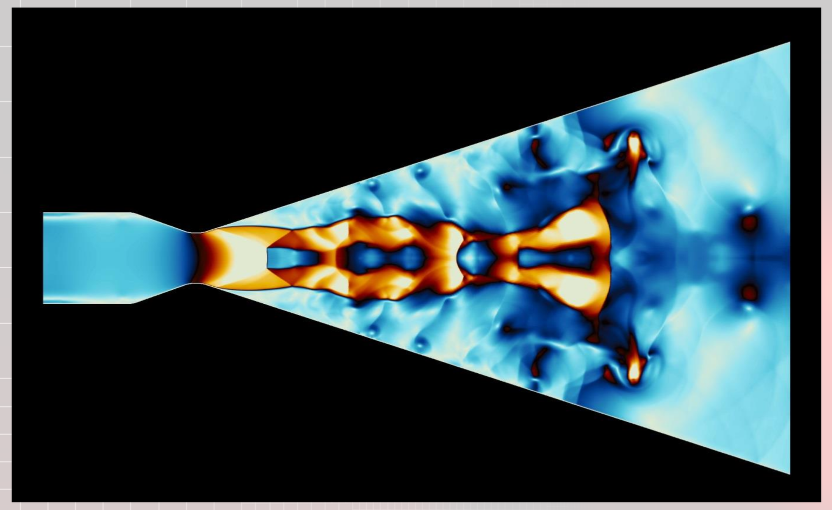
The Future of Rocket Engine Design

Rocket Engine Development



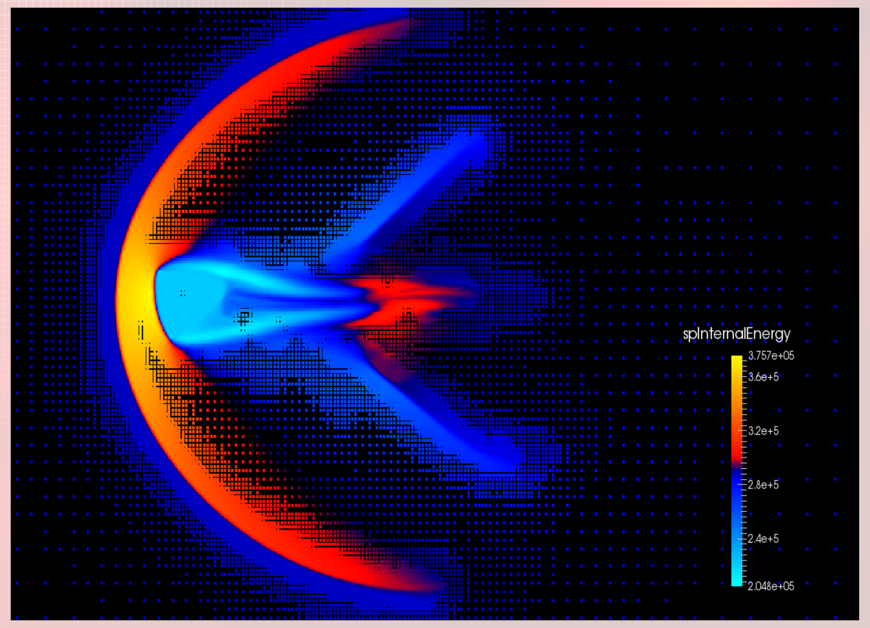
Simulation of an overexpanded nozzle

Rocket engine development continues to be driven by the intuition and experience of designers, progressing through extensive trial-and-error test campaigns. Extreme temperatures and pressures frustrate direct observation, and simulation is limited by

- Turbulent scale separation of up to 8 orders of magnitude
- Small scale mixing driving combustion
- High per-node-cost of chemistry and real-gas properties

Within engines, the highly nonlinear physics at the smallest scales is crucial for capturing the large scale dynamics which characterize stability and performance. The development of high fidelity, high performance, sparse-data simulation can reduce the need for costly stand testing.

Adaptive Wavelet Simulation



Supersonic flow past a capsule

Adaptive wavelet collocation *[1]* is a high order finite-difference framework for solving PDEs on an optimal, dynamic grid. It uses multiresolution analysis to identify coherent structures and maintain a sparse-data representation.

Adaptation involves transforming and filtering the flow field in wavelet space:

$$u(x) = \sum_{k \in K^0} c_k^0 \varphi_k^0 + \sum_{j=0} \sum_{l \in L_j} d_l^j \psi_l^j$$

- Transform via tensorial lifting scheme
- A priori error control

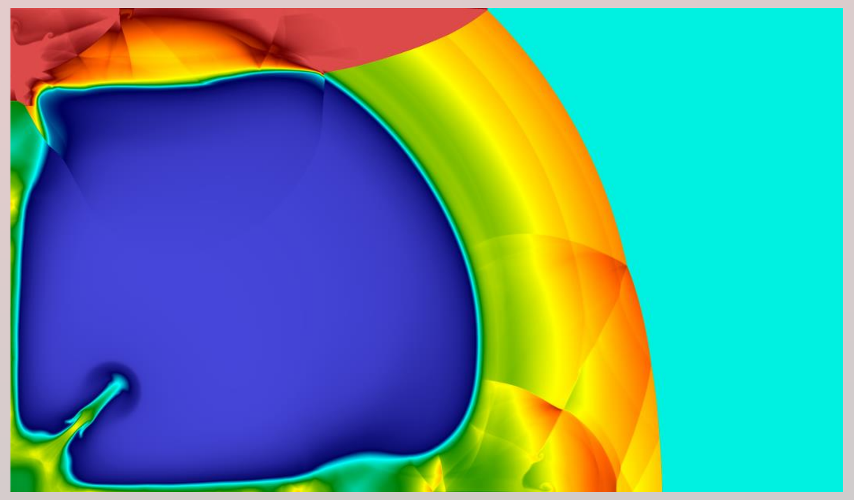
For hierarchical parallelism and implementation on GPU clusters, an asynchronous algorithm was designed. High throughput on manycore architecture is achieved by:

- Keeping data resident in GPU memory
- Maintaining coalesced memory access through sorting and permuting the data
- Reduced multi-node synchronization *[2]*

[1] Vasilyev, O.V. and Bowman, C., *Second Generation Wavelet Collocation Method for the Solution of Partial Differential Equations*. J. Comp. Phys., **165**, pp. 660-693, 2000.

[2] Nejadmalayeri, A., Vezolainen, A., Brown-Dymkoski, E., and Vasilyev, O.V., *Parallel Adaptive Wavelet Collocation Method for PDEs*, J. Comp. Phys, **298**, pp. 237-253, 2015

Computational Combustion



Deflagration to detonation test case

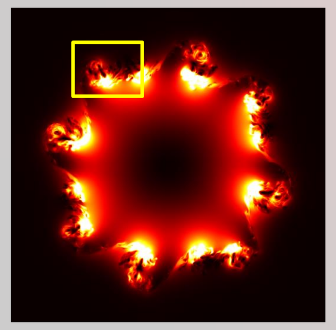
Adaptive wavelet compression is particularly beneficial for turbulence simulation:

- Exploits intermittency
- Identifies most coherent structures for improved LES performance

For predictive simulation, high fidelity thermo-chemical property models are included. By implementing a sparse-data representation, the very high cost is mitigated by drastically reducing the number of nodes, enabling

- Finite-rate kinetics
- Temperature-dependent and real-gas properties
- Highly accurate, optimized methane-oxygen reaction mechanism *[3]*

[3] Smith, Gregor P, et al, *GRI-Mech 3.0*, http://www.me.berkeley.edu/gri_mech/



DNS on a single GPU (Image): Portion of the kinetic energy field and grid at the turbulent interface of a counter-rotating flow.

- Fluid: Air
- Domain: 1m x 1m
- Finest resolution: 23.2µm
- Adaptive compression: 99.84%

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