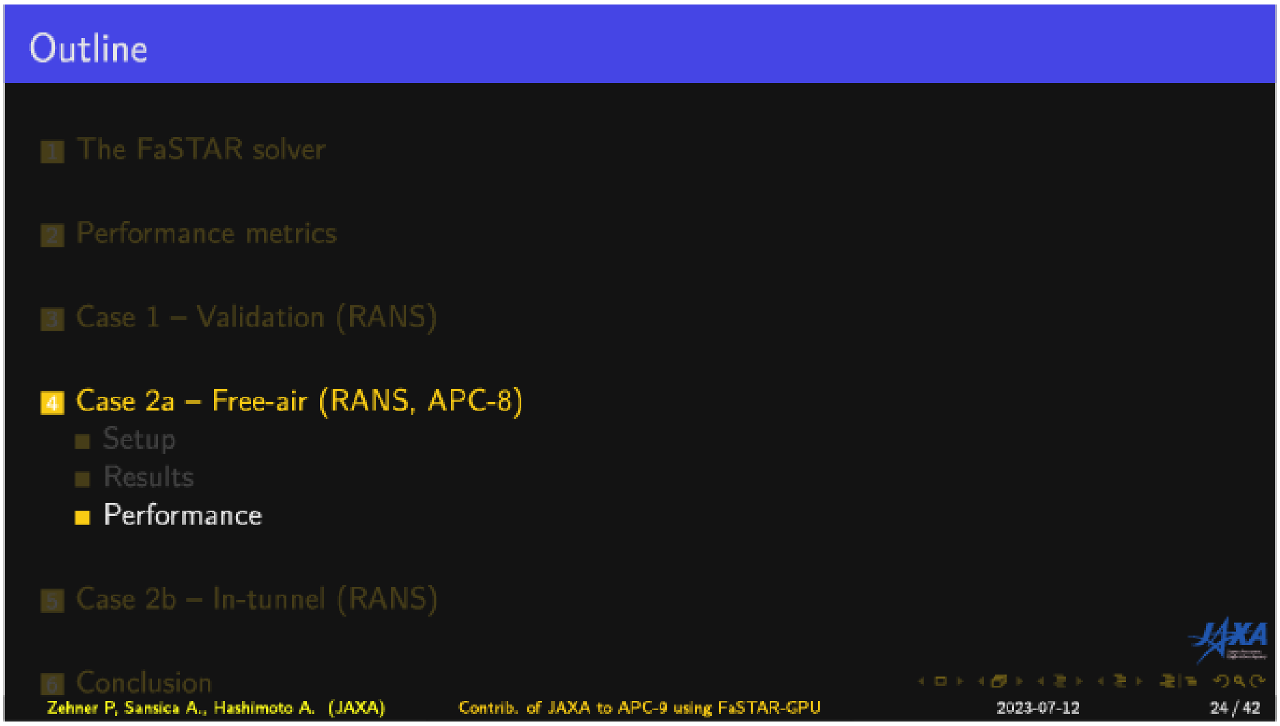


## Skin friction coefficient for case 2a $\alpha = 17.05°$

Note Both codes deliver very close results



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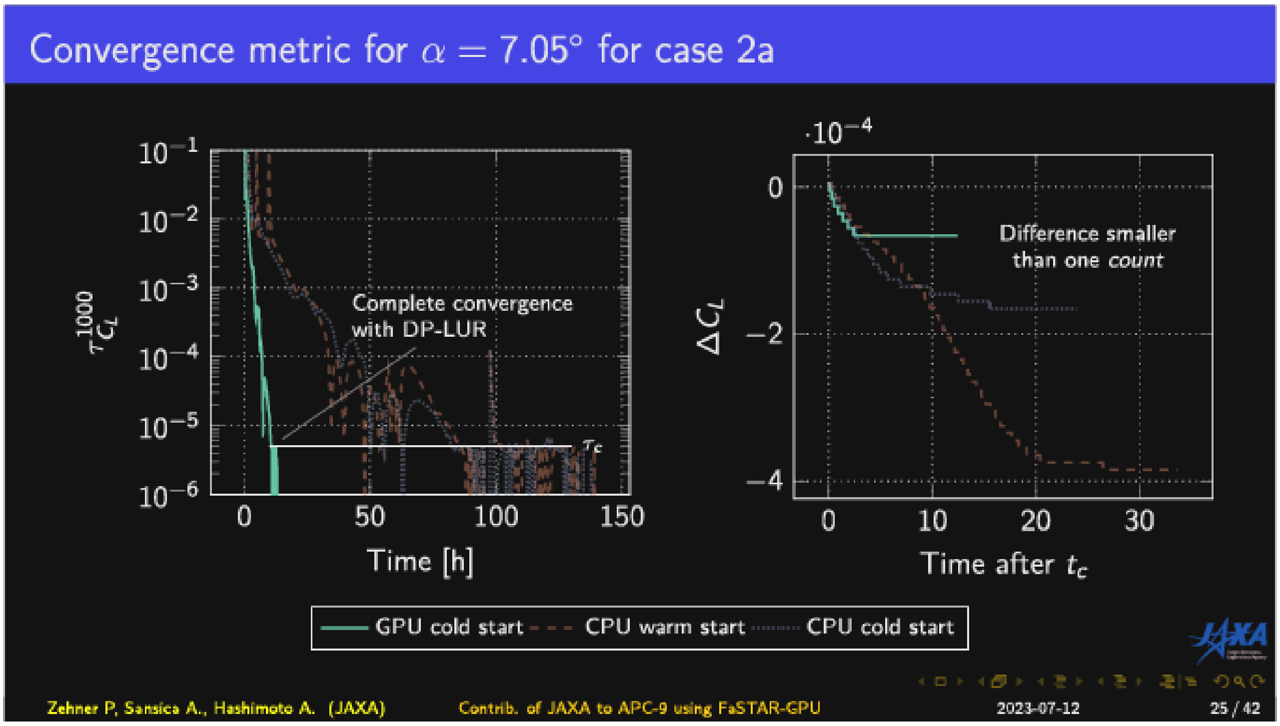
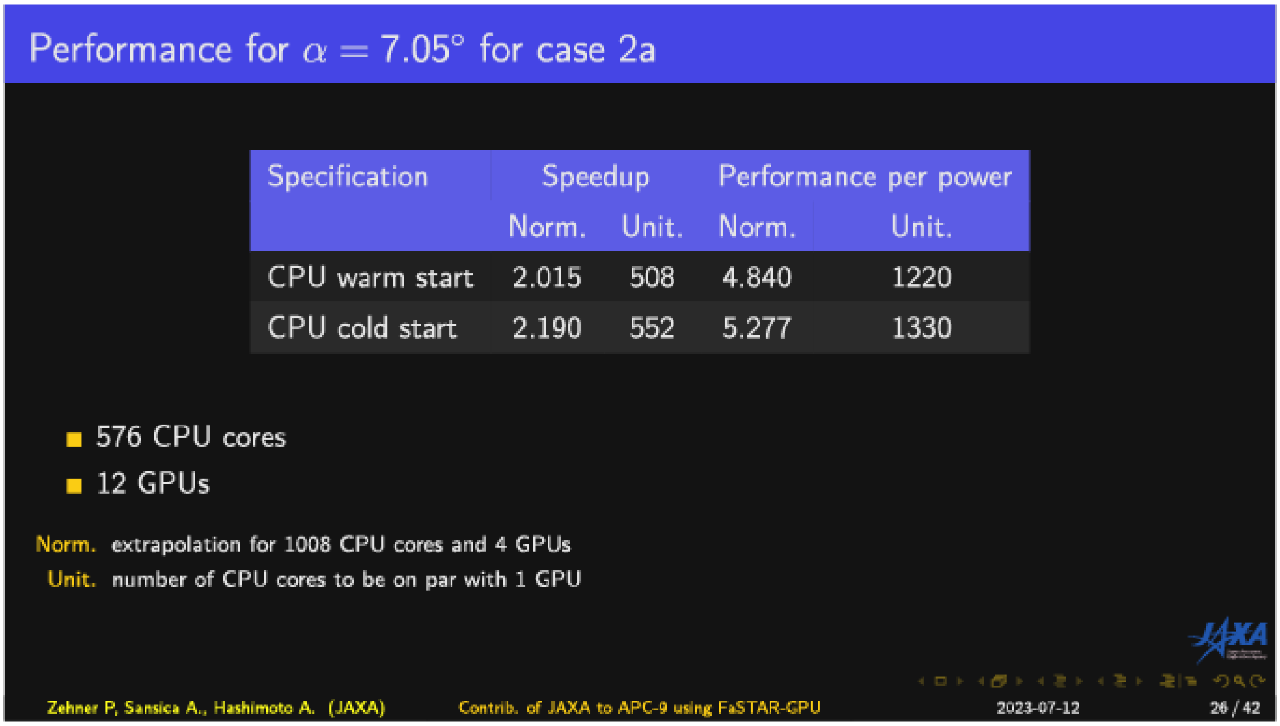


## Convergence metric for $\alpha = 7.05°$ for case 2a

Zehner P, Sansica A., Hashimoto A. (JAXA) Contrib. of JAXA to APC-9 using FaSTAR-GPU 2023-07-12 25 / 42



## Performance for $\alpha = 7.05°$ for case 2a

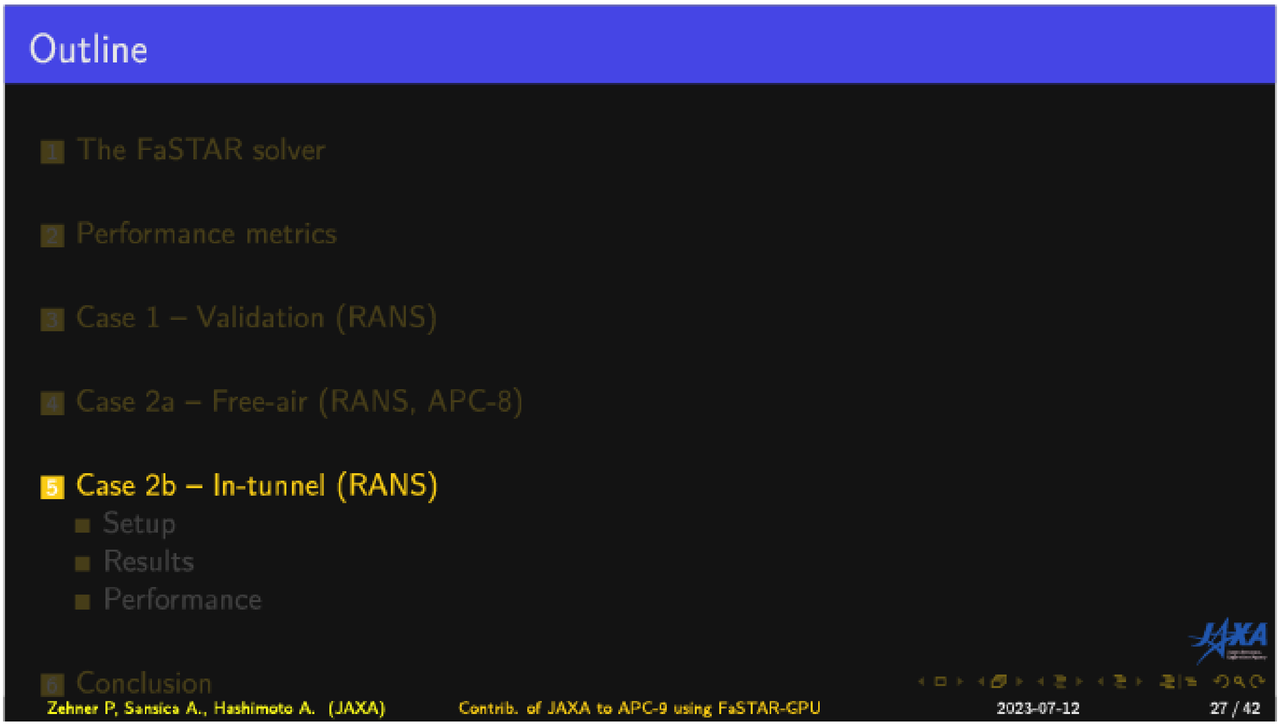
| Specification | Speedup | | Performance per power | |
|---|---|---|---|---|
| | Norm. | Unit. | Norm. | Unit. |
| CPU warm start | 2.015 | 508 | 4.840 | 1220 |
| CPU cold start | 2.190 | 552 | 5.277 | 1330 |

- 576 CPU cores
- 12 GPUs

**Norm.** extrapolation for 1008 CPU cores and 4 GPUs

**Unit.** number of CPU cores to be on par with 1 GPU

Zehner P, Sansica A., Hashimoto A. (JAXA) Contrib. of JAXA to APC-9 using FaSTAR-GPU 2023-07-12 26 / 42



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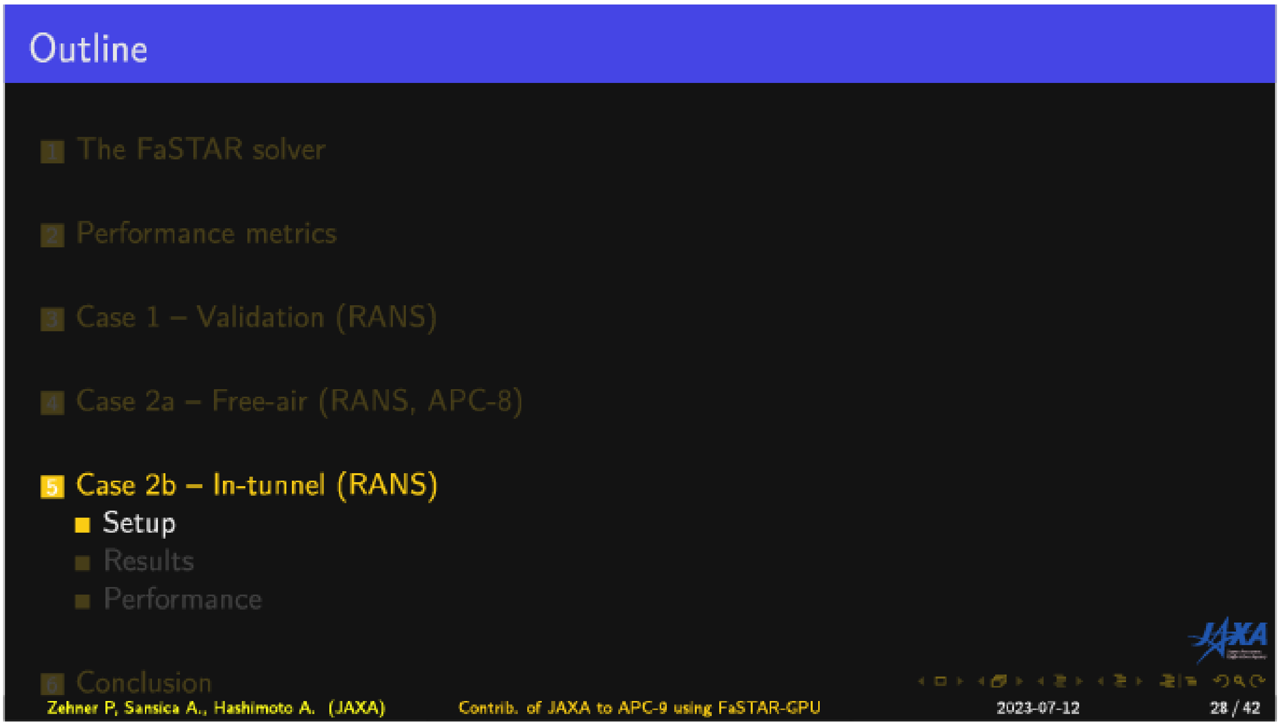
Zehner P, Sansica A., Hashimoto A. (JAXA) Contrib. of JAXA to APC-9 using FaSTAR-GPU 2023-07-12 27 / 42



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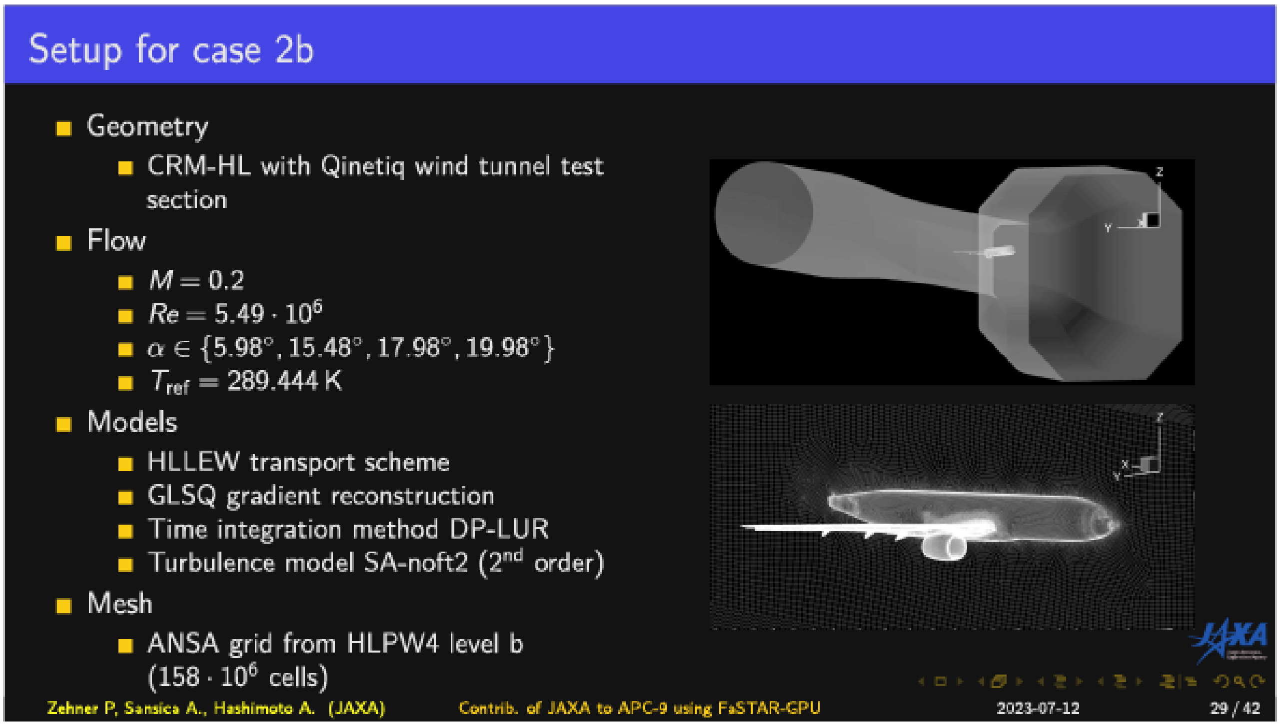
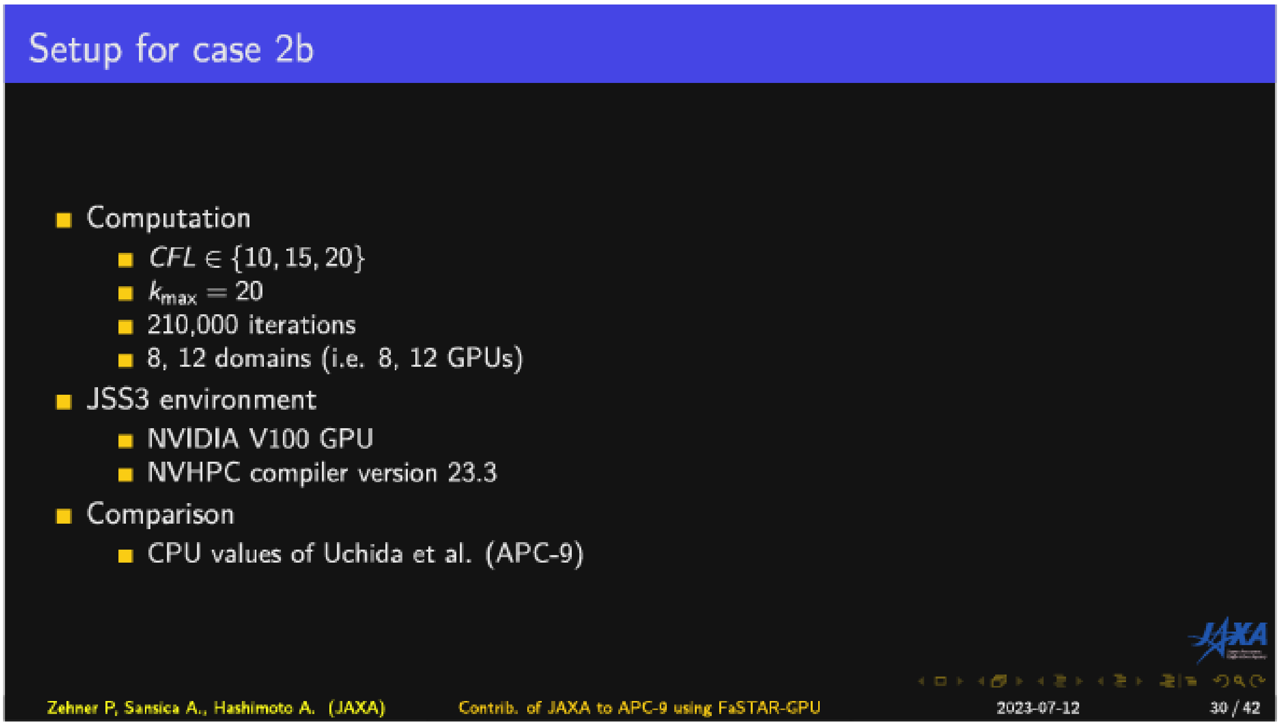


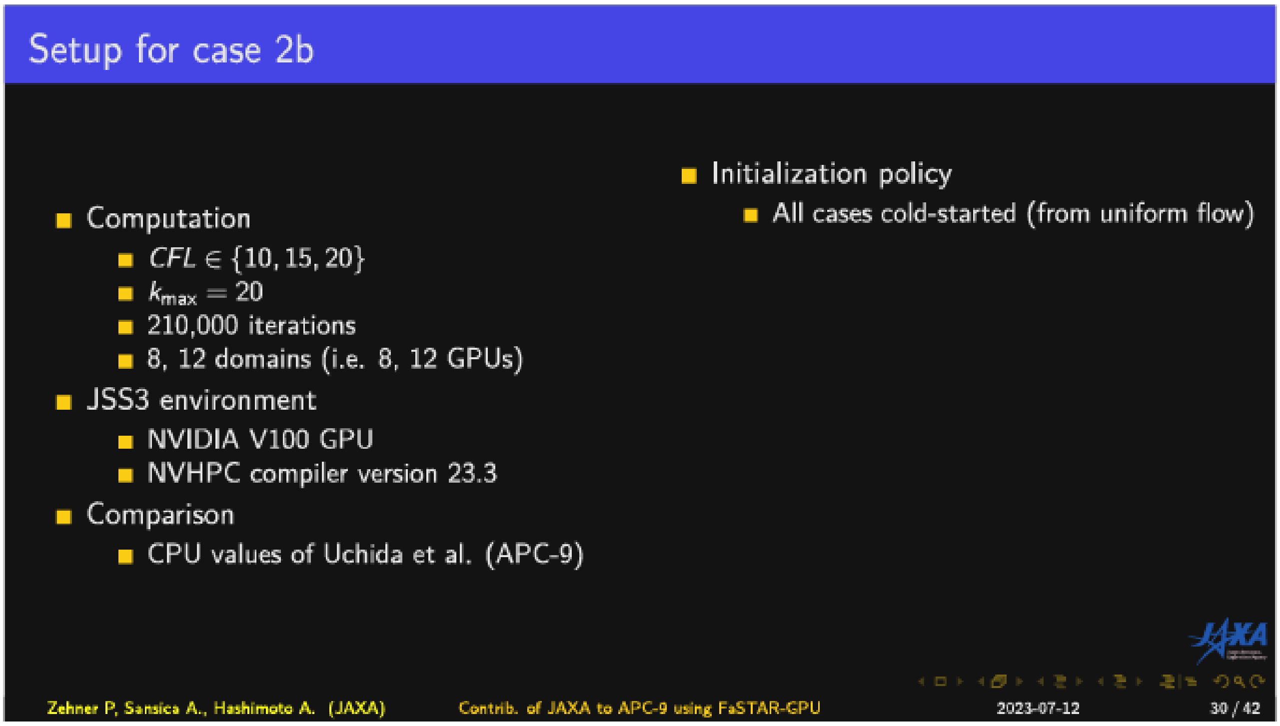
## Setup for case 2b

- Geometry
  - CRM-HL with Qinetiq wind tunnel test section
- Flow
  - $M = 0.2$
  - $Re = 5.49 \cdot 10^6$
  - $\alpha \in \{5.98^\circ, 15.48^\circ, 17.98^\circ, 19.98^\circ\}$
  - $T_{\mathrm{ref}} = 289.444\,\mathrm{K}$
- Models
  - HLLEW transport scheme
  - GLSQ gradient reconstruction
  - Time integration method DP-LUR
  - Turbulence model SA-noft2 ($2^{\mathrm{nd}}$ order)
- Mesh
  - ANSA grid from HLPW4 level b ($158 \cdot 10^6$ cells)



## Setup for case 2b

- Computation
  - $CFL \in \{10, 15, 20\}$
  - $k_{\mathrm{max}} = 20$
  - 210,000 iterations
  - 8, 12 domains (i.e. 8, 12 GPUs)
- JSS3 environment
  - NVIDIA V100 GPU
  - NVHPC compiler version 23.3
- Comparison
  - CPU values of Uchida et al. (APC-9)



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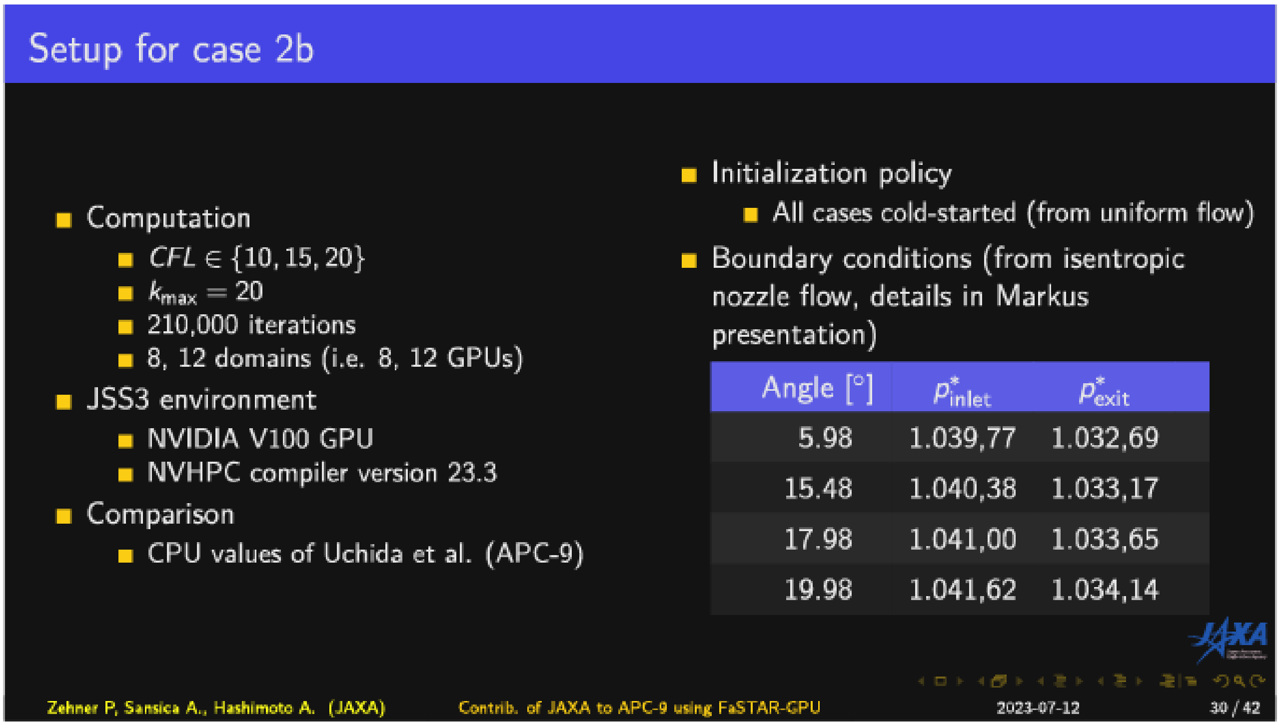
- Initialization policy
  - All cases cold-started (from uniform flow)



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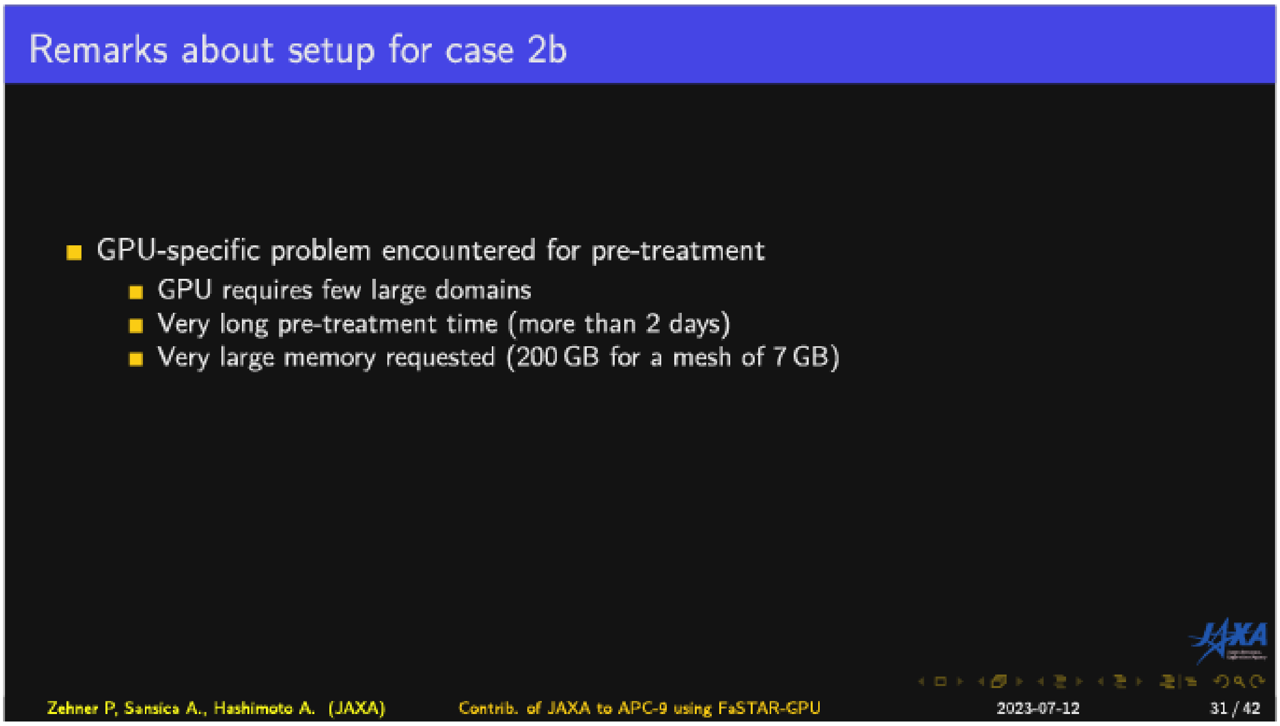
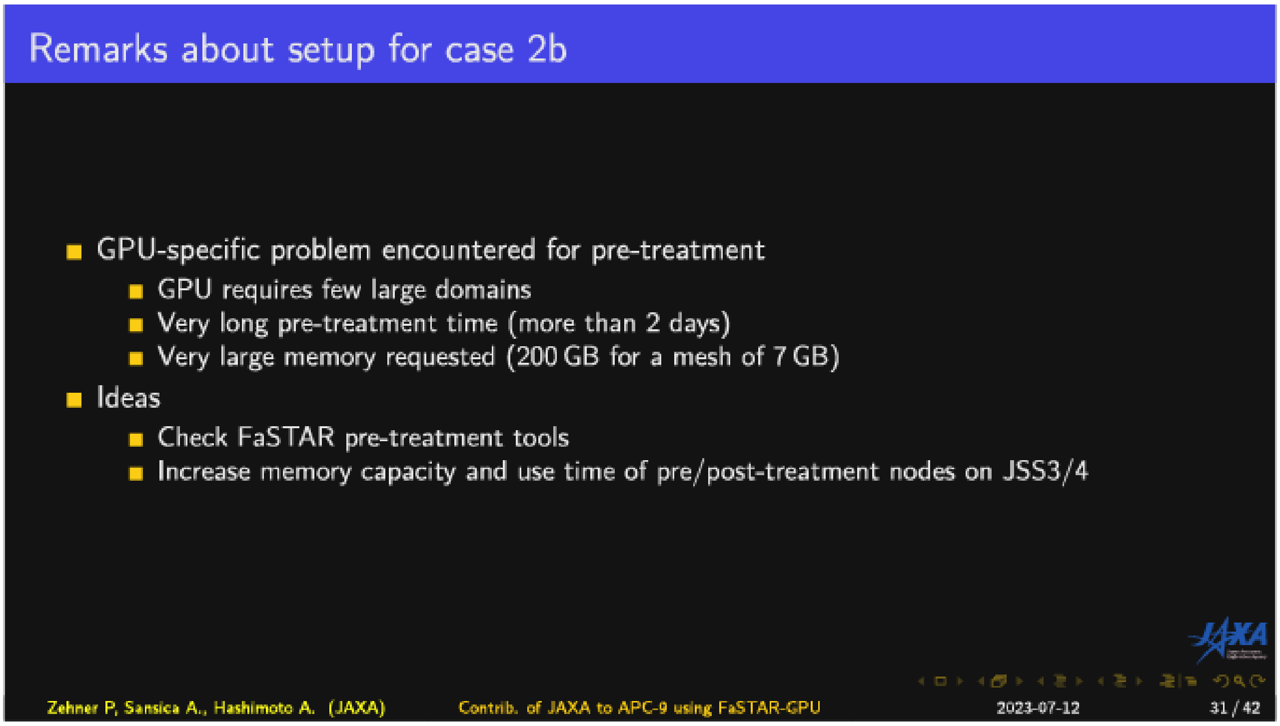
- Comparison
  - CPU values of Uchida et al. (APC-9)
- Initialization policy
  - All cases cold-started (from uniform flow)
- Boundary conditions (from isentropic nozzle flow, details in Markus presentation)

| Angle [°] | $p^*_{\text{inlet}}$ | $p^*_{\text{exit}}$ |
|---|---|---|
| 5.98 | 1.039,77 | 1.032,69 |
| 15.48 | 1.040,38 | 1.033,17 |
| 17.98 | 1.041,00 | 1.033,65 |
| 19.98 | 1.041,62 | 1.034,14 |



## Remarks about setup for case 2b

- GPU-specific problem encountered for pre-treatment
  - GPU requires few large domains
  - Very long pre-treatment time (more than 2 days)
  - Very large memory requested (200 GB for a mesh of 7 GB)



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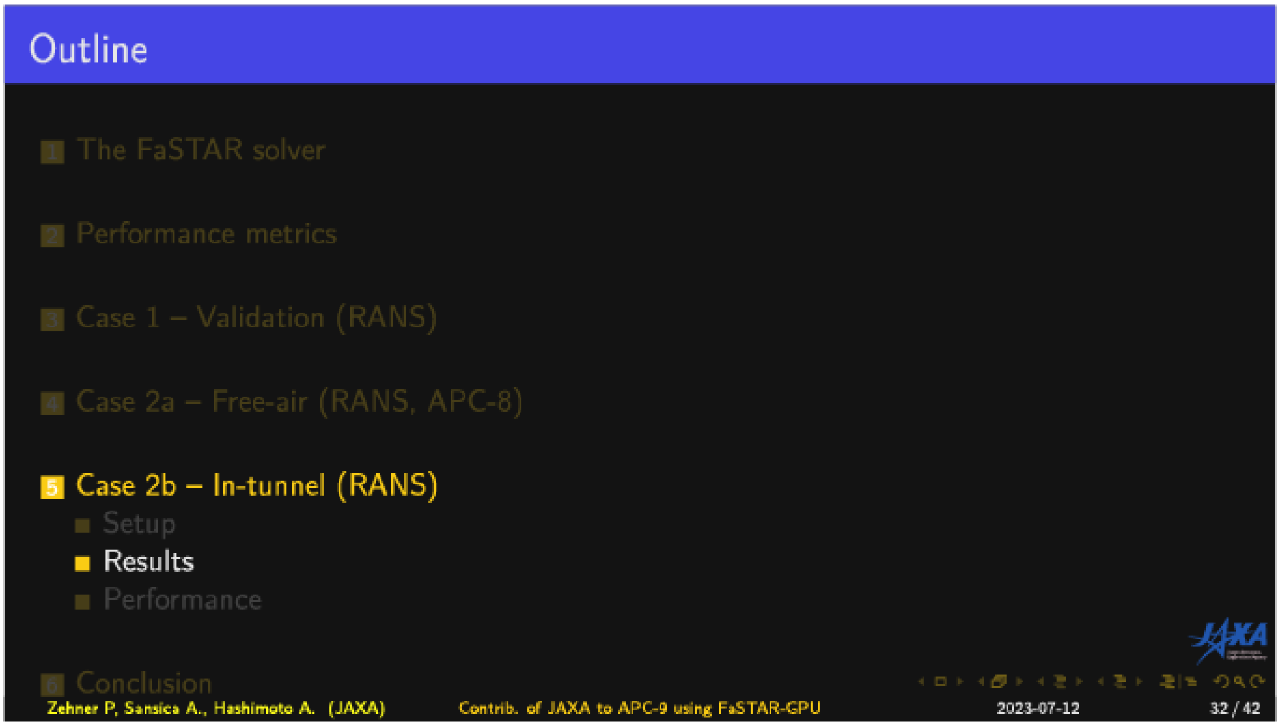
  - Very long pre-treatment time (more than 2 days)
  - Very large memory requested (200 GB for a mesh of 7 GB)
- Ideas
  - Check FaSTAR pre-treatment tools
  - Increase memory capacity and use time of pre/post-treatment nodes on JSS3/4



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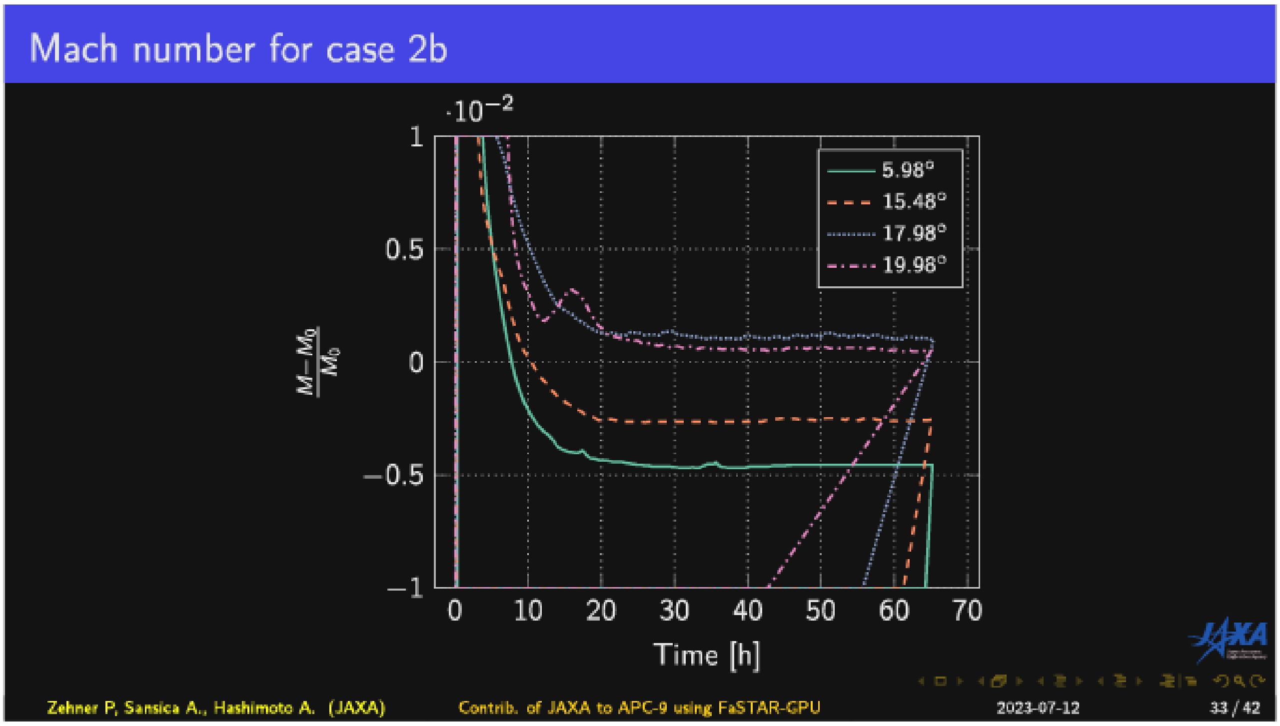
Zehner P, Sansica A., Hashimoto A. (JAXA) Contrib. of JAXA to APC-9 using FaSTAR-GPU 2023-07-12 32 / 42



## Mach number for case 2b

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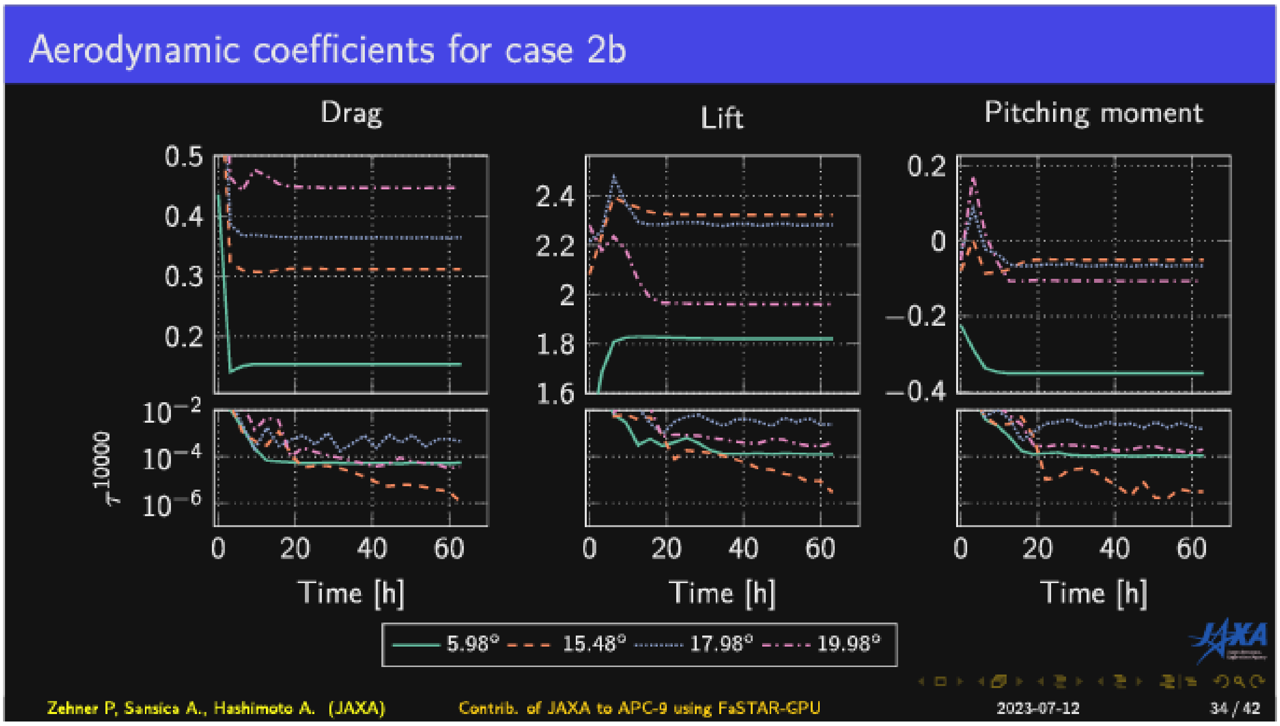

## Aerodynamic coefficients for case 2b

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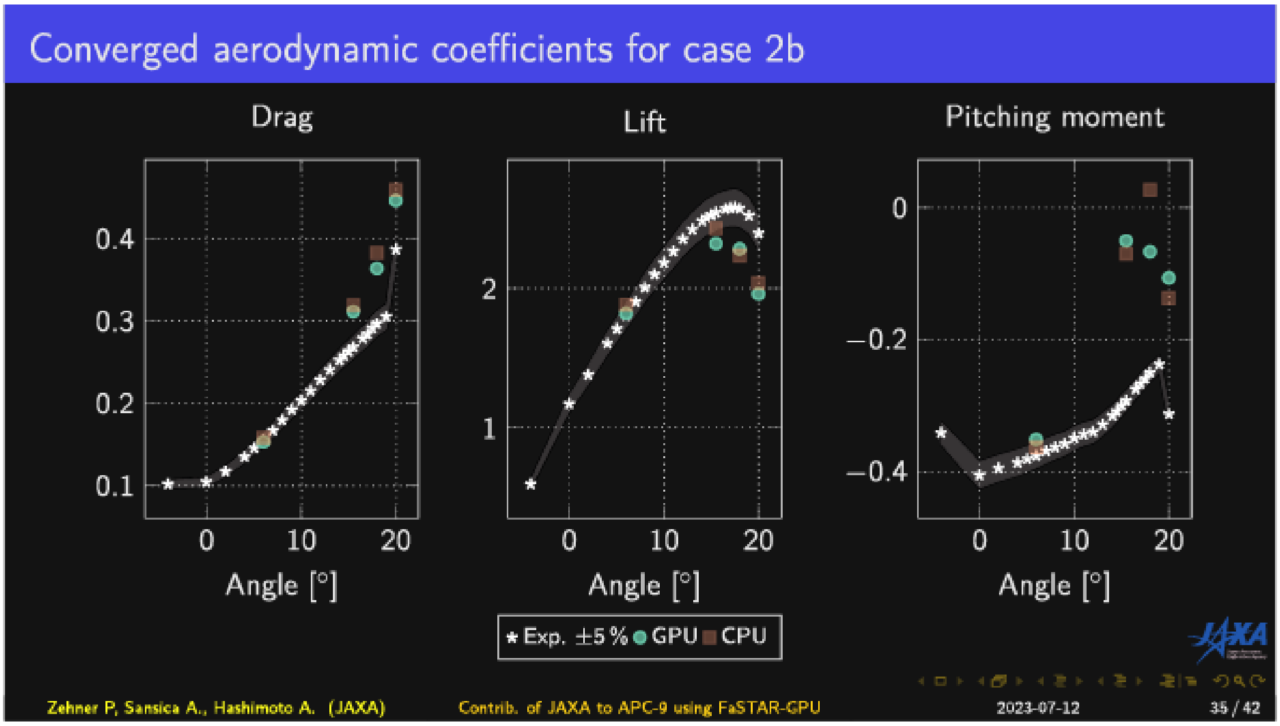
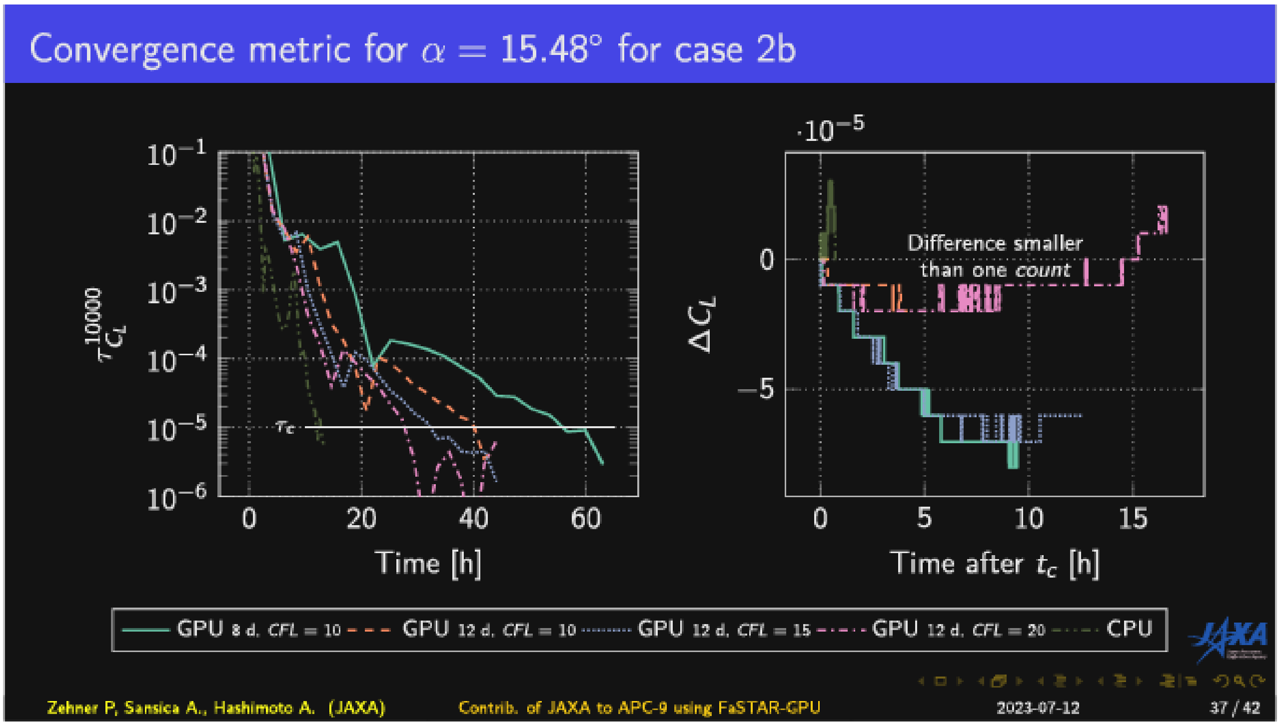


## Converged aerodynamic coefficients for case 2b

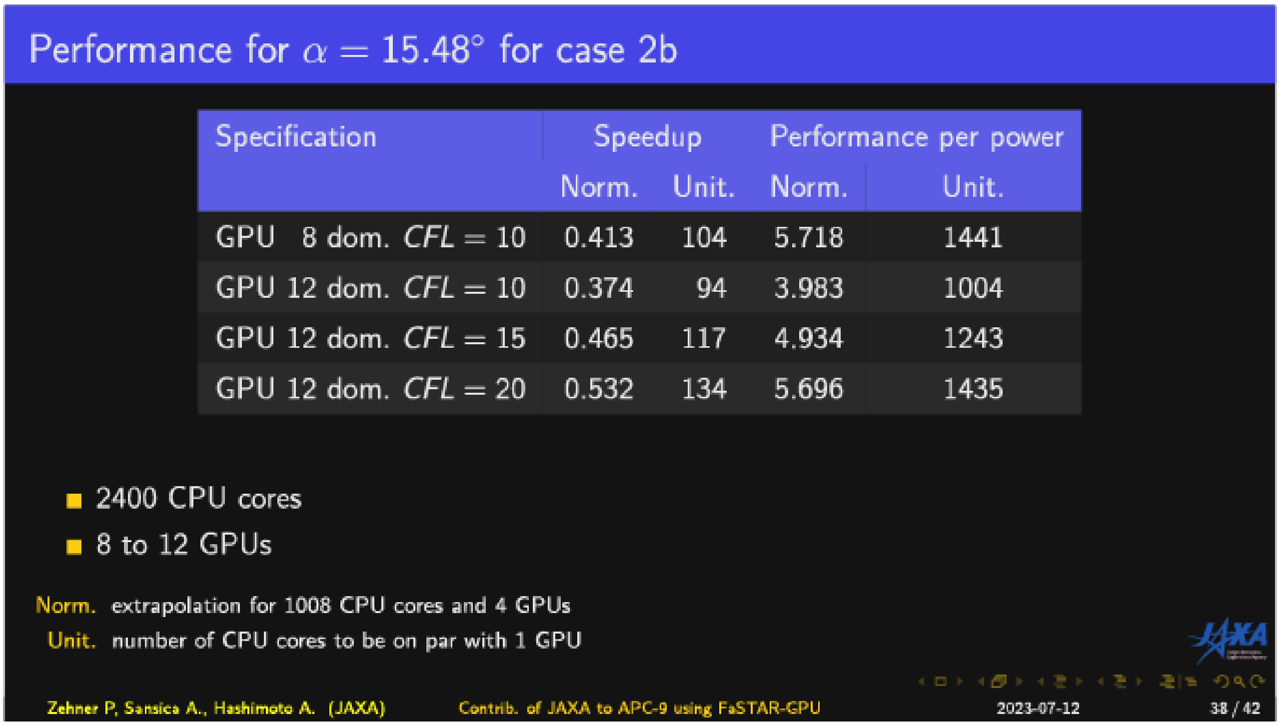
Zehner P, Sansica A., Hashimoto A. (JAXA) Contrib. of JAXA to APC-9 using FaSTAR-GPU 2023-07-12 35 / 42

## Outline

1. The FaSTAR solver
2. Performance metrics
3. Case 1 – Validation (RANS)
4. Case 2a – Free-air (RANS, APC-8)
5. Case 2b – In-tunnel (RANS)
    - Setup
    - Results
    - Performance
6. Conclusion



## Convergence metric for $\alpha = 15.48°$ for case 2b

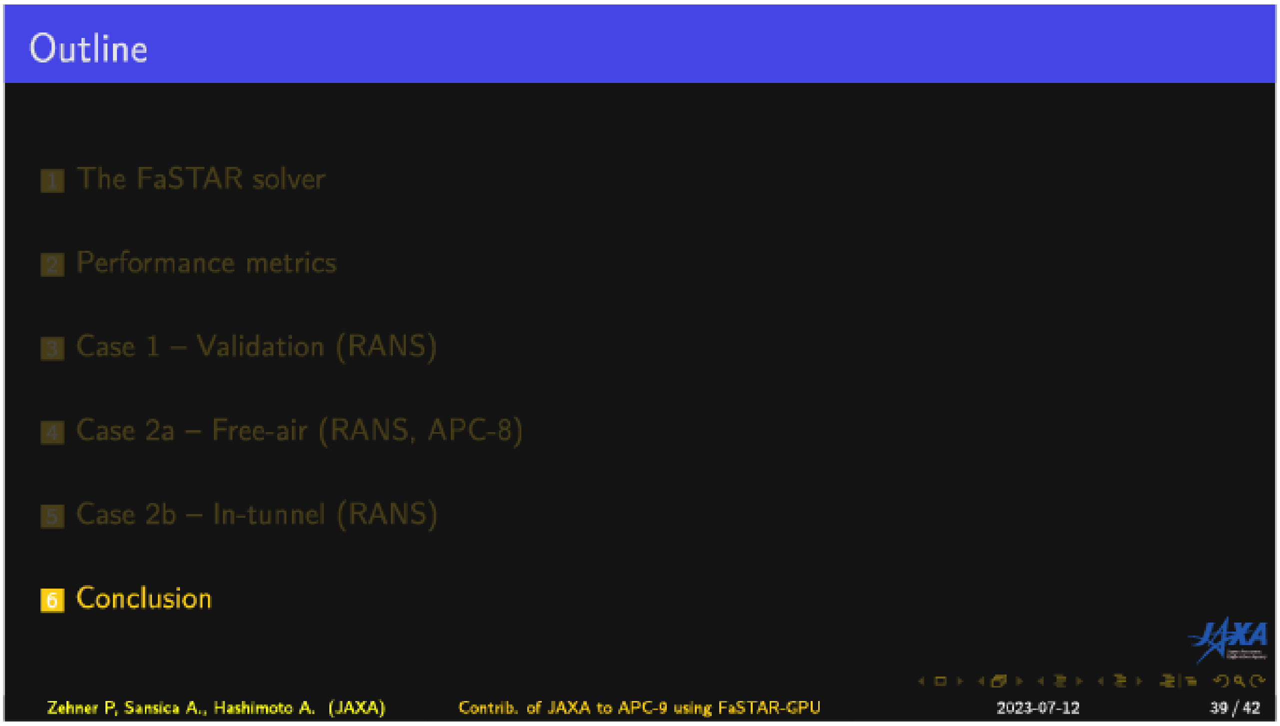


## Performance for $\alpha = 15.48°$ for case 2b

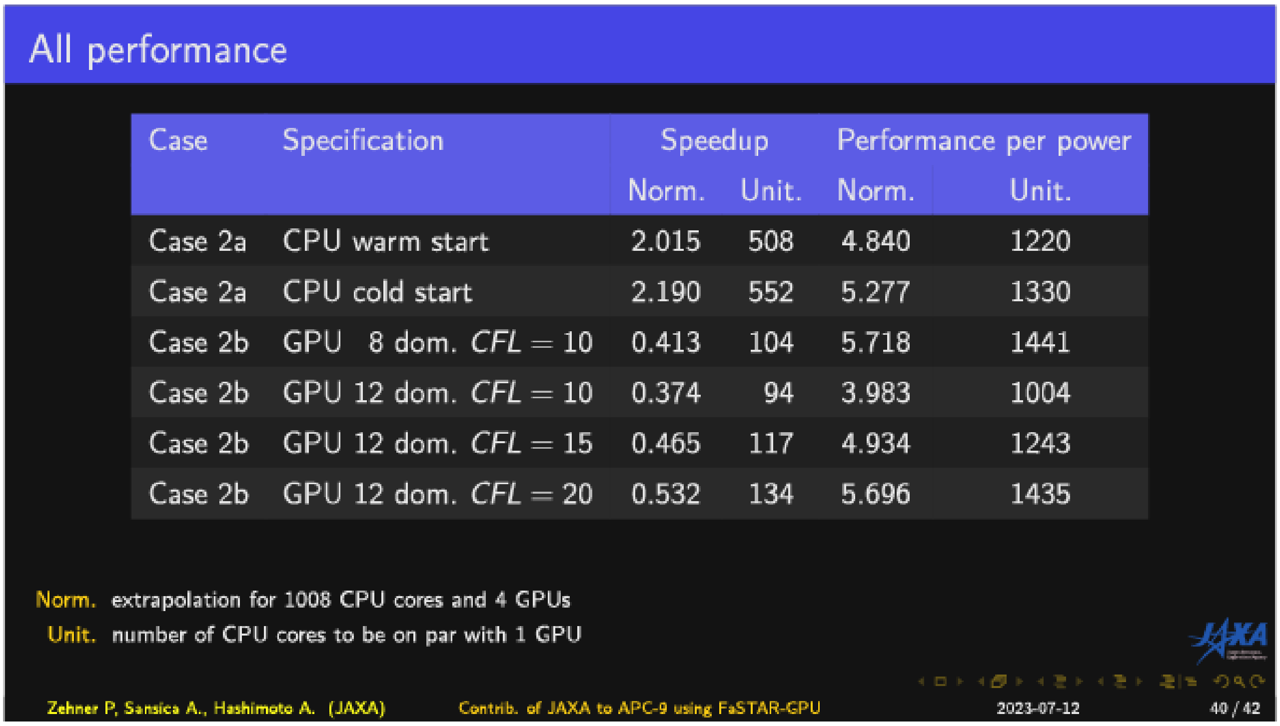
| Specification | Speedup | | Performance per power | |
|---|---|---|---|---|
| | Norm. | Unit. | Norm. | Unit. |
| GPU 8 dom. $CFL = 10$ | 0.413 | 104 | 5.718 | 1441 |
| GPU 12 dom. $CFL = 10$ | 0.374 | 94 | 3.983 | 1004 |
| GPU 12 dom. $CFL = 15$ | 0.465 | 117 | 4.934 | 1243 |
| GPU 12 dom. $CFL = 20$ | 0.532 | 134 | 5.696 | 1435 |

- 2400 CPU cores
- 8 to 12 GPUs

Norm. extrapolation for 1008 CPU cores and 4 GPUs
Unit. number of CPU cores to be on par with 1 GPU



## Outline



## All performance

| Case | Specification | Speedup | | Performance per power | |
|---|---|---|---|---|---|
| | | Norm. | Unit. | Norm. | Unit. |
| Case 2a | CPU warm start | 2.015 | 508 | 4.840 | 1220 |
| Case 2a | CPU cold start | 2.190 | 552 | 5.277 | 1330 |
| Case 2b | GPU 8 dom. $\mathit{CFL} = 10$ | 0.413 | 104 | 5.718 | 1441 |
| Case 2b | GPU 12 dom. $\mathit{CFL} = 10$ | 0.374 | 94 | 3.983 | 1004 |
| Case 2b | GPU 12 dom. $\mathit{CFL} = 15$ | 0.465 | 117 | 4.934 | 1243 |
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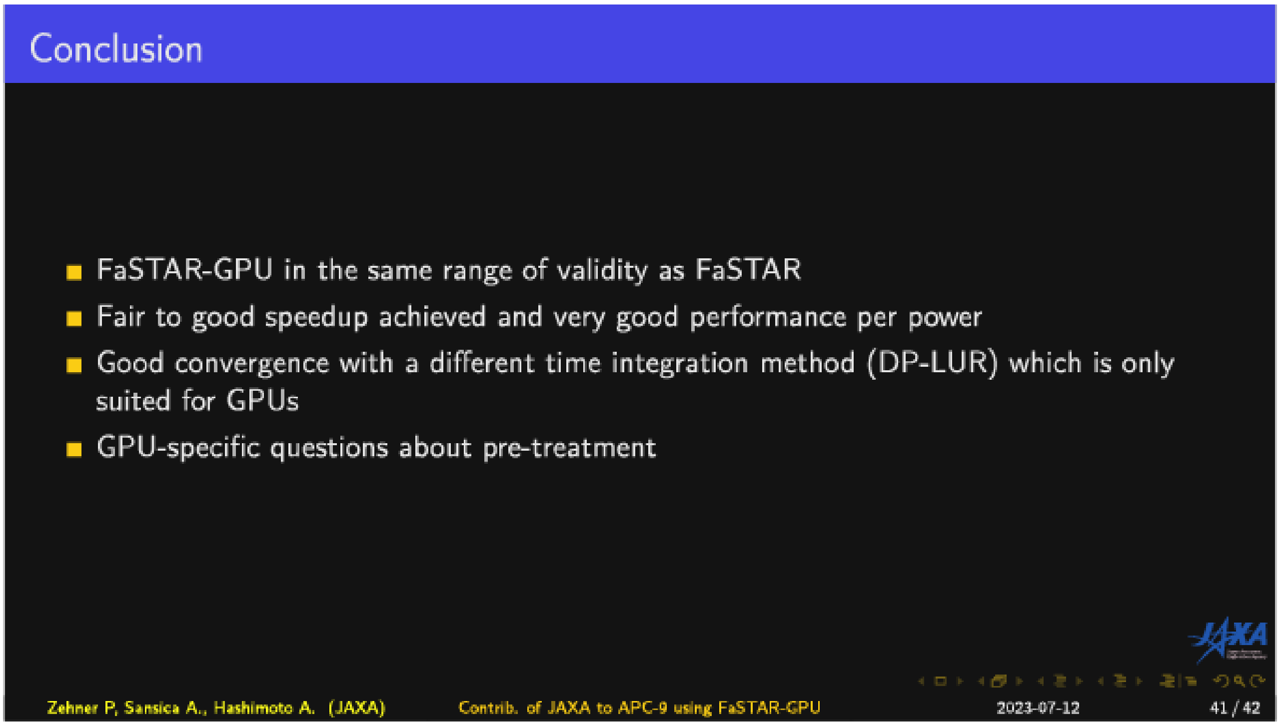
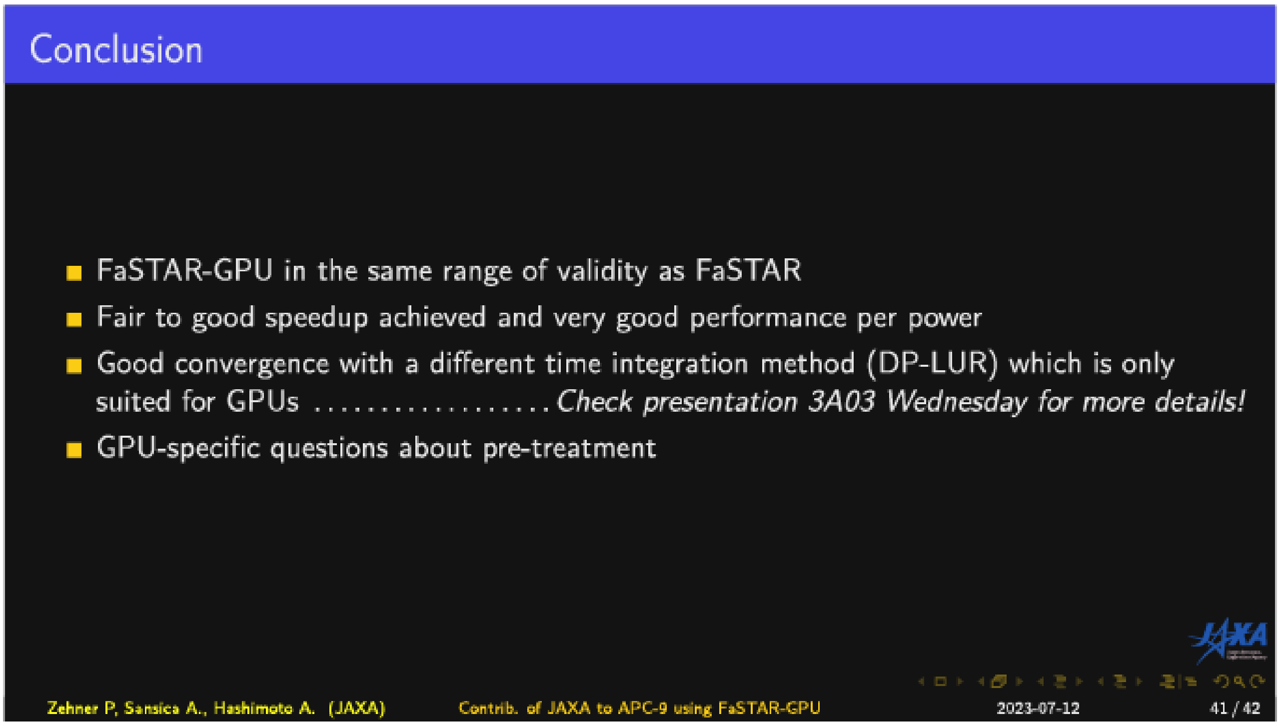
**Norm.** extrapolation for 1008 CPU cores and 4 GPUs
**Unit.** number of CPU cores to be on par with 1 GPU



## Conclusion

- FaSTAR-GPU in the same range of validity as FaSTAR
- Fair to good speedup achieved and very good performance per power
- Good convergence with a different time integration method (DP-LUR) which is only suited for GPUs
- GPU-specific questions about pre-treatment



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- GPU-specific questions about pre-treatment

# ご清聴ありがとうございました

ご質問がありますか

Thank you for your kind attention, any question?