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Human and Robotic Space Mission Use Cases for High-Performance Spaceflight Computing (HPSC)

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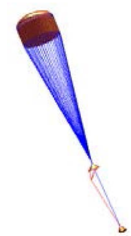
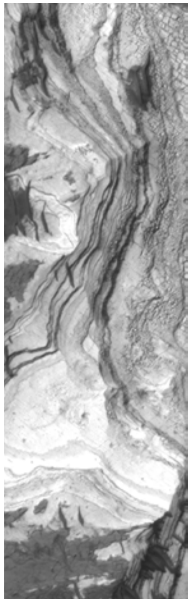
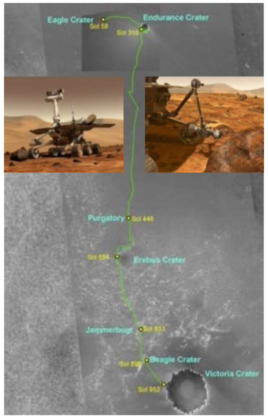
The NASA Need

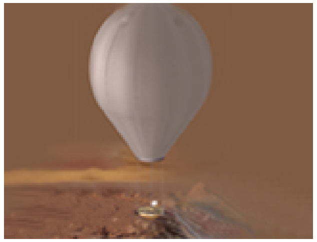
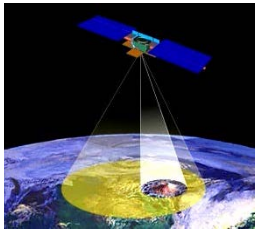
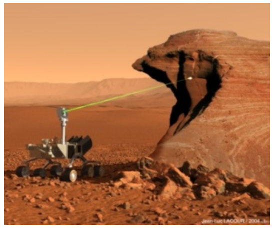
There are important mission scenarios that today cannot be accomplished robustly and cost-effectively

- Space-based computing has not kept up with the needs of current and future NASA missions
- Government and industry are developing high-performance space-qualifiable processors
- NASA continues to have unique requirements
  - Deep space, long duration, robotic and human missions
  - Higher performance, smaller spacecraft and lower cost
    - Onboard science data processing
    - Autonomous operations in uncertain environments
  - Extreme needs for low power and energy management, efficiency, fault tolerance and resilience

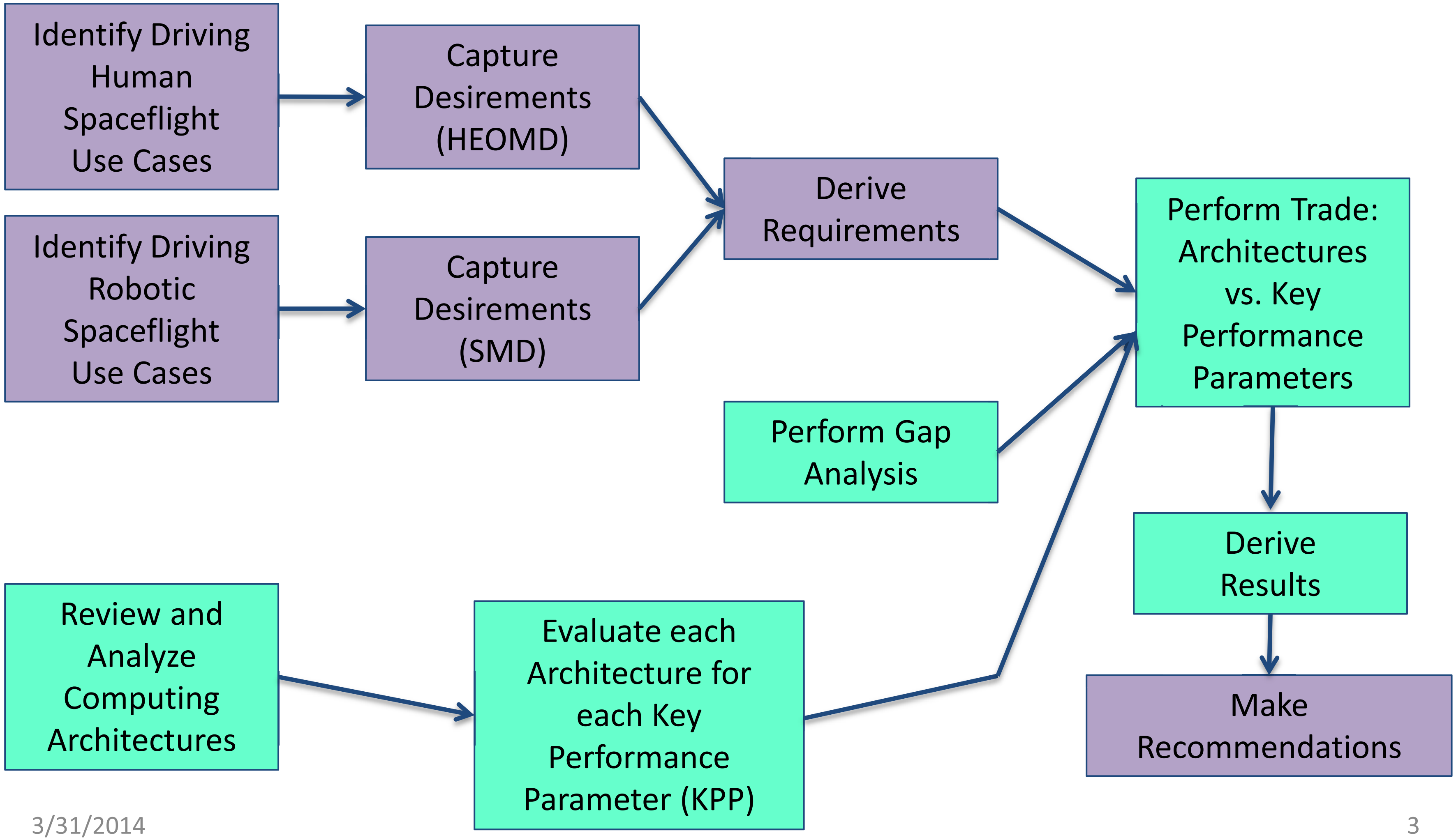




NASA Space Technology Program

HPSC Formulation Task (Game Changing)



HPSC Formulation Phase Study Summary

GP multi/many-core provides optimum ROI for NASA

The Assignment	The Results
Identify relevant NASA use cases What are the paradigm-shifting NASA space-based applications that will drive next generation flight computing?	Developed 9 human spaceflight (HEOMD) and 10 science mission (SMD) use cases for future flight computing, spanning critical mission functions, high data rate instruments, and autonomy utilizing model-based reasoning techniques
Derive requirements What are the future onboard computing requirements?	100X performance increase, low power (down to 7W) with scaling, support for a range of fault tolerance, common programming languages, avoidance of additional V&V effort, interoperable with co-processors
Perform a gap analysis How/where do commercial and defense industry developments in computing fall short of NASA's unique requirements and architectural needs?	No existing or emerging spaceflight processors possess all necessary performance, power efficiency, reliability, and programmability attributes
Trade architectures against defined Key Performance Parameters (KPPs) Which computing architecture will make the most difference?	Rad-hard general-purpose multi-core best addresses the future flight computing requirements and presents the most affordable gap against the KPPs
Make a recommendation How can NASA best invest limited resources to meet the future needs of its space systems?	Competed/directed program plan for rad-hard general-purpose multi-core, with solutions for power/energy, fault tolerance and other NASA requirements, leveraging other agency and industry investments

Development of use cases and derivation of requirements in following charts

NASA Use Cases

for High Performance Spaceflight Computing

HEOMD Use Cases

1. Cloud Services
2. Advanced Vehicle Health Management
3. Crew Knowledge Augmentation Systems
4. Improved Displays and Controls
5. Augmented Reality for Recognition and Cataloging
6. Tele-Presence
7. Autonomous & Tele-Robotic Construction
8. Automated Guidance, Navigation, and Control (GNC)
9. Human Movement Assist

SMD Use Cases

1. Extreme Terrain Landing
2. Proximity Operations / Formation Flying
3. Fast Traverse
4. New Surface Mobility Methods
5. Imaging Spectrometers
6. Radar
7. Low Latency Products for Disaster Response
8. Space Weather
9. Science Event Detection and Response
10. Immersive Environments for Science Ops / Outreach

High value and mission critical applications identified by NASA scientists and engineers

Human Spaceflight Mission Applications

Enable autonomous human-assist capabilities in next generation crewed vehicles and missions

HEOMD Use Cases

1. Cloud Services
2. **Advanced Vehicle Health Management**
3. Crew Knowledge Augmentation Systems
4. Improved Displays and Controls
5. **Augmented Reality for Recognition and Cataloging**
6. Tele-Presence
7. Autonomous & Tele-Robotic Construction
8. **Automated Guidance, Navigation, and Control (GNC)**
9. Human Movement Assist

Benefits to Missions

- **Advanced Vehicle Health Management**
  - Continuous monitoring/analysis of large vehicle data sets: problem detection and response, crew workload reduction, and improved vehicle maintenance during untended operations

- **Augmented Reality**
  - Augmented reality provides a real-time view of a physical, real-world environment, significantly improving crew efficiency and effectiveness; relevant to future human Near-Earth Asteroid, Lunar or Mars missions
- **Automated GNC**
  - Move compute-intensive GNC applications onboard for faster, safer docking; close proximity operations; collision avoidance; automated precision landing within an affordable power/propulsion budget

No longer need to size science / mission scope to flight computing capability

Science Mission Applications

10X improvement for existing applications

Enables new science and mission capabilities on future missions

SMD Use Cases

1. **Extreme Terrain Landing**
2. Proximity Operations / Formation Flying
3. **Fast Traverse**
4. New Surface Mobility Methods
5. Imaging Spectrometers
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7. **Low Latency Products for Disaster Response**
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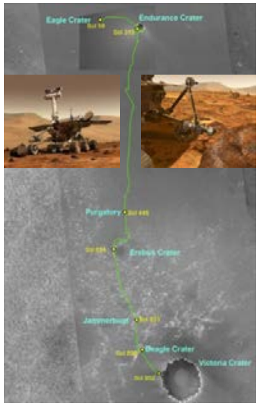
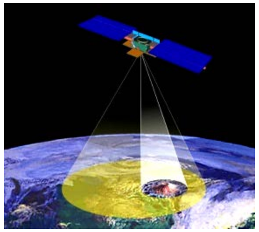
Benefits to Missions

- **Extreme Terrain Landing**
  - Enables reliable and safe landing in hazardous terrain: TRN and HDA algorithms benchmarked by Mars Program – required six (6) dedicated RAD750s
- **Fast Traverse**
  - Remove computation as a limiting factor to mobility – drive 10X faster and more safely, to the hardware limits of the mobility system
- **Low Latency Products for Disaster Response / Science Event Detection and Response**
  - Generalization of event detection and response across multiple platforms; enables rapid turnaround of products (hours/minutes vs. weeks); increase capture rate for dynamic, transient events from 10% to 75%, with <5% false positives





No longer need to size science / mission scope to flight computing capability

NASA Flight Computing High-Level Requirements

as derived from the NASA use cases

Computation Category	Mission Need	Objective of Computation	Flight Architecture Attribute	Processor Type and Requirements
Vision-based Algorithms with Real-Time Requirements	• Terrain Relative Navigation (TRN) • Hazard Avoidance • Entry, Descent & Landing (EDL) • Pinpoint Landing	• Conduct safe proximity operations around primitive bodies • Land safely and accurately • Achieve robust results within available timeframe as input to control decisions	• Severe fault tolerance and real-time requirements • Fail-operational • High peak power needs	**• Hard real time / mission critical** **• Continuous digital signal processing (DSP) + sequential control processing (fault protection)** **• High I/O rate** **• Irregular memory use** **• General-purpose (GP) processor (10's – 100's GFLOPS) + high I/O rate, augmented by co-processor(s)**
Model-Based Reasoning Techniques for Autonomy	• Mission planning, scheduling & resource management • Fault management in uncertain environments	• Contingency planning to mitigate execution failures • Detect, diagnose and recover from faults	• High computational complexity • Graceful degradation • Memory usage (data movement) impacts energy management	**• Soft real time / critical** **• Heuristic search, data base operations, Bayesian inference** **• Extreme intensive & irregular memory use (multi-GB/s)** **• > 1GOPS GP processor arrays with low latency interconnect**
High Rate Instrument Data Processing	High resolution sensors, e.g., SAR, Hyper-spectral	• Downlink images and products rather than raw data • Opportunistic science	• Distributed, dedicated processors at sensors • Less stringent fault tolerance	**• Soft real time** **• DSP/Vector processing with 10-100's GOPS (high data flow)** **• GP array (10-100's GFLOPS) required for feature ID / triage**

Future NASA use cases require dramatic improvement over RAD750

Mapping of Use Cases

to the Computation Categories

- Improved Displays & Controls
- Augmented reality for Recognition & Cataloging
- Crew Knowledge Augmentation Systems
- Automated Guidance, Nav & Controls (GNC)
- Human Movement Assist
- Extreme Terrain Landing
- Immersive Environments for Science Ops Outreach
- Fast Traverse

→ Vision Based Algorithms with Real Time Requirements

- Advanced Vehicle Health Management
- Autonomous & Tele-Robotic Construction
- Autonomous Mission Planning
- Proximity Operations / Formation Flying
- New Surface Mobility Methods

→ Model Based Reasoning Techniques

- Tel-Presence
- Cloud Services
- Low Latency Products for Disaster Response
- Imaging Spectrometers
- Radar
- Space Weather

→ High Rate Instrument Data Processing

SMD | HEOMD

Deriving Requirements

Requirements Template

- Space Environment(s)
  - Radiation environment at the time of application; e.g., geosynchronous (GEO), low-Earth orbit (LEO), deep space?
- Spacecraft Power Environment(s) / Constraint(s)
  - Available power for avionics and computing, e.g., small spacecraft or rover with limited power availability (6 Watts processor power, 10-15 Watts computer power), medium sized spacecraft (7-12 Watts processor power, 15-30 Watts computer power), or large spacecraft with large power budget (>12-25 Watts processor power, >30-100 Watts computer power)?
- Criticality/Fault Tolerance
  - Is this application life or mission critical, must it operate through faults, can it tolerate errors if detected?
- Real-Time
  - Does the application have a hard real-time deadline; if so, what is the required timing?
- Type(s) of Processing
  - Algorithm kernel(s). Is it primarily e.g., digital signal processing (DSP), data base query, is it parallelizable, is it amenable to a data flow approach?
- Memory Access Pattern
  - What is the primary data movement pattern, e.g., does it fetch data from memory once and then flow through a processing chain, or does it access data in a continuous random access pattern, or does it access sequential data in a continuous and regular pattern?
- Duty Cycle
  - What is the pattern of execution, e.g., is the application called continuously over a long period of time, is it called once and operate for only a short duration, is the application execution profile spiky and/or unpredictable?
- Data Rate
  - What are the I/O and memory access data rates?

Eigen-Applications

~60 application variants/derivatives reduced to 10 representative sets of requirements

App to Eigen-App Mapping	DSP	GP	P	Mission Critical	LP
Throughput = 1-10 GOPS					
Autonomous Mission Planning		X	X	X	X
Disaster Response	X	X			X
Hyspiri	X	X	X		
Throughput = 10-50 GOPS					
Fast Traverse	X	X	X	X	X
Extreme Terrain Landing	X	X	X	X	X
Adept		X	X		
Optimum Observation	X	X	X		X
Space Weather	X		X		X
Robotic Servicing	X	X	X	X	
Cloud Services	X	X	X		
Advanced ISHM		X	X		X
Autonomous and Telerobotic Construction		X	X	X	X
Througput = 50-100s GOPS					
Hyperspectral Imaging	X	X	X		X
RADAR Science	X	X	X		
RADAR EDL	X		X	X	X
Automated GN&C	X	X	X	X	
Human Movement Assist	X	X	X		X
Crew Knowledge Augmentation		X	X		
Improved Displays and Controls		X	X	X	X
Augmented Reality		X	X		X
Telepresence		X	X		X

- Requirements that represent groups of key cross cutting applications
- Derived by selecting low power applications from full applications set and grouping by throughput, processing type, mission criticality

Eigen-App	Throughput	DSP	GP	P	LP	MC
1	1-10 GOPS	X	X	X	X	
2	1-10 GOPS		X	X	X	X
3	10-50 GOPS	X	X	X	X	X
4	10-50 GOPS	X	X	X	X	
5	10-50 GOPS		X	X	X	X
6	10-50 GOPS		X	X	X	
7	50-100 GOPS	X	X	X	X	X
8	50-100 GOPS	X	X	X	X	
9	50-100 GOPS		X	X	X	X
10	50-100 GOPS		X	X	X	

KEY

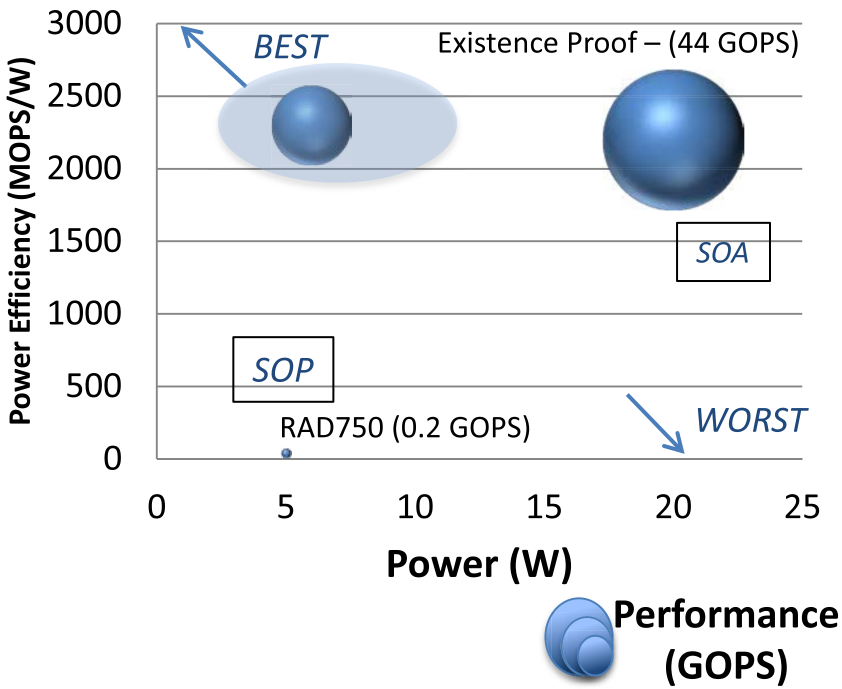
- DSP – Digital Signal Processing
- GP – General Purpose Processing
- P – Parallelizable
- Mission Critical – Requires Additional Fault Tolerance
- LP – Max Power Available for Processor Chip <6W

HPSC Formulation - Recommendation

Rad-hard General Purpose Multi-core

Rad-hard General Purpose Multicore

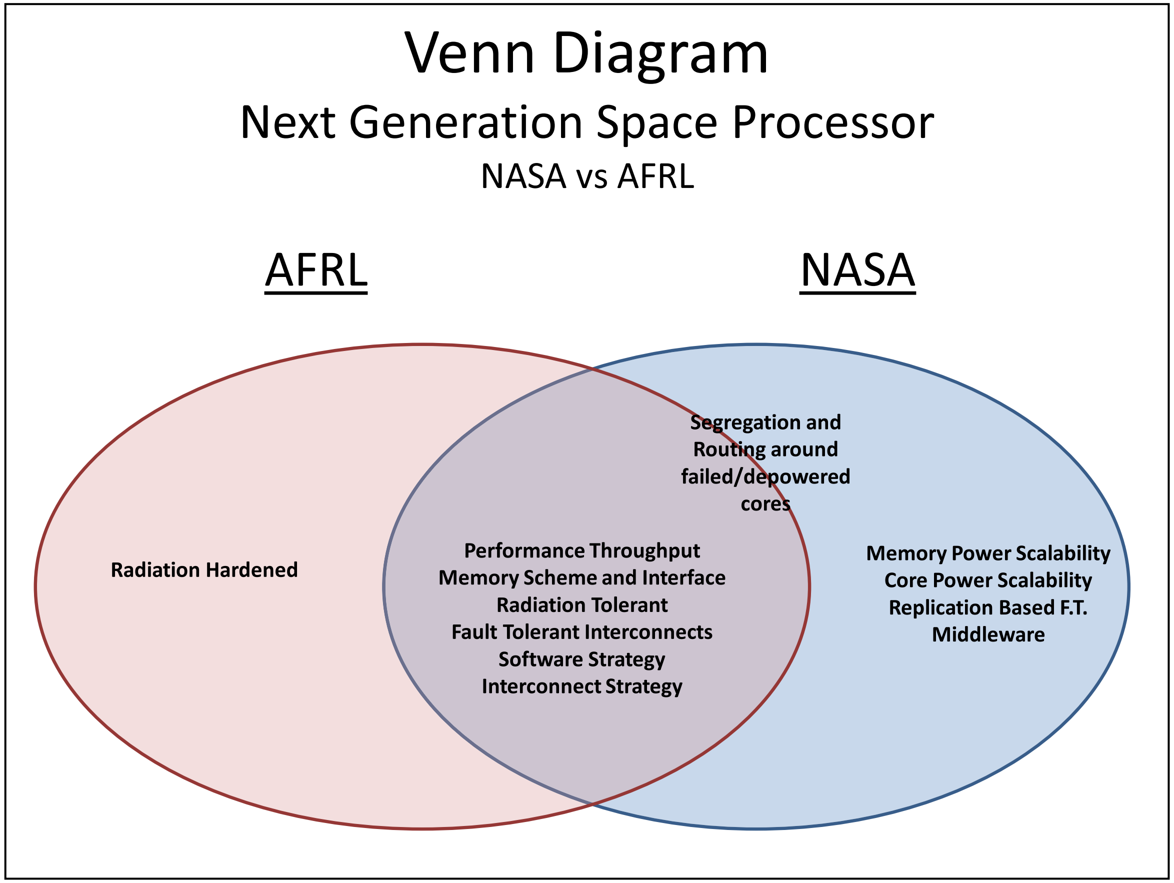
- **Best overall fit to application requirements** – provides both general purpose and some DSP capability as well as interoperability with co-processors (DSP, Reconfigurable)
- **Conducive to Power Scaling at core-level**
  - **Power Dissipation** issues to address fit within available investment resource envelope
- **Conducive to thread-based Fault Tolerance**
  - Fault detection/correction/isolation
  - Ability to segregate failed cores from the pool of available cores in support of graceful degradation
- **Scalable to 10x increase in the number of cores**
  - Combined with Power Scaling, allows the increased cores to consume power only as thread-load dictates



Computational Performance, Efficiency, and Scalability of Multi-core redefines general-purpose computing for space systems

Future Flight Computing

AFRL vs. NASA Requirements



Sufficient common ground to justify a joint AFRL-NASA program

Next Generation Space Processor Analysis Program

Joint AFRL/NASA Innovation Phase BAA
Top Level Objectives Summary

- Provide a minimum of 24 processor cores to support both highly parallel applications and to provide a high degree of granularity for power management, fault tolerance and program unit distribution.
- Providing 10GFLOPS, multiple 10Gb/s I/O and DDR 3 Memory Ports at 7 Watts
- Dynamically power scalable at core level granularity by powering and depowering cores in real time without disrupting system operation, with very low idle power load (<<1W)
- Based on commercially available hardware and software IP (processing cores, external I/O and memory interfaces, software stack and development environment)
- Able to reset individual cores or a cluster of cores, as determined by smallest unit of granularity
- Radiation hard to at least 1 Mrad TID, Latch up Immune to an LET of at least 90, with a hardware-uncorrected SEE rate of not greater than 0.01 event/day in Adams 90% worst case GEO environment
- Interoperable with other high performance computing architectures, e.g., FPGAs

***Proposers encouraged to offer alternatives ***

AFRL BAA-RVKV-2013-02
Closed - Proposal Due Date 5/29/13

Next Generation Space Processor Analysis Program

Status and FY13-14 Plans

- **April 2013**: AFRL/NASA BAA posted
  - Next-Generation Space Processor Analysis Program BAA-RVKV-2013-02
- **May 2013:** Proposals due
- **September 2013**: Contract let
  - Up to four awards
- **September 2013:** Project Kickoff Meeting
- **November 2013:** Technical Interchange Meeting
  - Contractor derived USAF requirements documents delivered
  - Finalized joint AFRL/NASA requirements document published
- **May 2014**: Benchmarks for NASA applications delivered to contractors
- **August 2014**: Innovation Phase concludes
  - Draft final reports delivered to AFRL/NASA
  - Software requirements available
  - Evaluation and selection of architecture(s) for implementation

Summary

Flight Computing for the Future

- Future NASA mission scenarios call out for significantly ***improved flight computing*** capability
- Several NASA OCT Roadmaps and the NRC report identify ***improved flight computing*** as a foundational technology
- AFRL independently identifies the need for ***improved flight computing***
- ***Improved flight computing*** means enhanced computational performance, energy efficiency, and fault tolerance
- Like power and propulsion, flight computing is a ***core flight capability***; a technology advance here will be a capability ***multiplier*** and will impact the return from all future missions

It is time to move beyond the 1990's technology of the RAD750

Reinventing the role of computing in space systems