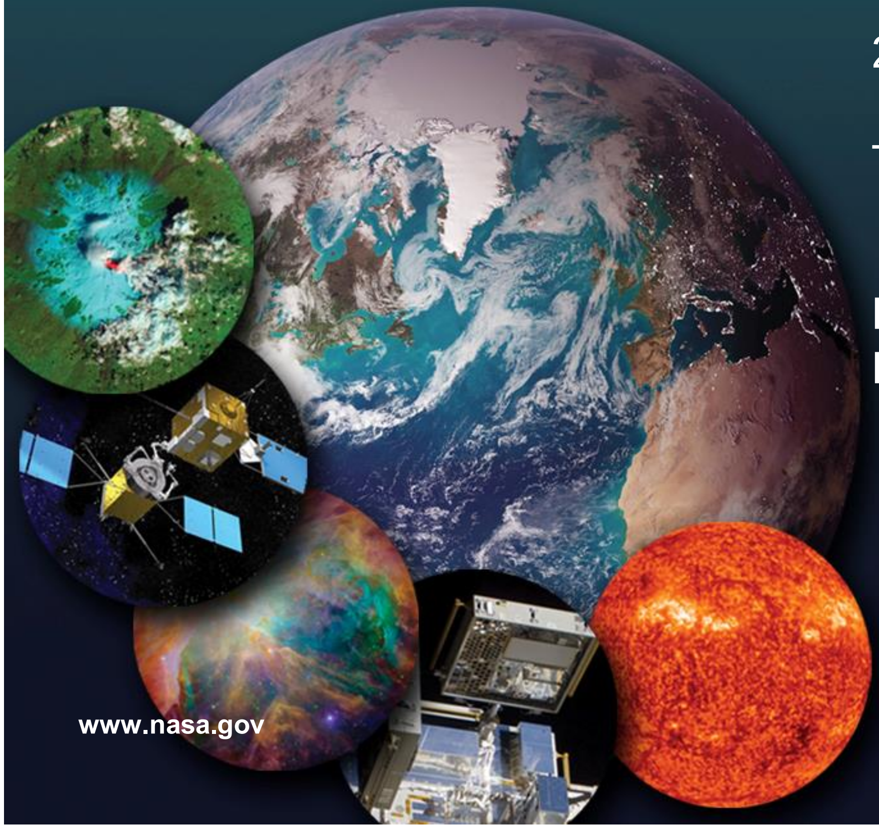
National Aeronautics and Space Administration

Adapting the Reconfigurable SpaceCube Processing System for Multiple Mission Applications



2014 IEEE Aerospace Conference

Track 7.05: Reconfigurable Computing Systems Technologies

Dave Petrick
Embedded Systems Group Leader

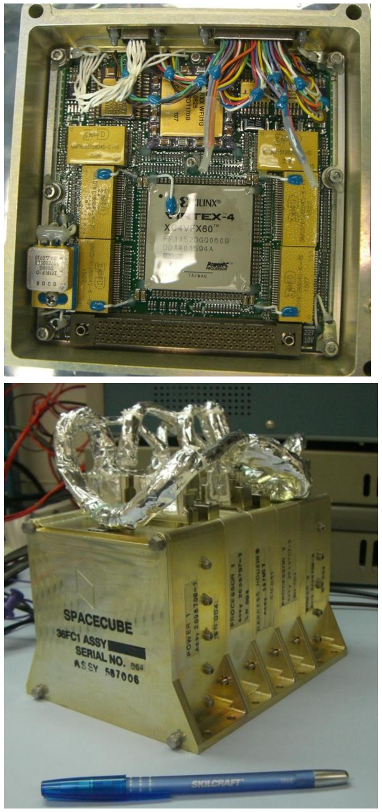
SpaceCube

SCIENCE DATA PROCESSING BRANCH
Code 587 ÅNASA GSFC

www.nasa.gov

SpaceCube Family Overview

v1.0

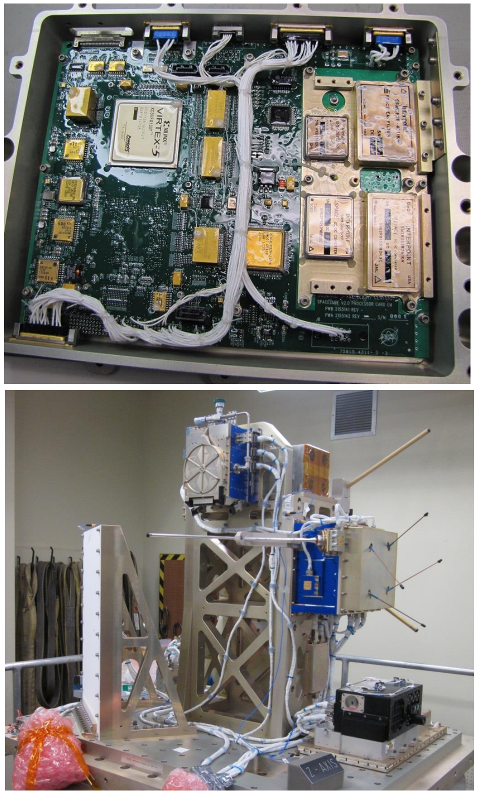


2009 STS-125
2009 MISSE-7
2013 STP-H4
2015 STP-H5

v1.5

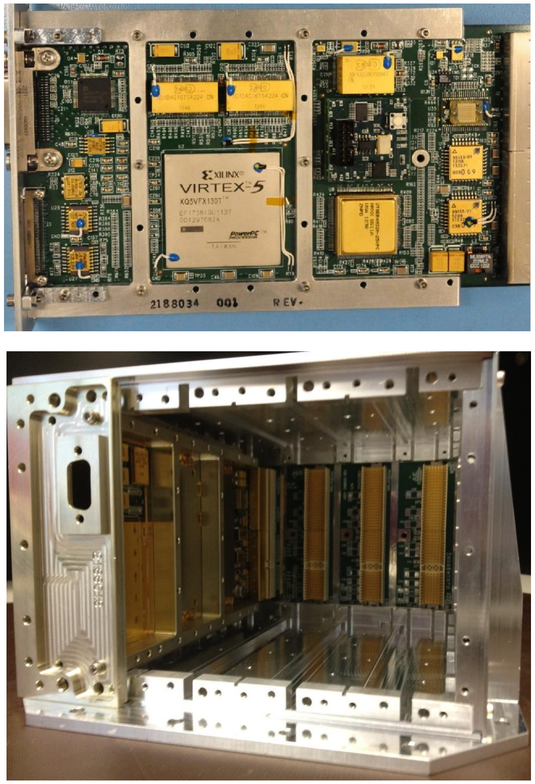
2012 SMART

v2.0-EM



2013 STP-H4
2015 STP-H5

v2.0-FLT



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

The Challenge

The next generation of NASA science missions will require "order of magnitude" improvements in on-board computing power

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**

Our Approach

- The traditional path of developing radiation hardened flight processor will not work … they are always one or two generations behind
- Science data does not need to be 100% perfect, 100% of the time … occasional “blips” are OK, especially if you can collect 100x MORE DATA using radiation tolerant* processing components
- Accept that radiation induced upsets will happen occasionally … and just deal with them
- Target 10x to 100x improvement in “MIPS/watt”

*Radiation tolerant – susceptible to radiation induced upsets (bit flips) but not radiation induced destructive failures (latch-up)

Our Solution

SpaceCube: a high performance reconfigurable science data processor based on Xilinx Virtex FPGAs

- **Hybrid processing … CPU, DSP and FPGA logic**
- **Integrated “radiation upset mitigation” techniques**
- **SpaceCube “core software” infrastructure**
- **Small “critical function” manager/watchdog**
- **Standard interfaces**

Note: SpaceCube 2.0 and SpaceCube Mini can be populated with either commercial Virtex 5 FX130T parts or radiation hardened Virtex 5 QV parts … offering system developers the option of trading computing performance for radiation performance

SpaceCube, Target Applications

- Small, light-weight, reconfigurable multi-processor platform for space flight applications demanding extreme processing capabilities
  - Reconfigurable Components: FPGA, Software, Mechanical
  - Promote reuse between applications
- Hybrid Flight Computing: hardware acceleration of algorithms to enable onboard data processing and increased mission capabilities

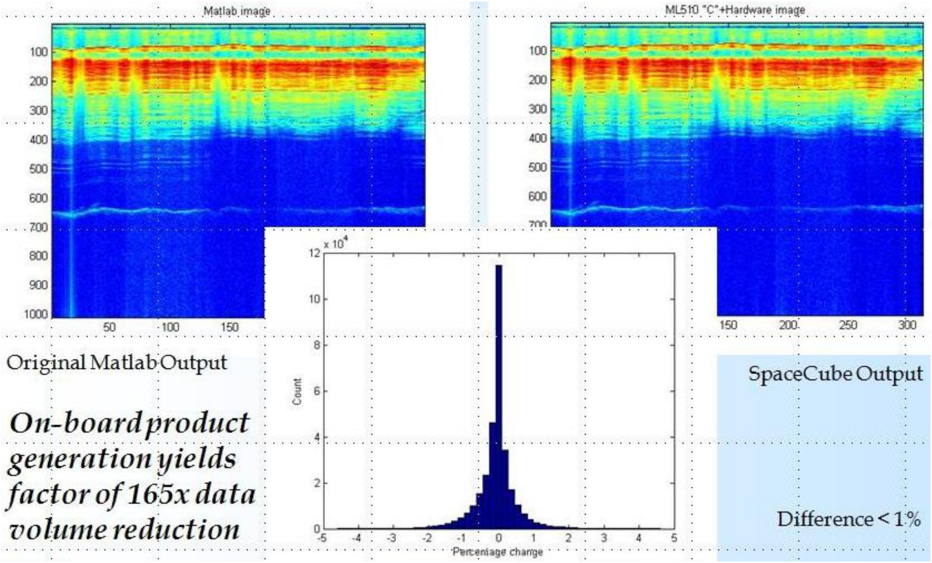
Hardware Algorithm Acceleration

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 GndSys Sun correction	Virtex-1 300E	**6x** vs Xeon Dual-Core (2.4GHz, 3000 MIPS)

Notes:

1) **All functions involve processing large data sets (1MB+)**
2) **All timing includes moving data to/from FPGA**
3) **SpaceCube 2.0 is 4x to 20x more capable than these earlier systems**

On-Board Data Reduction



Original Matlab Output

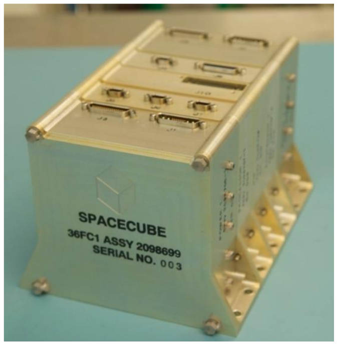
On-board product generation yields factor of 165x data volume reduction

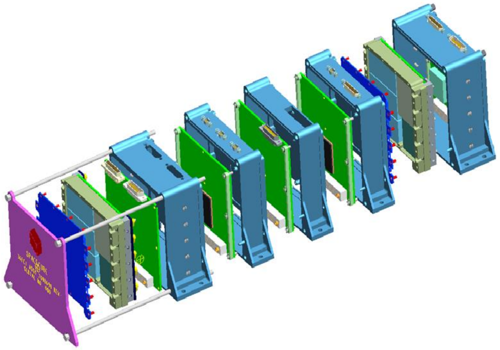
SpaceCube Output

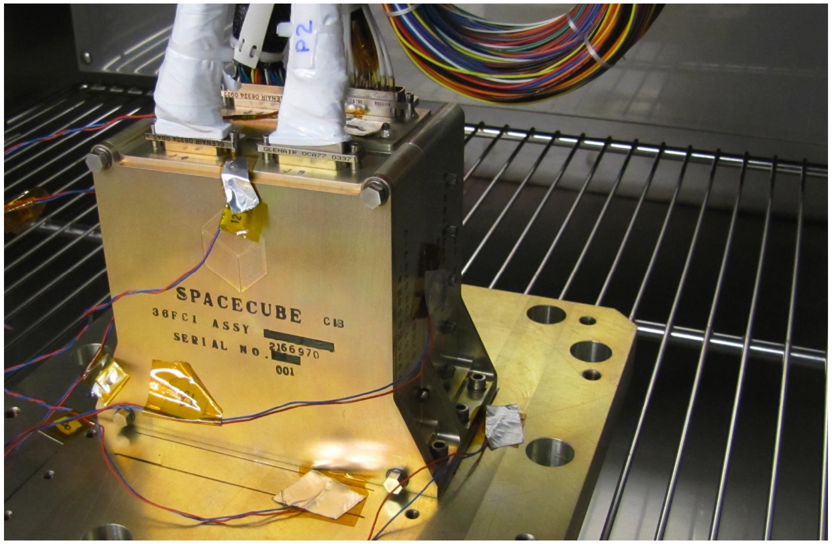
Difference < 1%

SpaceCube v1.0 System

Mechanical Slice Stacking Architecture





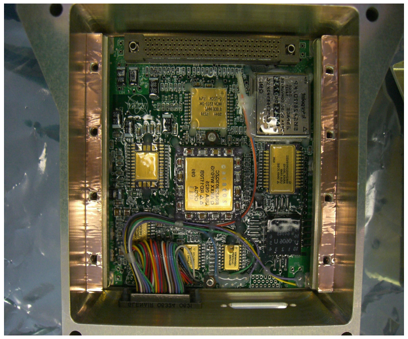


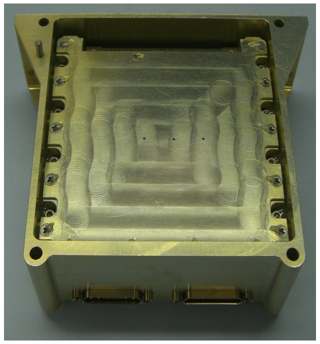
Base Unit Size: 4.5” x 4.3” x 3”
Operating Range: -30C to +55C
Power: 12-16W

Processor Slice, Back-to-Back Architecture

FPGAs: 2x Xilinx V4FX60, 2x Aeroflex UT6325
Memory: 1GB SDRAM, 1GB NAND Flash, PROM/SRAM
External I/O: 20ch LVDS/RS422

Power Slice, Two Cards

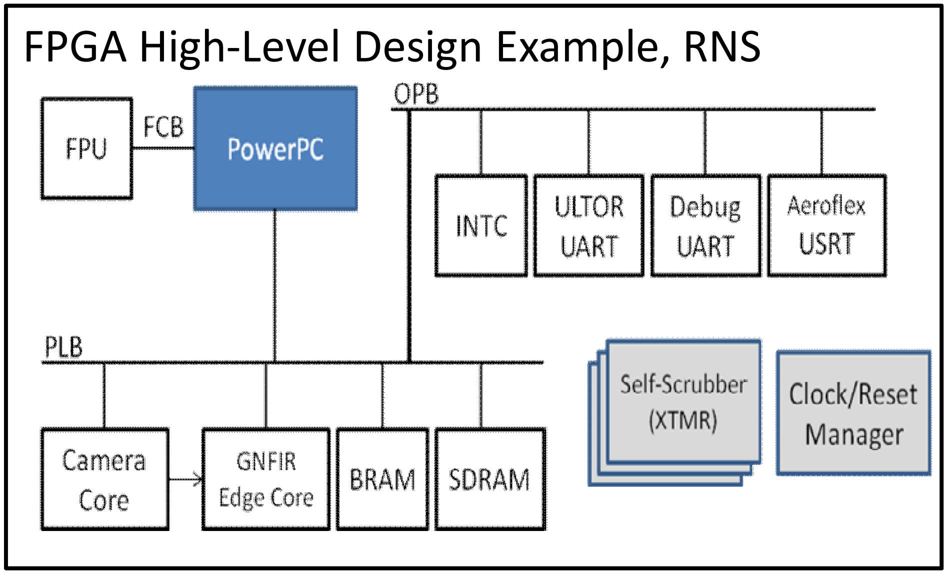




28V Input, 5V, 3.3V, 2.5V, 1.5V, +/-12V Outputs
External I/O: 1553, 10Base-T Ethernet, 4ch RS422

SpaceCube v1.0 Missions

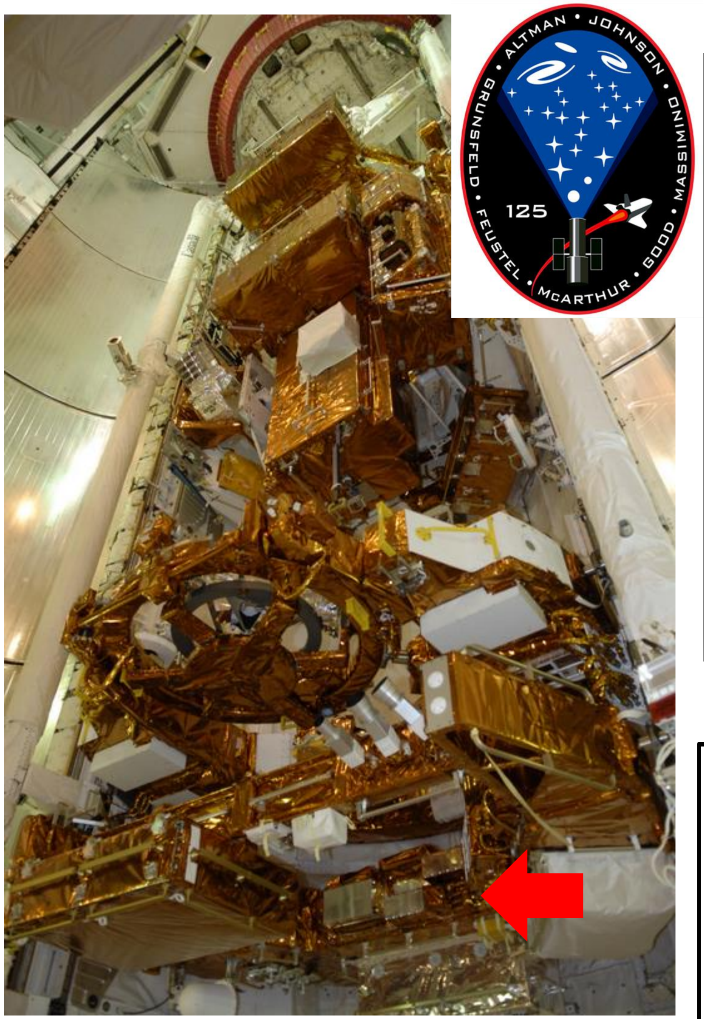
Year	Mission	Application
5/2009	Relative Navigation Sensors STS-125	Real-time image processing/tracking, data compression, shuttle interface
11/2009-Present	MISSE7/8	Radiation Experiment
2010-2011	Argon Robotic Ground Demo	Similar to RNS with additional instruments, upgraded algorithms
8/2013-Present	STP-H4, DoD Delivery	Payload Control, ISS Interface
2015	STP-H5, DoD Delivery	Payload Control, ISS Interface


FPGA High-Level Design Example, RNS

Leveraged Mechanical, Electrical, FPGA Design, and Flight Software on each subsequent project

→ **Reconfigurable System = Reduced $$ and Schedule**

RNS Payload on HST-SM4, STS-125



STS-125 Payload Bay

RNS System: 28 FPGAs

Long Range Camera on Rendezvous

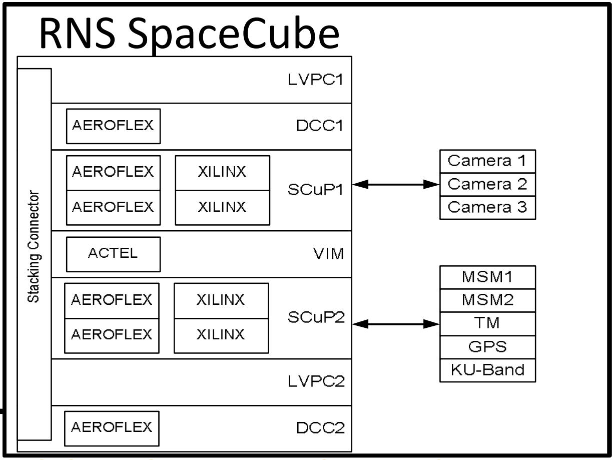
GNFIR POSE ESTIMATE
GMT: 133:16:28:43.757
Frame ID: 0x73F13002
Quaternion: 0.72654, -0.67387, 0.03428, 0.12983
Position (meters): 1.4498, 7.8250, -81.4431
Pose Quality Confidence: 88.235%

Flight Image **RNS Tracking Solution**

Short Range Camera on Deploy

GNFIR POSE ESTIMATE
GMT: 139:11:37:17.231
FrameID: 0x031724fb
Quaternion: -0.64660 0.27127 0.65614 -0.27891
Position [m]: -0.0979 -0.1355 -2.5048
Pose Quality Confidence: 84.706%

Flight Image **RNS Tracking Solution**



RNS SpaceCube

Stacking Connector
LVPC1
AEROFLEX DCC1
AEROFLEX XILINX AEROFLEX XILINX SCuP1
ACTEL VIM
AEROFLEX XILINX AEROFLEX XILINX SCuP2
LVPC2
AEROFLEX DCC2

SCuP1 ↔ Camera 1, Camera 2, Camera 3
SCuP2 ↔ MSM1, MSM2, TM, GPS, KU-Band

Compressed Image from HST Release

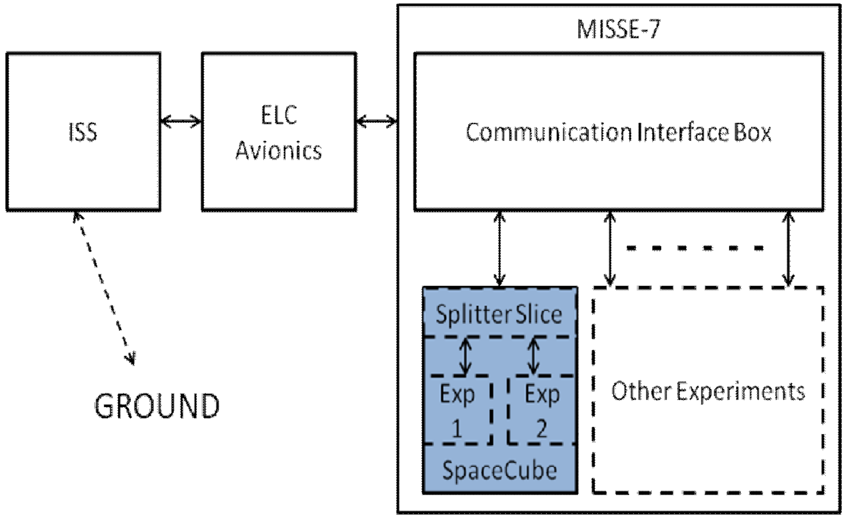
On-Board Image Processing

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

Rendezvous

Deploy

MISSE7/8 SpaceCube



ISS

ELC Avionics

MISSE-7

Communication Interface Box

Splitter Slice

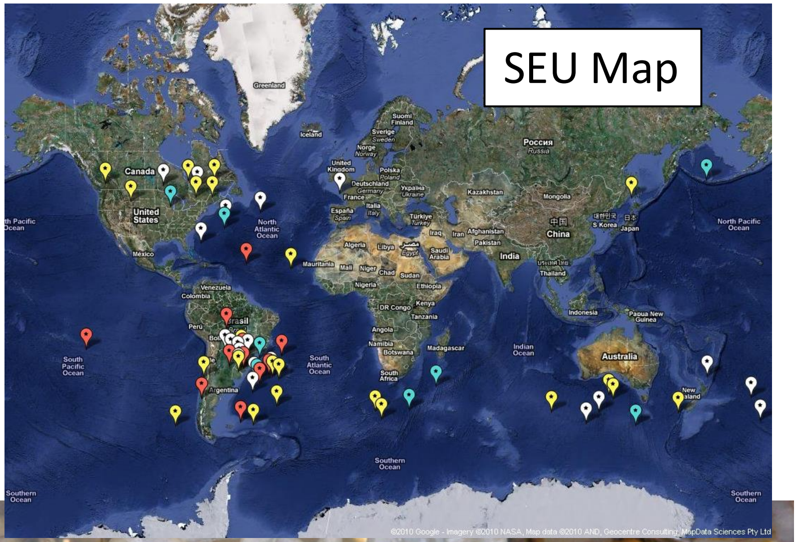
Exp 1

Exp 2

SpaceCube

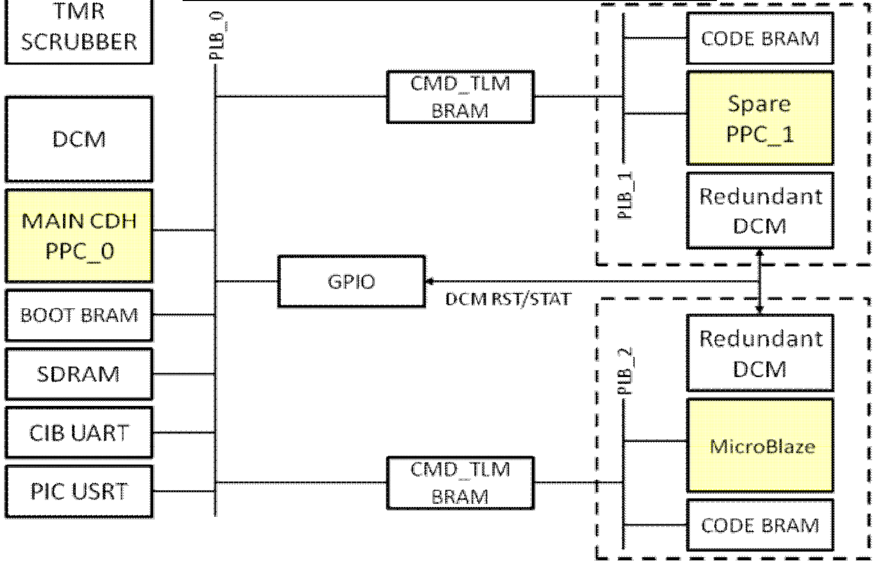
Other Experiments

GROUND



SEU Map

Embedded System Diagram



TMR SCRUBBER

DCM

MAIN CDH PPC_0

BOOT BRAM

SDRAM

CIB UART

PIC USRT

PLB_0

CMD_TLM BRAM

GPIO

DCM RST/STAT

CMD_TLM BRAM

PLB_1

CODE BRAM

Spare PPC_1

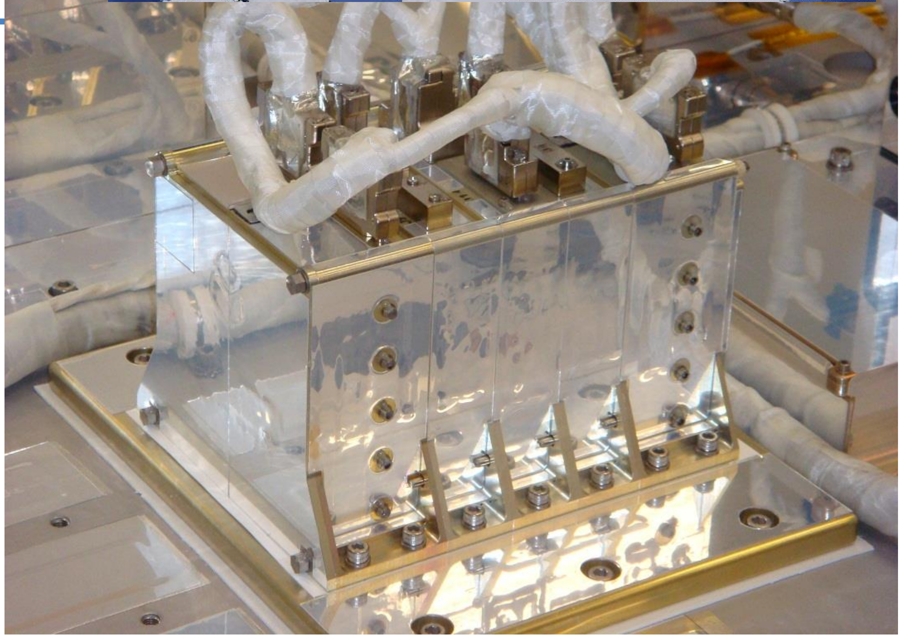
Redundant DCM

PLB_2

Redundant DCM

MicroBlaze

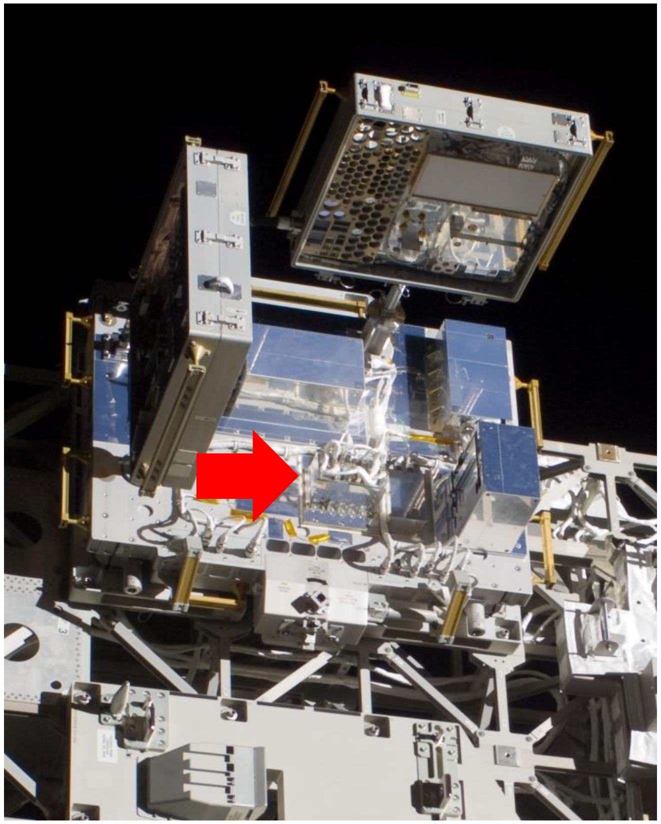
CODE BRAM



SpaceCube Upset Mitigation


→ FPGA and FSW successfully reconfigured on-orbit

GSFC SpaceCube v1.0 (Nov 2009):
Å"Radiation Hardened by Software" Experiment (RHBS)
ÅAutonomous Landing Application
ÅCollaboration with NRL and the DoD Space Test Program (STP)



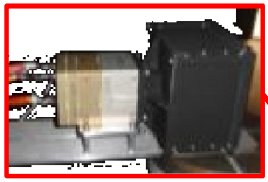
Data as of 3/1/2014

Days in orbit	**1500+**
Total SEUs detected & corrected	**200+**
Total SEU-induced resets	**6**
Total SEU-induced reset downtime	**30 min**
Total processor availability	**99.9979%**

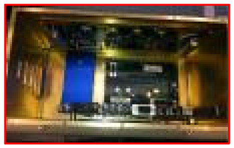
Argon AR&D Test Payload

IR Camera

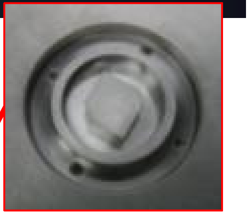
MDA RNS Cameras
And Baffles



Ball VNS



Power Control
Unit (PCU)



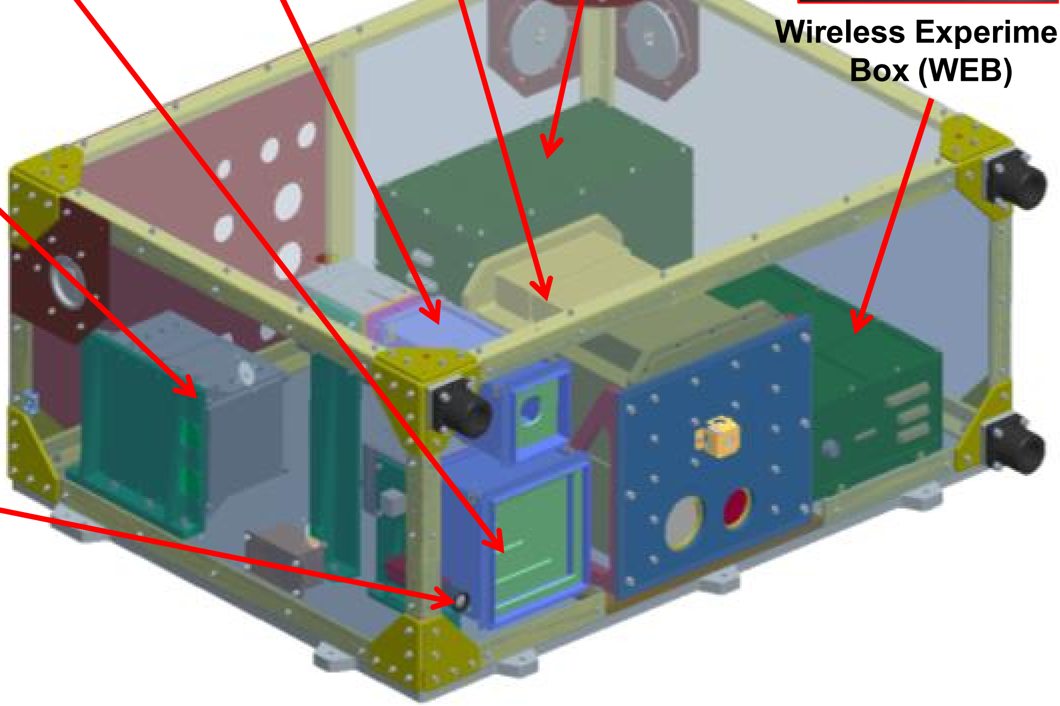
Wireless Patch
Antennas (x4)

Wireless Experiment
Box (WEB)

Neptec TriDAR

SpaceCube
(EDU)

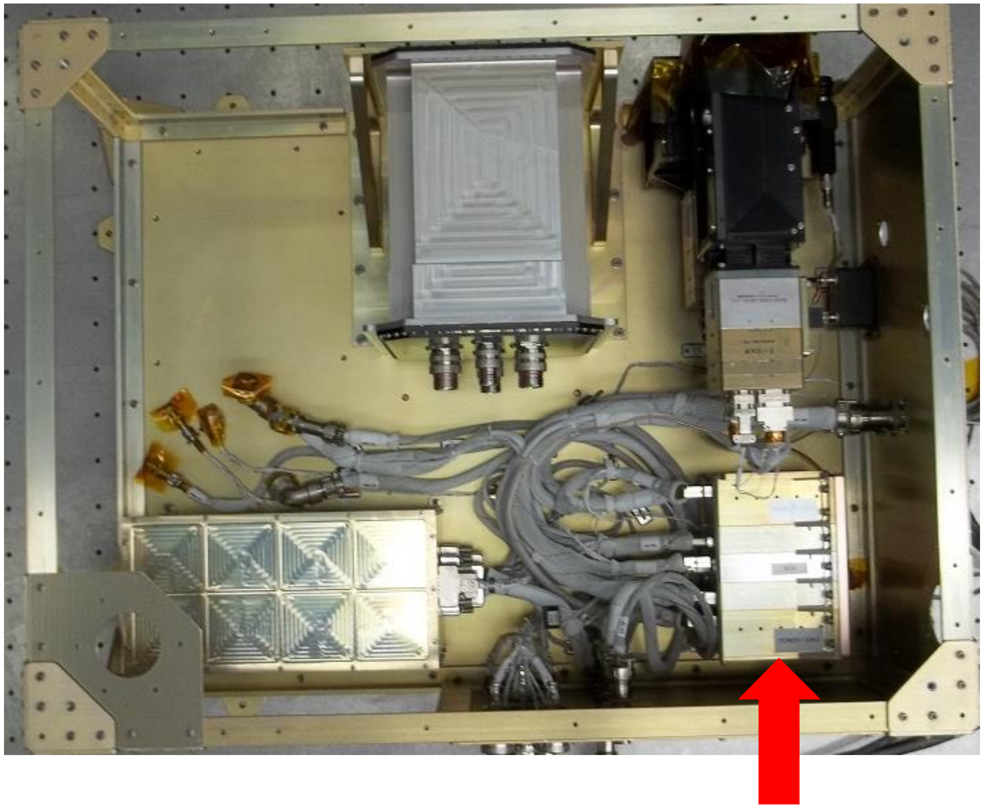
Ecliptic/Sony
Situational
Awareness
Camera



Estimated Mass:
140 lb

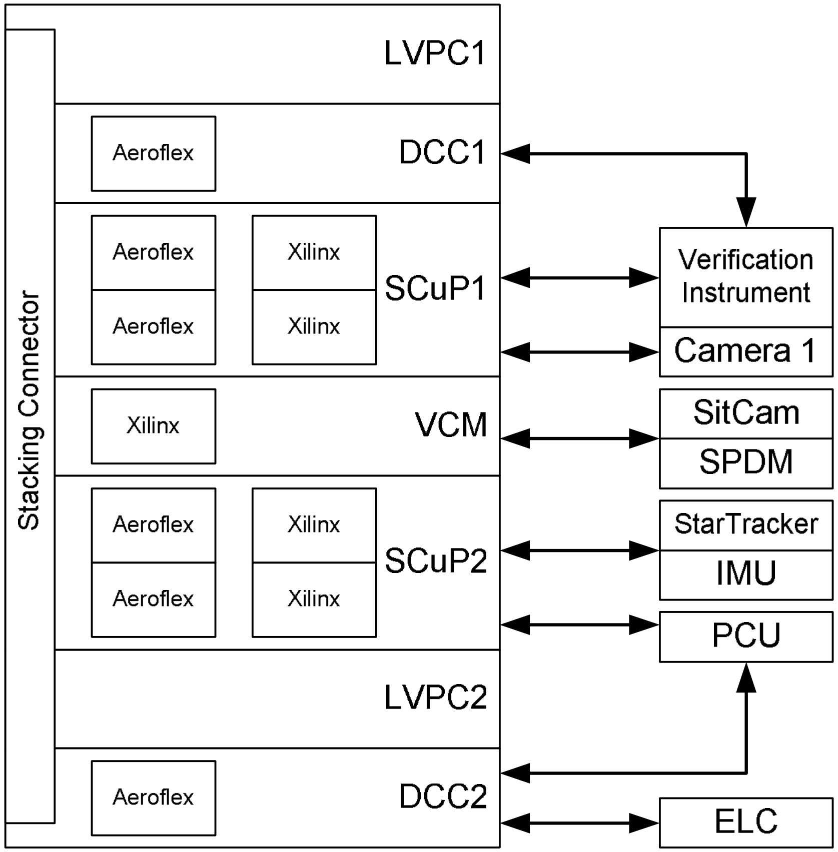
Rough Size:
25”x32”x14”

Argon Payload Assembly



SpaceCube

SpaceCube Interface Diagram



→ Embedded system consisted of 8 PowerPC405s

→ Reconfigurable system to support various instrument payloads

GSFC Satellite Servicing Lab

Testing with simulated 6-DOF motion of Argon and Target

- Rotopod and FANUC motion platforms simulate target-sensor dynamics
- Up to 13 m separation possible

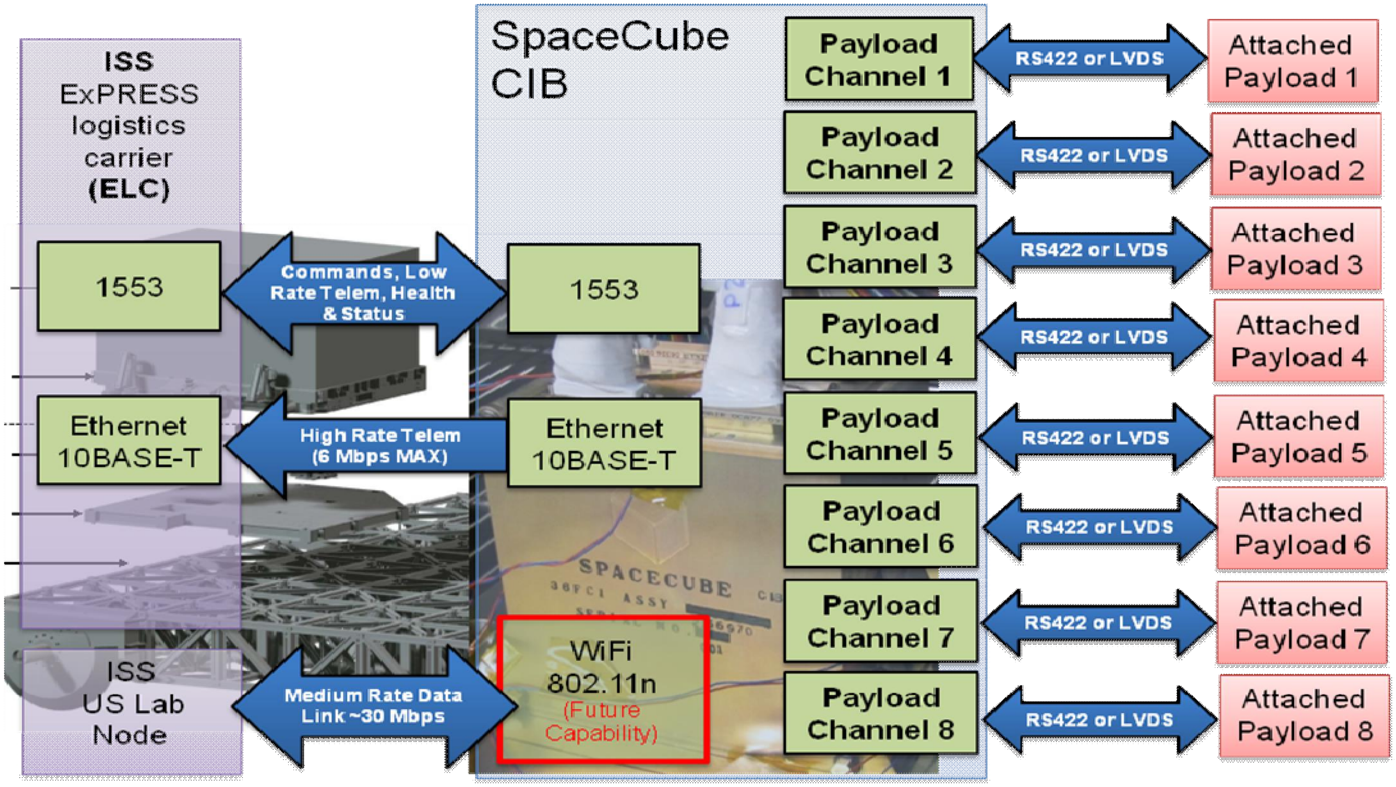
Testing conducted at GSFC in January-February 2012

- Motion includes closed-loop approach and non-cooperative “tumble”
- Open loop testing to characterize sensor/algorithm performance
- Closed-loop tests - evaluate end-to-end system (sensors, algorithms, control law) in real time

SpaceCube CIB, STP-H4

- Delivery to Space Test Program
- Interfaces with ELC and 8 attached payloads

→ Reflight of RNS Hardware



ISS ExPRESS logistics carrier (ELC)

1553

Ethernet 10BASE-T

ISS US Lab Node

Commands, Low Rate Telem, Health & Status

High Rate Telem (6 Mbps MAX)

Medium Rate Data Link ~30 Mbps

SpaceCube CIB

1553

Ethernet 10BASE-T

WiFi 802.11n (Future Capability)

Payload Channel 1 ↔ RS422 or LVDS ↔ Attached Payload 1

Payload Channel 2 ↔ RS422 or LVDS ↔ Attached Payload 2

Payload Channel 3 ↔ RS422 or LVDS ↔ Attached Payload 3

Payload Channel 4 ↔ RS422 or LVDS ↔ Attached Payload 4

Payload Channel 5 ↔ RS422 or LVDS ↔ Attached Payload 5

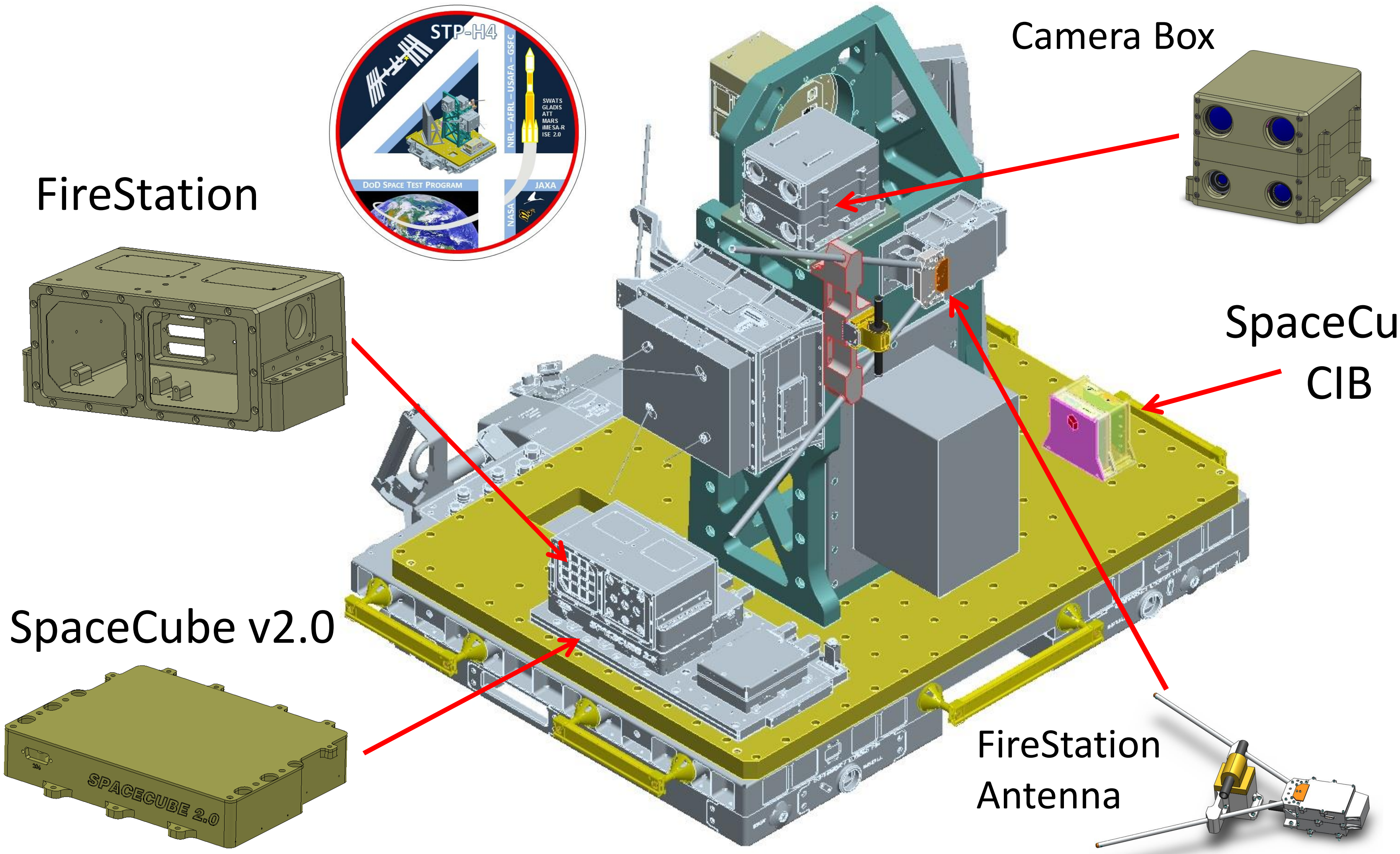
Payload Channel 6 ↔ RS422 or LVDS ↔ Attached Payload 6

Payload Channel 7 ↔ RS422 or LVDS ↔ Attached Payload 7

Payload Channel 8 ↔ RS422 or LVDS ↔ Attached Payload 8

Days in orbit	**200+**
Total SEUs detected & corrected	**20+ (as of 3/1/2014)**
Total SEU-induced resets	**1**

ISS SpaceCube Experiment 2.0



Camera Box

FireStation

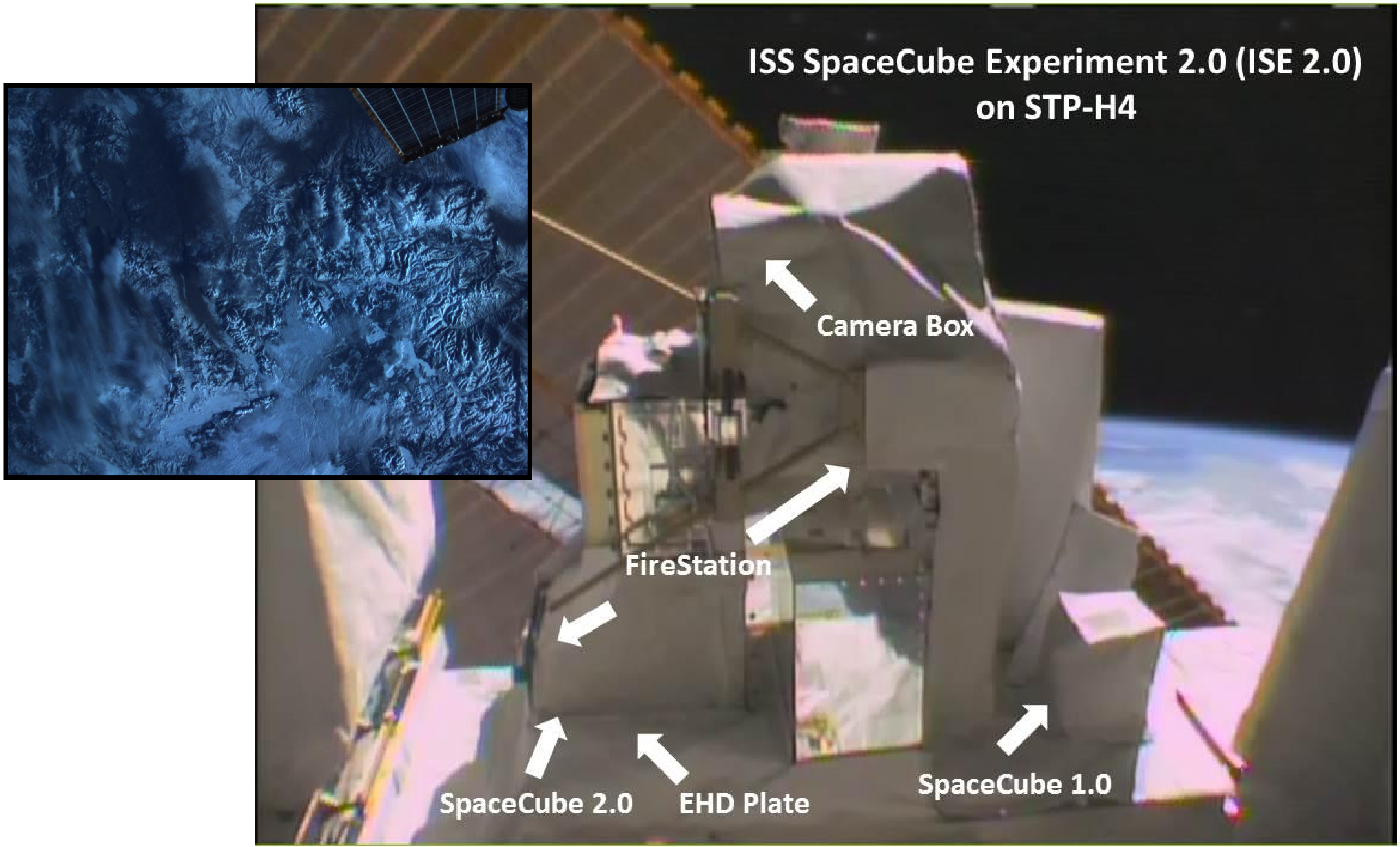
SpaceCube CIB

SpaceCube v2.0

FireStation Antenna

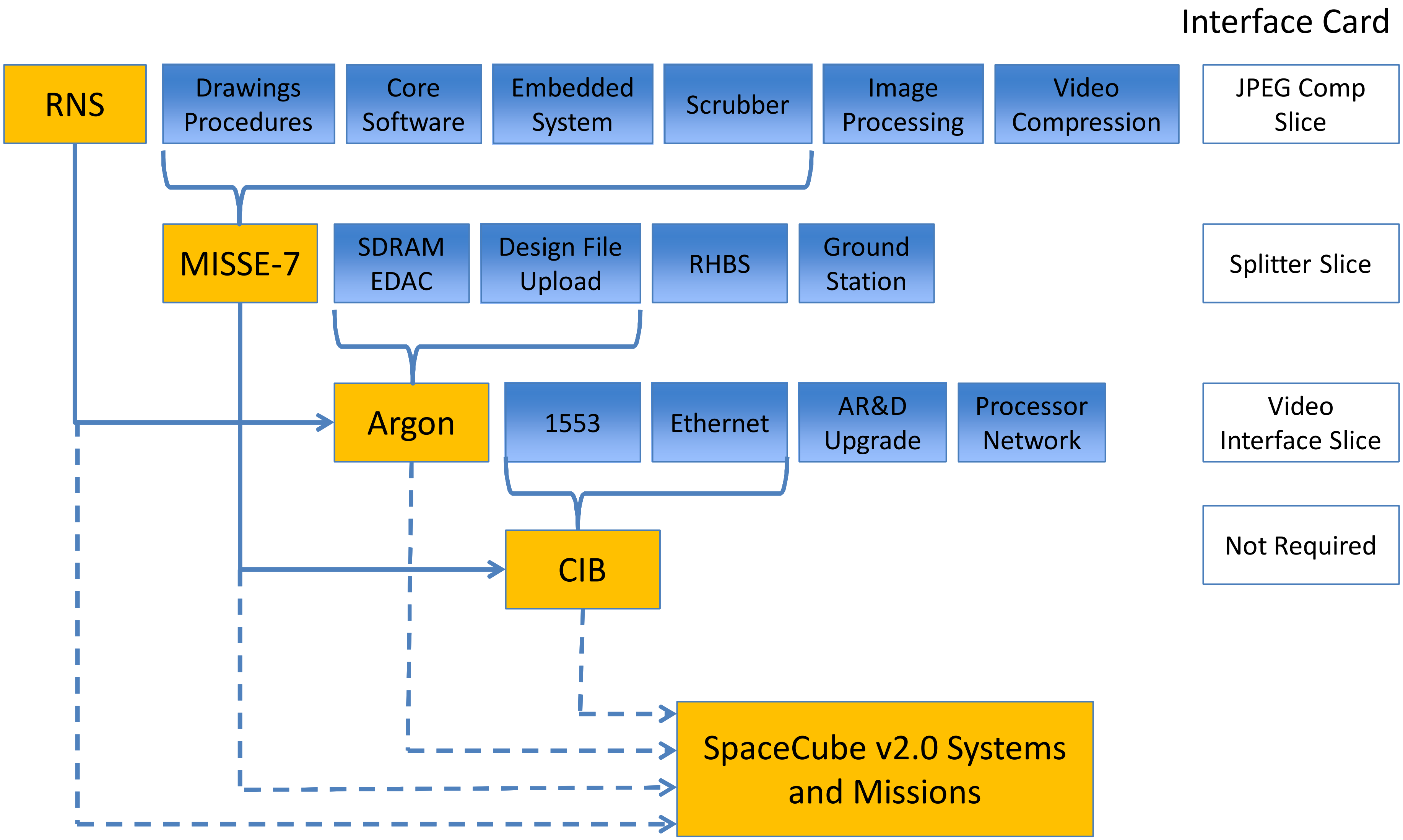
Image Credit: DoD Space Test Program

STP-H4 Operational on ISS



Next Up: STP-H5 and Robotic Refueling Mission 3 in 2015

System Reuse and Reconfiguration



Interface Card

RNS

Drawings Procedures

Core Software

Embedded System

Scrubber

Image Processing

Video Compression

JPEG Comp Slice

MISSE-7

SDRAM EDAC

Design File Upload

RHBS

Ground Station

Splitter Slice

Argon

1553

Ethernet

AR&D Upgrade

Processor Network

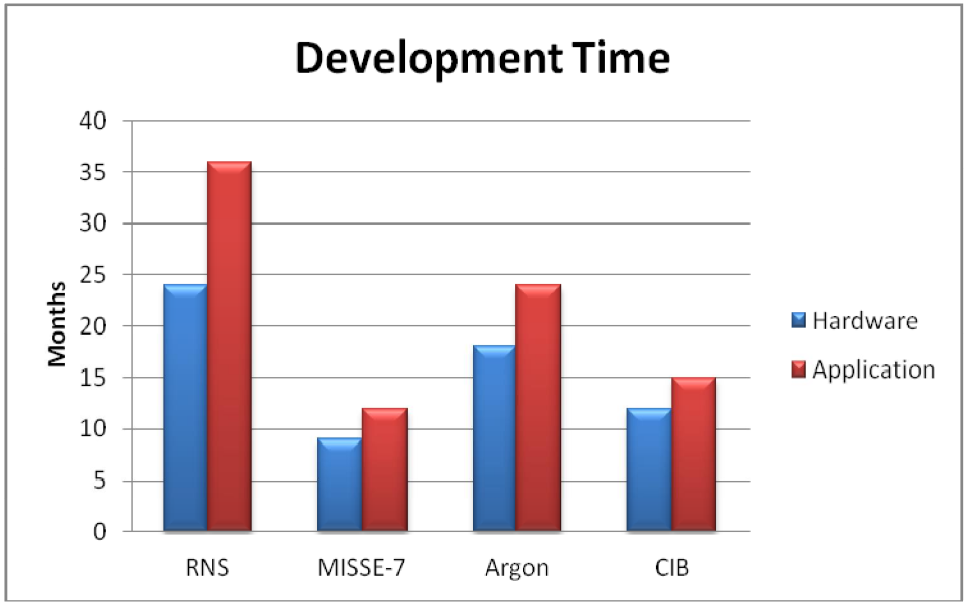
Video Interface Slice

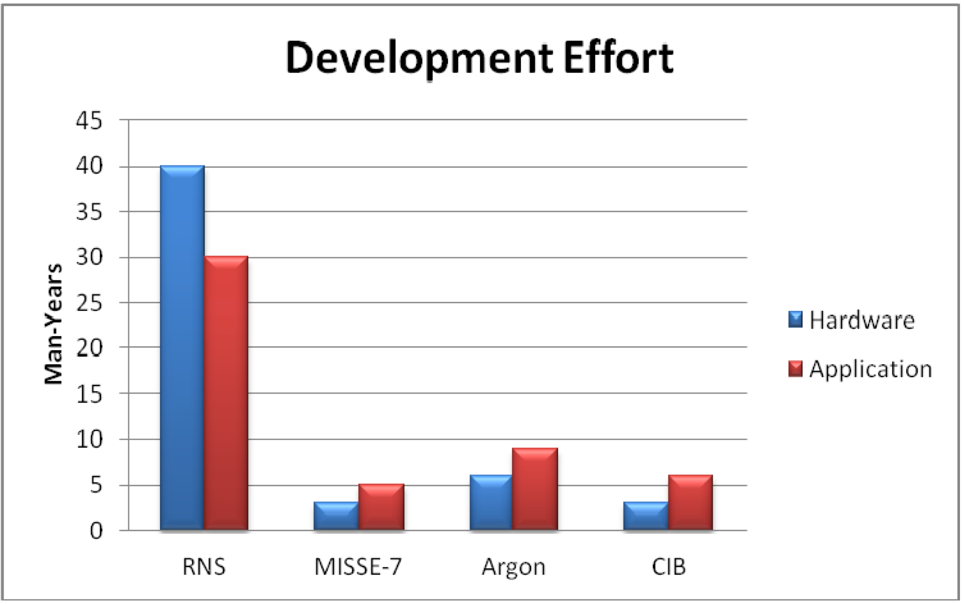
CIB

Not Required

SpaceCube v2.0 Systems and Missions

Conclusions





→Designing a new system has significant non-recurring engineering cost
→Firm embedded system infrastructure and reconfigurable file structure is critical
→A reconfigurable and adaptable system enables low-cost, quick-turn missions
→A scalable mechanical/electrical system can easily adapt to new interface requirements
→Reconfigurable system enables accelerated requirements creep: **BE FIRM!**