Applications of GPU Computing to Mission Design and Satellite Operations at NASA's Goddard Space Flight Center

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Presentation Roadmap

Part 0: Crash course on Magnetic Reconnection

Part 1: The ambitious space mission to study MR, Magnetospheric Multi-Scale mission (MMS)

Part 2: How GPU computing plays central role in MMS mission operations

Part 3: Brief look at additional GPU applications
Magnetic Reconnection

The Sun and the Earth’s magnetosphere

Image credit: ESA
Magnetic Reconnection

The Earth as a Laboratory

Image credit: Charles Day, 2001

Physics Today 54(10), 16 (2001); doi: 10.1063/1.1420541
Magnetic Reconnection

Image credit: Southwest Research Institute
Magnetic Reconnection

MMS Satellites 1 and 2 During Construction - Stacked
Magnetic Reconnection

The MMS Launch Vehicle – Atlas V

Image credit: ULA
Magnetic Reconnection

The MMS Launch Vehicle – Atlas V
Magnetic Reconnection

The MMS Launch Vehicle – Atlas V
Magnetic Reconnection

Rotate and Expand MMS Orbit to Search for Reconnection Events

Image credit: Scientific Visualization Studio, GSFC
Magnetic Reconnection

Rotate and Expand MMS Orbit to Search for Reconnection Events
Magnetic Reconnection

Two sides of mission complexity:
Must also keep spacecraft in tight tetrahedron formation

Video credit: Scientific Visualization Studio, GSFC
Magnetic Reconnection

NASA Magnetosphere Multiscale (MMS) Mission to Study Reconnection Events

Formation flying on this scale has never been attempted before on NASA mission.

$1 billion mission, 10 years in development

$120 satellite maneuvers throughout mission lifecycle

Maneuver satellites nominally every two weeks!

DON’T CRASH THE SATELLITES!
Magnetic Reconnection

MMS Maneuvers – Sources of Error

Why so many maneuvers?

- Formation Maintenance
- Formation Resize
- Orbital resize (change search pattern)

DON’T CRASH THE SATELLITES!
Magnetic Reconnection

MMS Maneuvers – Sources of Error

• Satellite position velocity uncertainty?
• Planned maneuver not optimal?
• Thrusters don’t do what you tell them to do!
  — Might fire early, might fire late?
  — Some thrusters might only partially burn?
  — Some thrusters might not burn at all?
  — Thruster(s) dies mid-burn?
  — Run out of gas?
Satellite Operations

Simulating Spacecraft Orbits in Real-time

How to model all this uncertainty?

Run huge Monte Carlo simulations on-the-fly every day and after every maneuver.

Basically, simulate all possible scenarios as fast as possible.
Satellite Operations

Simulating Spacecraft Orbits in Real-time – Uncertainty in 2D
Satellite Operations

Simulating Spacecraft Orbits in Real-time – Where is the Spacecraft?

Most probable location

Spacecraft 1

Small probability could be here instead!

Most probable location

Spacecraft 2

a.i. solutions
Smarter approaches. Better results.
Satellite Operations

Simulating Spacecraft Orbits in Real-time – The Workflow: Step + Check

State Propagation (numerical integration)

Check for collisions

\( t_1 \) \hspace{1cm} \( t_2 \)
Satellite Operations

Simulating Spacecraft Orbits in Real-time – The Workflow: Step + Check

Time
Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

Possibly multiple maneuvers in a single day requiring many Monte Carlo simulations very quickly. Need to answer: “how well did maneuver go?”
Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

Talk to the satellites to get position velocity estimates

Create uncertainty point clouds for each satellite (75,000 pts x 4)

Propagate point clouds forward in time for 10 day collision forecast

Check for collisions and compute the probability of collision at each time step \( t_i \)

HURRY HURRY HURRY!
Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

To create a probability of collision at single point in time:

- numerically integrate high fidelity force model for 300,000 total points (4 x 75,000 pts)

- check 6 * 75,000 * 75,000 possible point pairs for collision

\[33,750,000,000\]

possible point collisions at every time step
Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

300,000 numerical integrations
+ Scan 33,750,000,000 possible point collisions
× 172,800 steps

Time to compute full 10-day collision forecast:
Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

300,000 numerical integrations
+ Scan 33,750,000,000 possible point collisions
× 172,800 steps

Time to compute full 10-day collision forecast:

CPU performance: +2 weeks

But we need a probability of collision “right now”!
Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

300,000 numerical integrations

+ Scan 33,750,000,000 possible point collisions

× 172,800 steps

Time to compute full 10-day collision forecast:

GPU performance: 20 minutes!
GPU Performance

Technical Details

• Using dual K20 + K5000 in operations

• Fixed step numerical integrator to mitigate thread divergence

• Ping pong buffers for simultaneous data xfer and computation

• Constant memory:
  - Planetary ephemerides
  - Coordinate frame transformation matrices

• Texture memory:
  - Store and interpolate huge pre-computed gravity grids

• Parallel construction of binary radix trees for collision detection
Additional GPU Applications

Pushing the Boundaries of Possibility

1. Space Debris Modeling
2. James Webb Space Telescope
3. Zero Energy Pathways
Additional Applications

Pushing the Boundaries of Possibility - Space Debris Modeling

Frames Per Sec (FPS): 299.2
Epoch (days): 0.79211
Step Size (sec): 0.825
Hard Body Radius (km): 10

Additional Applications

Pushing the Boundaries of Possibility - JWST Solar Radiation Pressure
Additional Applications

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Additional Applications

Pushing the Boundaries of Possibility - Searching for Zero Energy Pathways

Special pathways exist between solar system bodies that reflect the natural flow created by interacting gravitational forces.
Additional Applications

Pushing the Boundaries of Possibility - Searching for Zero Energy Pathways

These 'dynamical channels’ require no fuel expenditure as they “flow” naturally toward a target destination.

Short and Howell @ Purdue University
In Summary

Huge Performance Gains

MMS Satellite Operations: 1000x

Space Debris Modeling: 1000x

JSWT SRP Modeling: 1000x

Zero Energy Pathway Search: 100x

Not only faster but also higher fidelity!
In Summary

Huge Performance Gains

GPU computing is essential for next generation space exploration

GPU computing is becoming a cornerstone technology in astrodynamics, aerospace, and defense industries
THANK YOU!