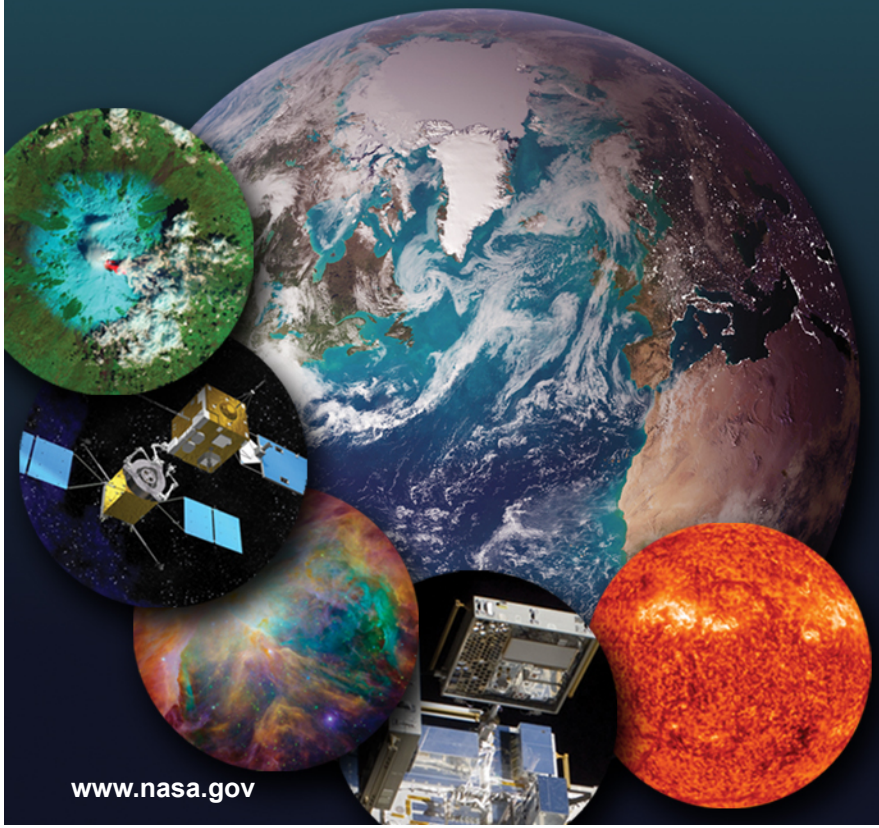
National Aeronautics and Space Administration

SpaceCube™

High Performance Hybrid Data Space Processing System



SpaceCube

IS&T Colloquium: Goddard Showcase
November 17, 2014

Presenter: Dave Petrick

SCIENCE DATA PROCESSING BRANCH
Code 587 • NASA GSFC

www.nasa.gov

SpaceCube

- Reconfigurable high performance hybrid data processor for space
  - Hybrid parallel processing = CPU + FPGA + DSP
- "CLOSES THE GAP" with commercial grade processors
- Started in 2006 as an IRAD

"*I've dealt with hundreds of new and emerging technologies for over a decade. I can think of no other cross-cutting technology that offers greater potential impact to NASA's future space missions due to the significant improvements of on-board space computing performance and reduction of size, mass, and cost compared to the current practice. SpaceCube will transform science and exploration space missions and will be the poster-child of a "mission-enabling" technology for years to come.*"

-- Peter Hughes, GSFC Chief Technologist

Funding Sources – Collaborators

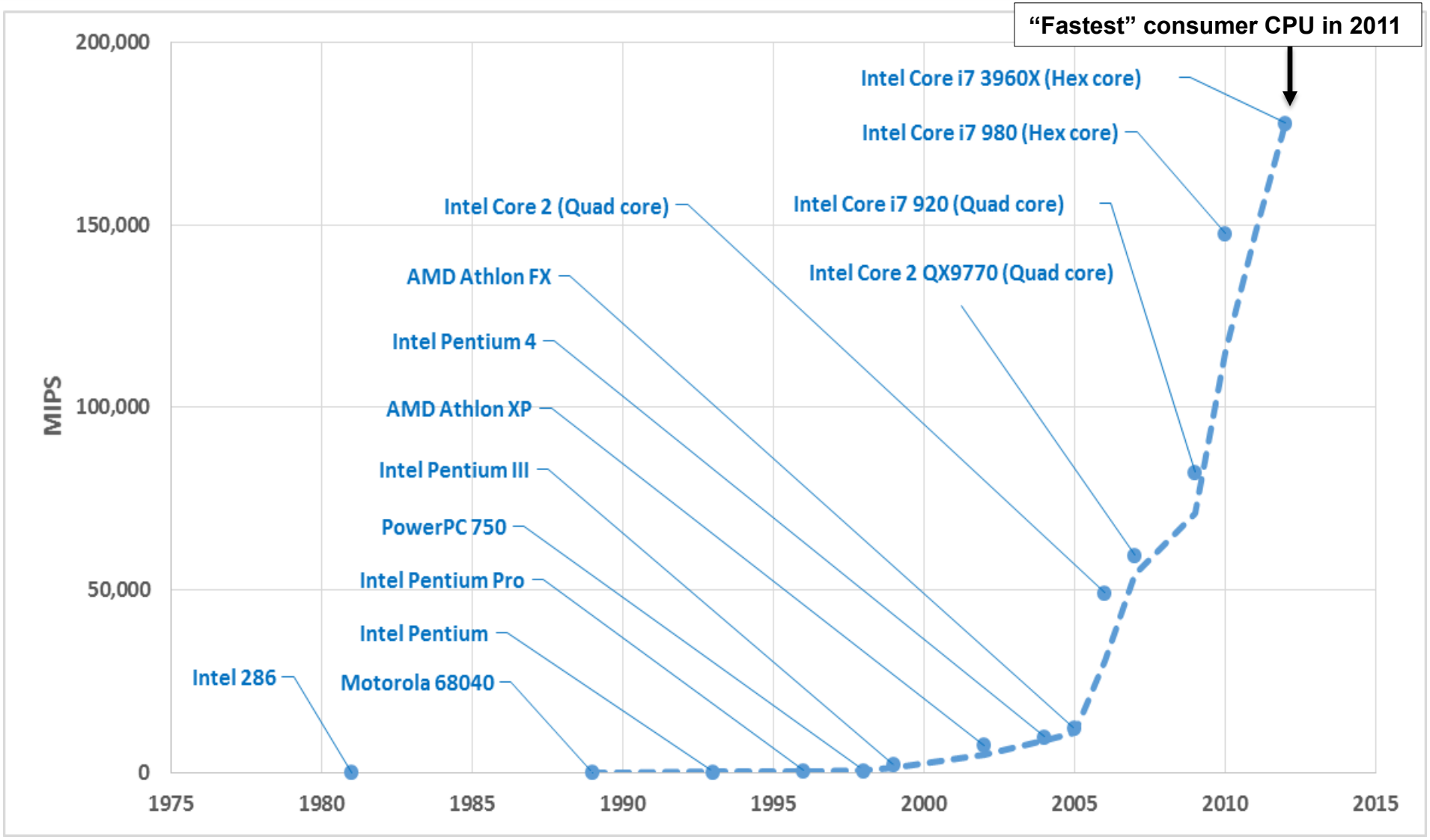
GSFC IRAD Program

OPERATIONALLY RESPONSIVE SPACE
ORS

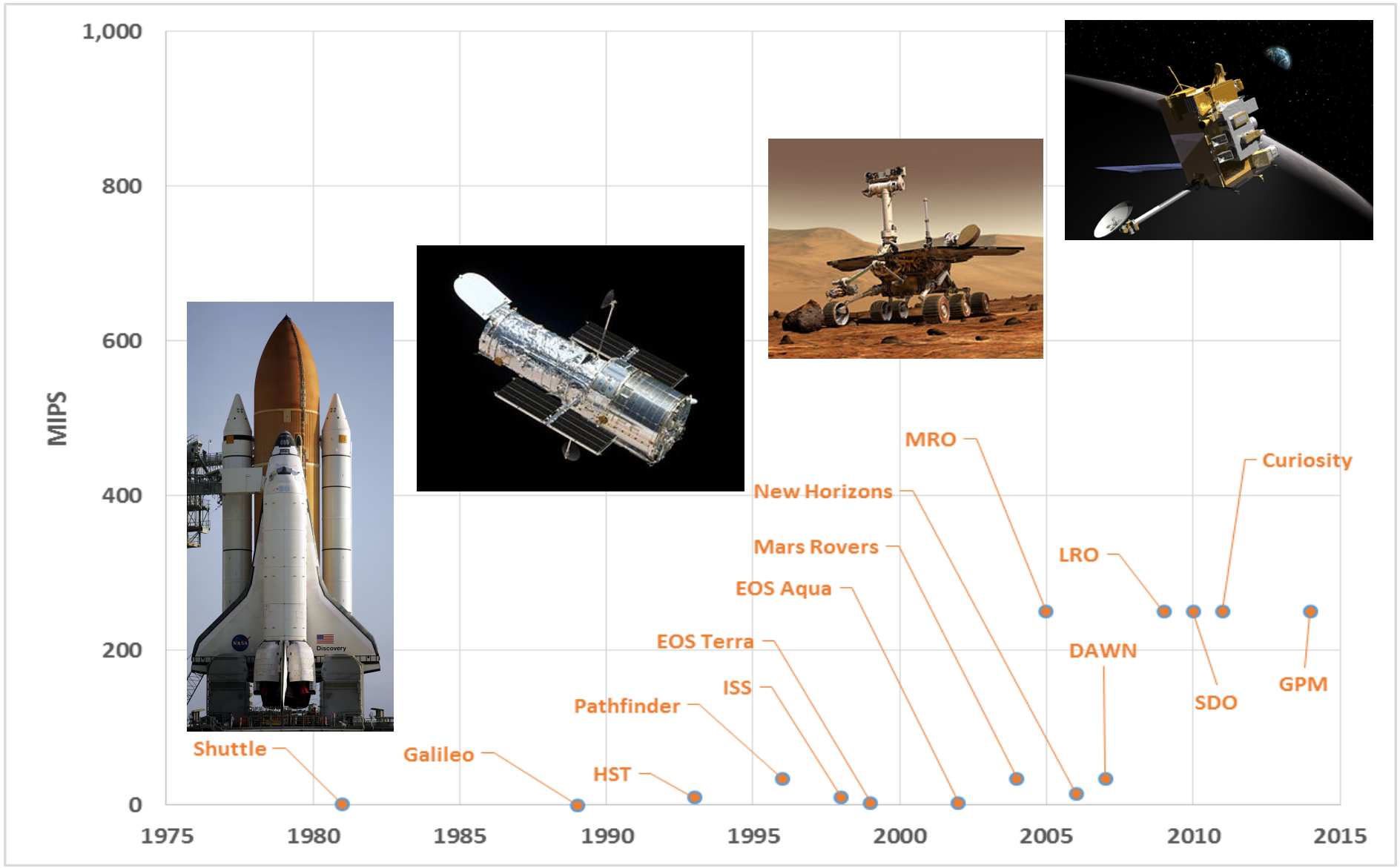
ESTO
Earth Science Technology Office

AETD Division Collaborators
580: Software Engineering
560: Electrical Engineering
590: Mission/Systems Engineering
540: Mechanical Systems

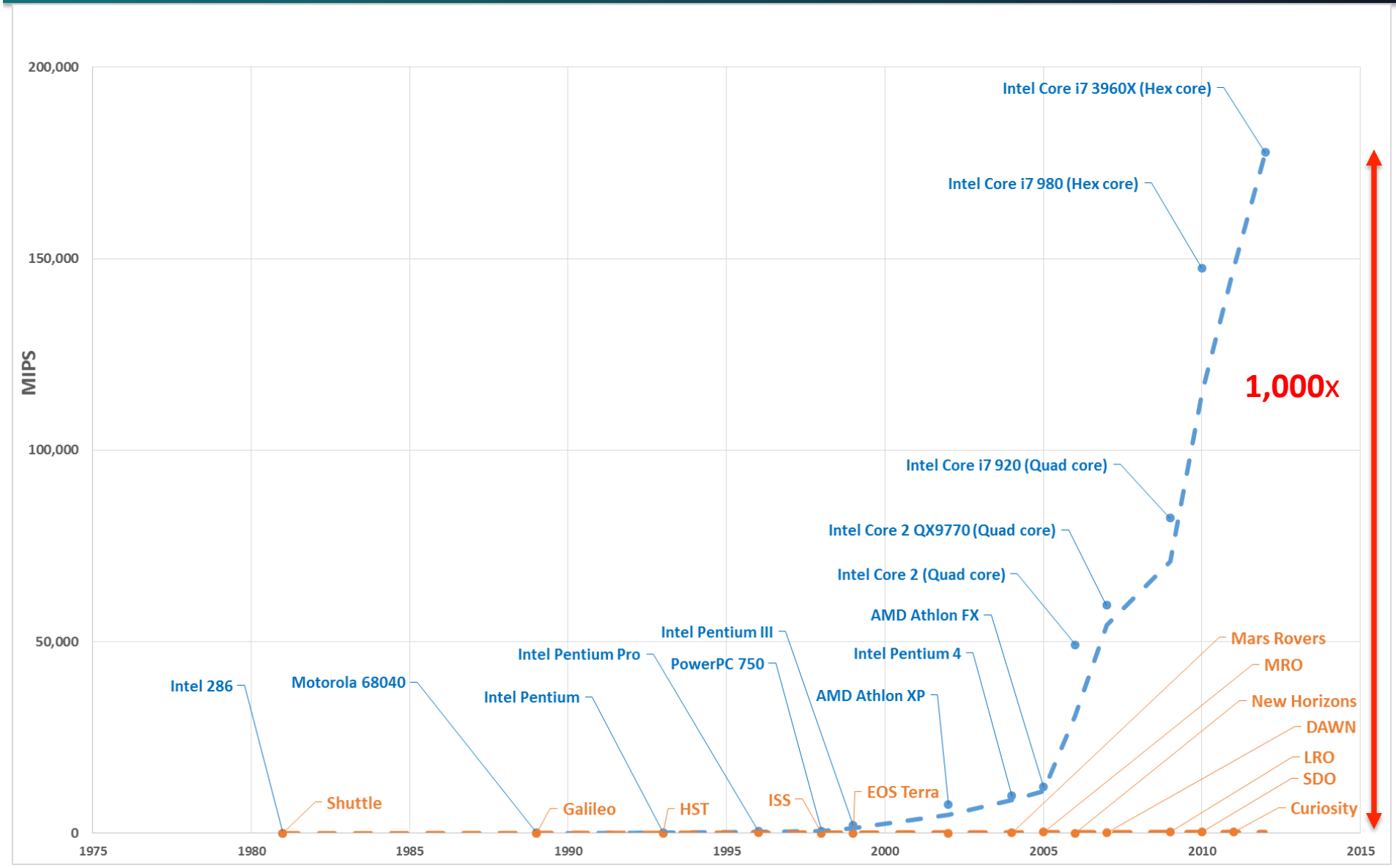
Commercial Processor Trend



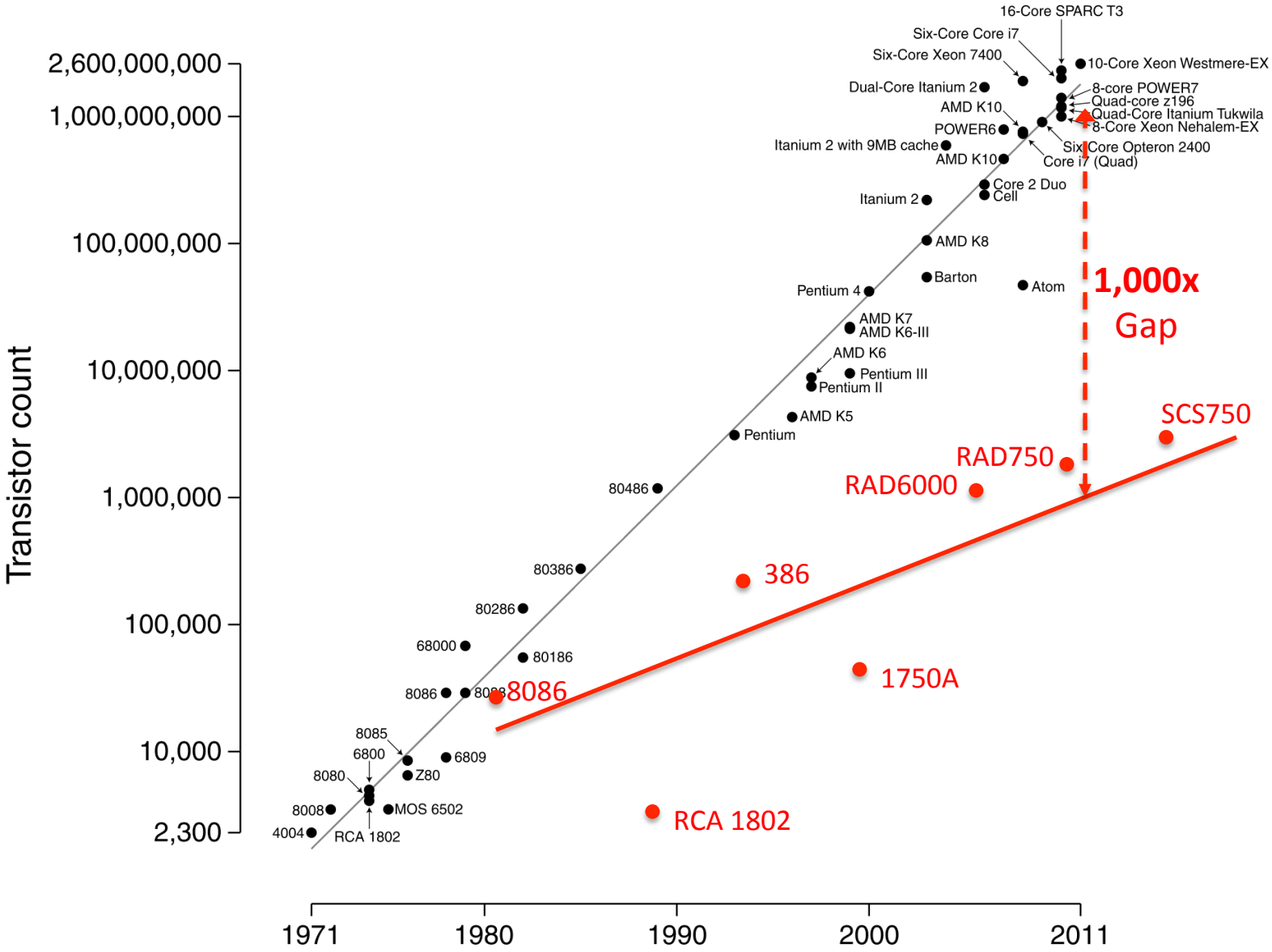
Space Processor Trend



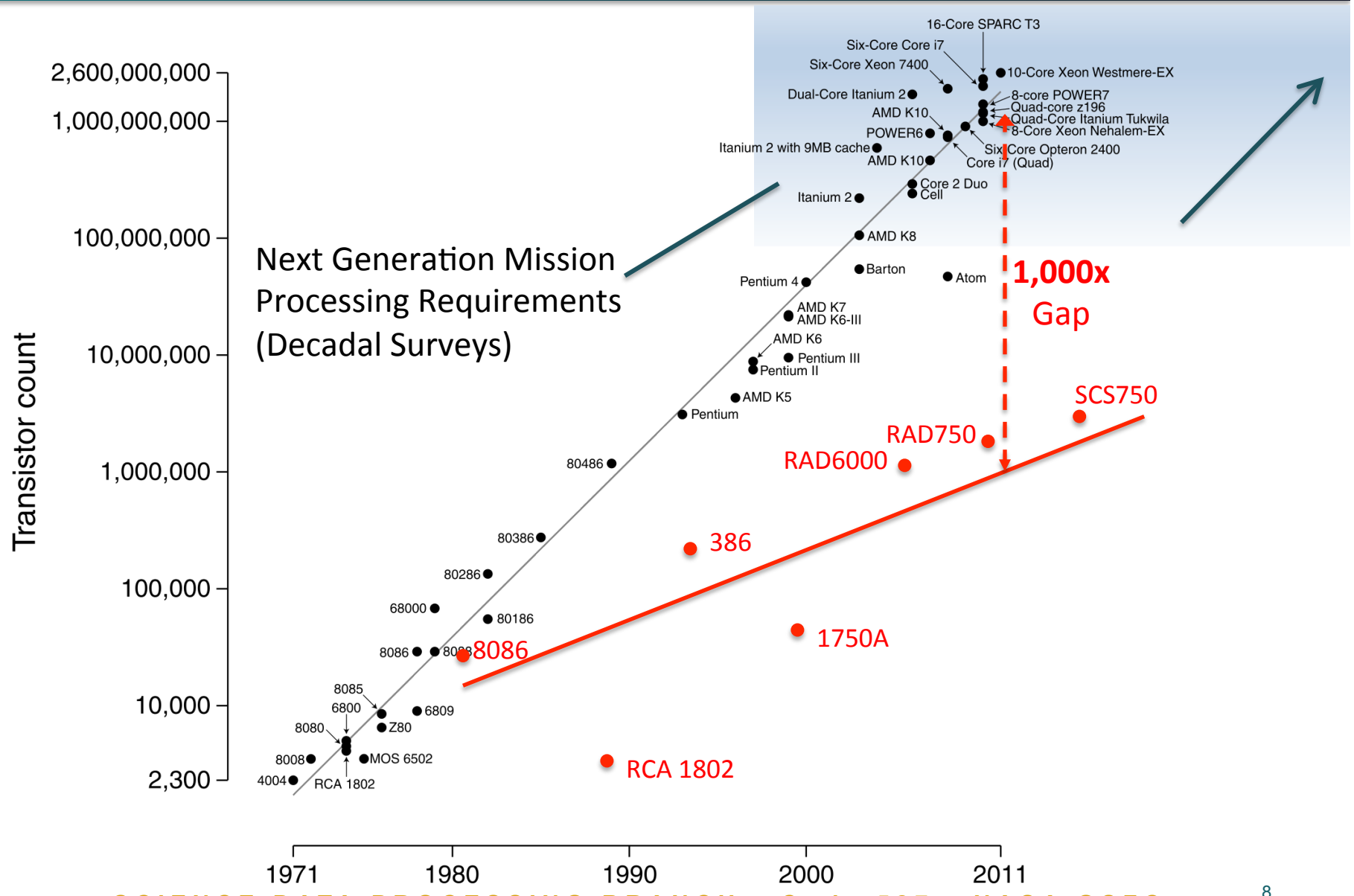
Processor Trend Comparison



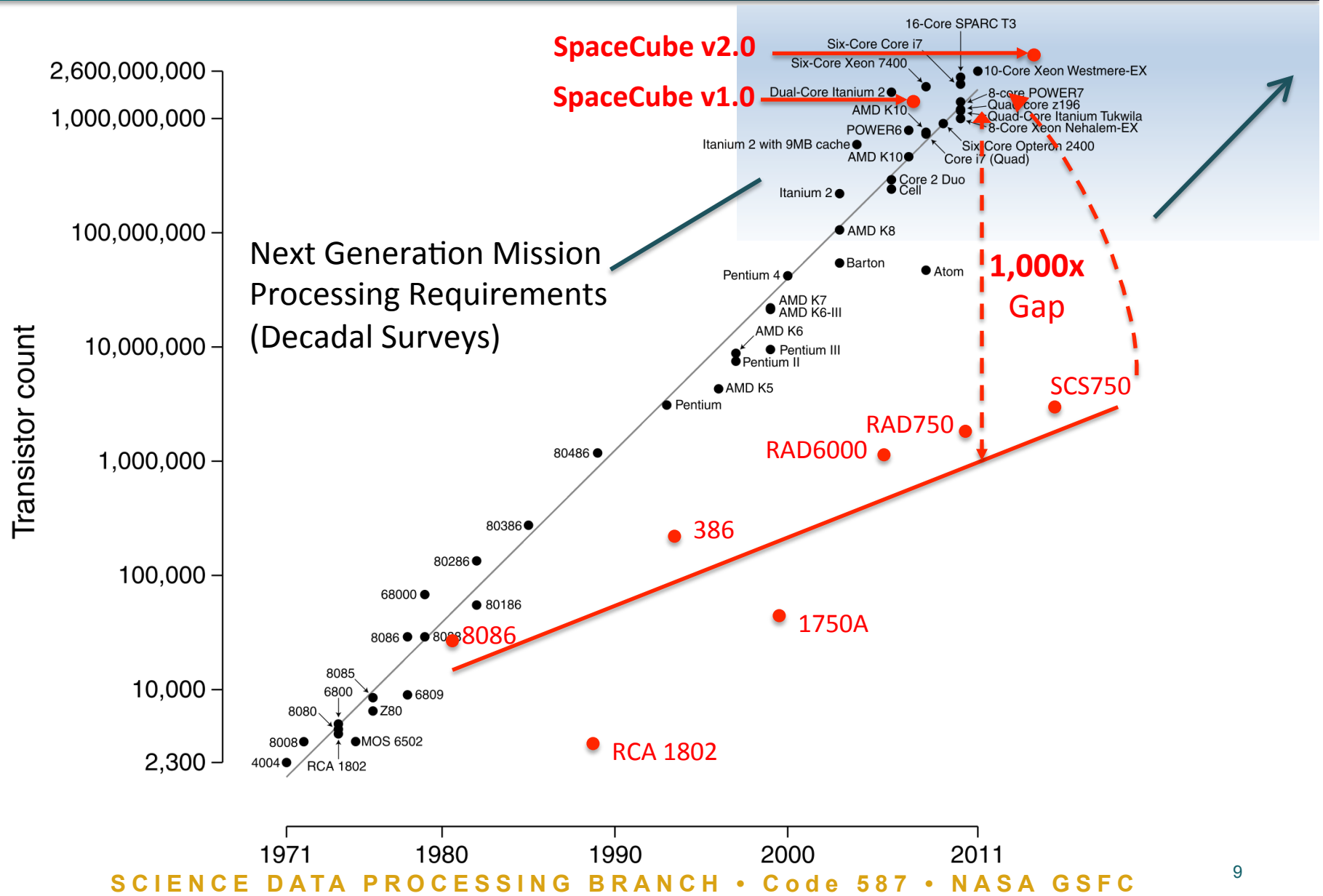
Processor Trend Comparison



Future Space Processing Requirement



SpaceCube Closes the Gap



High Performance Space Processing

- **Facts**
  - "Next Generation Missions" are demanding extreme data processing capacity
  - Traditional Rad-Hard processors will not meet requirements
- **Challenge**
  - Improve processing capabilities by orders of magnitude
  - Maximize Reliability
  - Minimize Size and Power
- **Our Solution**
  - Hybrid parallel processing = CPU + FPGA + DSP
  - Run-Time Reconfigurable
    - Adapt to new mission requirements
    - Hardware, Software, Data
  - Back-to-Back architecture

Xilinx Virtex-5 FPGA

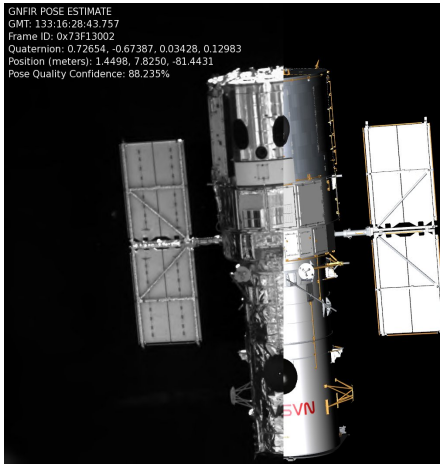
SpaceCube is a Mission-Enabling Technology

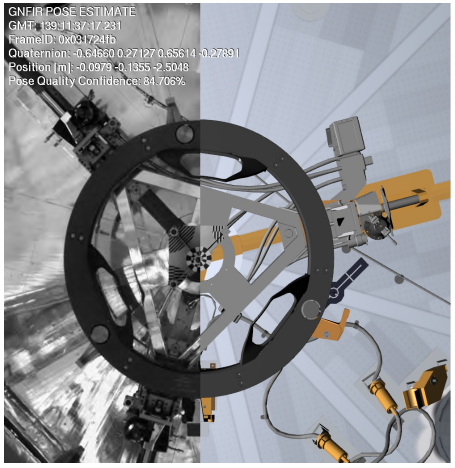
Hardware Acceleration Evolution

Application	Xilinx Device	Acceleration vs CPU
SAR Altimeter	Virtex-4 FX60	**79x** vs PowerPC 405 (250MHz, 300 MIPS)
RNS GNFIR FPU, Edge	Virtex-4 FX60	**25x** vs PowerPC 405 (250MHz, 300 MIPS)
HHT EMD, Spline	Virtex-1 2000	**3x** vs Xeon Dual-Core (2.4GHz, 3000 MIPS)
Hyperspectral Data Compression	Virtex-1 1000	**2x** vs Xeon Dual-Core (2.4GHz, 3000 MIPS)
GOES-8 Ground System Sun correction	Virtex-1 300E	**6x** vs Xeon Dual-Core (2.4GHz, 3000 MIPS)

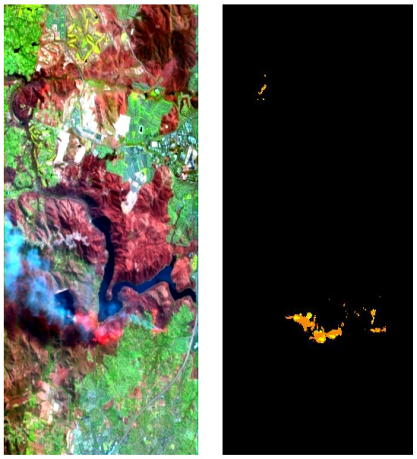
- All functions involve processing large data sets (1MB+)
- All timing includes moving data to/from FPGA
- SpaceCube v2.0 is 10-100x more capable than these earlier systems

SpaceCube Applications

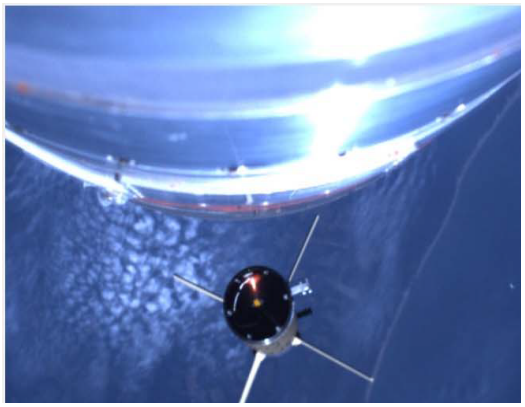




Real-Time Image Tracking of Hubble



Fire Classification



Gigabit Instrument Interfacing

SpaceCube ISS Radiation Data

Spectrometer Data Reduction

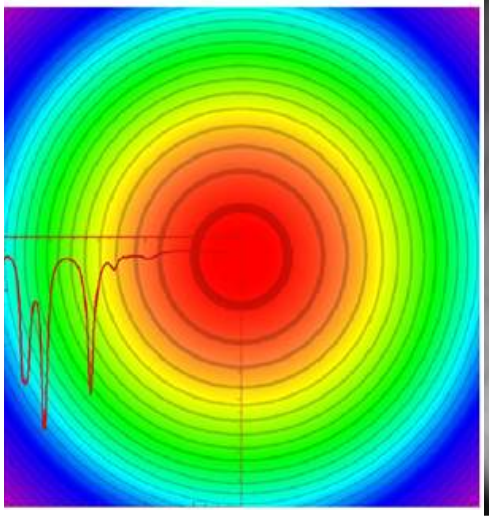
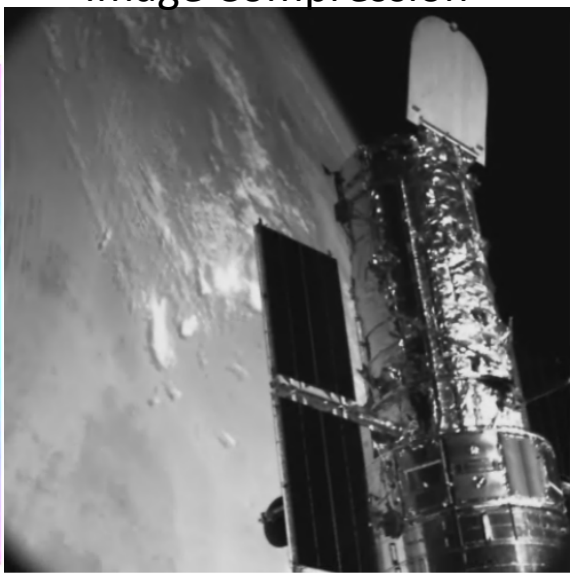
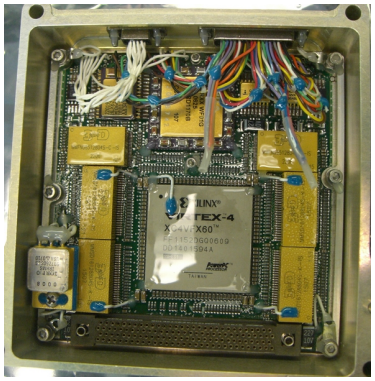


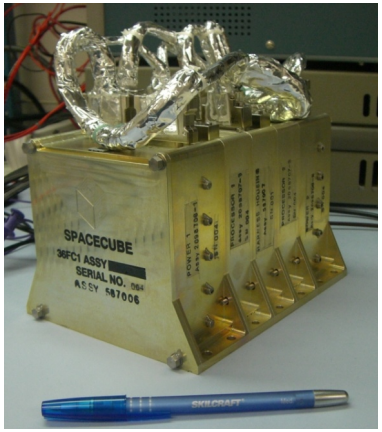
Image Compression



SpaceCube Family Overview

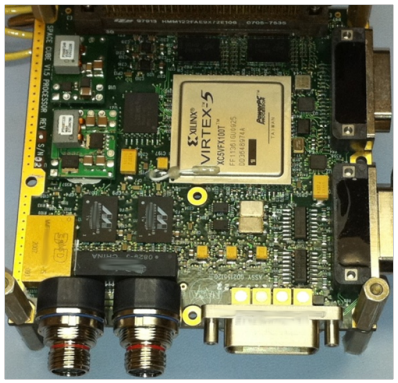
v1.0

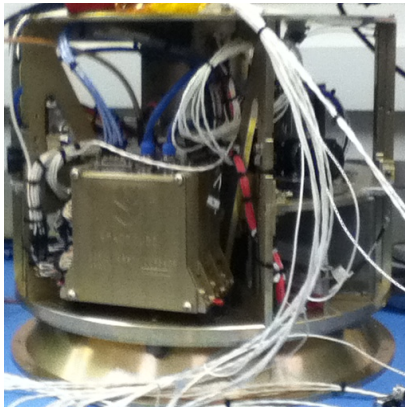




2009 STS-125
2009 MISSE-7
2013 STP-H4
2016 STP-H5

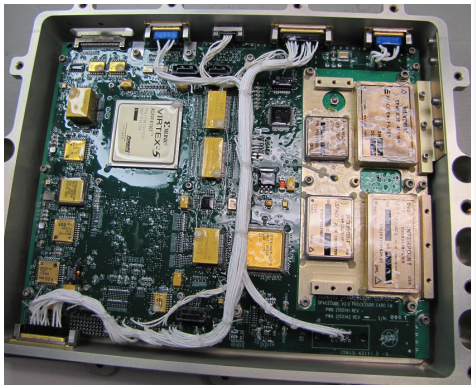
v1.5

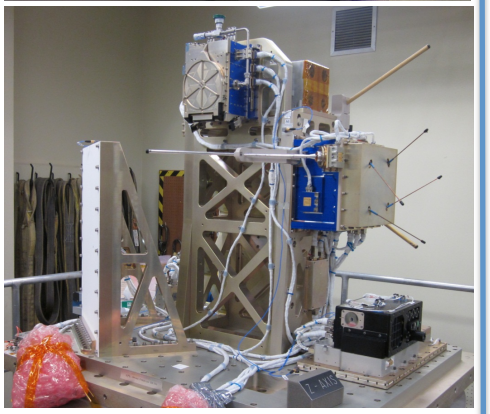




2012 SMART

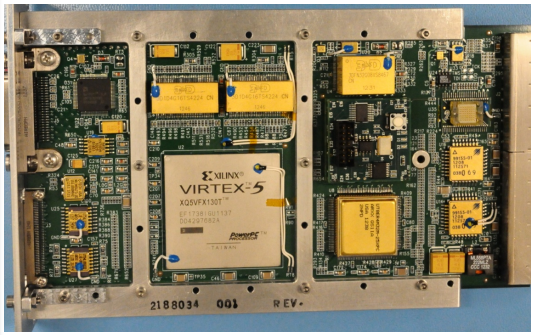
v2.0-EM

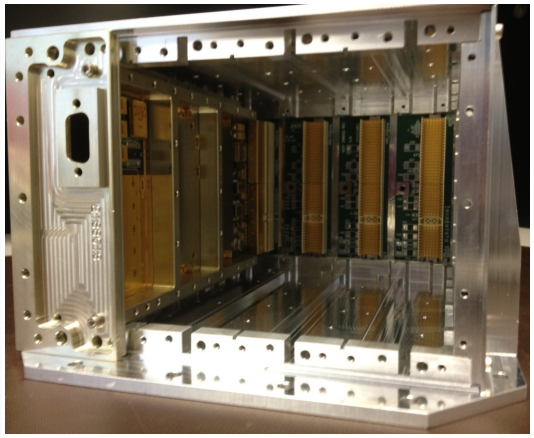




2013 STP-H4
2016 STP-H5

v2.0-FLT

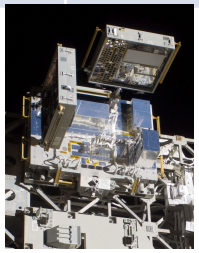
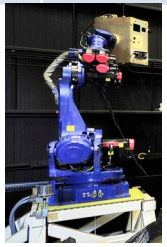
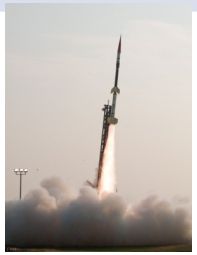
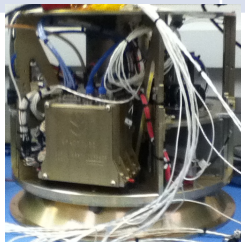
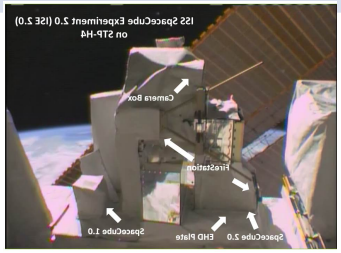


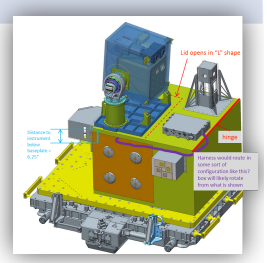


2015 GPS Demo
- Robotic Servicing
- Numerous proposals for Earth/Space/Helio

SpaceCube Missions

Year	System	Mission	Application
2009	v1.0	Relative Navigation Sensors STS-125	Real-time image tracking, data compression
2009-Present	v1.0	MISSE-7	Radiation Experiment
2010-2011	v1.0	Argon Robotic Demo	Closed-loop pointing
2012	v1.5	SMART, DoD Payload	Sounding rocket avionics
2013-Present	v1.0 v2.0	STP-H4, DoD Delivery STP-H4, ISE2.0	- Payload Control, ISS Interface - v2.0 TRL increase
2015	v2.0	GPS Sounding Rocket	SpaceCube/GPS TRL increase
2016	v1.0 v2.0 Mini	STP-H5, DoD Delivery STP-H5, SSCO Delivery STP-H5, ISEM	- Payload Control, ISS Interface - In-Bound Vehicle Tracking - Mini TRL increase

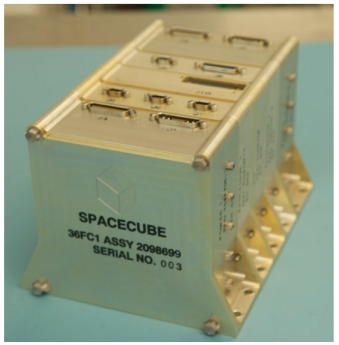






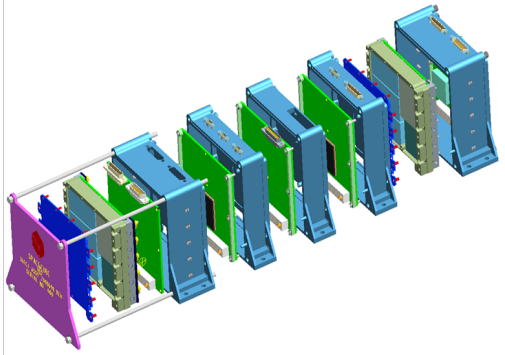


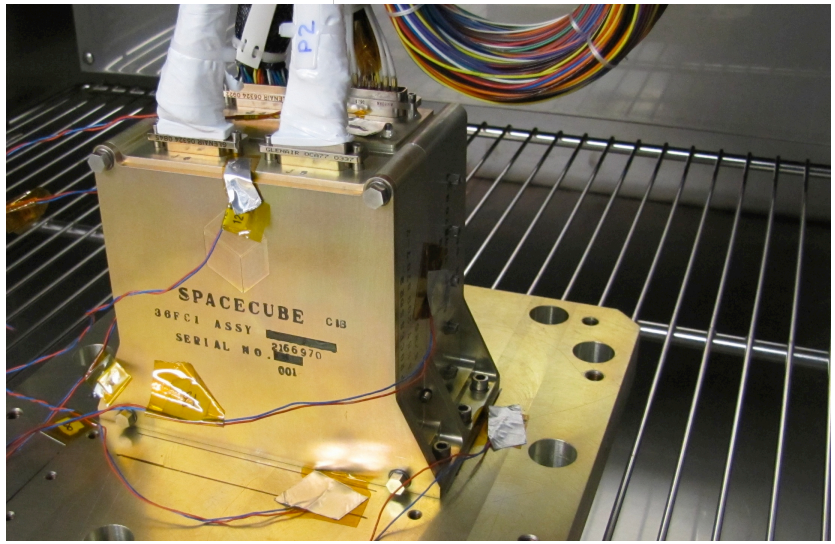
By 2016, 9 systems flown, 22 Xilinxs in space
SpaceCube Leads NASA in Advanced Avionics

SpaceCube v1.0 System

Mechanical Slice Stacking Architecture







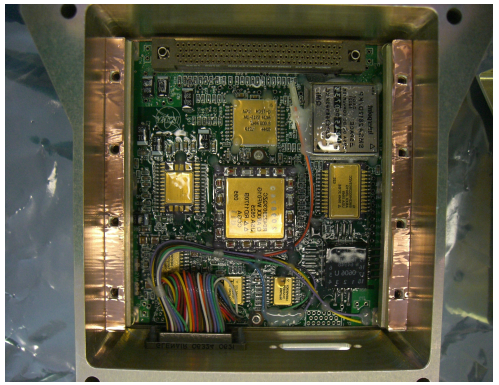
Base Unit Size: 4.5” x 4.3” x 3”
Operating Range: -30C to +55C
Power: 12-16W

Processor Slice
Back-to-Back Architecture

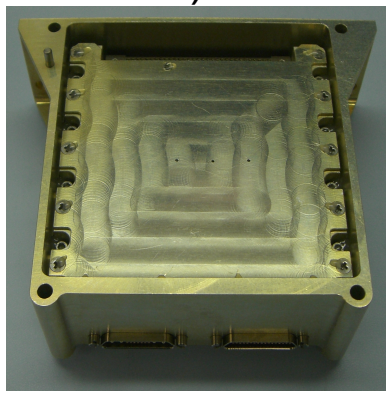
TOP

BOTTOM

Power Slice (Two Cards)



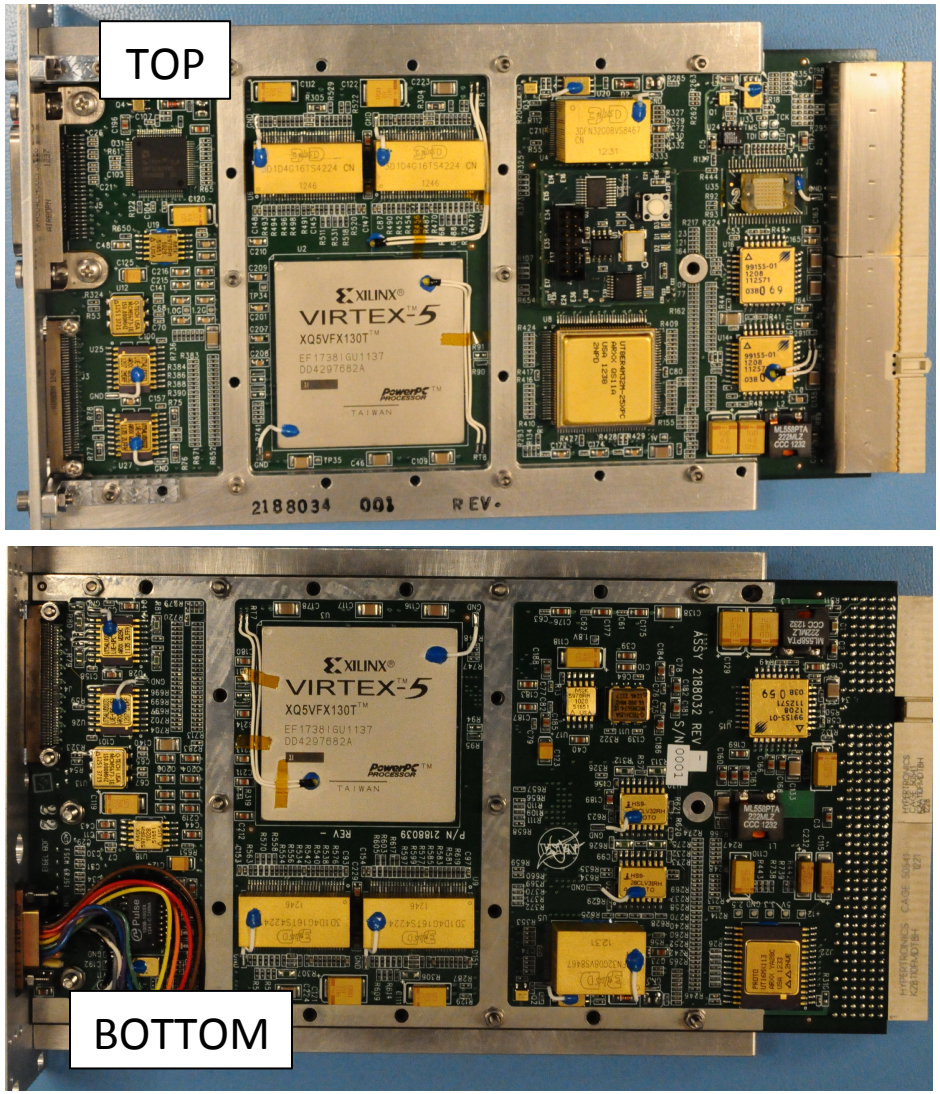
Digital Control



LVPC

SpaceCube v2.0 Flight System

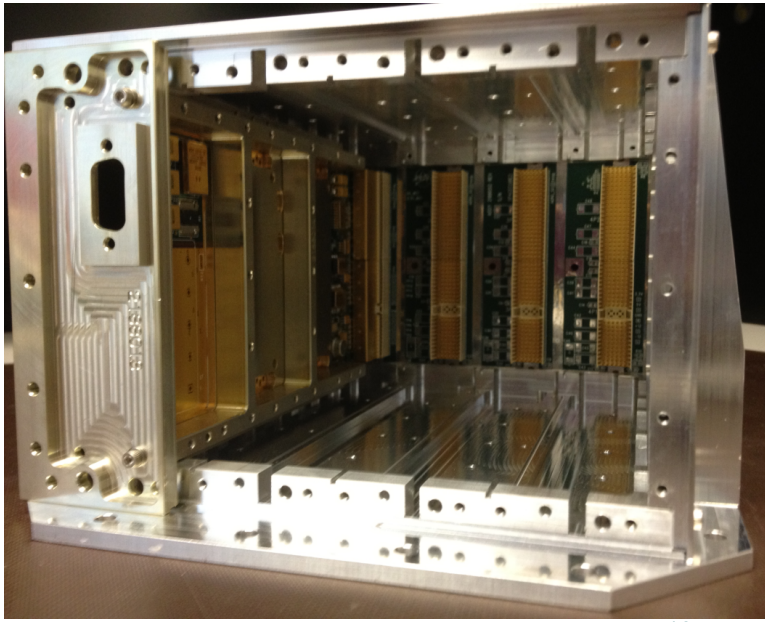
Processor Card



Highlights

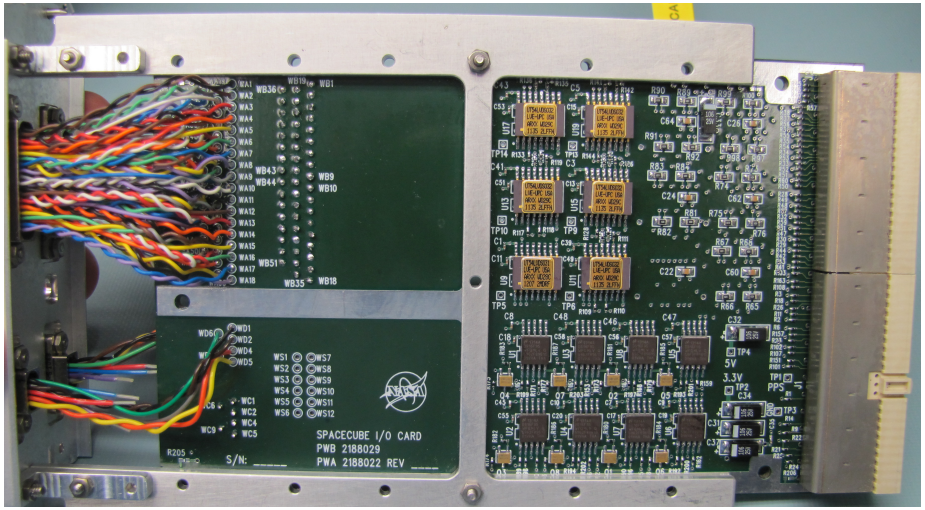
- Meets IPC 6012B Class 3/A Spec
- Commercial or Flight FPGAs
- Supporting 3 Applications
- Mission-Unique Interface Cards

Chassis 5” x 7” x 9”

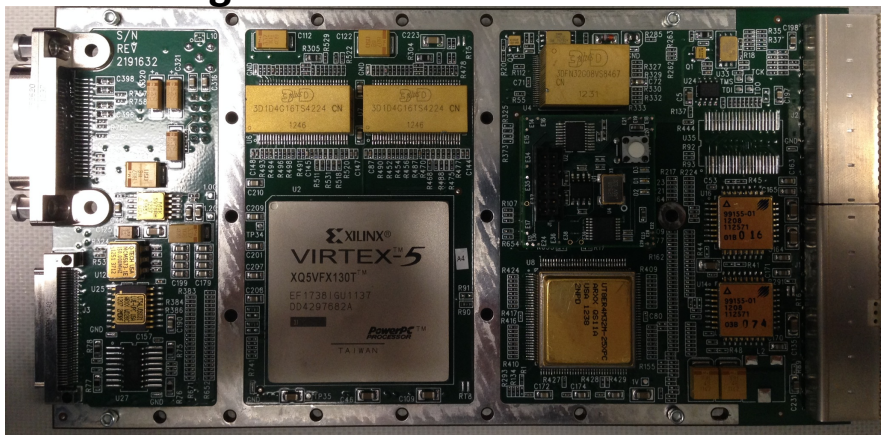


SpaceCube v2.0 I/O Cards

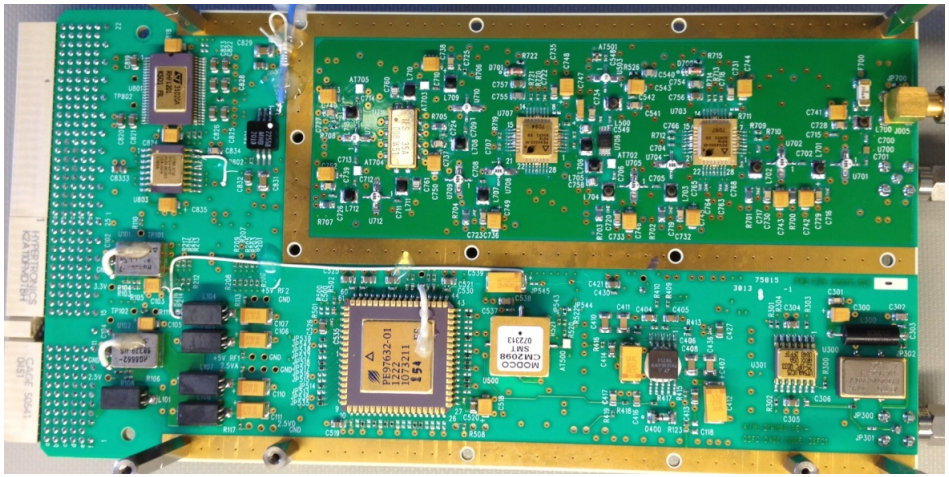
Video/Spacecraft Interface Card



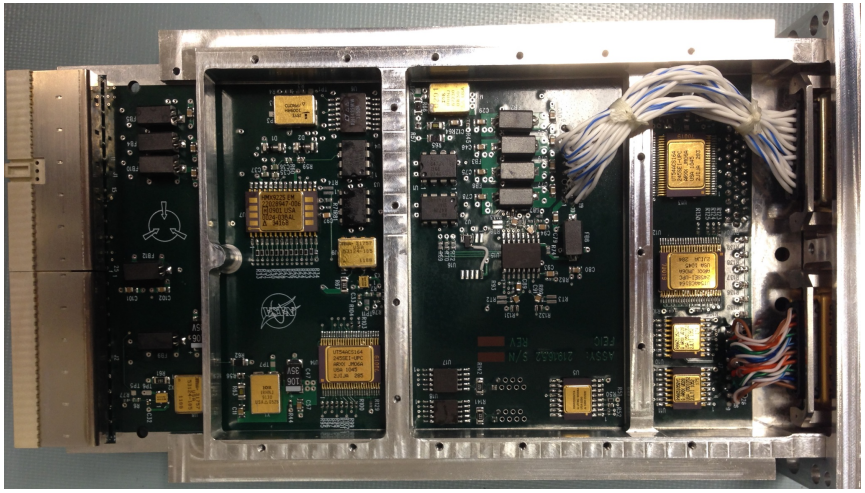
LIDAR Digitizer



GPS RF Front-End Interface Card

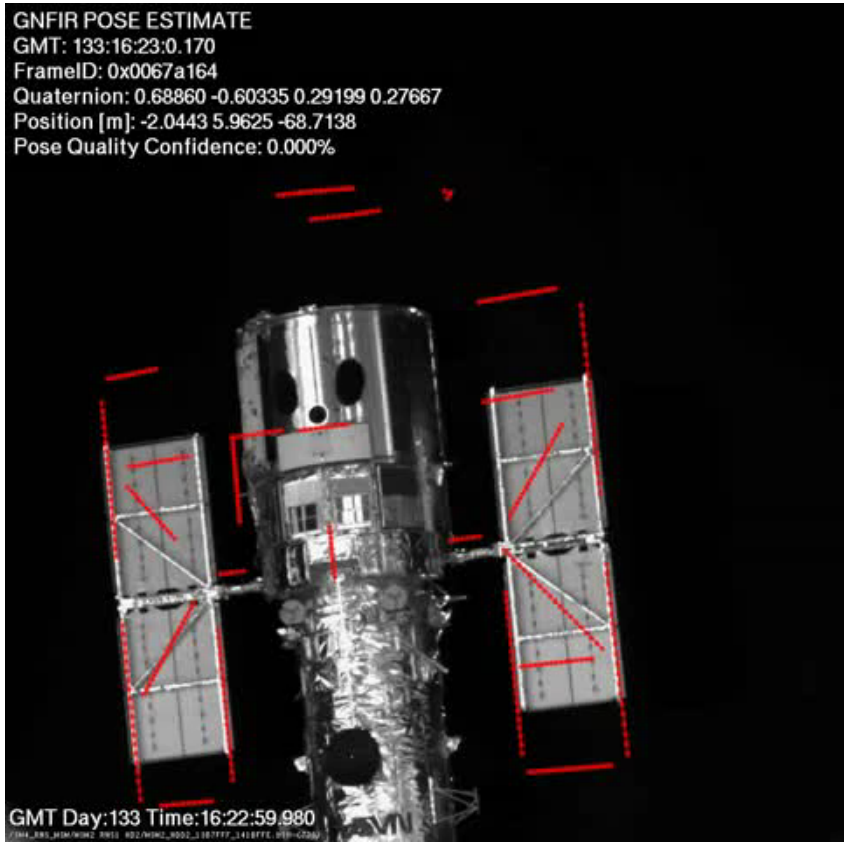


LIDAR Front-End Interface Card

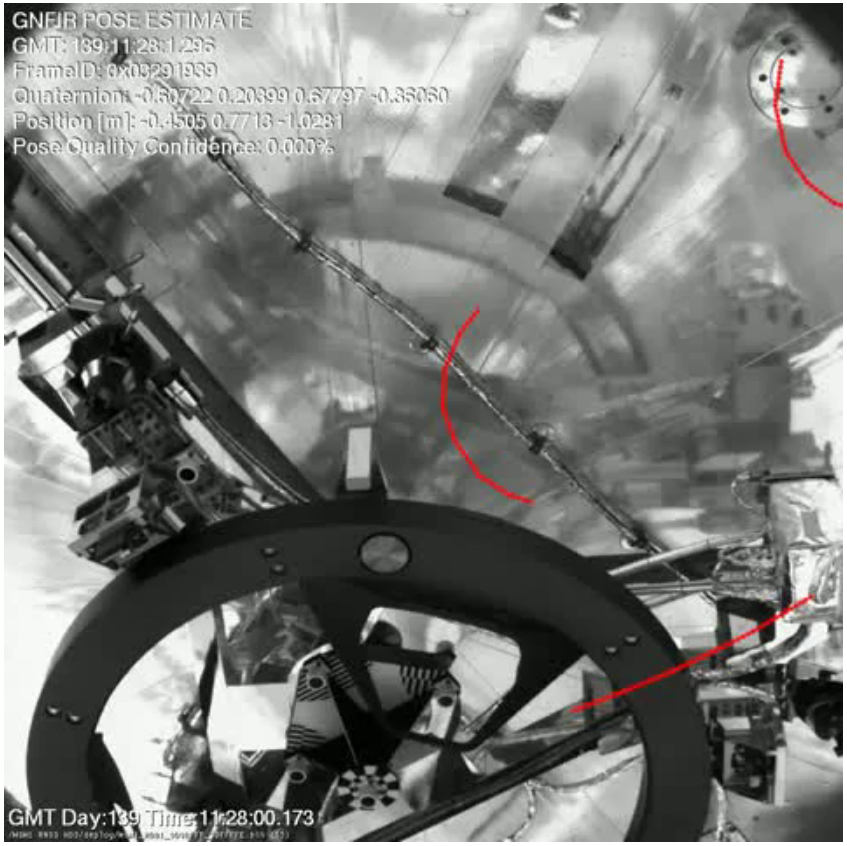


On-Board Image Processing

→ Successfully tracked Hubble position and orientation in real-time operations
→ FPGA Algorithm Acceleration was required to meet 3Hz loop requirement



Rendezvous



Deploy (Docking Ring)

→ Typical space flight processors are 25-100x too slow for this application

RNS Implementation: SpaceCube vs RAD750

25 RAD750 6U Processor Cards

=

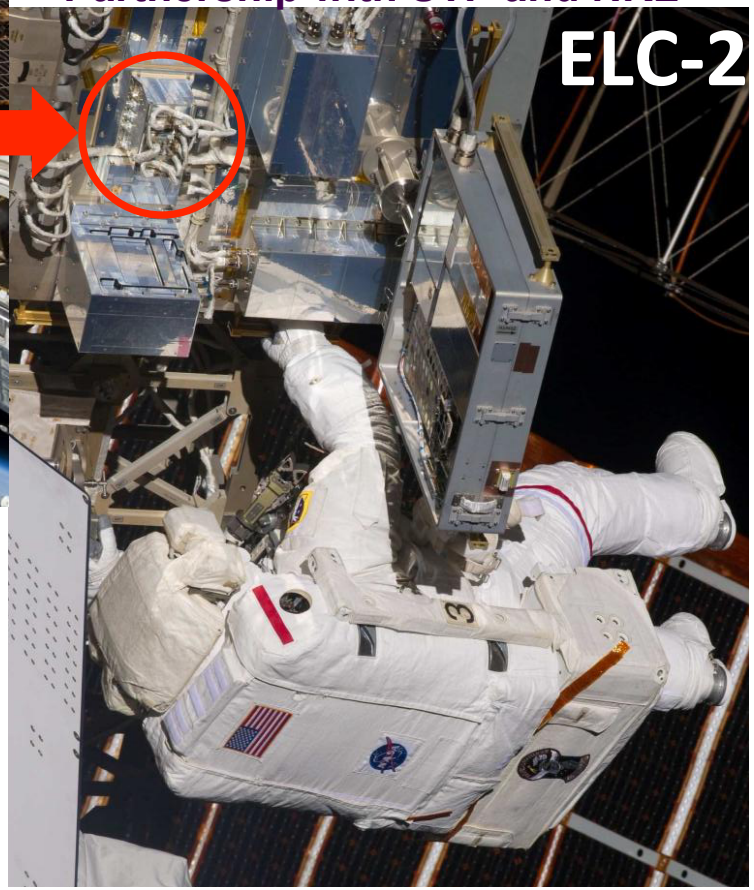
1 SpaceCube Processor Card

Power	600W
Weight	100-lbs
Volume	48.6 cu-ft

Power	37W
Weight	7.5-lbs
Volume	1.2 cu-ft

SpaceCube Upset Mitigation

- Software based Upset Mitigation
- Autonomous Fault Recovery
- Autonomous Landing Application
- Partnership with STP and NRL

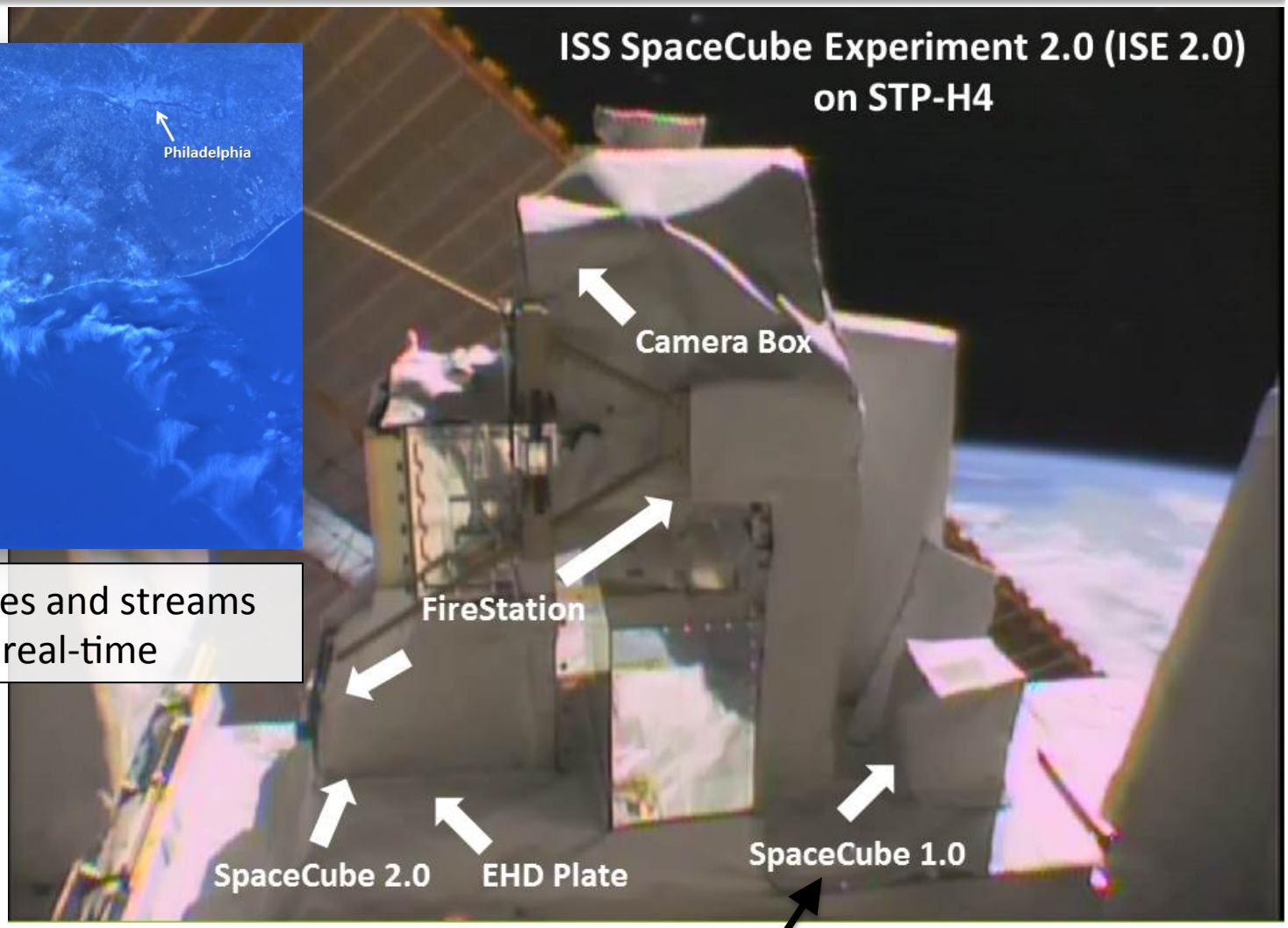


Years on Orbit	**4.5**
SEU Rates	**0.1 SEU/FPGA/Day**

→ On-Orbit Reconfiguration of FPGA and Software

STP-H4 Operational on ISS

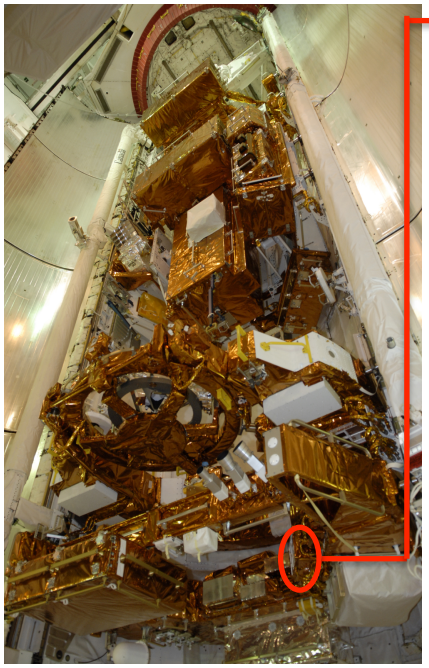
SpaceCube processes and streams HD images in real-time



SpaceCube v1.0 providing data interface for 6 DoD experiments

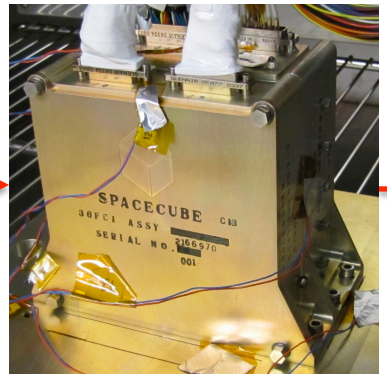
Benefits of a Reconfigurable System

RNS Hardware

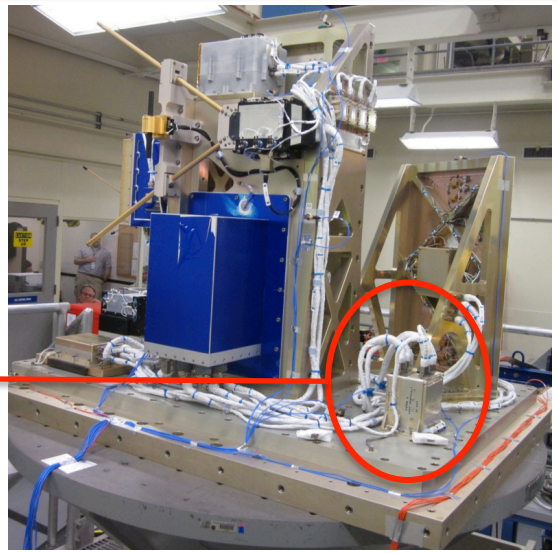


Reconfigure FPGA
Update Software

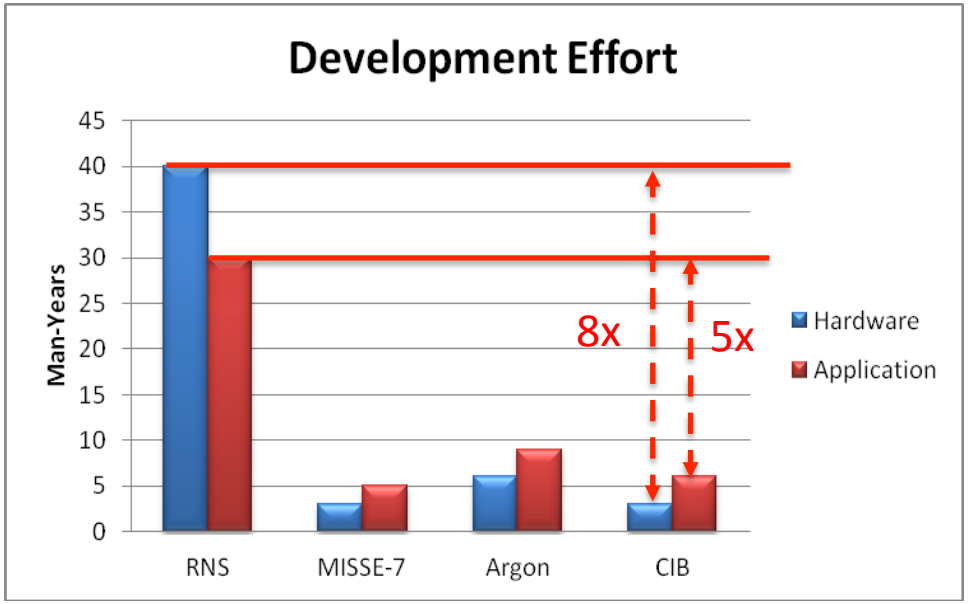
Test



Deliver
CIB to
STP-H4



STP-H4

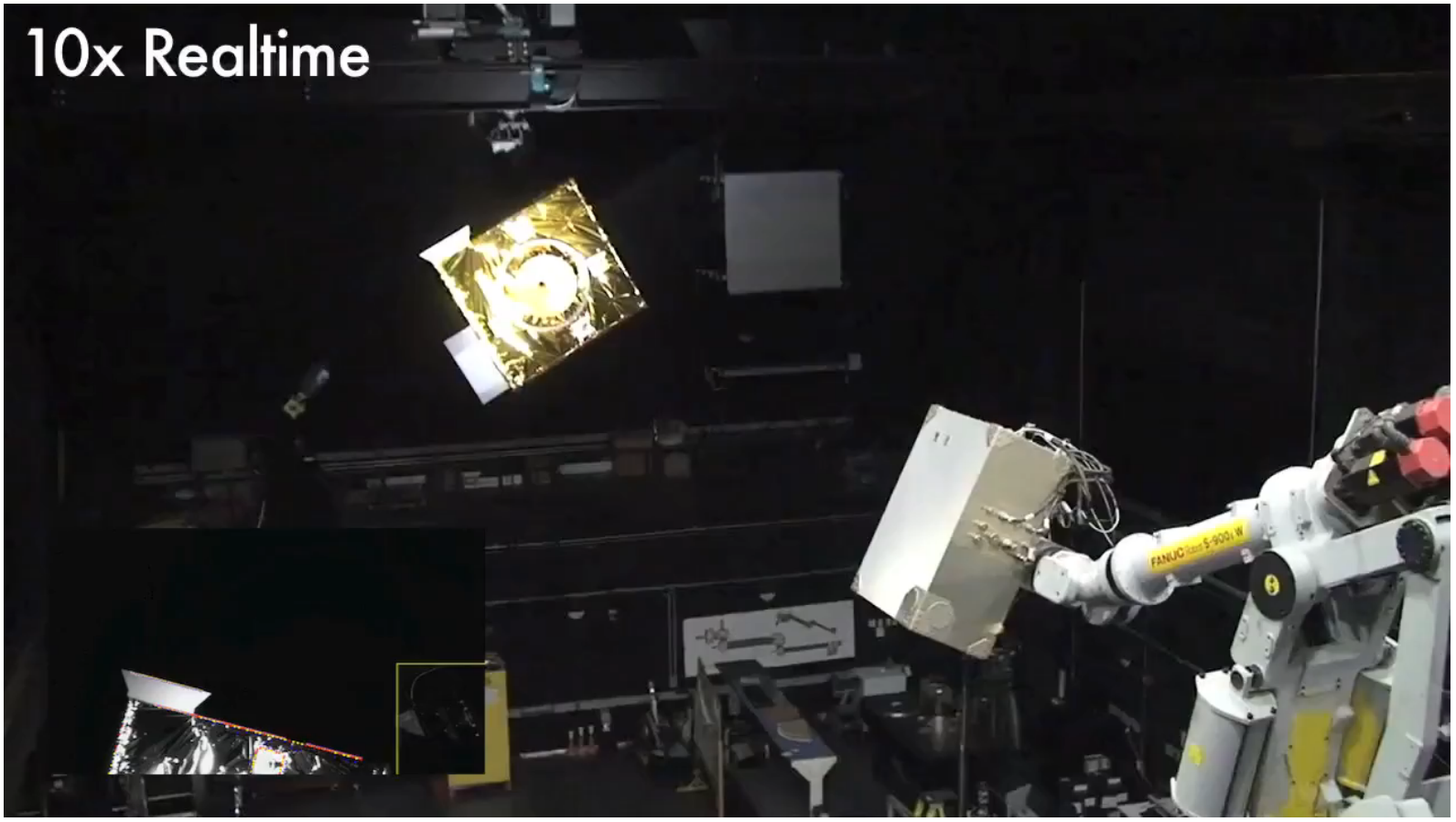


COST
SAVINGS
$10M

Enabling Satellite Servicing

"Satellite Servicing is dependent on Autonomous Rendezvous and Autonomous Capture for a non-cooperative client. This autonomy hinges on machine vision algorithms processing real-time high data rates. SpaceCube's ability to handle these heavy processing loads in a radiation fault-tolerant manner is a critical enabler for satellite servicing."

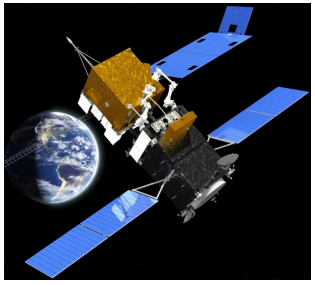
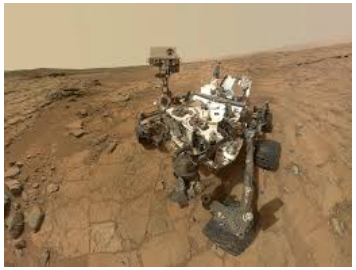
-- Frank Cepollina, Director of Satellite Servicing Capabilities Office



Cross-Cutting Technology

Mission-Enabling Science Algorithms & Applications

- Real-time Wavefront Sensing and Control
- On-Board Data Volume Reduction
- Real-time Image Processing
- Autonomous Operations
- On-Board Product Generation
- Real-time Event / Feature Detection
- Real-time "Situational Awareness"
- Intelligent Data Compression
- Real-time Calibration / Correction
- On-Board Classification
- Inter-platform Collaboration
- Rover Traction Control
- Entry, Descent and Landing (EDL)

Summary

SpaceCube:

- Closes the gap with commercial processors
- Cross-Cutting Technology
- Small → Innovative back-to-back architecture
- Meets NASA's highest standards for board design
- Reconfigurable
  - Reduced Cost and Schedule
  - On-orbit adaptation to new mission requirements
- 1 Patent, 8 pending
- The most powerful data processor for space

"SpaceCube represents an outstanding technical achievement for NASA. Not only is it the most powerful computing system available for space applications today, its reconfigurability makes it a workhorse easily tailored to support virtually any mission. As a NASA flagship processor for the future, it stands to reap significant savings over commercially available options."

-- Jose Florez, Former GSFC Electrical Engineering Division Chief Engineer

QUESTIONS?

"*SpaceCube represents a leap forward in scalable high-performance computing in space, and demonstrates the modularity that is required for us to extend our reach into the solar system.*"

-- John M Grunsfeld, Associate Administrator for Science/Astronaut

"*The SpaceCube has been a key enabler to the DoD Space Test Program's Multi-experiment platforms that fly on the International Space Station. The SpaceCube provides a robust C&DH interface that is adaptable, repeatable, and responsive to our streamlined payload development process. The 'can-do' support we get from the GSFC SpaceCube team and their SpaceCube hardware is key to our ability to deliver our payloads on-time, on-budget, with solid on-orbit performance.*"

-- Craig Lamb, Deputy Director, DoD Human Spaceflight Payloads

ESTO Support

"*As far as SpaceCube's value to ESTO I would emphasize the anticipated role that on-board processing will play in the measurement strategy for our climate missions. In particular I would mention Tier-II missions such as HysplRI, ACE, ASCENDS, and GEOCAPE, but in the longer term as well PATH, LIST, and GACM have requirements for on-board processing that can't be satisfied today*."

-- Michael Seablom, Program Manager, Advanced Information Systems Technology

"*ESTO invests in ever more capable science instruments which typically generate higher data volumes. It is both cost-prohibitive and sometimes even physically to downlink all of this data. Having a technology like the SpaceCube enables scientists to move some elements of the ground data processing on-board. The SpaceCube also allows for "quick-look" science products to be sent to the ground to modify future observing scenarios to increase the value of the mission*."

-- Michael Pasciuto, Program Manager, Earth Science Technology Office

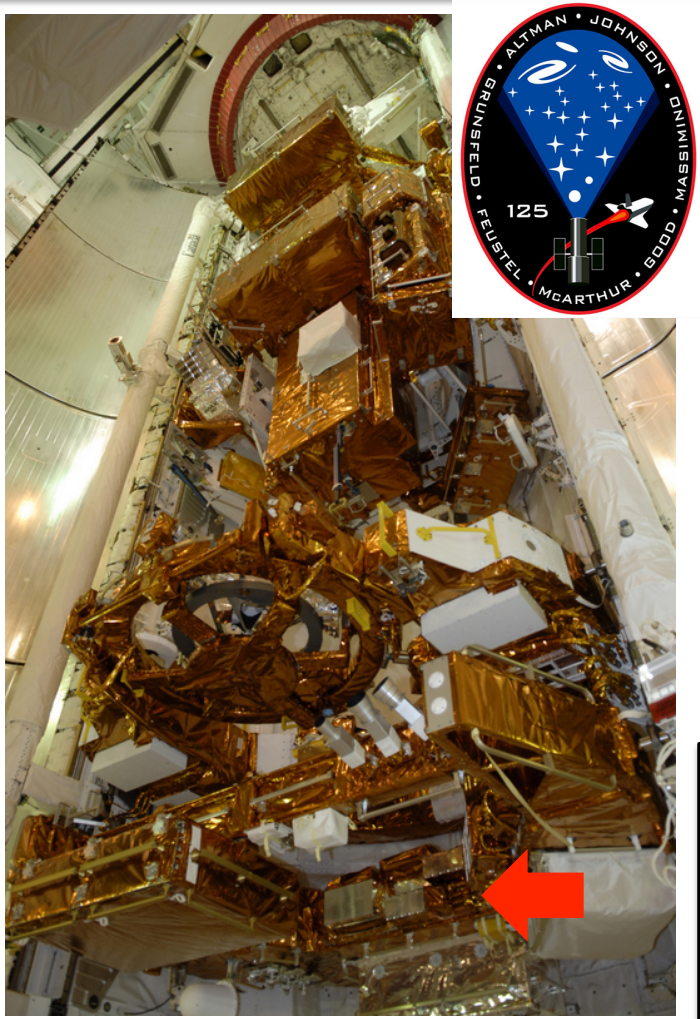
ESTO
Earth Science Technology Office

BACKUP

"SpaceCube is the most advanced high performance computing system we have for space."

-- JPL Technologist

RNS Payload on HST-SM4, STS-125



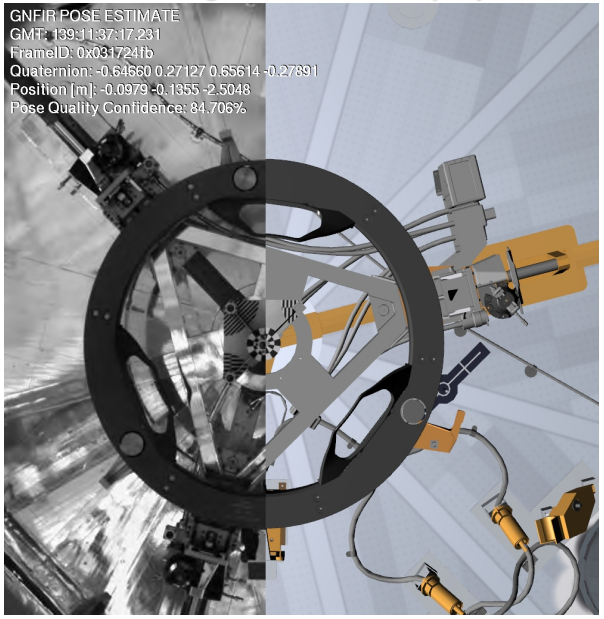
STS-125 Payload Bay

Long Range Camera on Rendezvous

Flight Image

RNS Tracking Solution

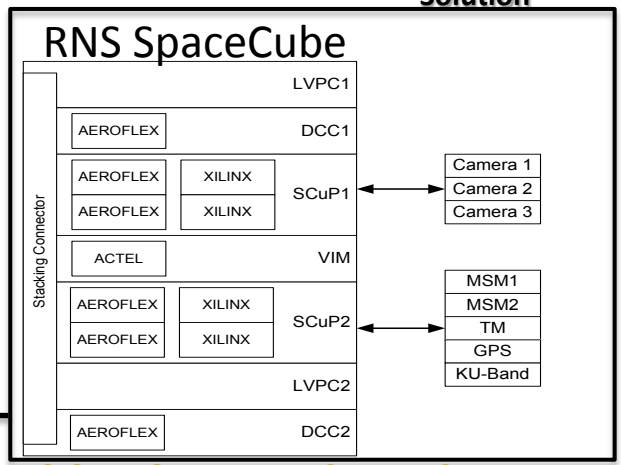
Short Range Camera on Deploy



Flight Image

RNS Tracking Solution

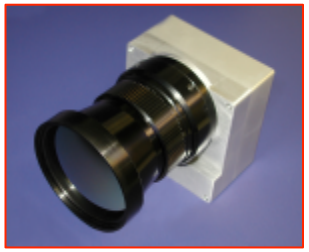
RNS SpaceCube



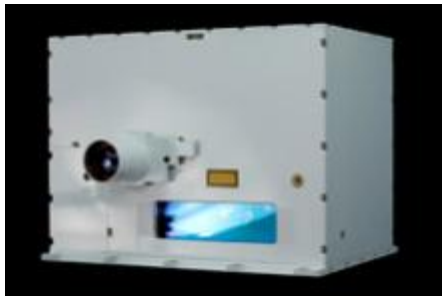
RNS System: 28 FPGAs

Compressed Image from HST Release

Argon AR&D Test Payload



IR Camera

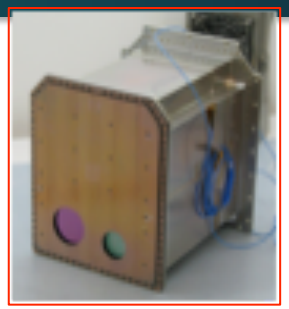


Neptec TriDAR

MDA RNS Cameras And Baffles

SpaceCube (EDU)

Ecliptic/Sony Situational Awareness Camera

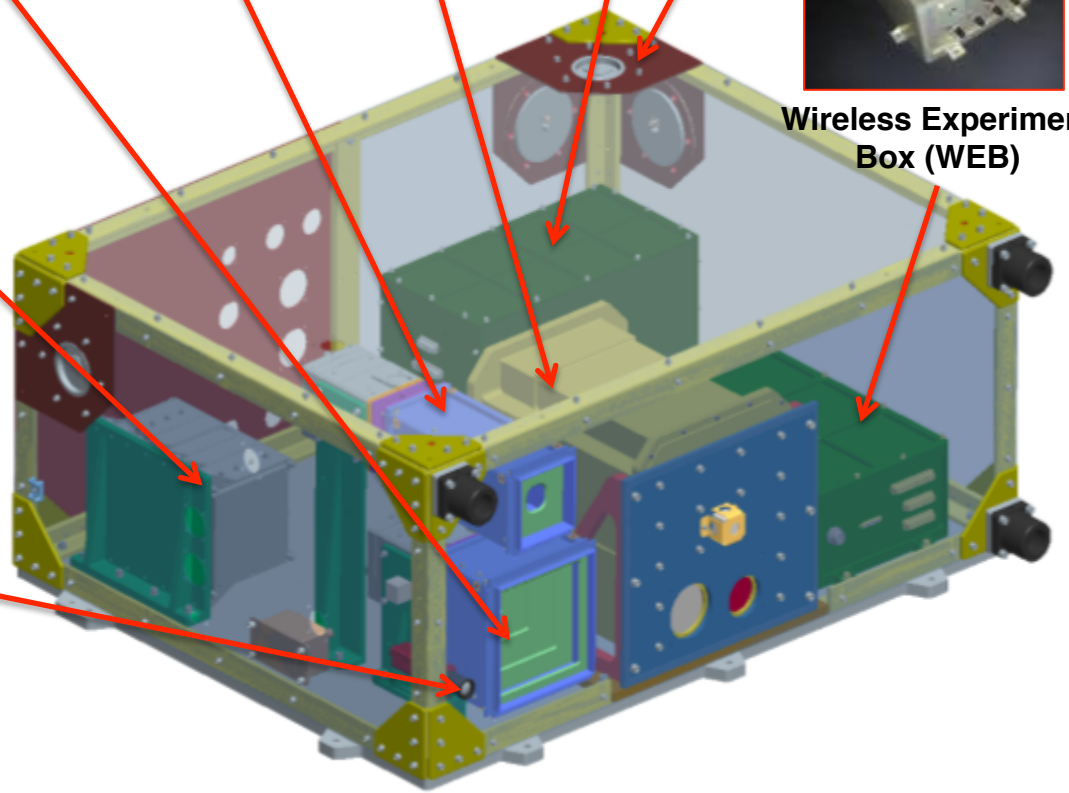


Ball VNS

Power Control Unit (PCU)

Wireless Patch Antennas (x4)

Wireless Experiment Box (WEB)



Estimated Mass:
140 lb

Rough Size:
25”x32”x14”

E DATA PROCESS

ISS SpaceCube Experiment 2.0

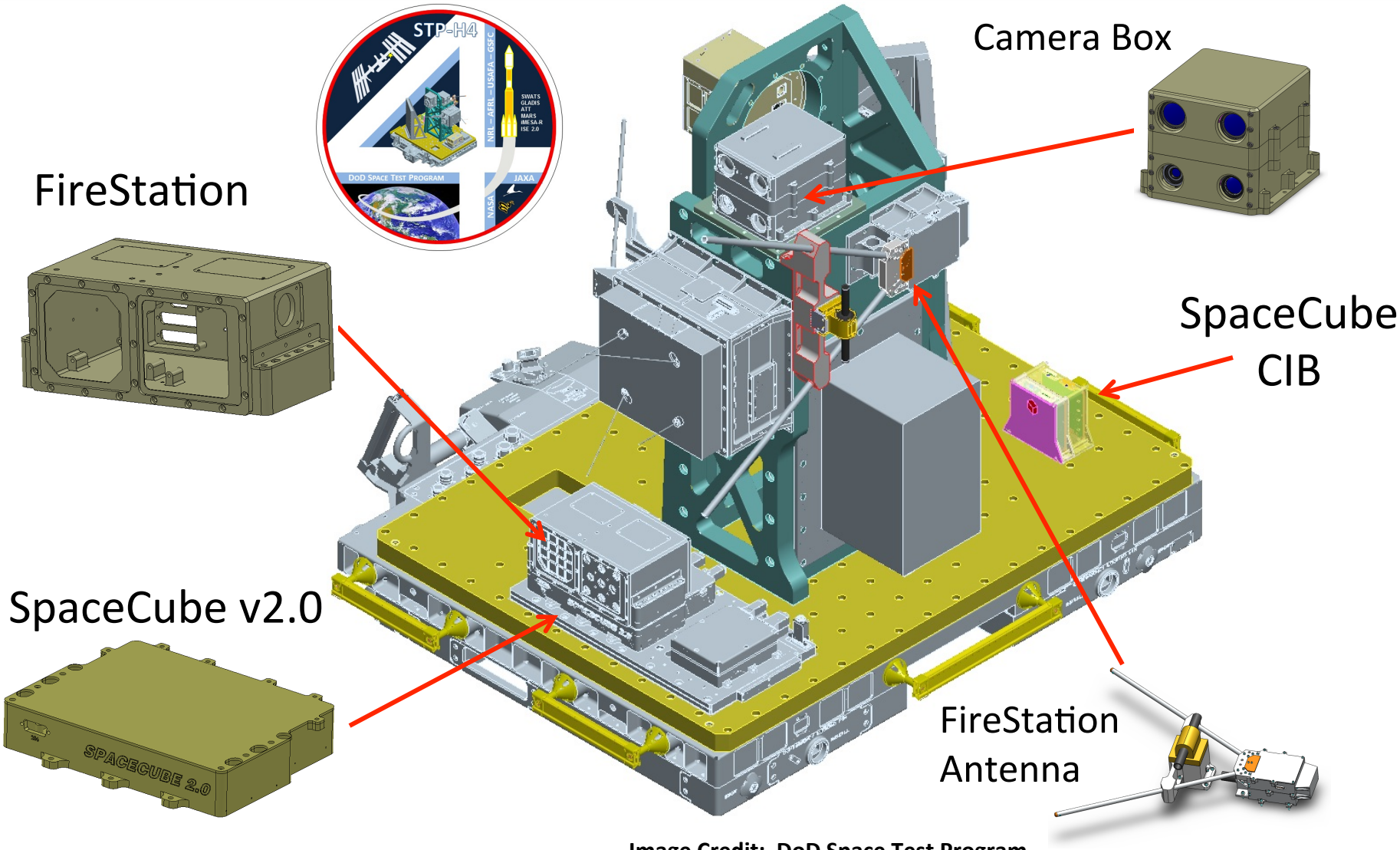
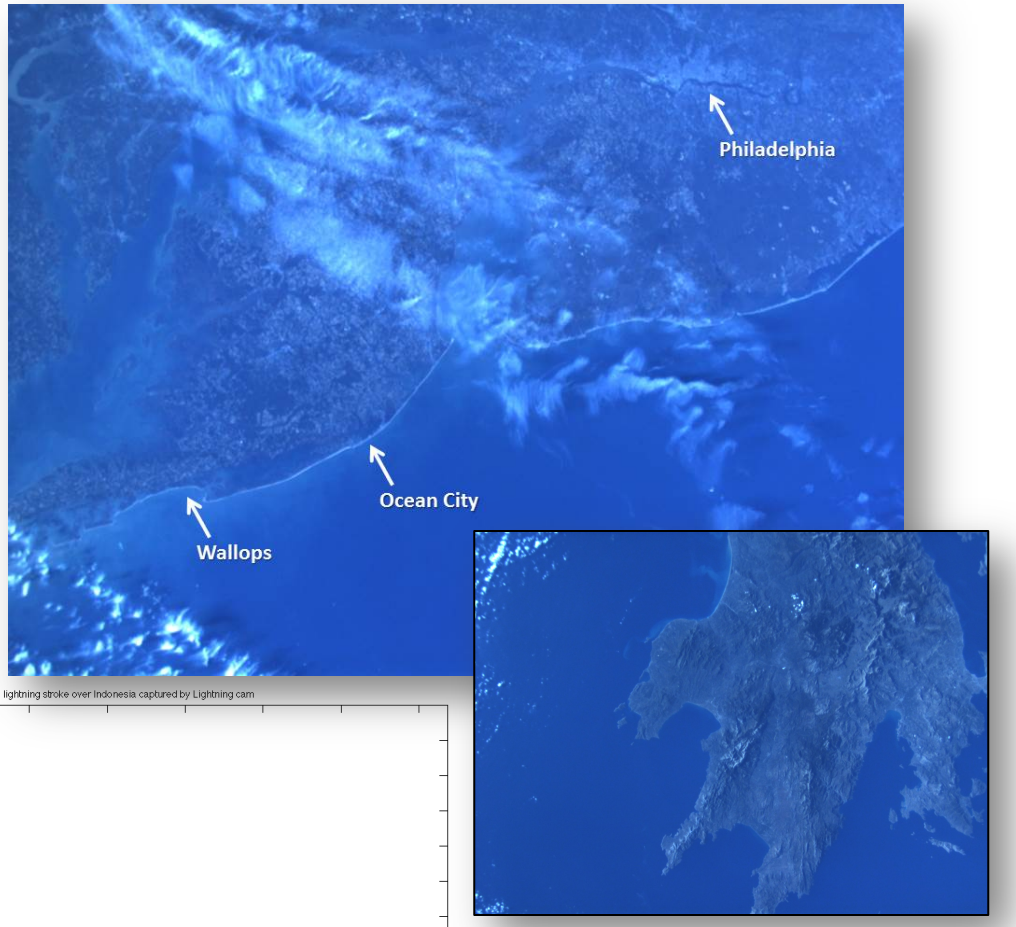


Image Credit: DoD Space Test Program

ISE2.0 Results

Operations
- GSFC Command Center
- August 2013 - Present

HD Images Received: 200,000+

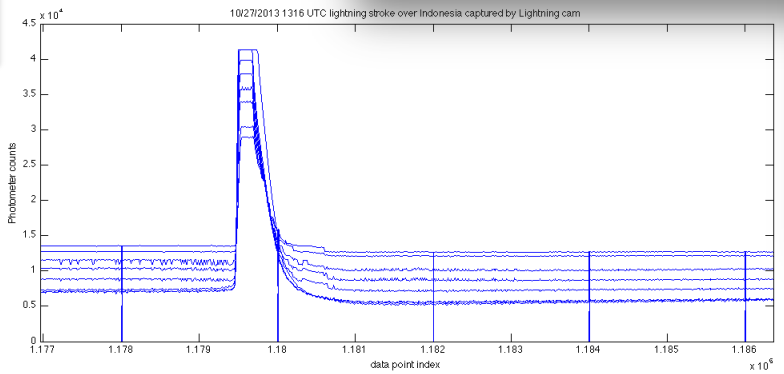


Radiation

FPGA	SEUs
1	23
2	21
3	30

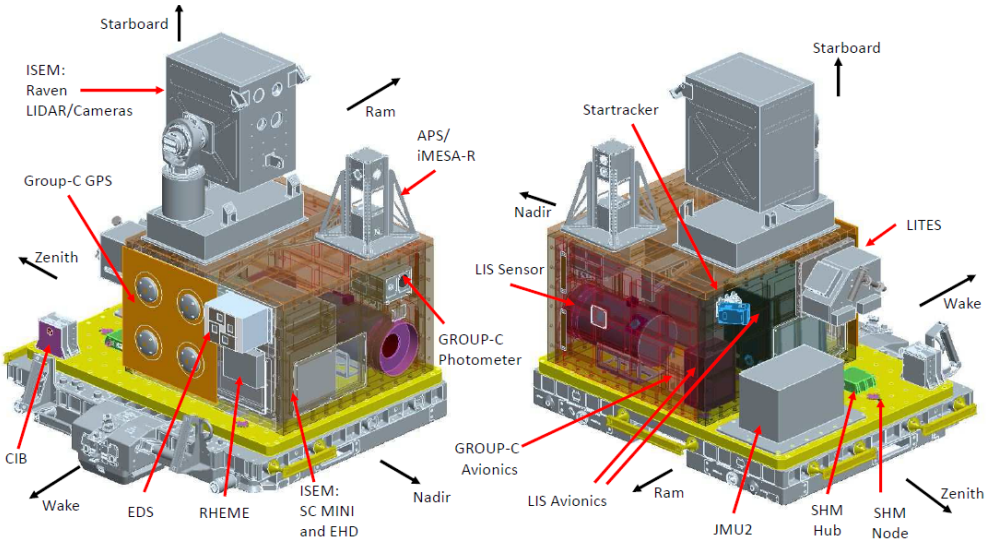
~1 SEU/FPGA/Week
FPGA Resets: 3

FireStation Instrument Data Processing



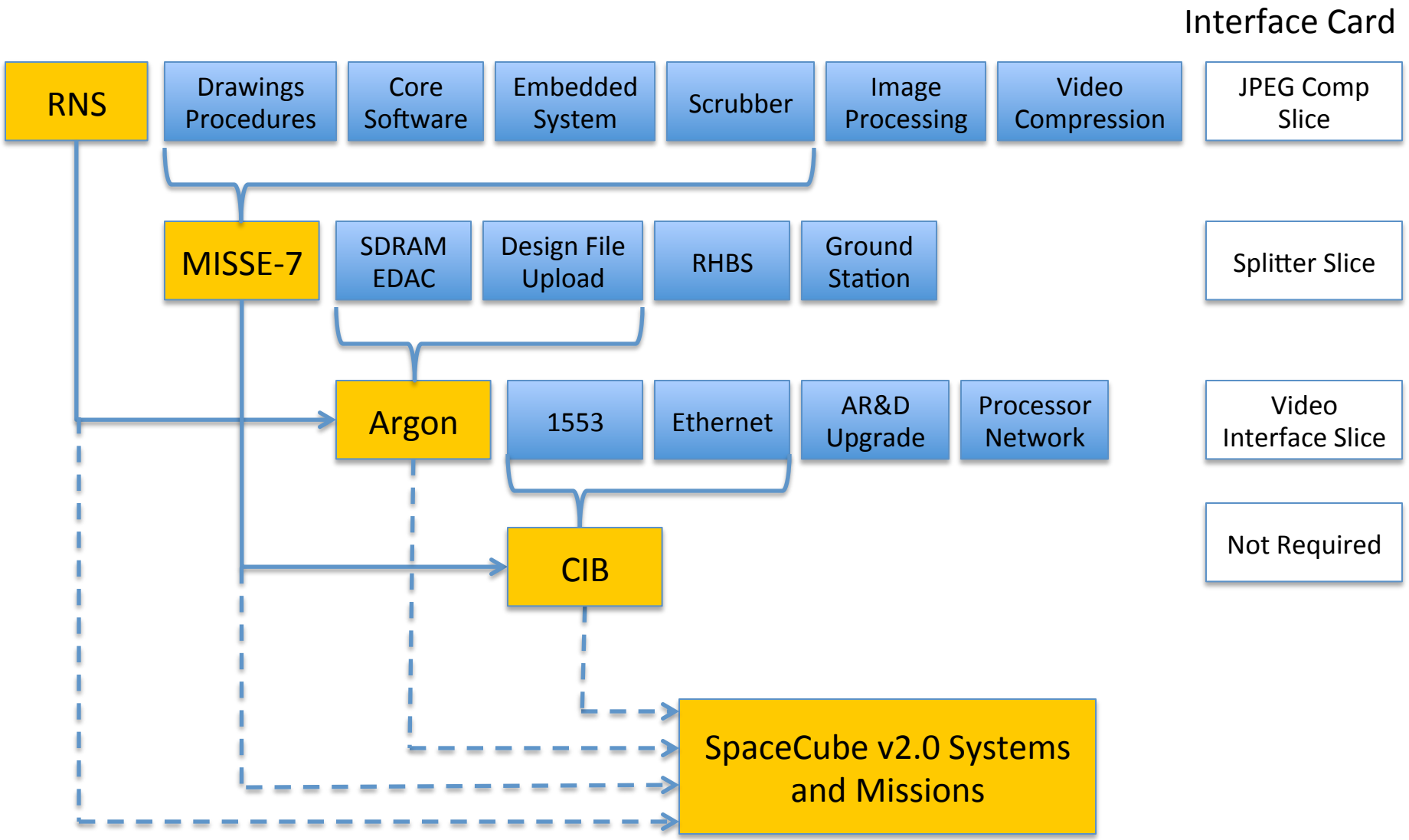
SpaceCube™ Mini

- Features a Xilinx Virtex-5 and a Rad-Hard Aeroflex FPGA
- High Performance, high reliability Space Processor
- CubeSat Form Factor
- Low Mass, Low Power



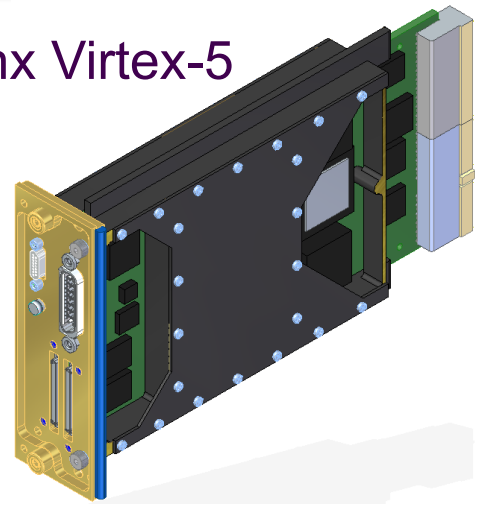
- Avionics for ISEM ISS Experiment on STP-H5 (2016)
  - Primary Communications Bus for DoD Payloads and CHREC Space Processor
  - Hosting Fabry Perot Spectrometer and EHD Experiment Science Experiment

System Reuse and Reconfiguration

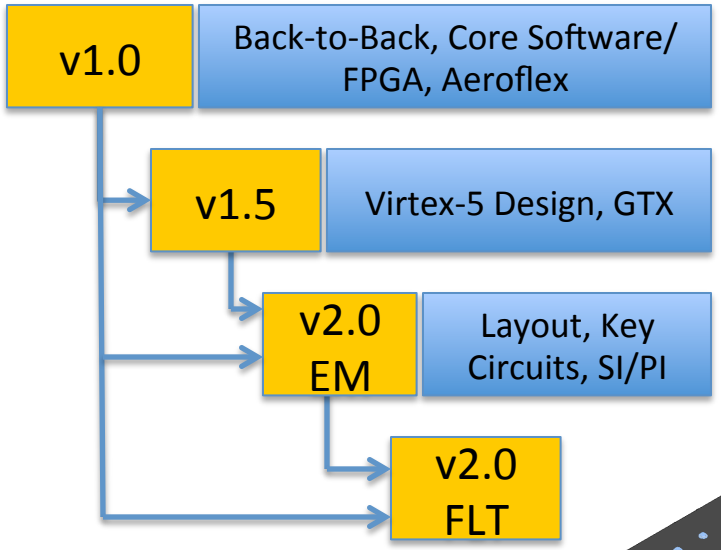


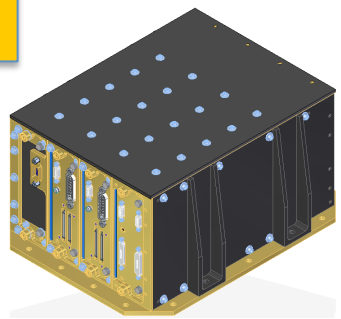
SpaceCube v2.0 System

- Reconfigurable multi-processing platform based on Xilinx Virtex-5 FPGAs
- Extended 3U Compact PCI mechanical standard



Design Heritage



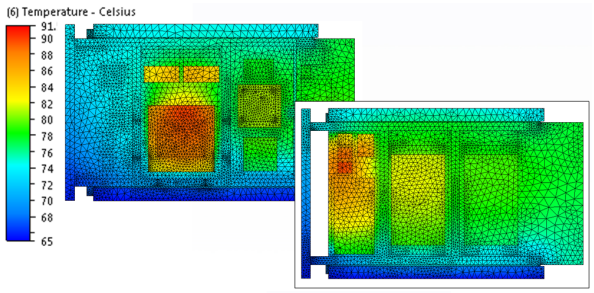


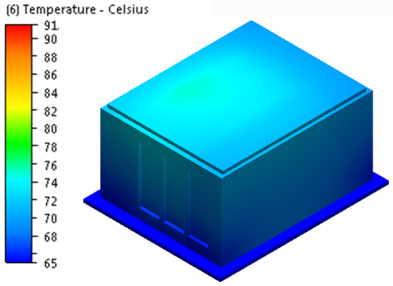
Processor Comparison

Processor	MIPS	Power	MIPS/W
MIL-STD-1750A	3	15W	0.2
RAD6000	35	15W	2.33
ColdFire	60	7W	8
RAD750	250	14W	18
LEON 3FT	89	5.5W	16
LEON3FT Dual-Core	200	10W	20
BRE440 (PowerPC)	266	5W	53
Maxwell SCS750	1200	25W	48
SpaceCube 1.0	3000	7.5W	400
SpaceCube 2.0			
PowerPC (4x)	5000	9W	550
MicroBlaze (4x)	600	8W	75
SpaceCube Mini	2500	5W	400

Design Analysis

Thermal: -40°C to 65°C

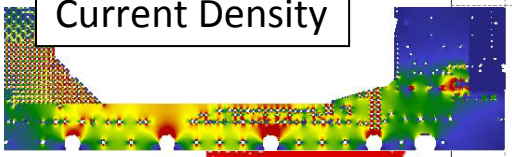


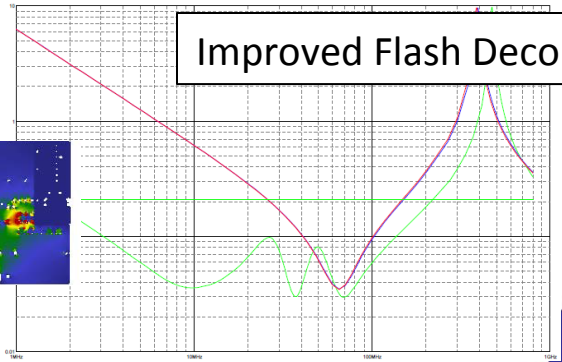


Power Integrity

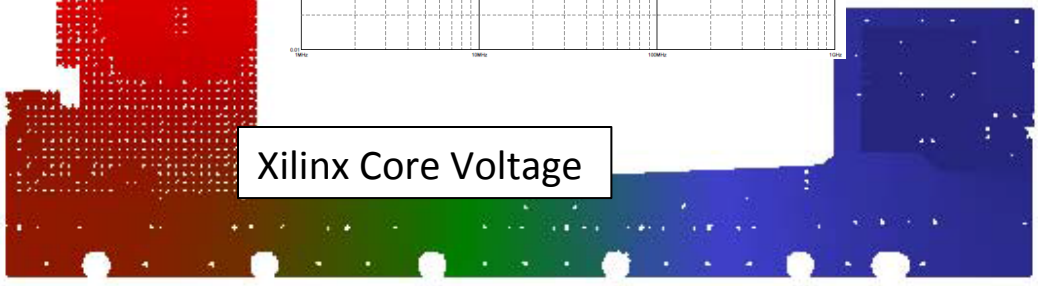
Improved Flash Decoupling

Current Density

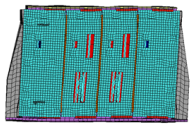




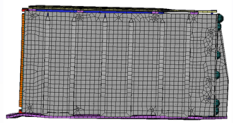
Xilinx Core Voltage



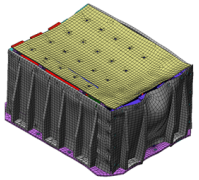
Structural



1st Box Mode (Z) – 790 Hz

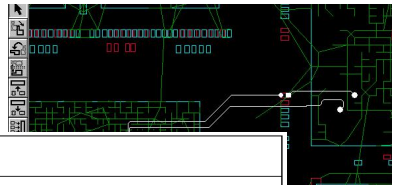


2nd Box Mode (X) – 970 Hz

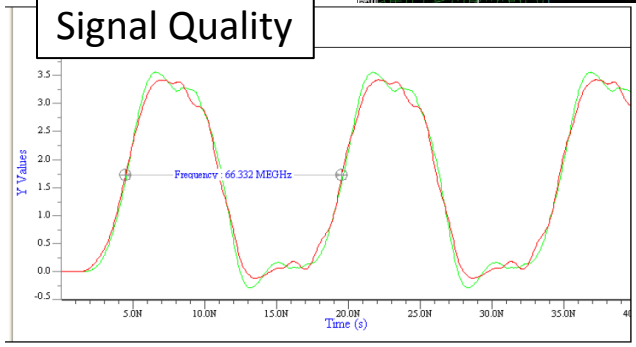


3rd Box Mode (Y) – 1090 Hz

Signal Integrity

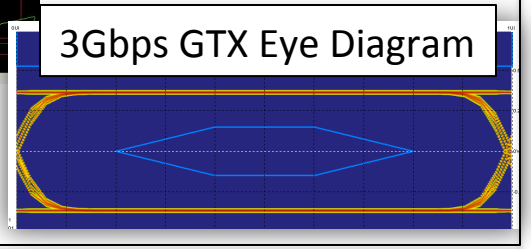


Signal Quality



Crosstalk:
- Critical net < 10mV
- Non Critical net < 70mV

3Gbps GTX Eye Diagram



Acronyms

- ARGON: Autonomous rendezvous and docking ground test
- C&DH: Command and Data Handling
- CHREC: NSF Center for High-Performance Reconfigurable Computing
- CIB: Communication Interface Box
- CPU: Central Processing Unit
- DoD: Department of Defense
- DSP: Digital Signal Processor
- EHD: Electrohydrodynamic
- ELC: ExPRESS logistics carrier
- EMD: Empirical Mode Decomposition
- ESTO: Earth Science Technology Office
- FPGA: Field Programmable Gate Array
- FPU: Floating point unit
- GNFIR: Goddard Natural Feature Image Recognition
- GOES: Geostationary Operational Environmental Satellite
- GPM: Global Precipitation Measurement
- GPS: Global Positioning System
- HD: High Definition
- HHT: Hilbert Huang Transform
- HST: Hubble Space Telescope
- IRAD: Internal Research and Development
- ISE: International Space Station SpaceCube Experiment
- ISEM: International Space Station SpaceCube Experiment Mini
- ISS: International Space Station
- LRO: Lunar Reconnaissance Orbiter
- LVPS: Low Voltage Power Supply
- MB: MegaByte
- MIPS: Million instructions per second
- MISSE7: Materials on International Space Station Experiment 7
- MRO: Mars Reconnaissance Orbiter
- NRL: Naval research lab
- RNS: Relative Navigations Sensors
- SAR: Synthetic Aperture Radar
- SDO: Solar Dynamics Observatory
- SEU: Single Event Upset
- SSCO: Satellite Servicing Capabilities Office
- STP: Space Test Program
- STP-H4: Space Test Program Houston 4
- TRL: Technology Readiness Level