National Aeronautics and Space Administration

Reinventing the Role of Computing in Space

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HPSC | Nebulae Workshop, Keck Institute For Space Studies, Caltech | 08.26.19

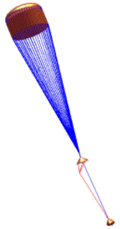
Strategic Importance of Flight Computing
Future Mission Needs

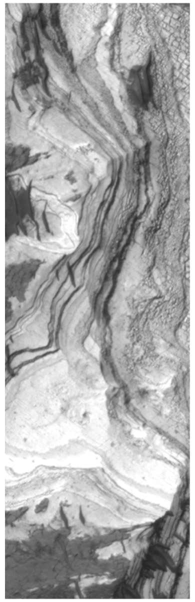
Space-based computing has not kept up with the needs of current and future missions

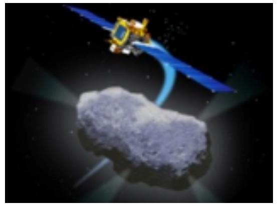
NASA has some unique requirements

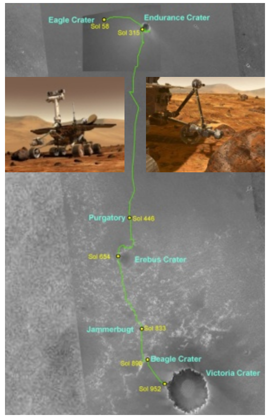
- Deep space, long duration, robotic and human missions
- Higher performance, smaller spacecraft and lower cost
  - Onboard science data processing
  - Autonomous operations
- Extreme needs for low power and energy management, efficiency, fault tolerance and resilience

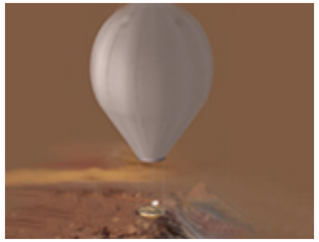
Based on alignment of interests and plans, USAF and NASA entered into a programmatic partnership for a joint investment in flight computing

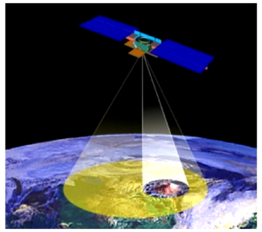


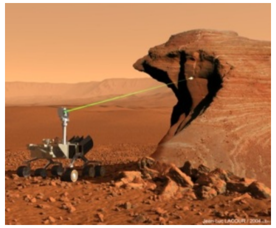




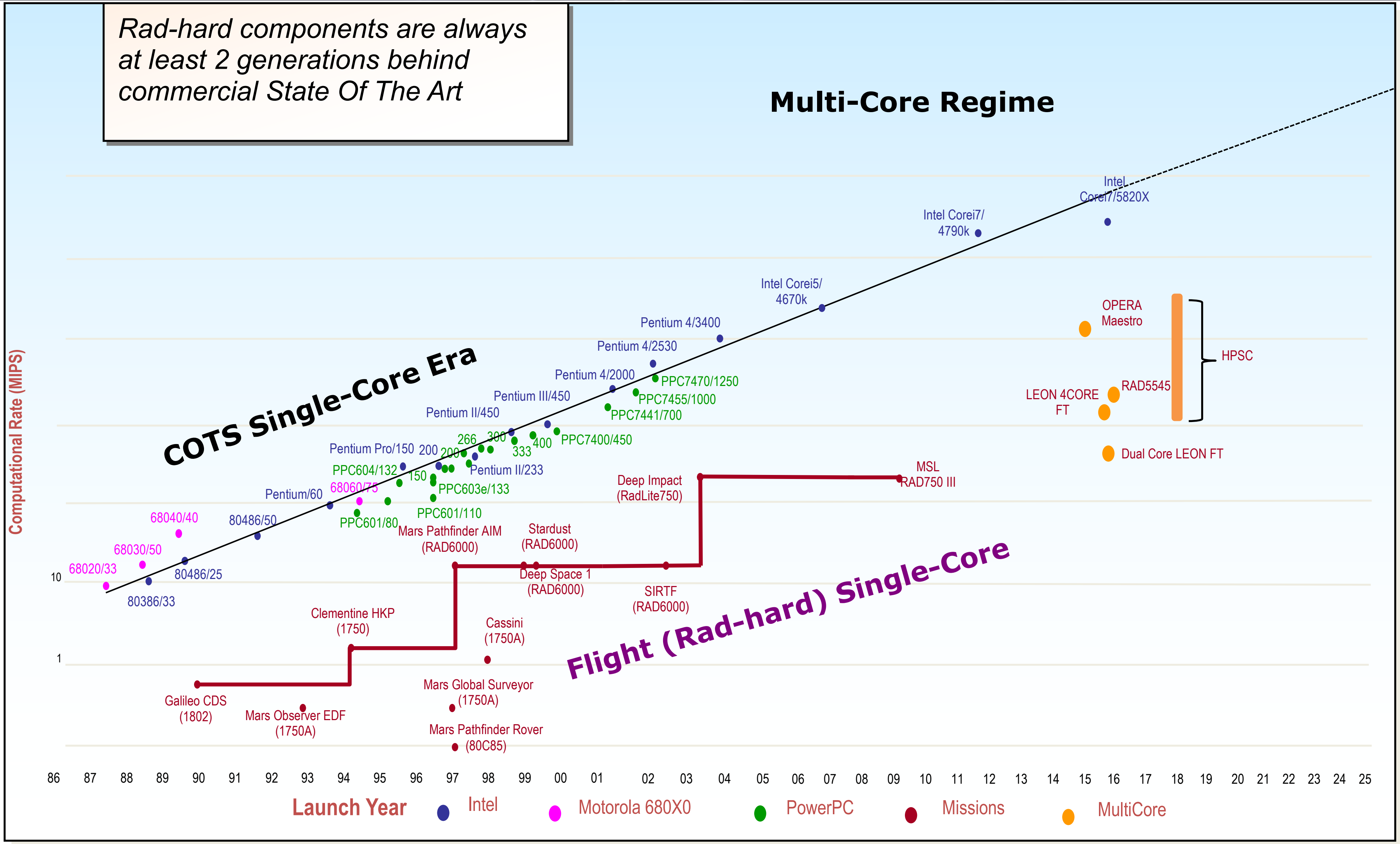








History of Spaceflight Avionics and Processors



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NASA Use Cases

Human Spaceflight (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 and Telerobotic Construction
8. Automated Guidance, Navigation, and Control (GNC)
9. Human Movement Assist

Science Mission (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 Operations / Outreach

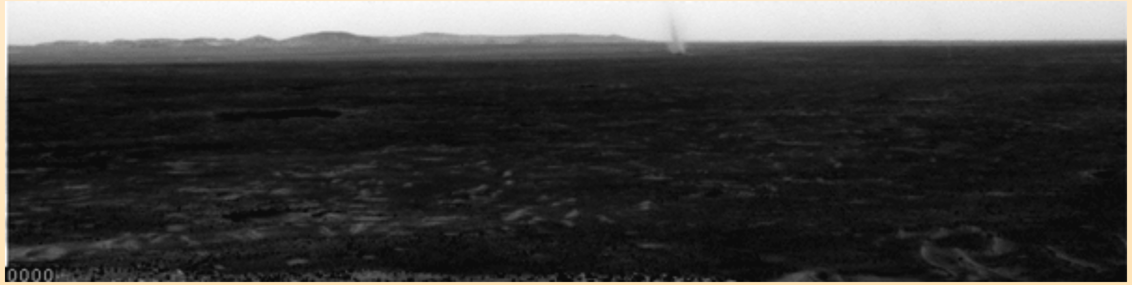
High value and mission critical applications identified by NASA scientists and engineers

Onboard Data Product Generation

Dust Devils on Mars

Dust devils are scientific phenomena of a transient nature that occur on Mars

- They occur year-round, with seasonally variable frequency
- They are challenging to reliably capture in images due to their dynamic nature
- Scientists accepted for decades that such phenomena could not be studied in real-time



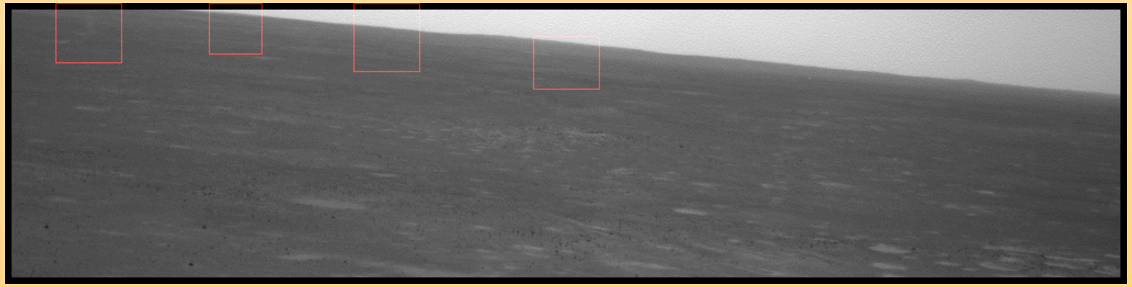
Spirit Sol 543 (July 13, 2005)

New onboard Mars rover capability (as of 2006)

- Collect images more frequently, analyze onboard to detect events, and only downlink images containing events of interest

Benefit

- < 100% accuracy can dramatically increase science event data returned to Earth
- *First notification includes a complete data product*



Credit: T. Estlin. B. Bornestein, A. Castano, J. Biesiadecki, L. Neakrase, P. Whelley, R. Greeley, M. Lemmon, R. Castano, S. Chien and MER project team

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NASA Flight Computing Drivers

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**

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Derived Eigen-Apps

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 Service	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

- Bundled 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

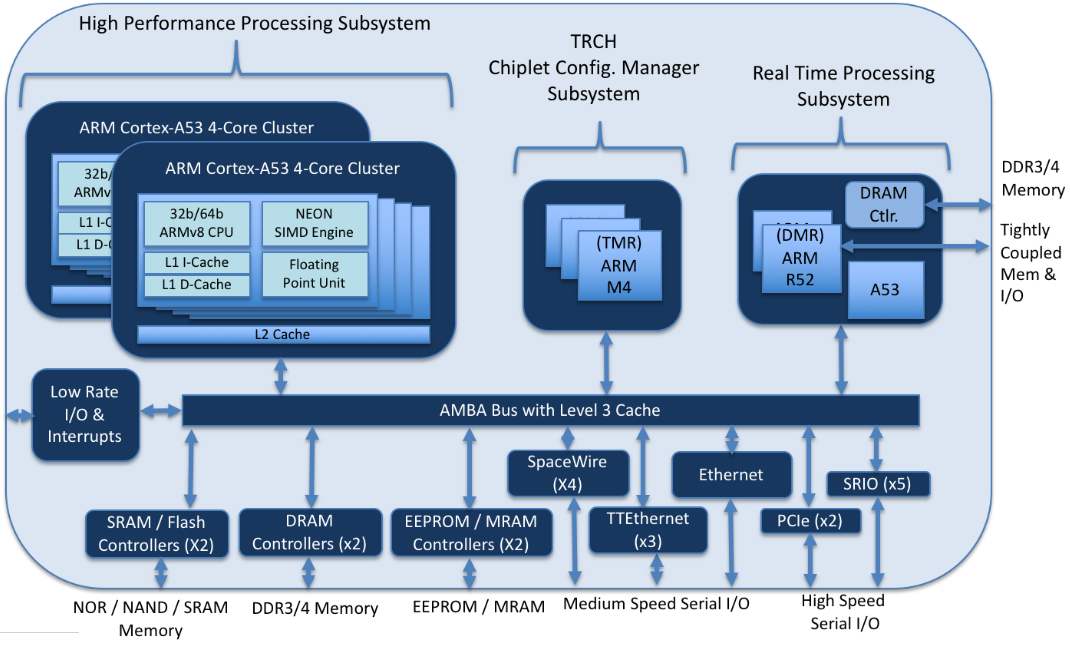
Eigen-App	Throughput	DSP	GP	P	LP	MC
1	1-10 GOPS	X	X	X	X	
2	1-10 GOPS		X	X	X	X
3	10-50 GOPS	X	X	X	X	X
4	10-50 GOPS	X	X	X	X	
5	10-50 GOPS		X	X	X	X
6	10-50 GOPS		X	X	X	
7	50-100 GOPS	X	X	X	X	X
8	50-100 GOPS	X	X	X	X	
9	50-100 GOPS		X	X	X	X
10	50-100 GOPS		X	X	X	

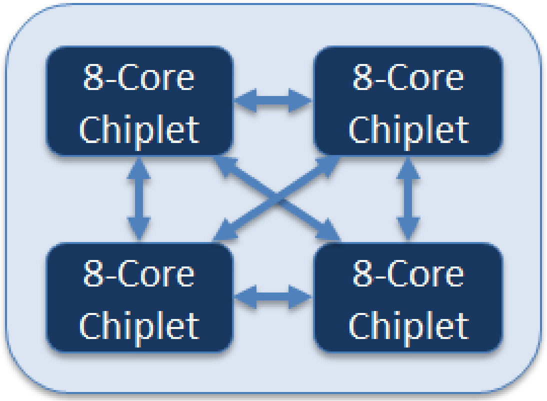
KEY
- DSP – Digital Signal Processing
- GP – General Purpose Processing
- P – Parallelizable
- Mission Critical – Requires Additional Fault Tolerance
- LP – Max Power Available for Processor Chip <6W

Credit: R. Some

HPSC – Technology Overview

Reinventing the Role of Computing in Space





- **HPSC** offers **a new flight computing architecture** to meet the needs of NASA missions through 2030 and beyond. Providing on the order of **100X the computational capacity of current flight processors for the same amount of power**, the multicore architecture of the HPSC chiplet provides **unprecedented flexibility** in a flight computing system by enabling the operating point to be set dynamically, **trading among needs for computational performance, energy management and fault tolerance**. This kind of operational flexibility has never been available before in a flight computing system.
- **HPSC has been conceived to be highly extensible**. Multiple **chiplets can be cascaded together** for more capable computing, or HPSC **can be configured with specialized co-processors** to meet the needs of specific payloads and missions.
- **HPSC is a technology multiplier**, amplifying existing spacecraft capabilities and enabling new ones. The HPSC team anticipates that the chiplet will be **used by virtually every future space mission**, all benefiting from more capable flight computing.

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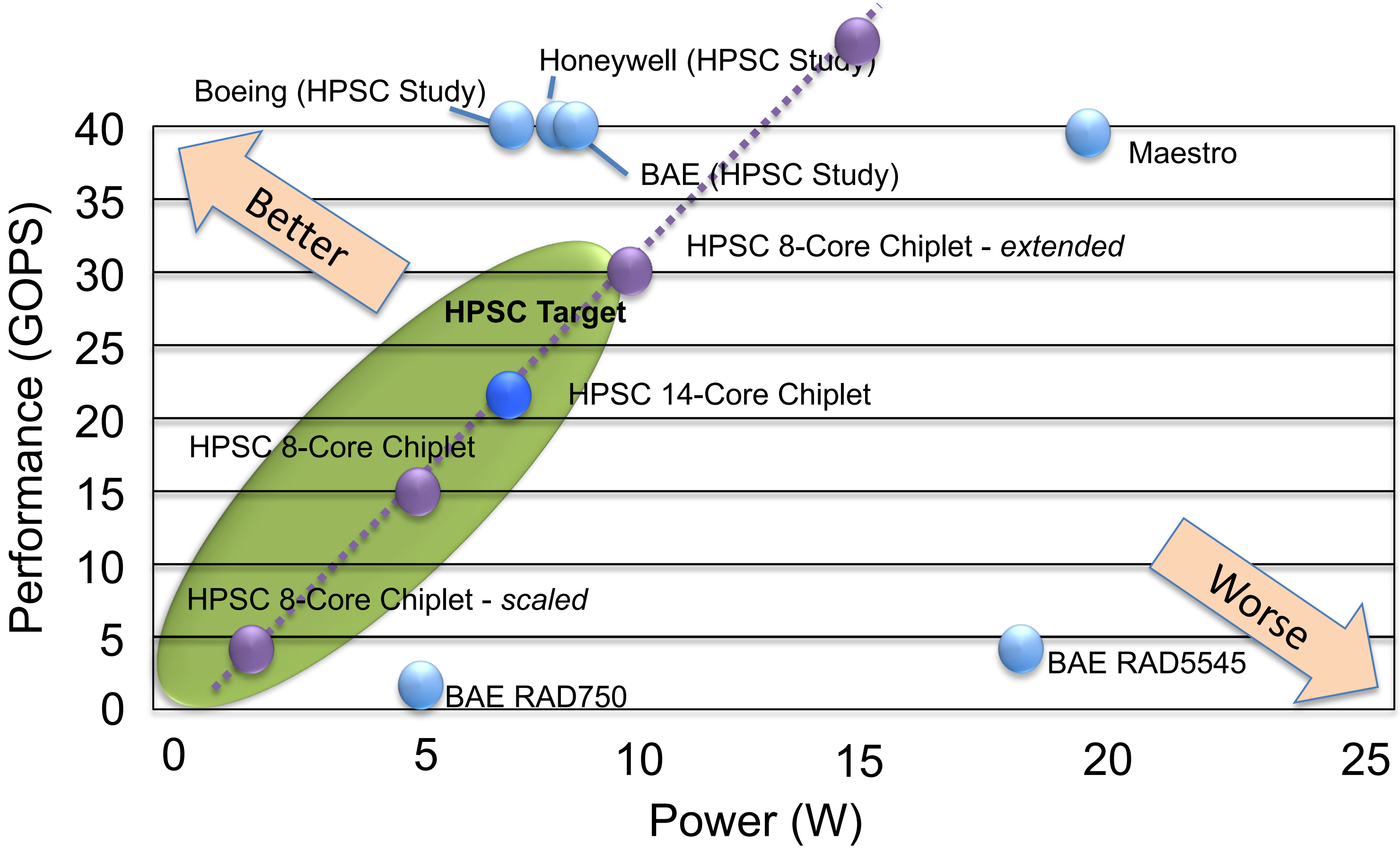
Power vs. Performance



It's time to move beyond 1990's technology and *reinvent the role of computing in space systems*

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Performance

Key Performance Parameters

Performance Parameter	State of the Art	Threshold Value	Project Goal	Estimated Current Value
Computational	350 MOPS	9 GOPS	15 GOPS	15 GP GOPS + Up to 100 SIMD GOPS
Power Scalability	10W	10W scalable to <1W	7W scalable to <1W	9.1W scalable to TBD W
Performance / Power	20 MOPS/W	0.9 GOPS/W	1.5 GOPS/W	1.5 GP GOPS/W + TBD SIMD GOPS/W
I/O Bandwidth	800 Mbps	40 Gbps (4 SRIO)	60 Gbps (6 SRIO)	240Gps (6 SRIO @ up to 40Gbs/port)
Fault Tolerance	Customized redundancy hardware	Application / middleware SW-level methods with timing, coverage and power advantages	Hardware / System SW-level methods with improved efficiency over application / middleware methods	Application / middleware SW-level methods with timing, coverage and power advantages
Extensibility	Generally not available	Cascade chiplets via SRIO	Cascade chiplets via SRIO transparently	Cascade chiplets via SRIO

Note: *Working estimates from PDR; high resolution updates by CDR.*

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Partners

NASA Team

USAF Team

Boeing Team

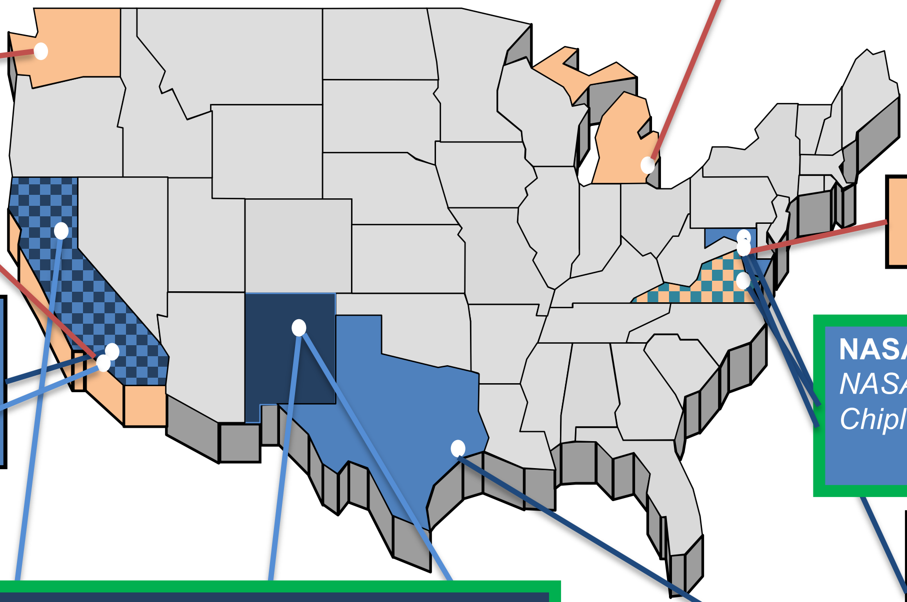
Sponsor

University of Michigan
ARM Design Sub-Contractor

Boeing SSED
Chiplet Development Contractor

Boeing BDS
Chiplet Development Contractor

USC Information Sciences Institute
SSW Development Sub-Contractor



JPL
Project Management, System Engineering, Middleware, SMD Mission Applications

NASA STMD (HQ)
NASA Game Changing Program Office
Chiplet Baseline and NASA SE/Oversight Sponsor

USAF/SMC
USAF/DoD Mission Programs
Chiplet Qualification
Chiplet Options Sponsor

AFRL/RV
USAF Space Electronics Program Office
Middleware Sponsor

NASA GSFC
Project Management, Procurement, System Engineering, Middleware, SMD Mission Applications

NASA JSC
HEOMD Mission Applications
SPLICE Project

TAPO
Trusted Applications Program Office

COSMIAC
USAF/DoD Qualification Subcontractor

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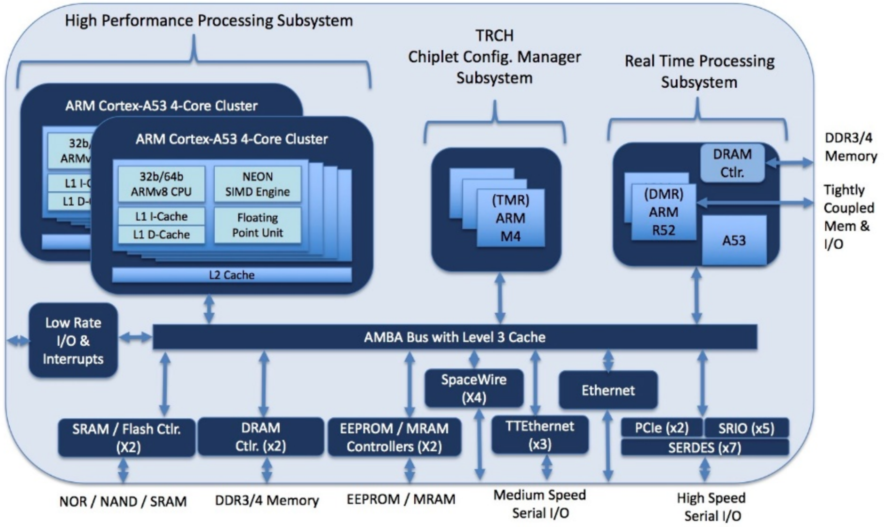
Flight Demonstration



NASA Commercial Lunar Payload Systems (CLPS)
Lunar Lander Technology Demonstration

Pre-Decisional Information – For Planning and Discussion Purposes Only

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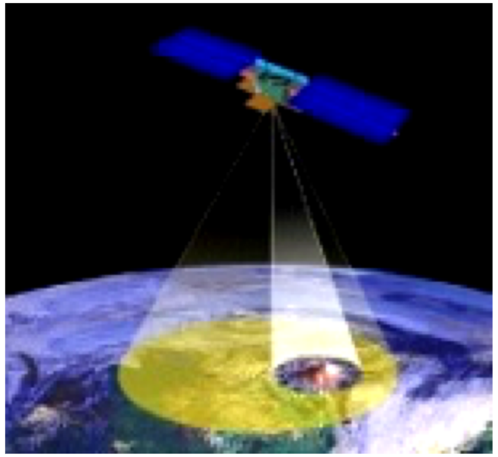
Mission Infusion

- The use cases provide a basis for requirements and an infusion framework for board-level solutions tailored to different mission application categories.

Deep Space

Surface Systems



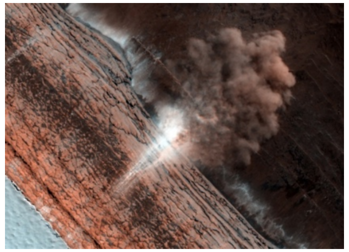
High Data Rate Instruments

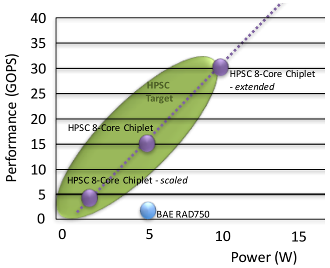
Human Spaceflight

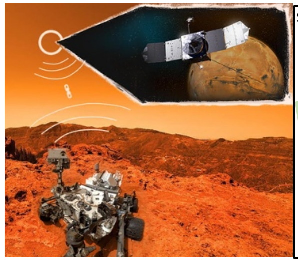
Landing Systems

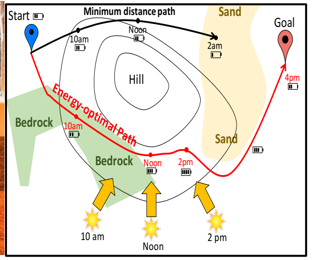
CubeSats, SmallSats

Onboard Analytics for Mars Exploration Enabled by HPSC









FUTURE OPPORTUNITY With the advent of more capable and flexible flight computing (High Performance Spaceflight Computing – HPSC) and onboard analytics (machine learning, data science), the timing is right to explore and develop scaled and newly enabled scenarios for science / engineering autonomy

STAKEHOLDERS

- *Mars orbiter and surface mission applications integrating autonomy, flight computing and deep space communications / networking*
- *Additional NASA and non-NASA mission applications*

Task	PI
1 COSMIC – Content-based On-board Summarization to Monitor Infrequent Change	Lukas Mandrake
2 MAARS – Machine Learning-based Analytics for Automated Rover Systems	Hiro Ono
3 MOSAIC – Mars On-Site Shared Analytics, Information, and Computing	Joshua Vander Hook

OBJECTIVES

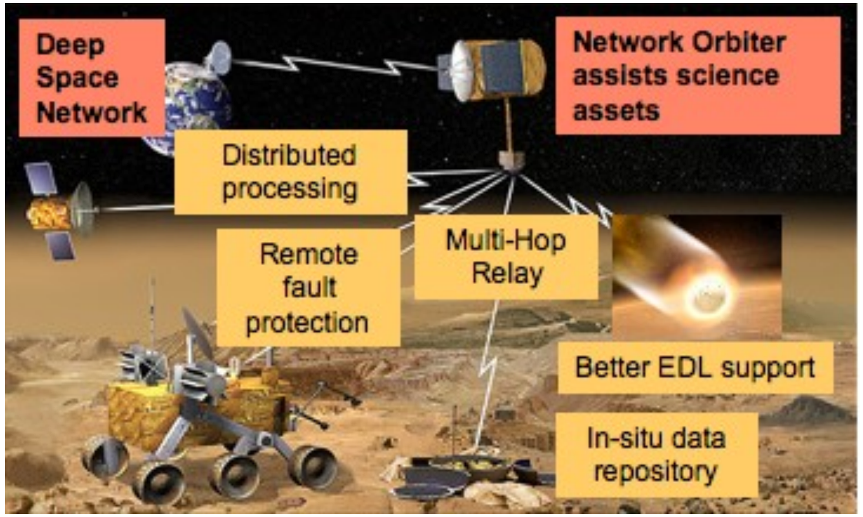
Prepare for a more capable future flight computing environment by validating enhanced and additional scenarios for science and engineering autonomy

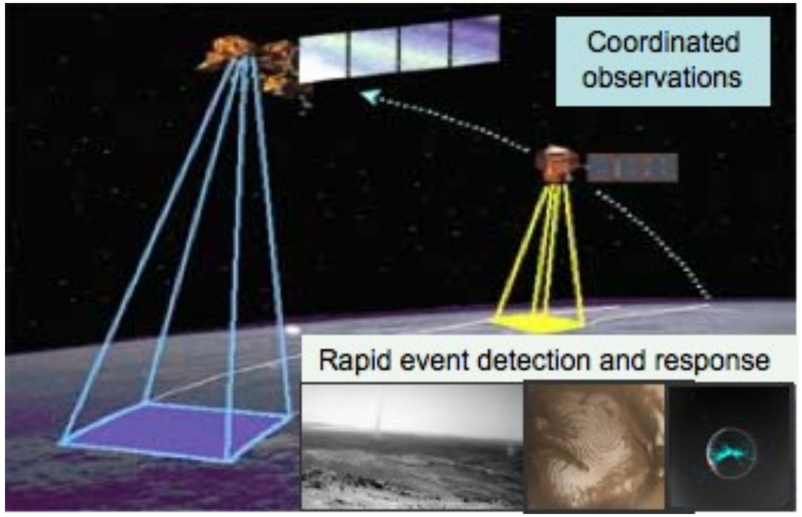
1) *Optimize the science return of Mars orbiters via onboard analytics such as change detection*
2) *Enable continuous science and more efficient and reliable operations for Mars surface assets*
3) *Benchmark autonomy software / analytics / against HPSC and co-processor (e.g., Emu) capability*
4) *Validate the feasibility and utility of sharing computing and memory resources in a planetary environment*

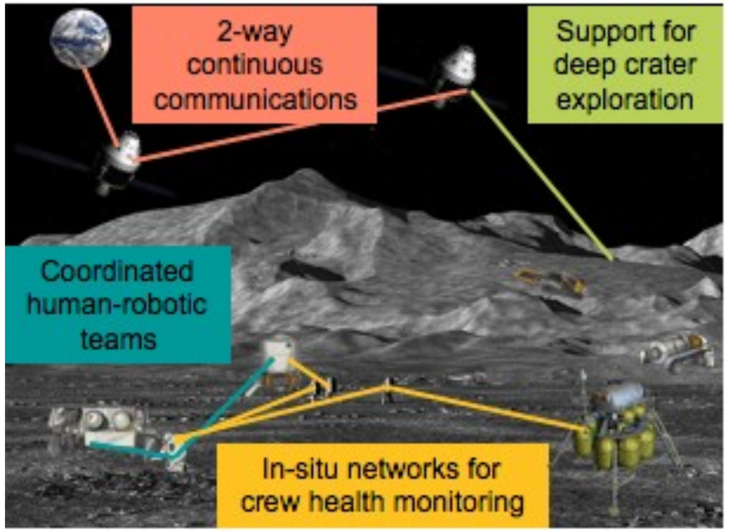
Milestones
Algorithm development for onboard science event detection, terrain classification, etc.
Architecture development for sharing computing and memory resources across primary / secondary Mars assets
Benchmarking of algorithms and analytics against emulated HPSC + Emu capability
NEMO-referenced and Fetch Rover-referenced demonstrations of science and engineering autonomy
Integrated technology demonstration of autonomy, computing, and networking in a Mars environment

Credit: L. Mandrake, H. Ono, J. Vander Hook

DTN Concepts for Space-based Networking







DTN enables new mission services and operational concepts

Applicable to deep space, near-Earth, and lunar missions

Pre-Decisional Information – For Planning and Discussion Purposes Only

Credit: J. Wyatt

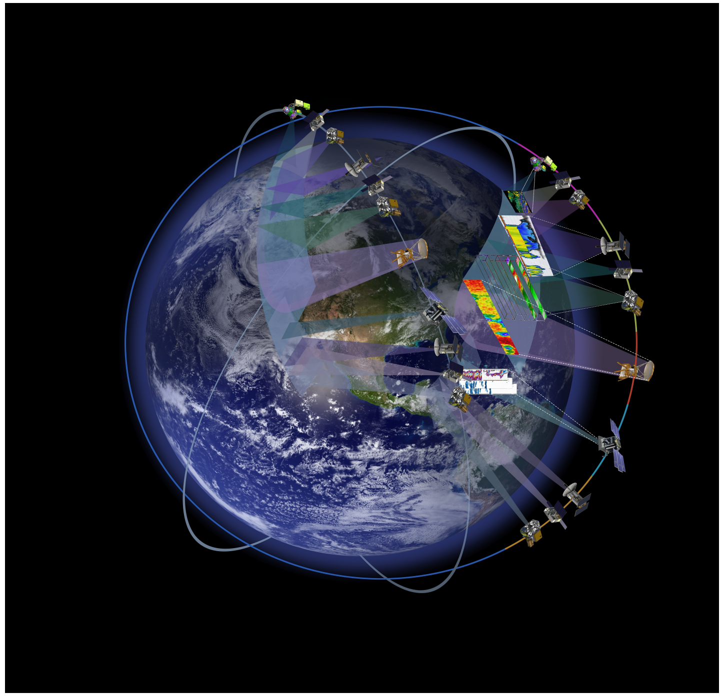
Earth-Observing Observatories of the Future

Observatories of the Future

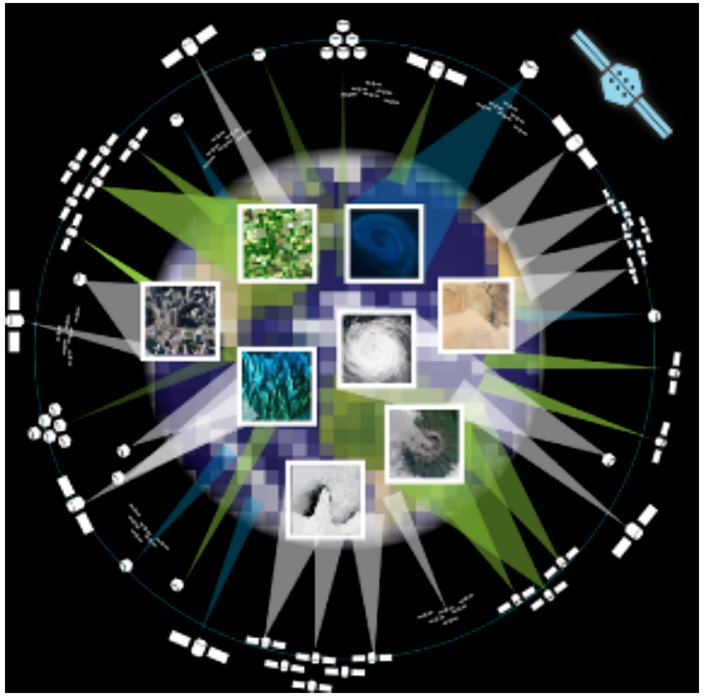
Autonomy Priority Example (8X)

Integrated autonomy architecture

- Event detection and response
- Formation flying
- Onboard data product generation



Earth-Observing Constellations



Credit: J. Hyon

Enabling Space Exploration and Scientific Discovery by Emplacing Scalable Infrastructure

- **Traditionally, space missions have been approached as having self-contained resource envelopes to accomplish specific objectives**
- **The concept of space platforms coming and going, supported by emplaced and accumulating infrastructure, already applies for Earth orbit and more and more, to Mars exploration**

- **This KISS study is about looking beyond, farther into the solar system, and exploring the possibilities for resources in the area of computing, data storage, and networking**

What are the possibilities?