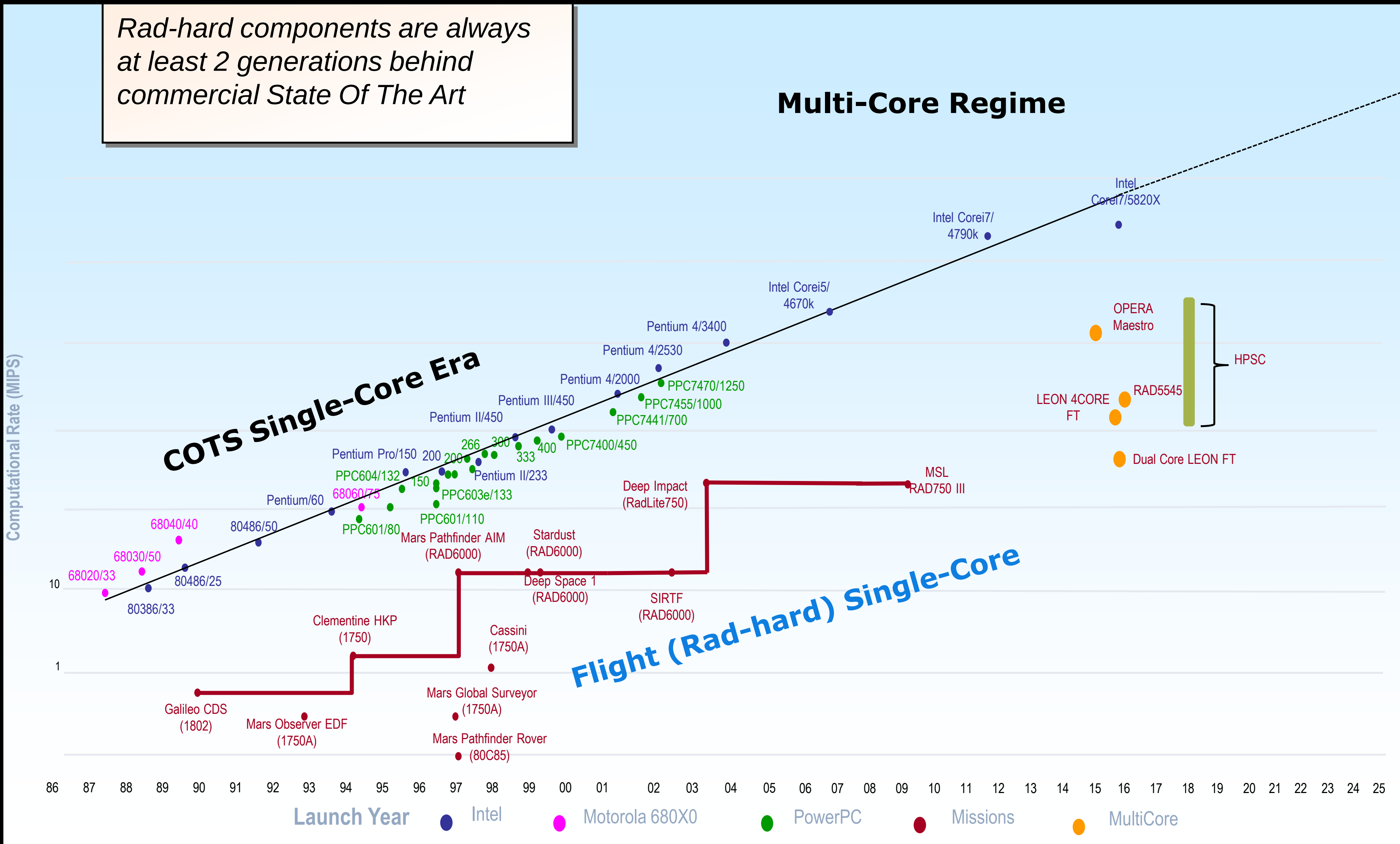
Vision and Challenges for Multicore Computing in Future Space Missions

Raphael R. Some
Chief Technologist: Autonomous Systems Division
Caltech JPL
NASA Technical Authority: High Performance Spaceflight Computing
rsome@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

The work described in this publication was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract from the National Aeronautics and Space Administration under the STMD GCD Program. Government sponsorship acknowledged.

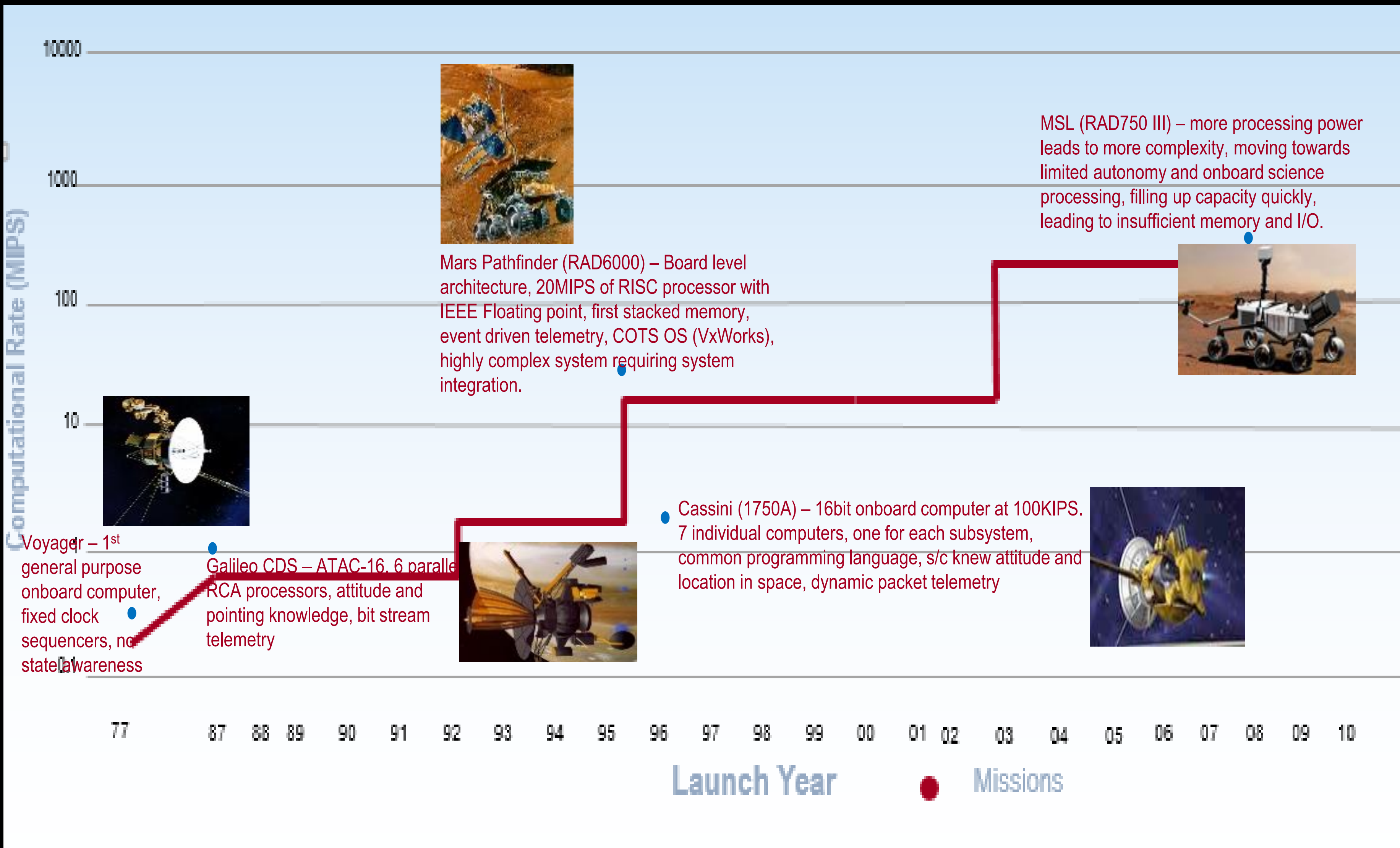
Space Flight Avionics and Microcomputer Processor History



Why are we always 2+ Generations Behind

- Want to start with a mature processor
  - Validated processor hardware design/IP
  - Available peripherals and ancillary hardware
  - Available software support: OS, compilers, debuggers,
  - Knowledgeable engineers and coders
- Mil/space, rad hard chip development
  - Chip development is slow and expensive compared to COTS
    - Rad hardness impacts both design time/cost and useable process node
    - Extended Temp and Vcc
    - 15-20 year life
  - Small market + high NRE
    - Semiconductor mfg paradigm based on large markets and high volumes are not consistent with our small markets and low volume
    - High NRE due to space grade hardware requirements and need to minimize software costs impacts willingness to continually upgrade
- Time to market
  - Need to generate market in order to obtain funding

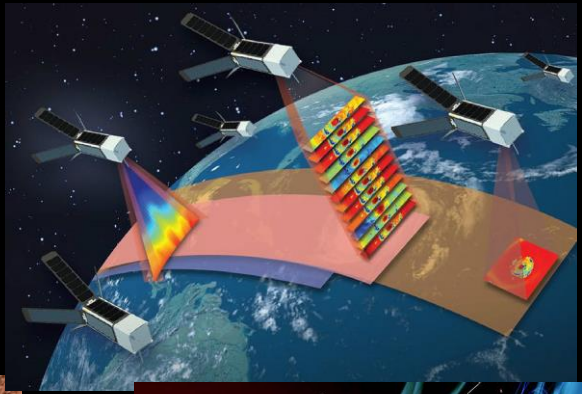
Space Flight Avionics
Radiation Hardened Processors in Space

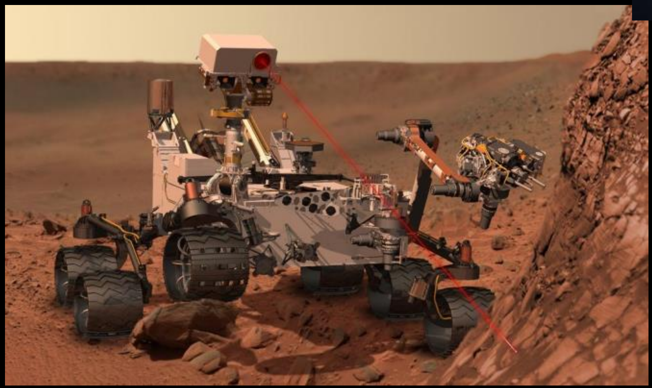


Mission Visions - Robotics

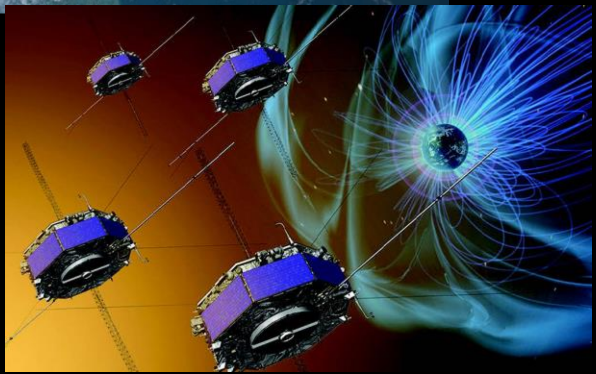
Health Management

Mission planning and execution under changing circumstances





Goal driven behavior



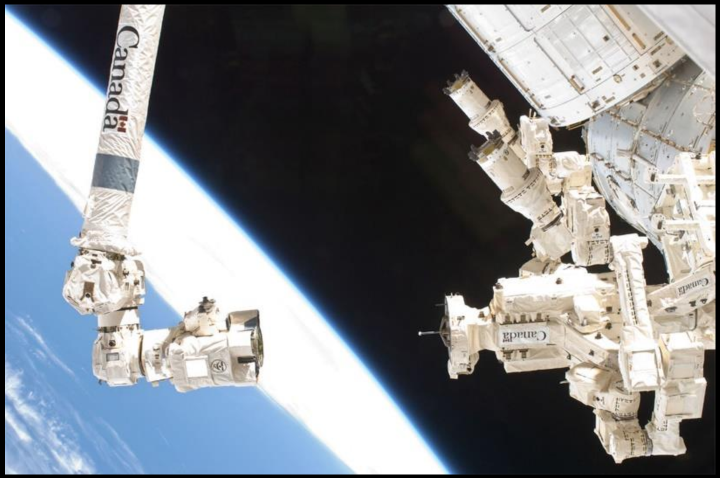
Constellation & Formation flying

Onboard image processing

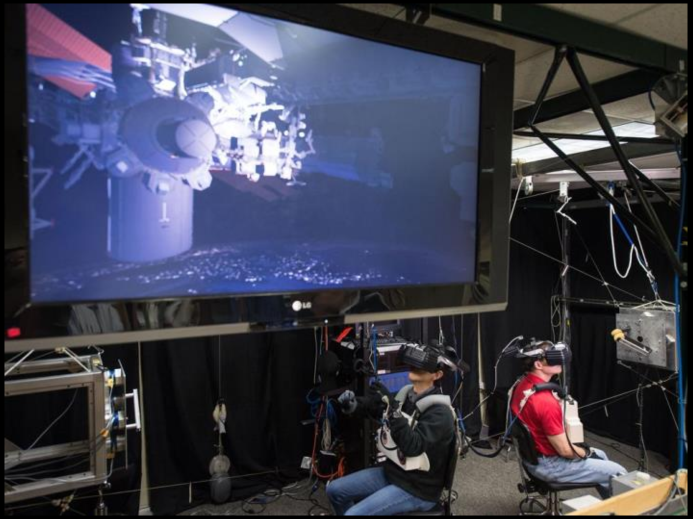
HPC and Autonomy for Robotic Science and Exploration

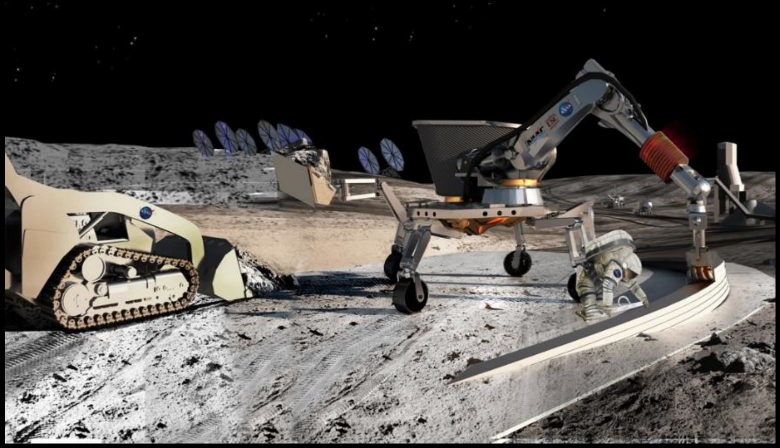
- Hierarchy of autonomy
  - First take care of yourself (*state awareness, fault handling*)
  - Second perform defined mission (*mission planning and execution* under changing conditions)
  - Third determine what to do in order to perform extended exploration and science, i.e., beyond explicitly specified (*goal driven mission planning, opportunistic science*) with available resources (*system capability knowledge)* in the changing environment (*situational awareness*)
  - Fourth cooperate with other robots (*constellation, team, swarm operations*)
  - Fifth science data processing onboard, send back new knowledge (*autonomous science*)

Visions: Crewed missions



Autonomous repair


Virtual Reality, Augmented Reality


Work independently with minimal direction


Interact with humans on a task

HPC and Autonomy for Crewed Missions

- Take care of vehicle and crew
  - Astronaut Assist
  - System health monitoring and diagnostics
  - Fault Handling
  - Maintenance and Repair
- Make it seem like they're at home
  - Virtual reality
  - Internet in space and delay tolerant communication
  - Augmented Reality
  - Visualizations of missions, remote crew & robotics operations
- Work independently for the human crew with minimal direction
  - Repairs, building habitats, or remote stations…
    - Teleoperation and virtual presence
- Work with the crew in a mixed team, understanding what to do with minimal direction and with maximal safely of humans
  - Medical lab, surgeries

2012 Use Case Study

Human Spaceflight (HEOMD) Use Cases

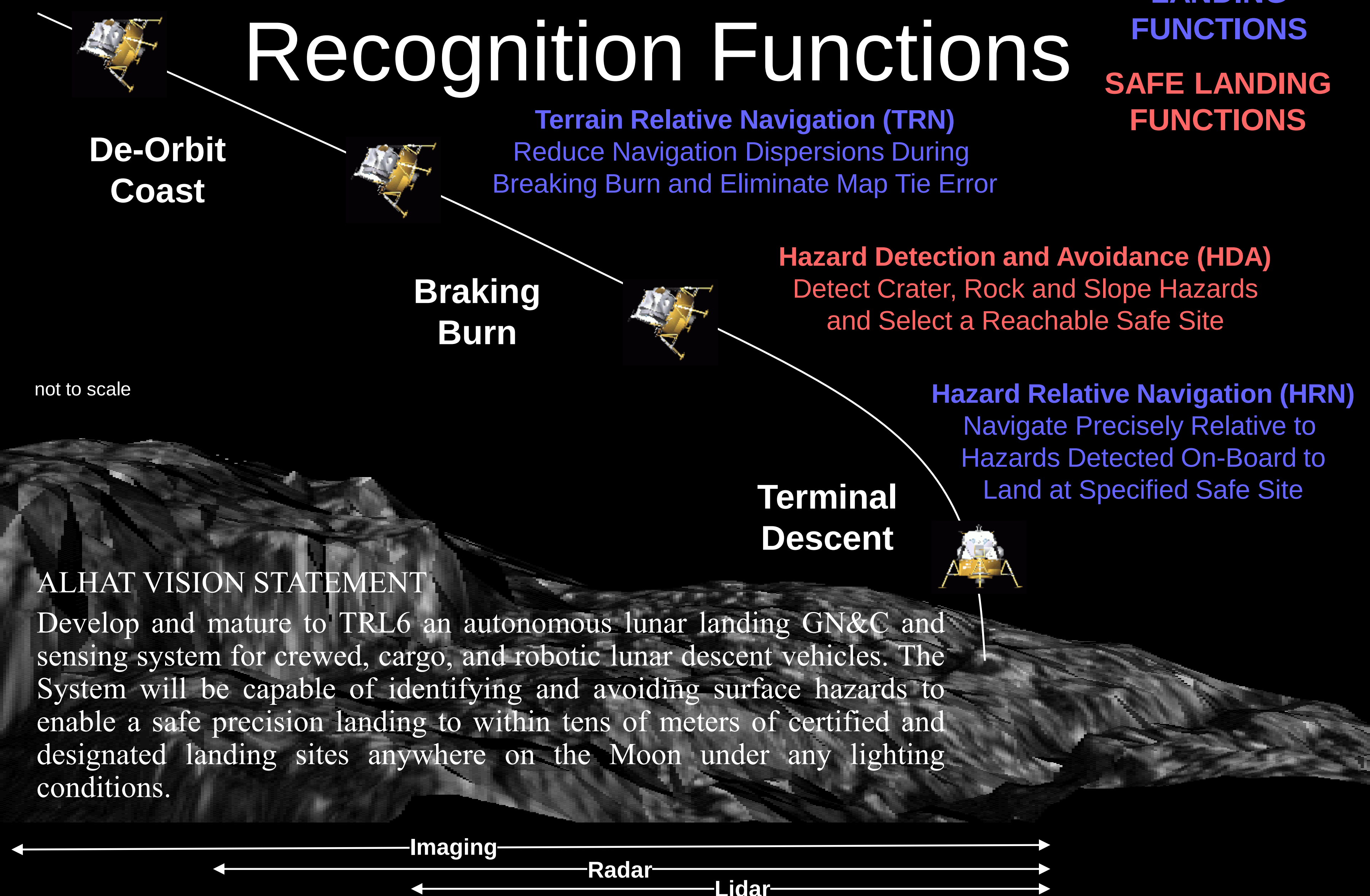
1. Cloud Services
2. Advanced Vehicle Health Management
3. Crew Knowledge Augmentation Systems
4. Improved Displays and Controls
5. Augmented Reality for Recognition and Cataloging
6. Tele-Presence
7. Autonomous & Tele-Robotic Construction
8. Automated Guidance, Navigation, and Control (GNC)
9. Human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

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

Terrain Sensing and Recognition Functions



ALHAT VISION STATEMENT

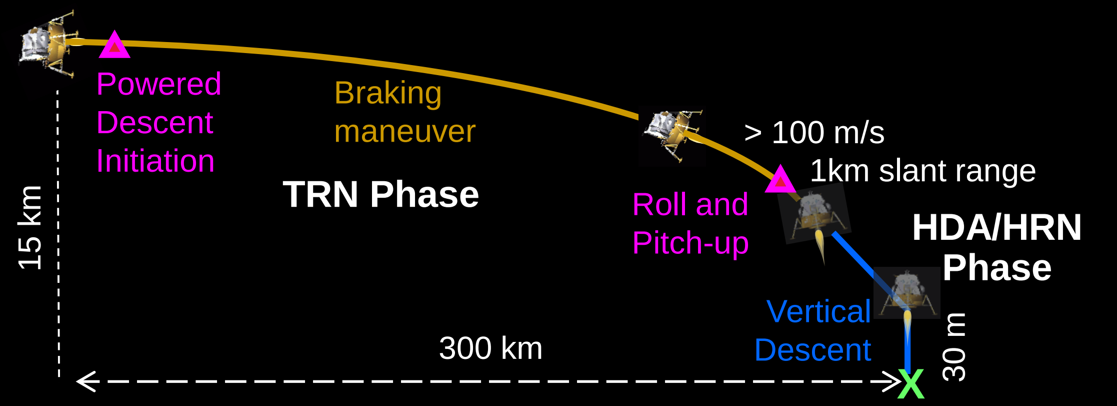
Develop and mature to TRL6 an autonomous lunar landing GN&C and sensing system for crewed, cargo, and robotic lunar descent vehicles. The System will be capable of identifying and avoiding surface hazards to enable a safe precision landing to within tens of meters of certified and designated landing sites anywhere on the Moon under any lighting conditions.

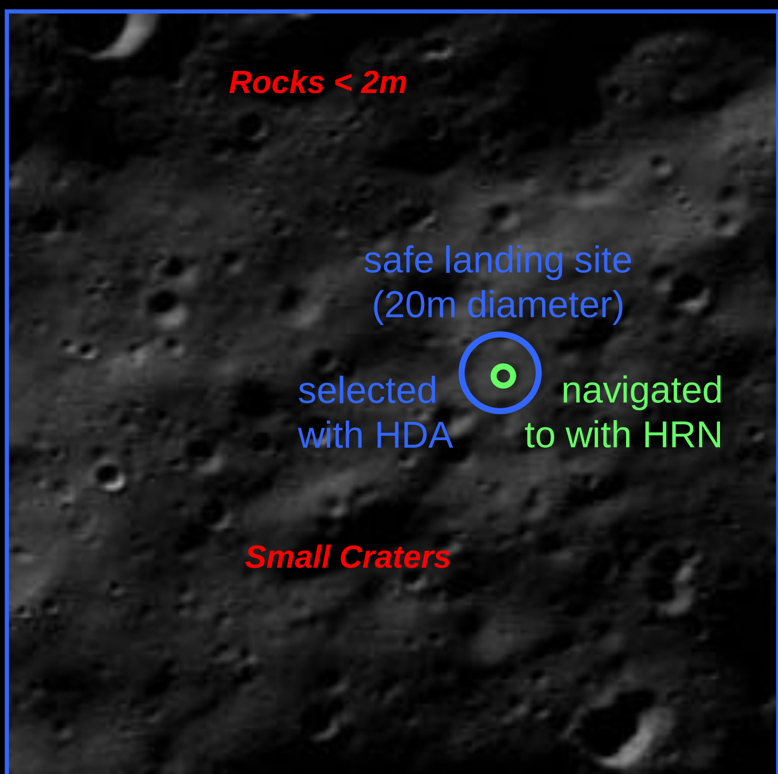
ALHAT
Extreme Terrain Pinpoint Landing

TRN = Terrain Relative Navigation

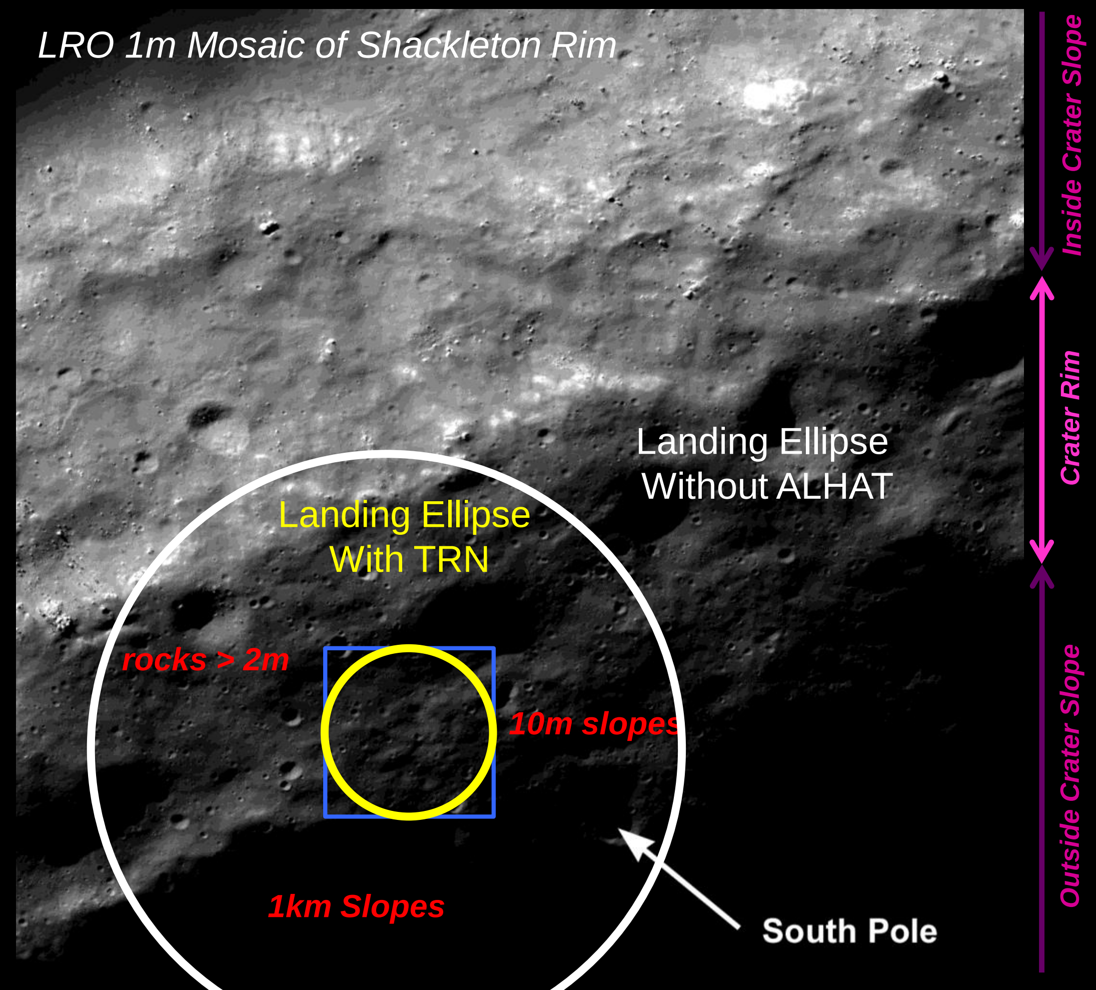
HDA = Hazard Detection and Avoidance

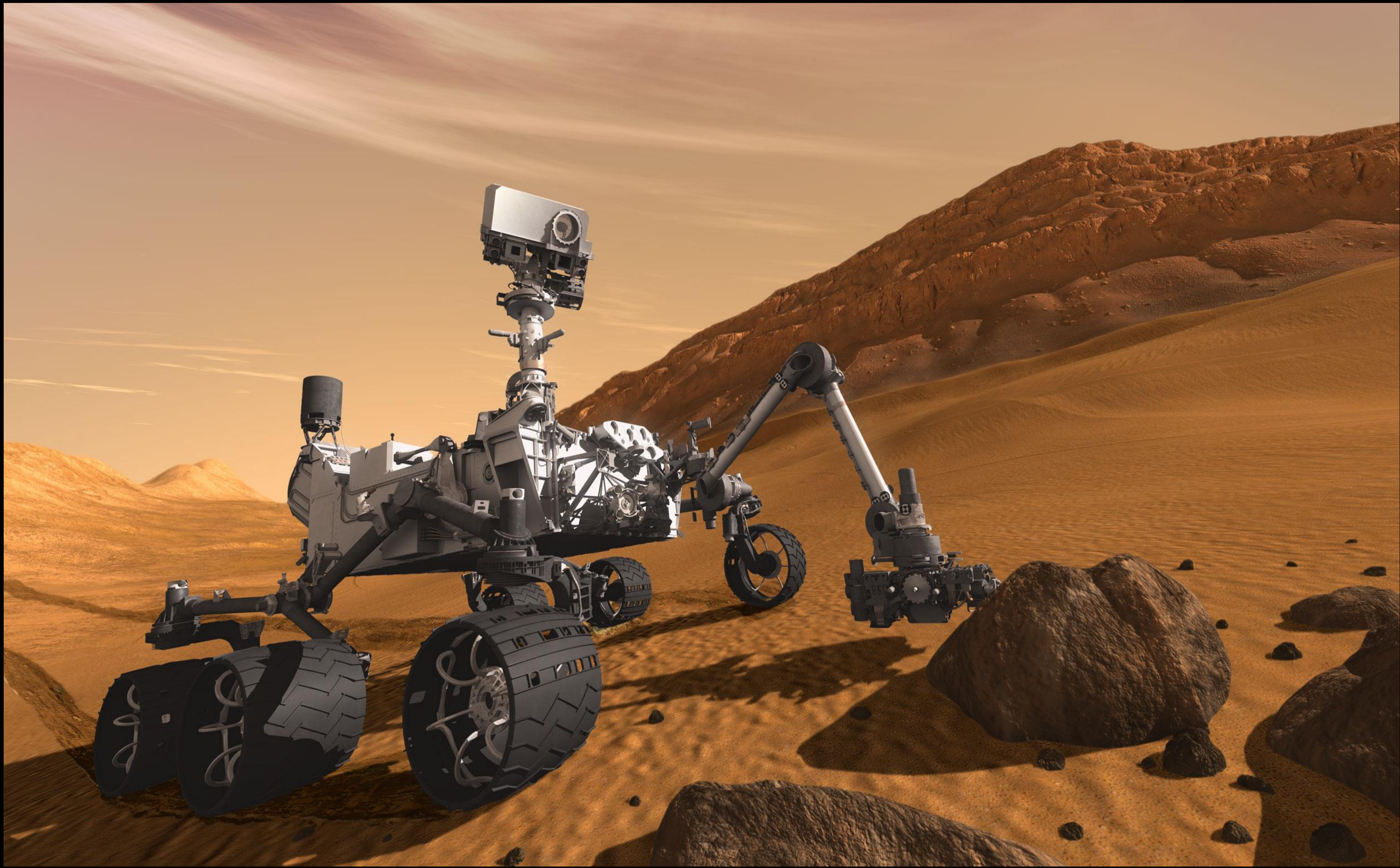
HRN = Hazard Relative Navigation





Hazard Map Area



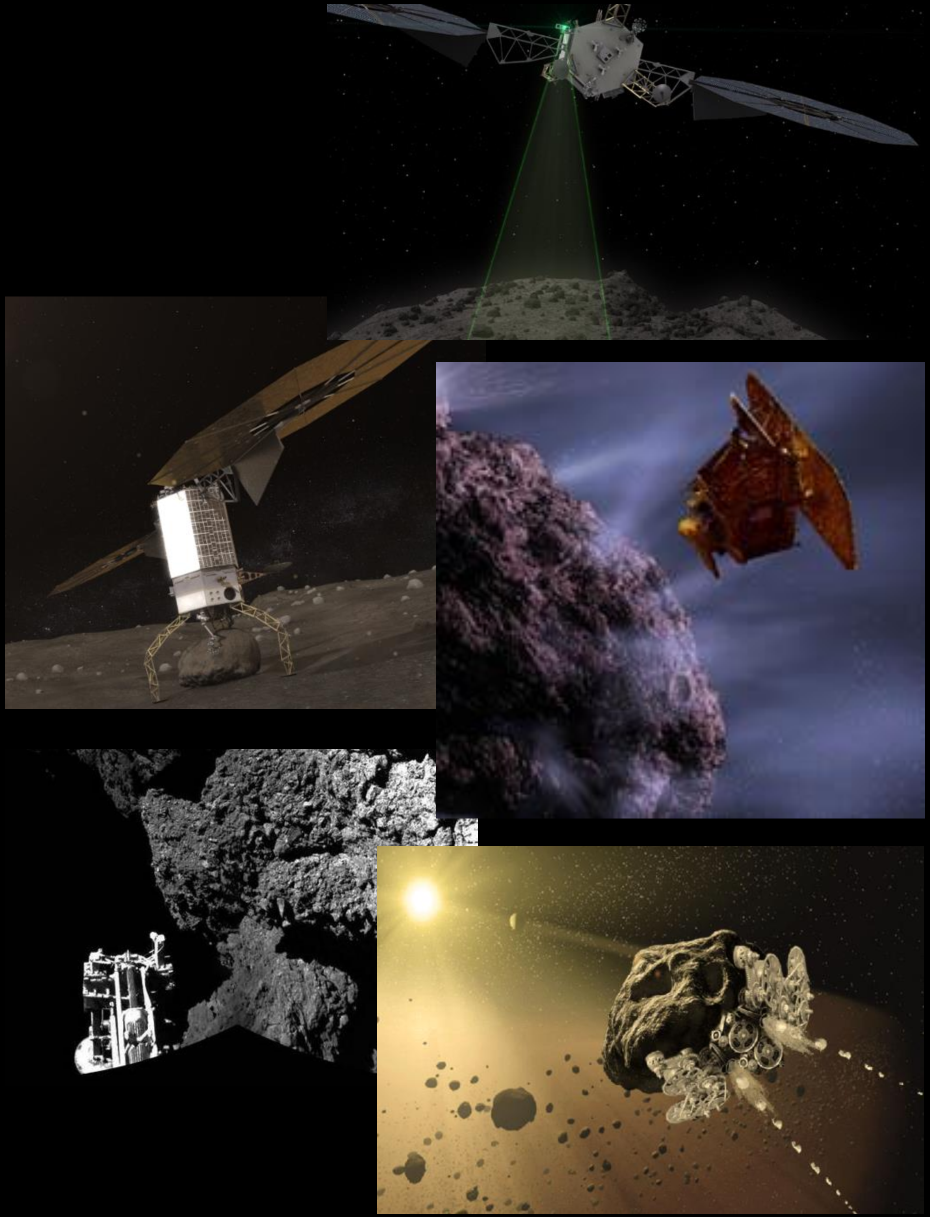


Rover Mobility

- Currently we can’t walk and think at the same time
  - Look -> Think -> Walk -> Repeat
  - Stereoscopic photos, analyze terrain, plan path, turn wheels,
  - Extremely slow traverse
  - No significant science while driving (opportunistic science)
- What we’d like to do with high performance processing onboard
  - Real time terrain processing including soil/sand rock analysis
  - Real time situational awareness (internal and external)
  - Highly enervated (high density tactile, chemical sensors) robotics for engineering and science
  - High speed traverse over unknown terrain utilizing proprioception, wheel/chassis dynamics sensing, environmental sensing
  - Opportunistic science and autonomous science driven replan
  - Coordination with orbiter and high resolution remote sense platform via overhead cloud computing resources
  - Coordination of multi-rover teams, swarms, helicopters

Close Proximity Operations

- Unknown and dynamically changing environment
- Science requires both remote sense and in situ/sampling operations
  - Gravity mapping
  - Terrain/topology mapping
  - Imaging and spectroscopy
  - Sample acquisition and analysis
- Multiple visits
  - Different sites
  - Follow up
- Mult1-platform teams and swarms
  - Specialized platforms for different science and follow up visits
  - Coordination and collaboration
- Multiple-body extended missions
- Virtual (reality) visitation
  - Delay Tolerant Network Comm
  - Downlink bandwidth minimization
    - Knowledge transmission (vs data)



Ocean Worlds (e.g. Europa) Ocean Exploration

- Autonomous exploration and science
  - Minimal communication under Ice and Ocean
  - Occasional low data rate comm to surface and lander/orbiter via small, low power relays
- Autonomous under water navigation and mapping
  - SLAM (Simultaneous Location and Mapping)
  - Dead reckoning and relay assisted navigation
  - Chemical and thermal mapping and gradient/boundary detection
- Aqueous science
- Life detection
- Ice-bottom and ocean bottom science
- Multi-platform collaboration and coordination

Applications by Category

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**

Application Processing Requirements
Robotic Science Missions

Application	Criticality/ Fault Tolerance	Throughput (GOPS)	Real Time	Type of Processing	Memory Access	Data Rate
Autonomous Mission Planning	Mission/ Life critical	1 GOP+	Soft Real Time – seconds	• Database ops • Heuristic search • Parallelizable • Standard Math, Non-DSP, Floating Point preferred	• Random • Memory Intensive	Memory: 1Gb/S+ I/O: 100Mb/S+
Hyperspectral Imaging	Error detection	10s-100s GOPS+	Soft Real Time	• DSP • Parallelizable • FP Desirable • Matrix/ vector math	• Random access • Repeated passes through a data set.	Memory: Multi Gb/S
Radar – science	Error detection	10s-100s GOPS	Soft Real Time	• DSP • Data Base Ops • Parallelizable • Data Flow Amenable	• Continuous access • Sequential access • Random access	Memory: 1Gb/S+

Application Processing Requirements
Robotic Science Missions

Application	Criticality/ Fault Tolerance	Throughput (GOPS)	Real Time	Type of Processing	Memory Access	Data Rate
Extreme Terrain Landing	Mission critical	25-50 GOPS	Hard Real Time - 1 second	• DSP • Control Code • Parallelizable • FP Desirable	• Continuous access • Sequential access • Random access	Memory: 30-50MB/S
Disaster Response Constellation	Not safety critical, and some data loss is permissible	1-10 GOPS	Soft Real Time	• DSP • Onboard spectral signature matching • Real-time High-Def video compression and data handling • Standard Earth land/ocean data product generation pipeline, migrated to space platforms • Change detection (various strategies)	• Regular Sequential access • Possible multi-instrument data fusion. • Random access	Memory: 200MB/S-1Gb/S

Application Processing Requirements Crewed Exploration Missions

Application	Criticality/ Fault Tolerance	Throughput (GOPS)	Real Time	Type of Processing	Memory Access	Data Rate
Advanced Vehicle Health Management	Failure could lead to Mission degradation Shutdown due to fault should recover automatically	18 GIPS/27 GOPS and 18 GFLOPS currently	Multiple second response times are acceptable	• Model-Based Reasoning Techniques • High Rate Instrument Data Processing • Knowledge Retrieval / Synthesis	• Continuous interleaved and irregular or random reads and writes	Memory: 10 – 50 Gb/S I/O: 1 – 10 Gb/S
Crew Knowledge Augmentation System (Watson in Space)	Failure could lead to Mission degradation Shutdown due to fault should recover automatically Live lock-ups and manual restarts acceptable	18 GIPS/27 GOPS and 18 GFLOPS currently	Soft Real Time	• Model-Based Reasoning Techniques • High Rate Instrument Data Processing • Knowledge Retrieval / Synthesis	• Continuous interleaved and irregular or random reads and writes	Memory: 10 – 50 Gb/S I/O: 1 – 10 Gb/S
Augmented Reality	Failure could lead to Mission degradation Shutdown due to fault should recover automatically	24 GIPS/36 GOPS and 24 GFLOPS	Timing requirement is < 1 sec	• Vision-Based Algorithms. • High Rate Instrument Data Processing. • Knowledge Retrieval / Synthesis.	• Continuous interleaved and irregular or random reads and writes	Memory: 100+ Gb/S I/O: 50+ Gb/S

Application Processing Requirements Crewed Exploration Missions

Application	Criticality/ Fault Tolerance	Throughput (GOPS)	Real Time	Type of Processing	Memory Access	Data Rate
Telepresence	Failure could lead to Mission degradation Shutdown due to fault should recover automatically Live lock-ups and manual restarts acceptable	24 GIPS/36 GOPS and 24 GFLOPS currently	Timing requirement is < 1 sec	• Vision-Based Algorithms. • High Rate Instrument Data Processing.	• Continuous interleaved and irregular or random reads and writes	Memory: 100+ Gb/S I/O: 50+ Gb/S

Application Processing Requirements Robotic Missions

Autonomous Mission Planning
1+GOP, Soft real time, 1Gb/S+

Extreme Terrain Landing
25-50GOPS, Hard real time, Memory: 30-50Mb/S

Disaster Response Constellation
1-10GOPS, Soft real time, 200Mb/S-1Gb/S+

Radar – Science
10-100sGOPS+, Soft real time, 1Gb/S+

Hyperspectral Imaging
10-100GOPS+, Soft real time, Multi Gb/S

Application Processing Requirements Crewed Missions

Advanced Vehicle Health Management
10-50GOPS, Multiple seconds, Memory: 10-50Gb/S

Crew Knowledge Augmentation System
18 GIPS/27 GOPS and 18 GFLOPS, Multiple seconds, 50-100Gb/S

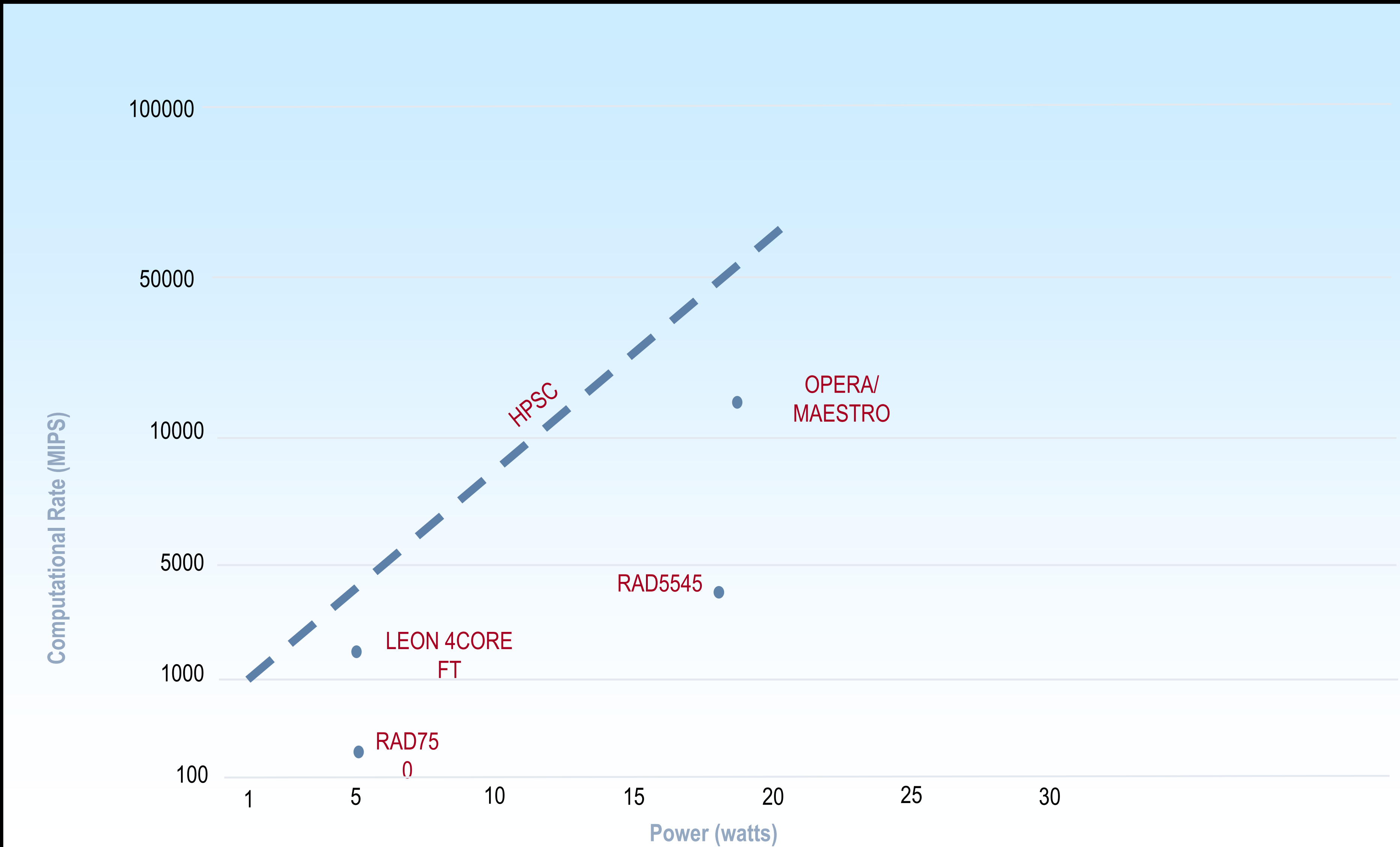
Augmented Reality
24 GIPS/36 GOPS and 24 GFLOPS, <1second, 100+Gb/S

Telepresence
24 GIPS/36 GOPS and 24 GFLOPS, <1second, 100+ Gb/S

What will we need to Achieve These Capabilities?

- Tens to Hundreds of GOPS of throughput
  - Specialized custom co-processors in a
  - Heterogeneous Computing Environment
- Extremely high reliability
  - Hardware
  - Software
  - System operation
- Ability to withstand faults and damage without compromising delivered service
- Ability to gracefully and intelligently degrade in performance while maintaining safety and high priority services
- Tens to Hundreds of Gb/s I/O data rates
- Tens to Hundreds of GB/s memory data rates
- Tens of TB of memory capacity
- At extremely low SWaP-C

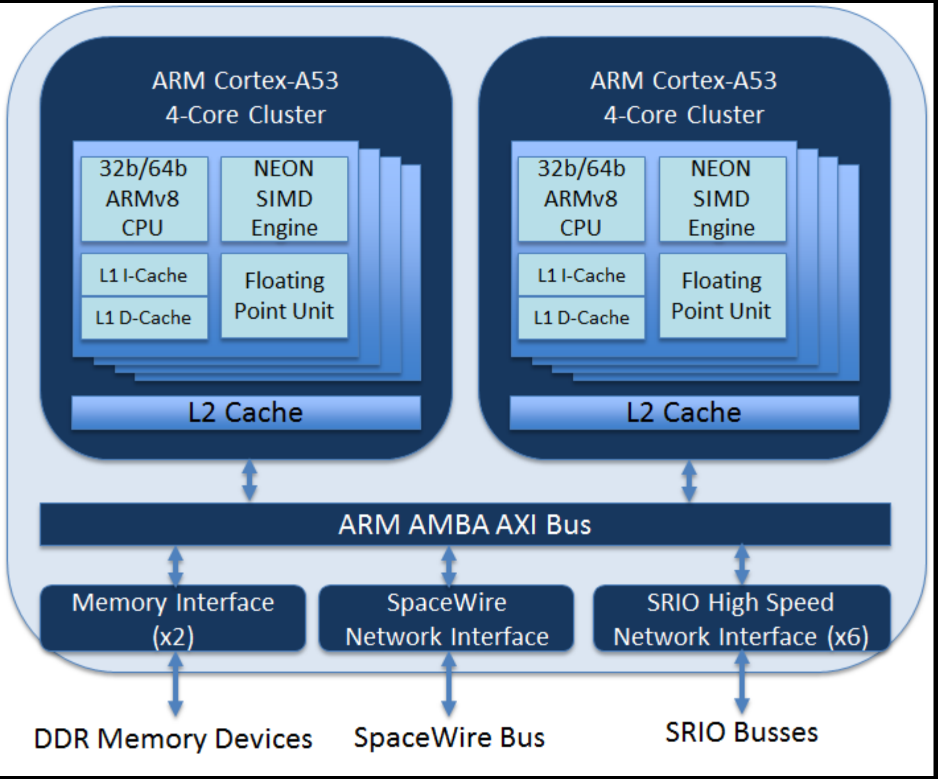
Multicore Rad Hard Processors Performance:Power

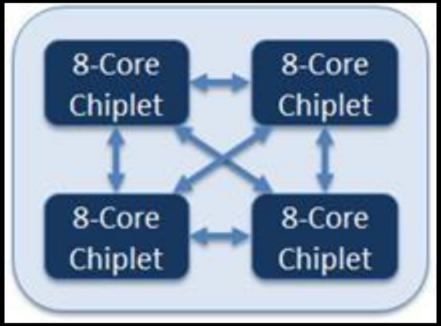


Current Multicore Processors

- Leon 4 & variants, RAD 5545 “System on a Chip” Architectures
- Self contained
  - Complete system, but limited extensibility
- 4 processing cores + I/O + memory interface
- Limited power management
- Limited fault tolerance strategies
- Limited resource utilization strategies
  - Binding of “subsystem” to processing core
    - CDH, GnC, Comm, Instrument processing & control
  - Classical SMP
    - Allocation of processor core to next task or thread
  - Other strategies, e.g. AMP, possible, but limited benefit vs complexity
- Bottlenecks can be a significant issue depending on application
  - Especially memory
- Straightforward programming with standard OS, compilers, debuggers

HPSC Reference Architecture
8-Core Extensible Chiplet





- A53 clusters for high bandwidth processing provide ~15 GOPS
- Typical device power is ~5-7 Watts (depending on memory and I/O utilization)
- On chip AMBA interconnect,
- 2 72-bit DDR3/4 memory interfaces
- 6 Serial RapidIO (SRIO) busses (10Gbaud each) to interconnect other chiplets, and high bandwidth instruments and subsystems
- 6 XAUI port (10Gbaud each)
- Misc I/O: NVM, SRAM, GPIO, Boot ROM
- Power Management – unused cores can be dynamically de-powered or put to sleep
- Multiple levels of fault tolerance – hardware and software implemented – some mandatory, some optional

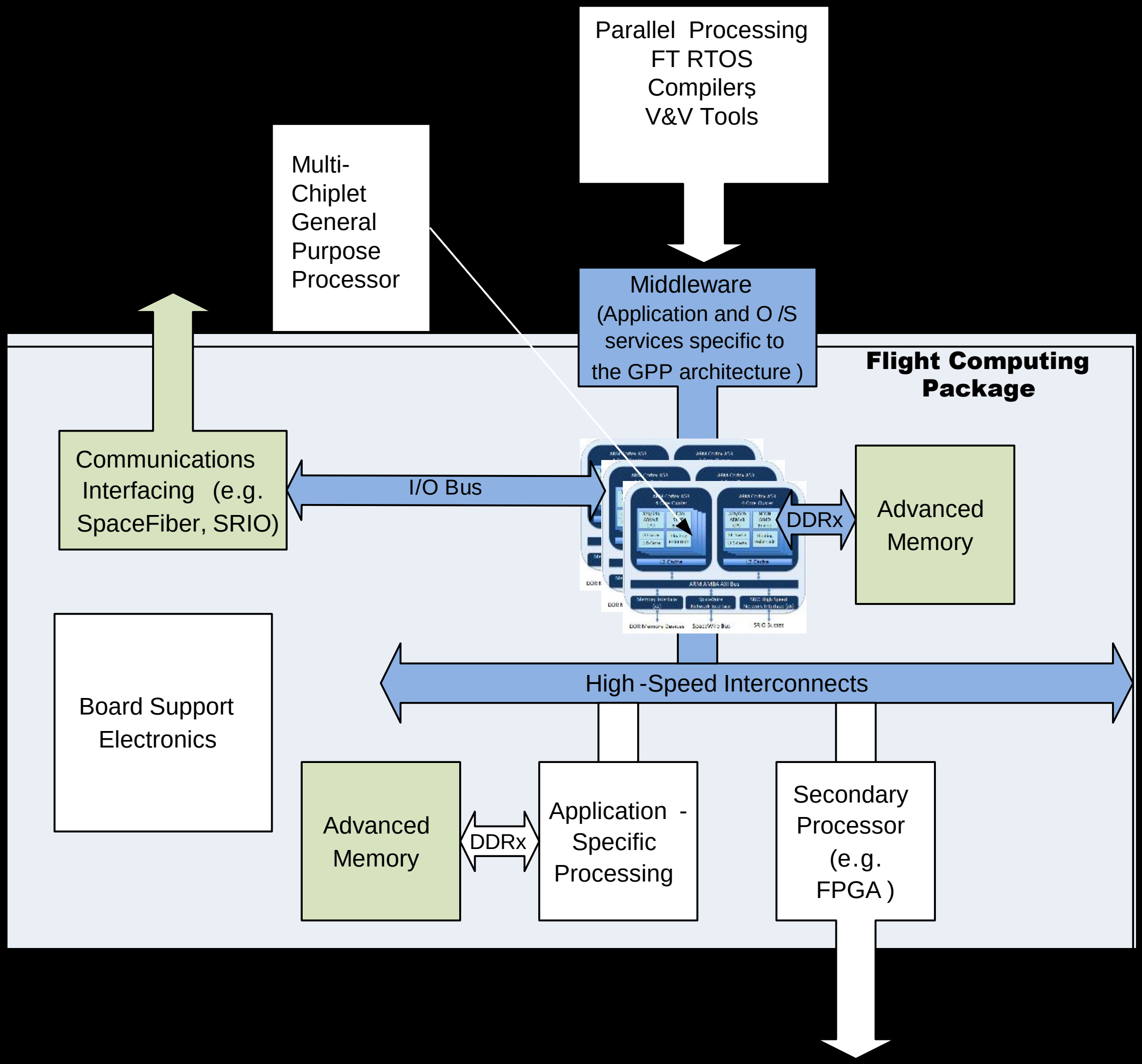
The Chiplet Concept

- System in Package (SIP) vs System on a Chip
  - Build complex systems from small, reusable modules, aka Chiplets
  - Flexibility/Scalability
    - Multiple Chiplets in arbitrary topology
    - Mix & match Chiplet technologies/generations
    - Multiple modes/levels of fault tolerance, power, dynamically manageable
    - Single Chip, 2.5D, 3D packaging (& chiplet configurations)
  - Extensibility
    - Coprocessors: PIM, Neuromorphic, Robotic, DSP via SRIO
    - FPGA via XAUI/SRIO
  - Evolvability
    - Low cost, rapid evolution of:
      - Chiplets
      - Chiplet-based SIP Computers
  - Affordability
    - Low cost, rapid development
      - Chiplet
      - Processor/computer package/board

The Chiplet Concept

- But at the cost of complexity
  - Software needs to handle
    - Multiple widely varying hardware configurations and capabilities
    - Parallel processing (not just multithreading)
    - Dynamically varying hardware resources
    - Dynamically varying software loads with different optimization strategies
  - Software development challenge
    - Rapid (10M LOC in 2-3 years)
    - Highly reliable
    - 100% V&V coverage
  - Spacecraft System Level
    - Distributed computing as well as centralized
    - Fault tolerance
    - Code migration

HPSC Ecological Elements



Expandable to additional chiplets or application specific computing elements for redundancy, specialized processing, etc. as required.

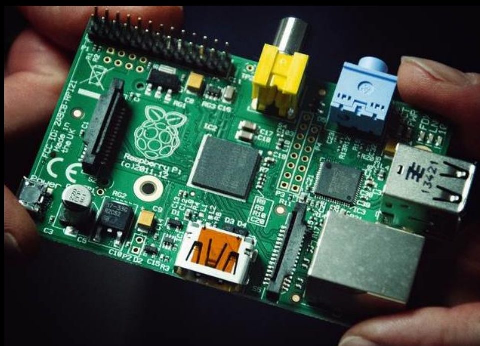
The overall High Performance Spaceflight Computing (HPSC) architecture is an "ecology" formed by the processor and supporting hardware and software elements to make a modern, scalable, rad hard computing environment.

Challenges

- Hardware:
  - Cost!
  - Heterogeneous configurations – tailored to application
  - Keep up with COTS capabilities and tools
  - Robustness, life time, radiation hardness…. in a shrinking geometry
  - Can we build a rapidly evolving, easy to use, plugnplay tool kit?
- Software:
  - 10s of Millions of LOC in 2-3 years guaranteed correct and dynamically V&V'd with 100% coverage
  - Easy to use development system
  - Highly complex parallel codes for science and autonomy
  - At an affordable price!

Do we want to show a conceptual architecture – I think so??

Final Thoughts



COTS

\+ $ +

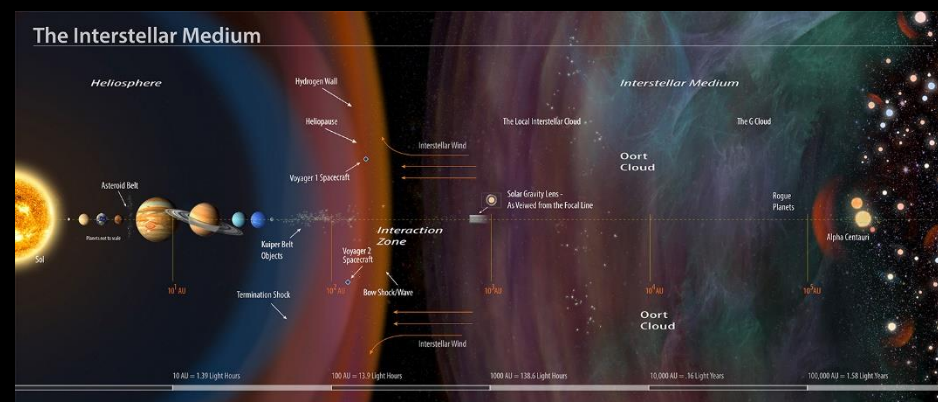
COST

COMPLEXITY

\+

VERIFICATION

=



THE FUTURE

Jet Propulsion Laboratory
California Institute of Technology