
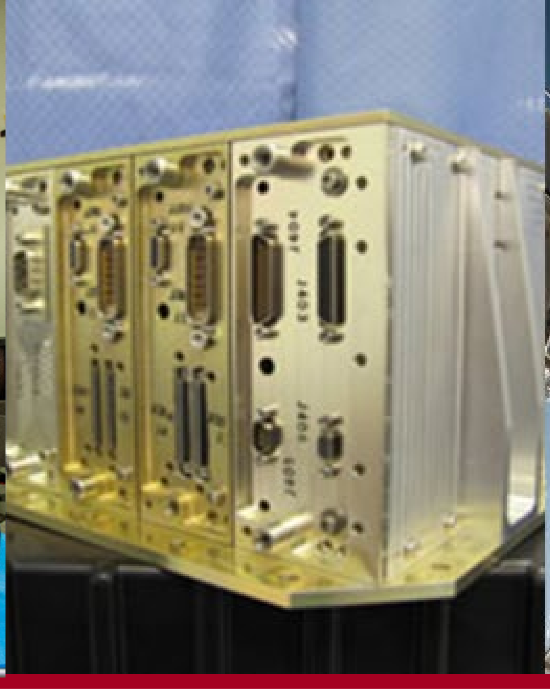

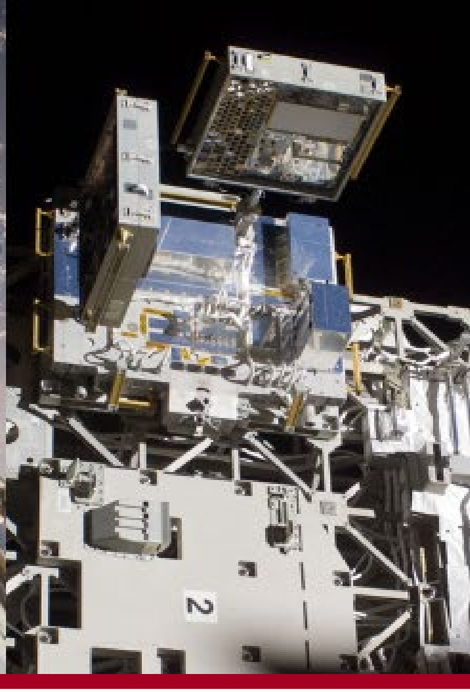

Edited and Presented by: Dave Petrick, GSFC S&MA Assistant Director for Technical

SPACECUBE OVERVIEW AND USE OF COTS PARTS IN SPACE

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Embedded Processing Group

2020 NEPP ETW

15 June 2020

SPACE FLIGHT CENTER

Outline

I. Background

II. SpaceCube Introduction

III. SpaceCube Design Approach

IV. SpaceCube Flight History

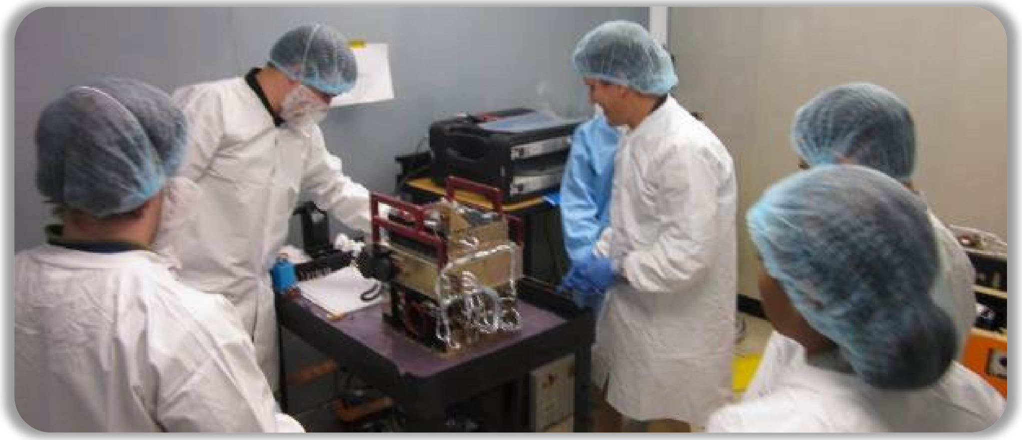
V. Use of COTS Parts

VI. Conclusion

Embedded Processing Group (EPG)

EPG Group Specializes in Embedded Development

- Hardware acceleration of algorithms and applications
- Intelligence, autonomy, and novel architectures
- Flight software integration for development platforms
- Advanced architectures and research platforms



Advanced Platforms for Spaceflight

- SpaceCube v1.0
- SpaceCube v2.0 and v2.0 Mini
- SpaceCube v3.0 and v3.0 Mini
- SpaceCube Mini-Z and Mini-Z45

Key Tools and Skills

- **Flight Software**: cFE/cFS, driver integration, flight algorithms
- **GSE**: COSMOS, GMSEC, system testbeds
- **FPGA Design**: Hardware acceleration, fault-tolerant structures
- **Mission Support**: Supporting flight cards, algorithm development
- **On-board Autonomy and Analysis**: deep-learning and machine-learning frameworks, unique architectures

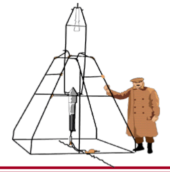
Background

Challenge

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

Mission Enabling Science Algorithms & Applications

- **Real-time Sensing and Control**
- **On-Board Data Volume Reduction**
- **Real-time Image Processing**
- **Autonomous Operations**
- **On-Board Product Generation**
- **Real-time Event / Feature Detection**
- **On-Board Classification**
- **Real-time "Situational Awareness"**
- **"Intelligent Instrument" Data Selection / Compression**
- **Real-time Calibration / Correction**
- **Inter-platform Collaboration**



Background (for context)

- SpaceCube's first mission use was for the HST Servicing Mission 4....which came with the strict HST design and mission assurance mindset of:
  - Thou shalt fly only Level 1 parts → major screening/qual plan for Xilinx Virtex-4 FX60 FPGAs
  - Thou shalt fly only IPC 6012B Class 3/A circuit boards → much time wasted
  - Thou shalt mitigate ALL possibilities of SEUs → QMR was baseline mitigation....QMR!!!
- What happened: we nearly didn't make it due to unneeded requirements
  - Schedule for screening started to slip and costs were sky-rocketing
    → terminated the effort
  - Cost/schedule growth for figuring out 6012 Class 3/A for a back-to-back 1mm-pitch FPGA
    → went with Class 2/3
  - Converging on a QMR voting structure for 4 PowerPC processors was more challenging than "sold", risking not making the mission
    →single-string, simple watchdog, internal TMR'd self scrubbing
- Did I mention this was for an Autonomous docking tech demo that only had to operate for roughly 24 hours???

The General Mentality in 2007....maybe still?

Unless you have 6012B Class 3/A circuit boards and Level 1 or 2 parts, it will never fly and never work

We want our mission to work, so we need Level 1 parts

Introduction

Our Solution

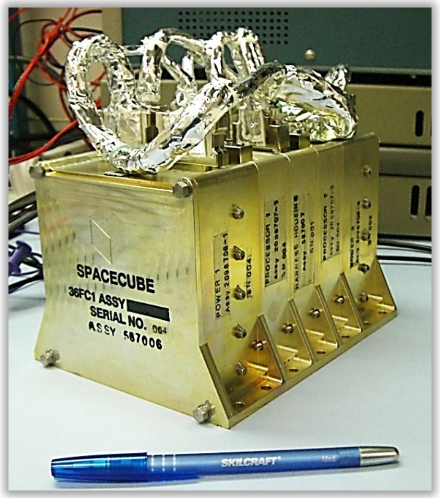
SpaceCube

A family of NASA developed space processors that established a **hybrid-processing approach** combining radiation-hardened and commercial components while emphasizing a novel architecture **harmonizing** the best capabilities of CPUs, DSPs, and FPGAs

High-performance reconfigurable science / mission data processor based on Xilinx FPGAs

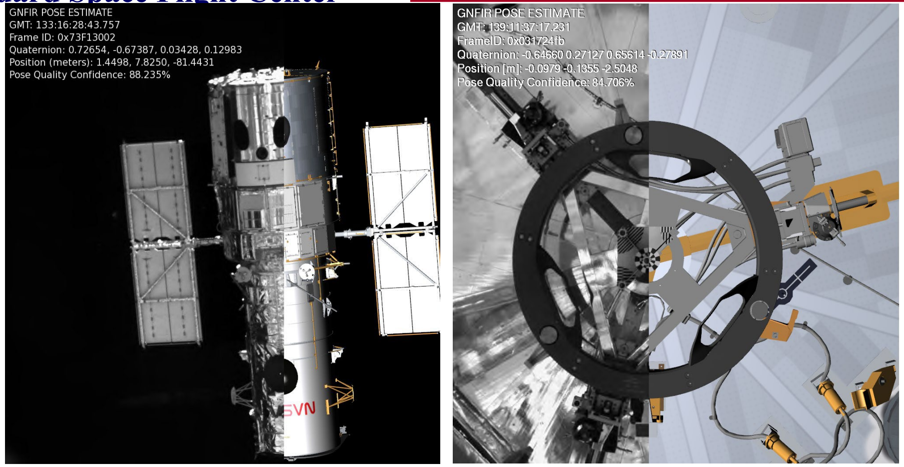
- **Hybrid processing - algorithm profiling and partitioning to CPU, DSP, and FPGA logic**
- **Integrated "radiation upset mitigation" techniques**
- **SpaceCube "core software" infrastructure (SCSDK) – Example (cFE/cFS and "SpaceCube Linux" with Xenomai)**
- **Small "critical function" manager/watchdog**
- **Standard high-speed (multi-Gbps) interfaces**

SpaceCube v1.0

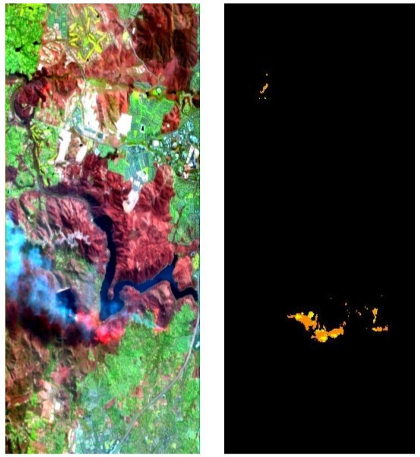


SpaceCube is Hybrid Processing...

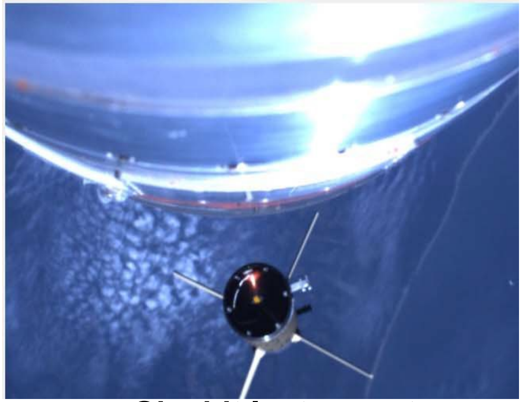
Example SpaceCube Processing



Real-Time Image Tracking of Hubble



Fire Classification



Gigabit Instrument Interfacing

Xilinx ISS Radiation Data

Spectrometer Data Reduction

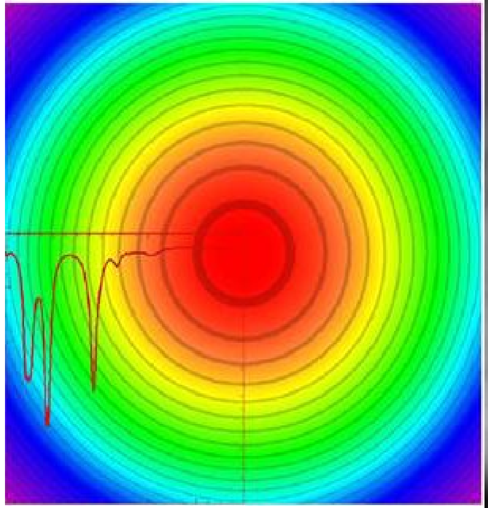


Image Compression

SpaceCube Approach

Our Approach

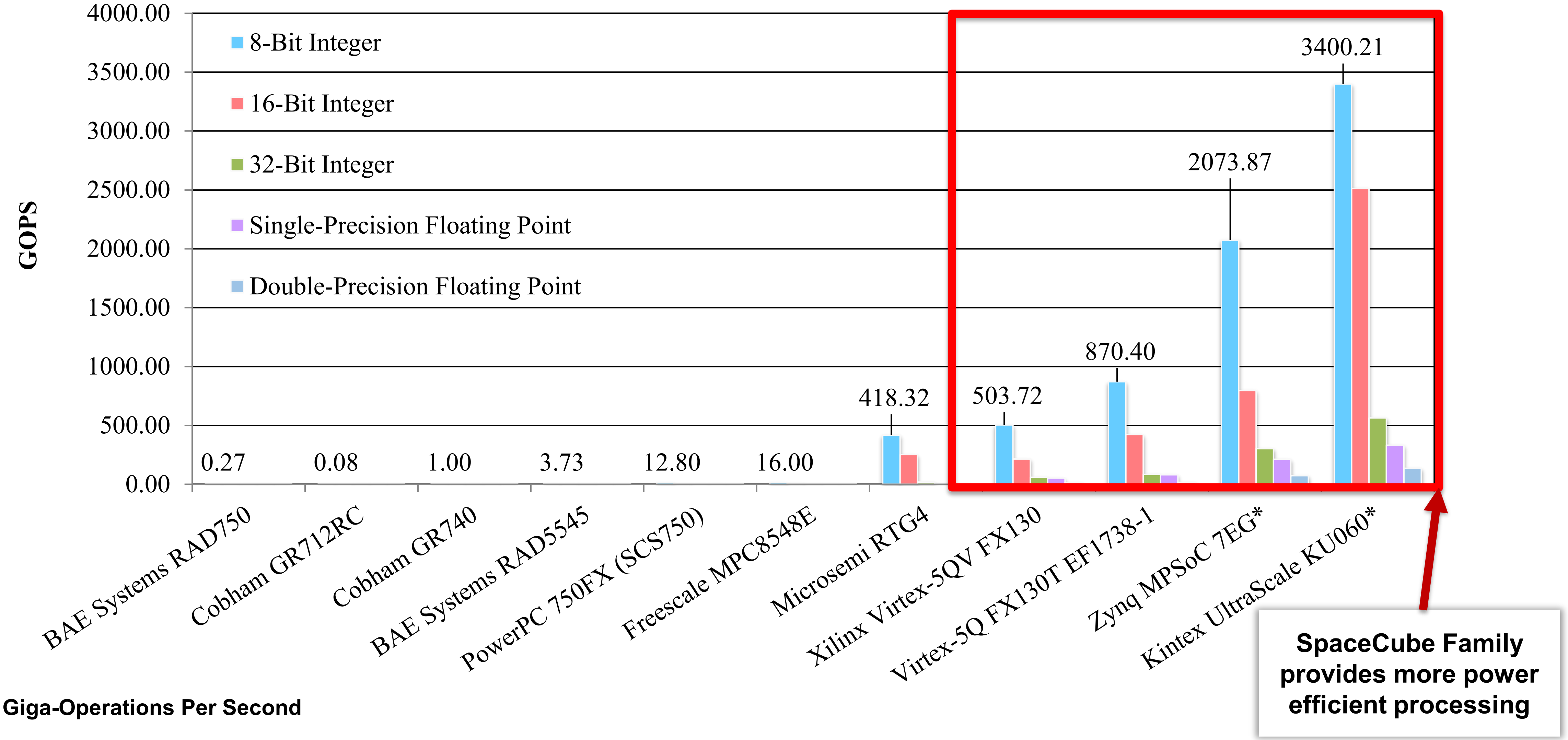
01 The traditional path of developing radiation-hardened flight processor will not work … they are always one or two generations behind

02 Use latest radiation-tolerant* processing elements to achieve massive improvement in computing performance per Watt (for reduced size/weight/power)

03 Accept that radiation-induced upsets may happen occasionally and just deal with them appropriately … any level of reliability can be achieved via smart system design!

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

Device Comparisons



GOPS = Giga-Operations Per Second

T. M. Lovelly and A.D. George, "Comparative Analysis of Present and Future Space-Grade Processors with Device Metrics," AIAA Journal of Aerospace Information Systems, vol. 14, no. 3, pp. 184-197, Mar. 2017.

*UltraScale results are an estimate based off of existing data, new metrics are in progress but not currently available

Reconfigurability

Being Reconfigurable …
… equals BIG SAVINGS (both time and money)

During mission development and testing

- Design changes without PCB changes
- "Late" fixes without breaking integration

During mission operations

- On-orbit hybrid algorithm updates
- Adaptive processing modes
  - hi-reliability vs. high-performance
  - intelligently adapt to current environment

From mission to mission

- Same avionics reconfigured for new mission

Reliability Analysis (SpaceCube v2.0)

SpaceCube is rooted on solid design, analysis and test practices

Analysis	Status
Parts Stress and De-rating	Complete
Signal/Power Integrity	Complete
Reliability Block Diagram	Complete (specific to Restore-L use)
Worst Case Circuit Analysis	Complete
FMECA	Complete (specific to Restore-L use)
Radiation TID Analysis	Complete
Radiation SEE Rate Estimation	Complete for Polar, ISS, Mars
Back-to-Back CGA Solder Joint Fatigue	Complete

Test	Status
PWB Coupon Tests	Complete – All PASS IPC 6012B 3/A
Qual TVAC/Vibe per GEVS	Complete - PASS
RRM3/NavCube SpaceCube TVAC/Vibe/EMI	Complete - PASS
“Quick-Look” EMI/EMC	Complete - PASS
4x CGA Life Test Articles (-55/+100C)	Complete - 5x MoS factor achieved

Reliability Spectrum (It's your choice)

Reliability

- Box redundancy
- Card redundancy
- Internal redundancy
- Higher Part levels (COTS, 3→2→1)
- Single string
- <u>Solid Robust Design Base</u>

Radiation Tolerance

- Full TMR/NMR
- Selective mitigation
- DDR ECC
- Fault-Tolerant processor
- Xilinx device type
- BRAM Mitigation
- Flash ECC
- Configuration Scrubbing
- SEL Monitors
- No Mitigation

Risk-based radiation assessment approach

The systems trades: Computing Performance vs. Radiation Performance
(adding levels of radiation tolerance requires some level of resources)

Mission Examples (low end to high end, in order of increasing cost):

- **Tech Demo (Do no harm): ISS, Single string, "EDU" parts, Config scrubbing, Flash ECC, Defense-grade Xilinx**
- **Class D: COTs, Level 3 parts, selective mitigation and redundancy, FT processing**
- **Class C: Level 3 parts, some redundancy, DDR ECC, FT processor for critical tasks, selective mitigation**
- **Class A/B critical function: Level 1/2 parts, Box redundancy, FT processor, memory EDAC, possibly full TMR**

<u>**COTS**</u>**:** Use-as-is from vendor, derated, most parts have "space" equivalent which gives some sense of radation performance, radiation assessment as needed. In some cases, DigiKey, Avnet, Mouser (as-is), "commercial" or "engineering model" versions of "flight" parts

Flight History

Goddard Space Flight Center

Closing the gap with commercial processors while retaining high reliability

(all industry/commercial/defense grade, no additional screening)

- 66+ Xilinx device-years on orbit
- 26 Xilinx FPGAs in space to date (2020)
- 11 systems in space to date (2020)

SpaceCube is Mission Enabling…

SpaceCube v1.0

STS-125, MISSE-7, STP-H4, STP-H5, STP-H6

SpaceCube v1.5

SMART (ORS)

SpaceCube v2.0-EM

STP-H4, STP-H5

SpaceCube v2.0-FLT

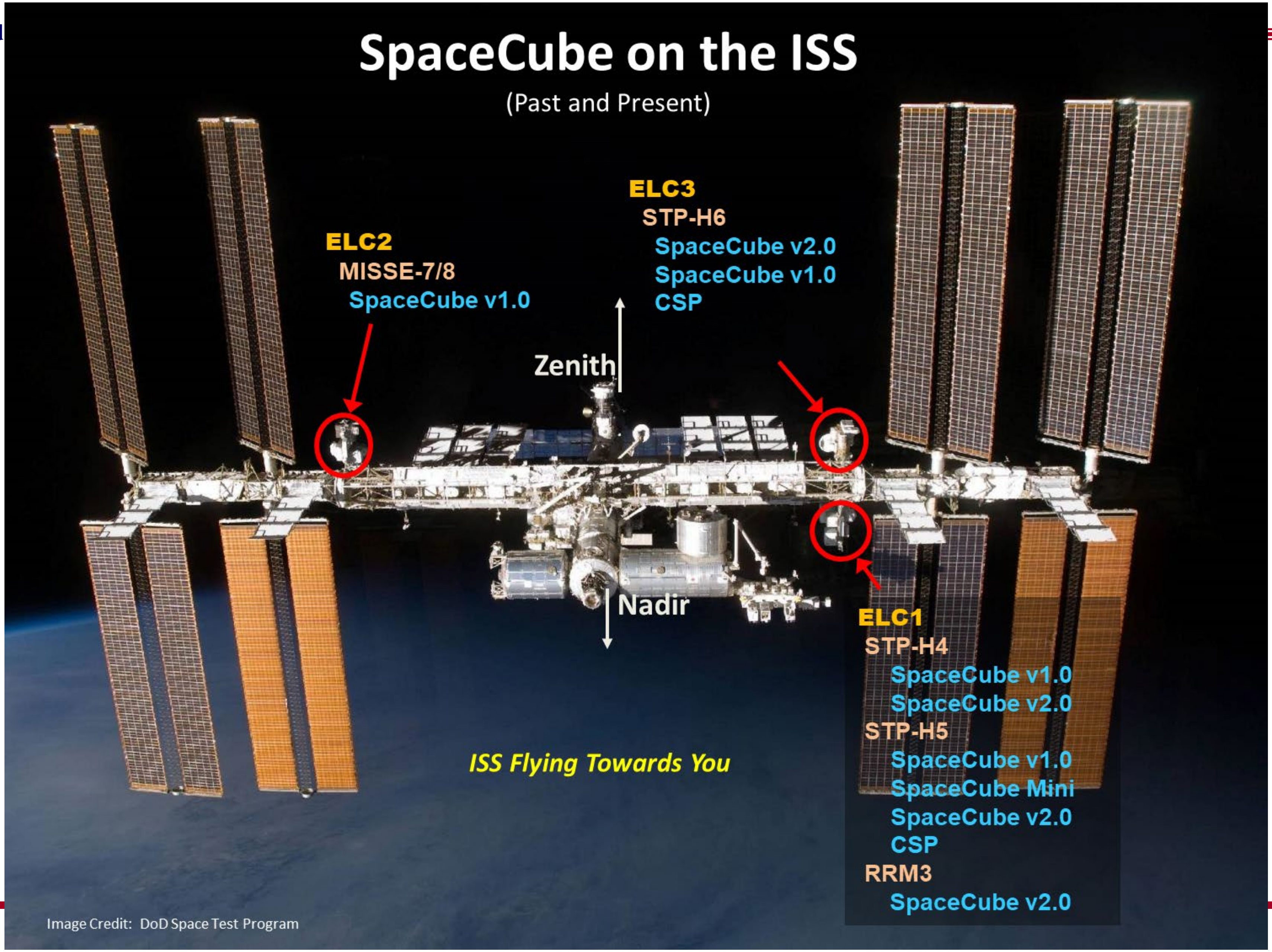
RRM3, STP-H6 (NavCube), NEODAC, Restore-L (Lidar)

SpaceCube v2.0 Mini

STP-H5, UVSC-GEO

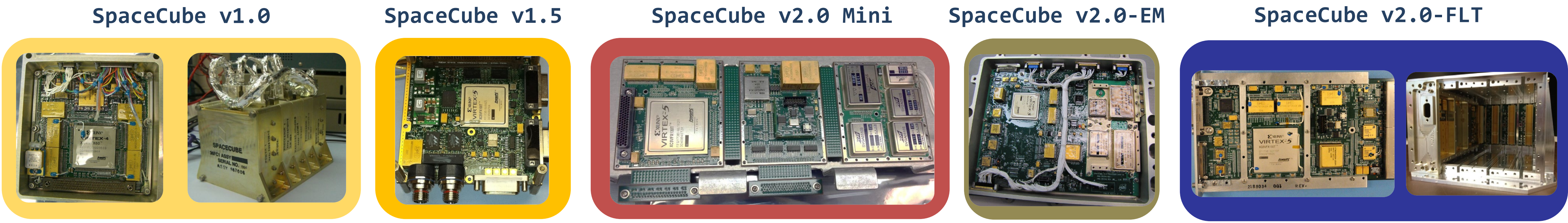
Flight Heritage

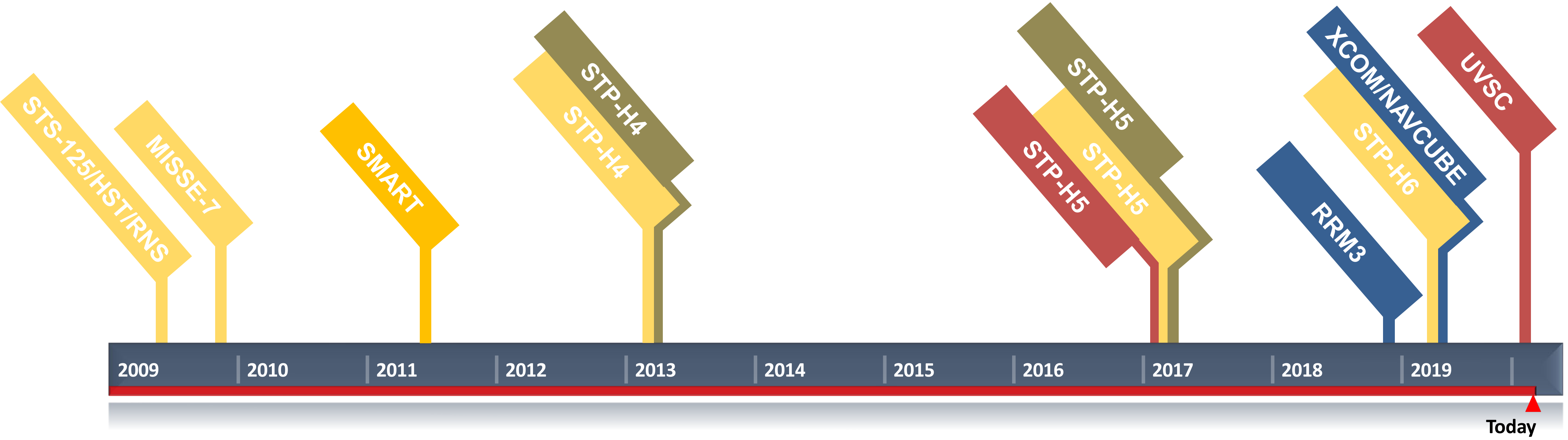
Goddard



SpaceCube Family Flight Mission Timeline

Goddard Space Flight Center





SpaceCube v2.0 Processor Card

Goddard Space Flight Center

Overview

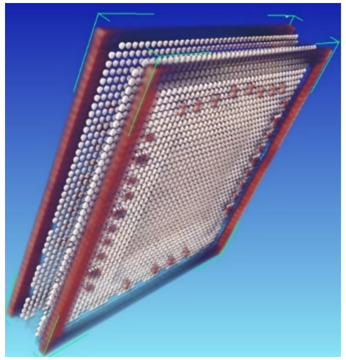
- TRL9 flight-proven processing system with unique Virtex back-to-back installed design methodology
- 3U cPCI (190 x 100mm) size
- Typical power draw: 8-10W
- 22-layer, via-in-pad, board design
- IPC 6012B Class 3/A PWB design

Back-to-Back FPGA Design

Key Features

- 2x Xilinx Virtex-5 (QR) FX130T FPGAs (FX200T Compatible)
- 1x Aeroflex CCGA FPGA
  - Xilinx Configuration, Watchdog, Timers
  - Auxiliary Command/Telemetry port
- 4x 512 MB DDR SDRAM
- 2x 4GB NAND Flash
- 1x 128Mb PROM, contains initial Xilinx configuration files
- 1x 16MB SRAM, rad-hard with auto EDAC/scrub feature
- 16-channel Analog/Digital circuit for system health
- Mechanical support for heat pipes and stiffener for Xilinx devices

- External Interfaces
  - Gigabit interfaces: 4x external, 2x on backplane
  - 12x Full-Duplex dedicated differential channels
  - 88 GPIO/LVDS channels directly to Xilinx FPGAs
- Debug Interfaces
  - Optional 10/100 Ethernet interface



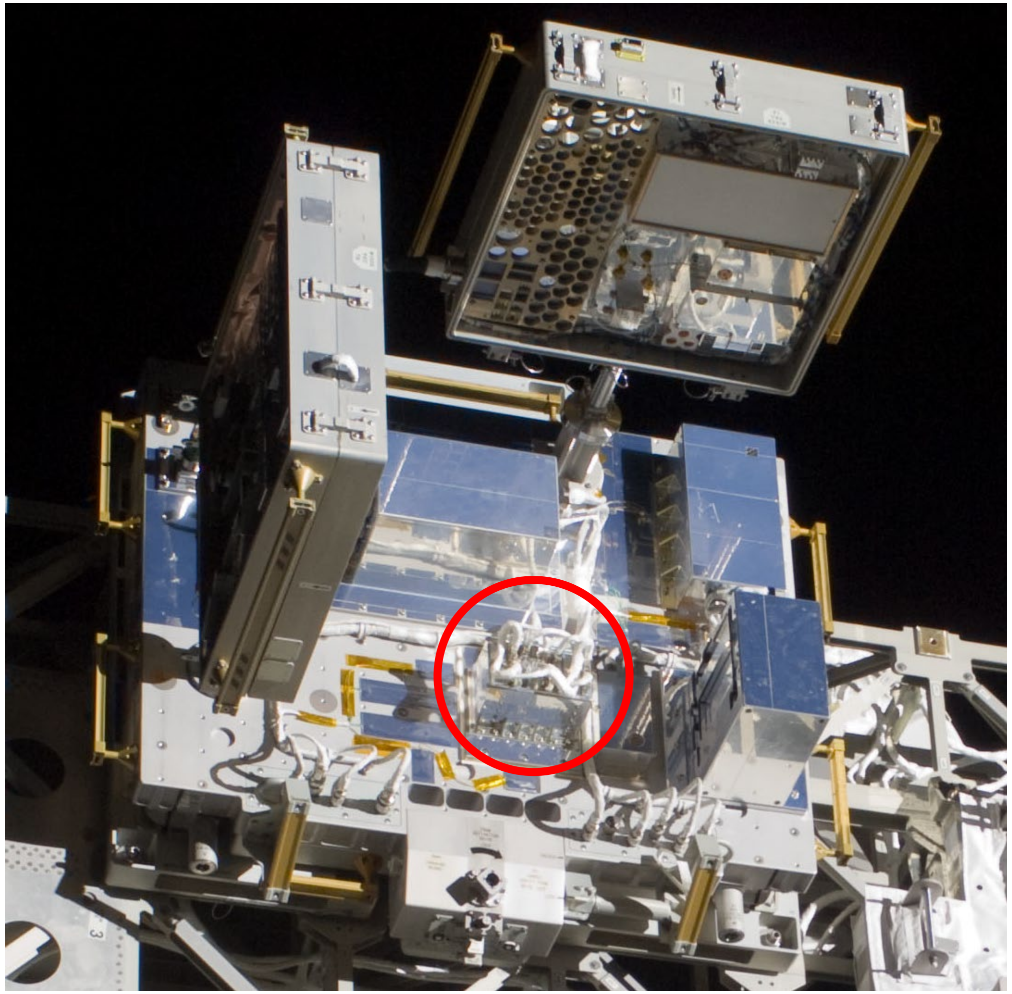
US Patents:
9,705,320
9,549,467
9,851,763
10,667,398
10,681,837

SpaceCube v1.0

STS-125 Shuttle Payload Bay

1% COTS Parts

MISSE-7/8 ISS Payload



2% COTS Parts

- 7 years of operation
- 4x Virtex-4 XC4VFX60: 0.1 SEU/FPGA/Week
- 2x on-orbit file uploads and reconfiguration

On-Board Image Processing

→ Successfully tracked Hubble position and orientation in real-time operations

→ FPGA Algorithm Acceleration was required to meet 3Hz loop requirement

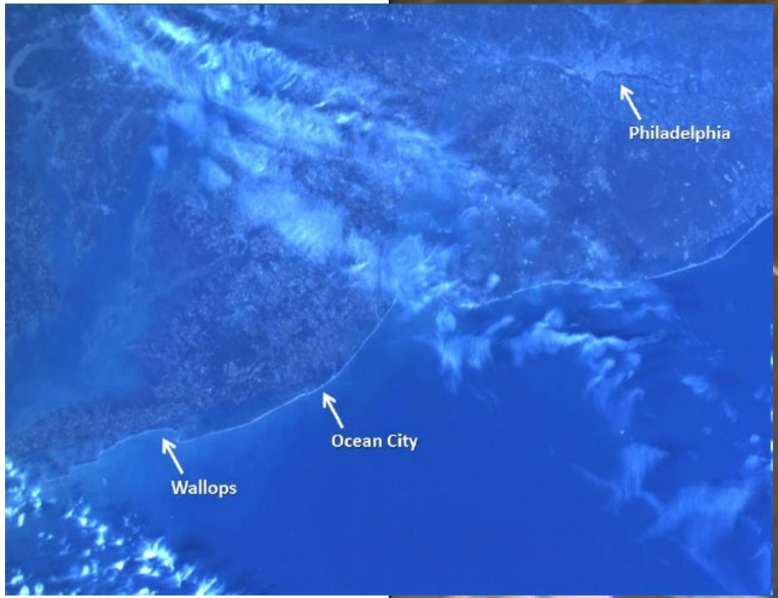
Rendezvous

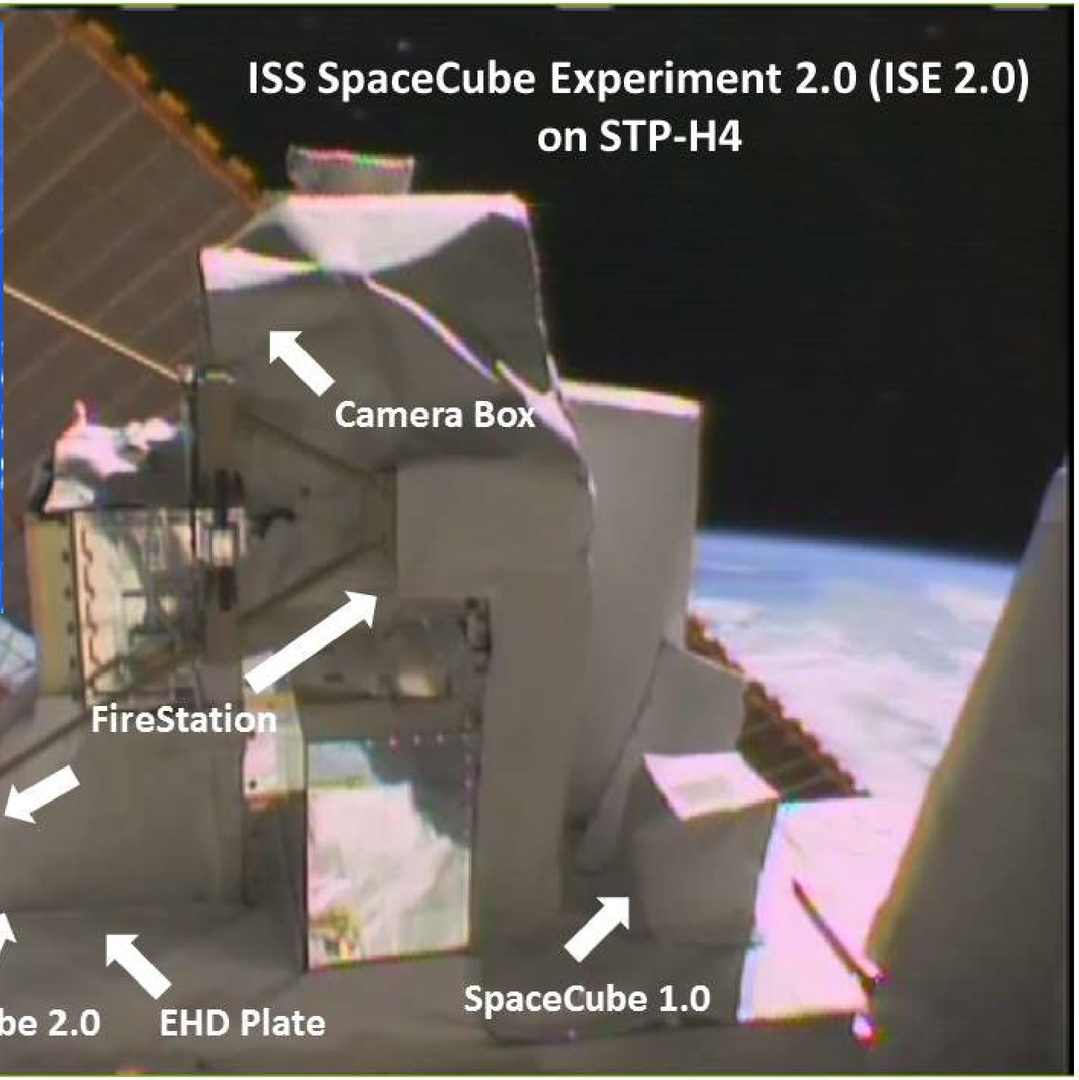
Deploy (Docking Ring)

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

STP-H4 ISS Payload

99% COTS Parts





COTS HD Cameras
COTS Ethernet Switch

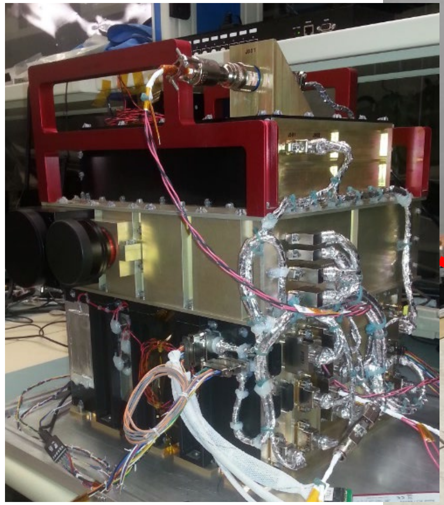
1% COTS Parts

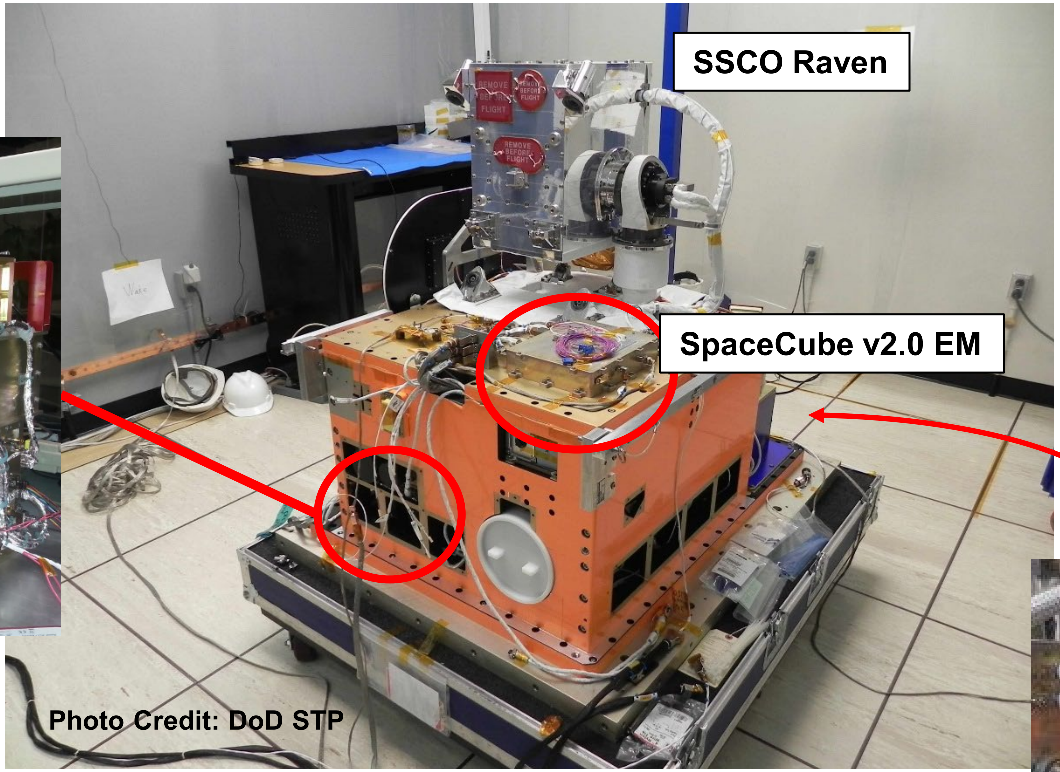
2 years of operation. 3x Virtex-5 XC5VFX130T: 1 SEU/FPGA/Week
Successful on-orbit file upload and reconfiguration

STP-H5 ISS Payload

98% COTS Parts

ISEM, SpaceCube Mini





99% COTS Parts

SpaceCube v1.0 CIB

1% COTS Parts

The Space Test Program-H5 (STP-H5) external payload, a complement of 13 unique experiments from seven government agencies, is integrated and flown under the management and direction of the Department of Defense's Space Test Program.

2/2017 - Current

Raven Payload

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eCube v2.0

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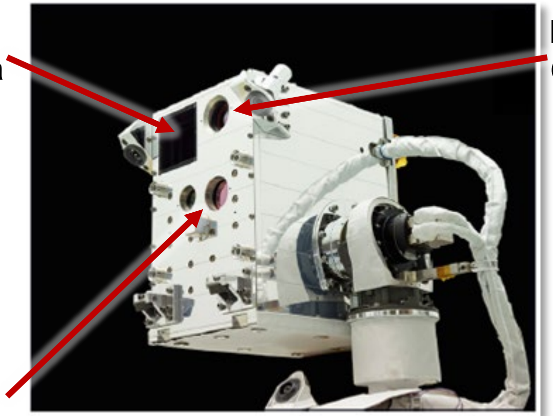
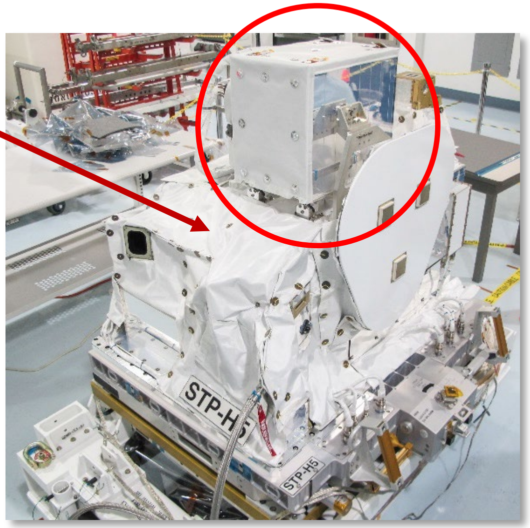


Raven
(Deployed Configuration)

$20M+ payload reliant on confidence in the SpaceCube computer, which in this case was pre-populated with 99% COTS Parts, and then thoroughly tested.



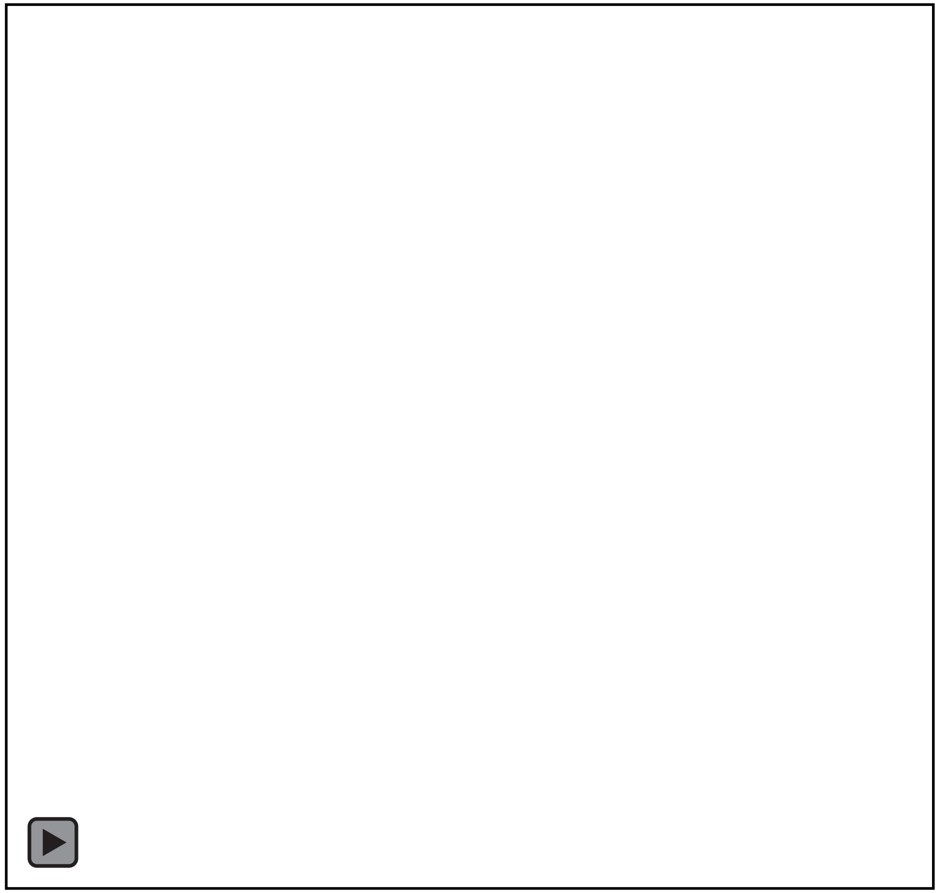
Raven installed on STP-H5
(Stowed Configuration)

Raven – Sample Data

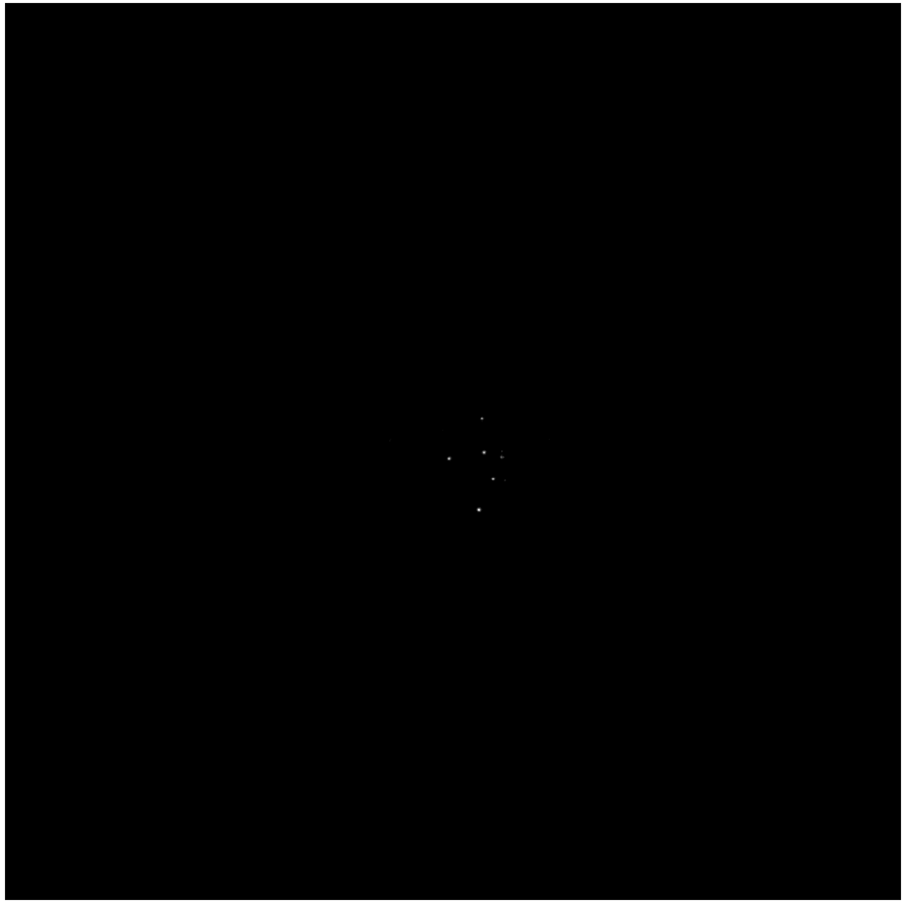
Goddard Space Flight Center

Raven is currently generating valuable science that is setting the groundwork for future NASA missions that require rendezvous and proximity operations systems

Dragon Tracking (VisCam)

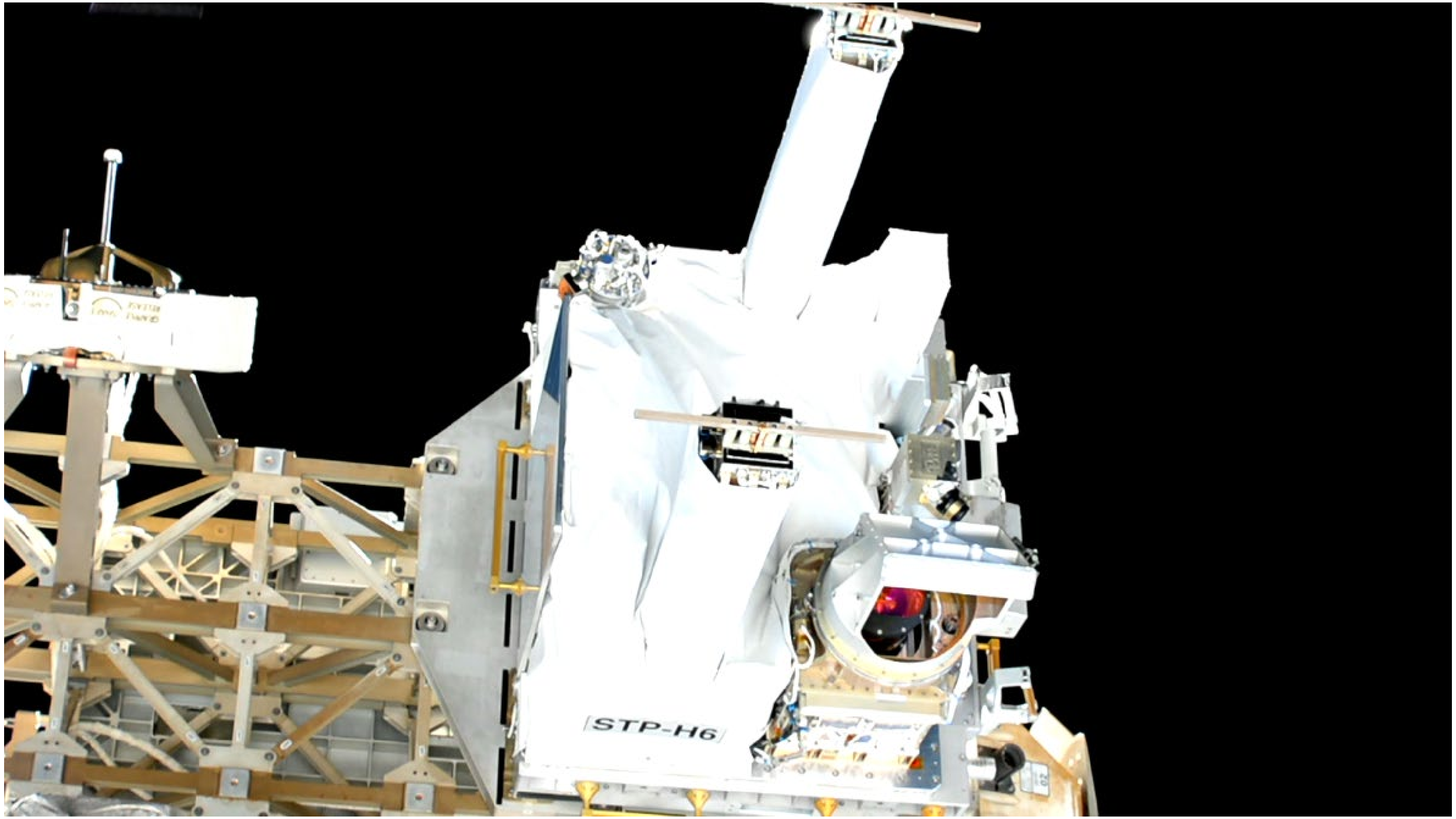


CygnusTracking (VisCam)



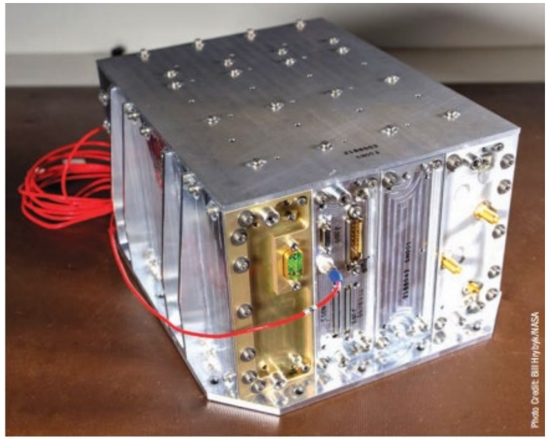
Raven demonstrated successful on-board vehicle tracking of all vehicles docking with ISS

STP-H6 Payload



99% COTS Parts

SpaceCube v2.0 NavCube

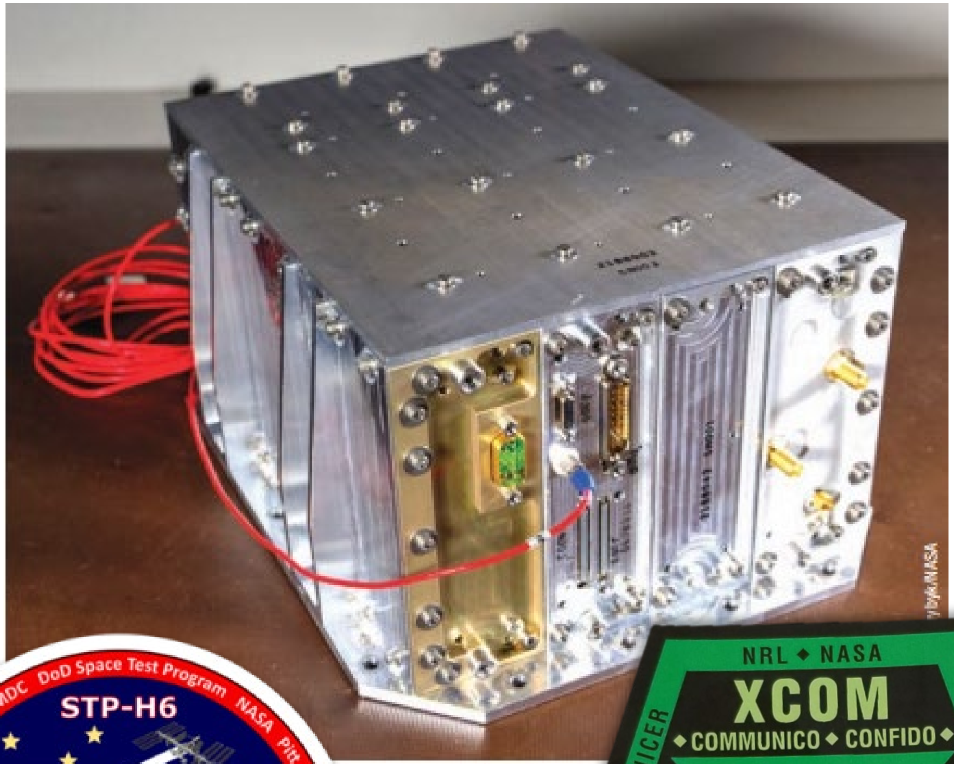


SpaceCube v1.0 CIB 1% COTS Parts

Infusion: NavCube on X-ray Communication Experiment (XCOM)

- **NavCube**: Union of Navigator GPS and SpaceCube technology
  - NavCube drives electronics for Modulated X-ray Source on Space Test Program-H6 (**STP-H6**) as part of X-ray Communications Experiment (**XCOM**)
  - 2016 Goddard Innovation of the Year
- Flexible SpaceCube design enabled **low-cost, rapid mission development**
  - Delivered Command and Data Handling FSW
  - Supports inflight updates of FPGA and software
  - Allowed significant software reuse leveraging key components from previous SpaceCube Missions
    - RRM3: Core FSW component
    - CeREs: AOS processing as part of cFS library
    - STP-H: Packet processing for CCSDS and STP protocols

99% COTS Parts



Accomplishments and Key Highlights: RRM3

95% COTS Parts

Goddard Space Flight Center

Overview

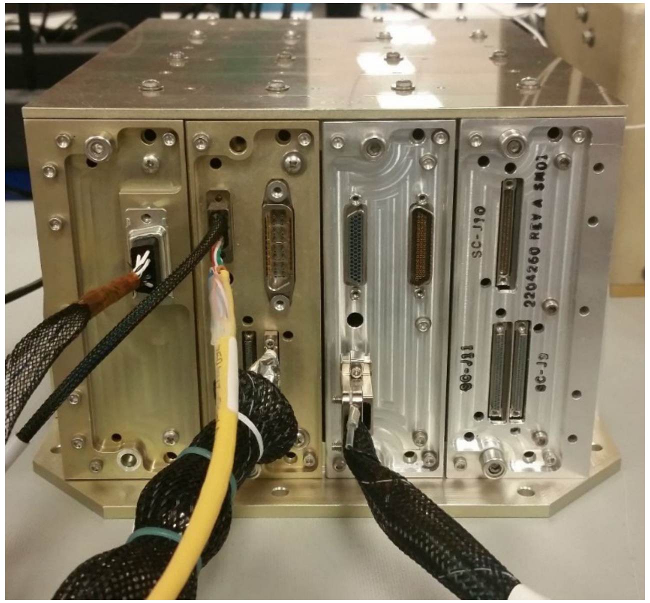
Robotic Refueling Mission 3 (RRM3)

- Technology demonstration experiment to highlight innovative methods to store and replenish cryogenic fluid in space

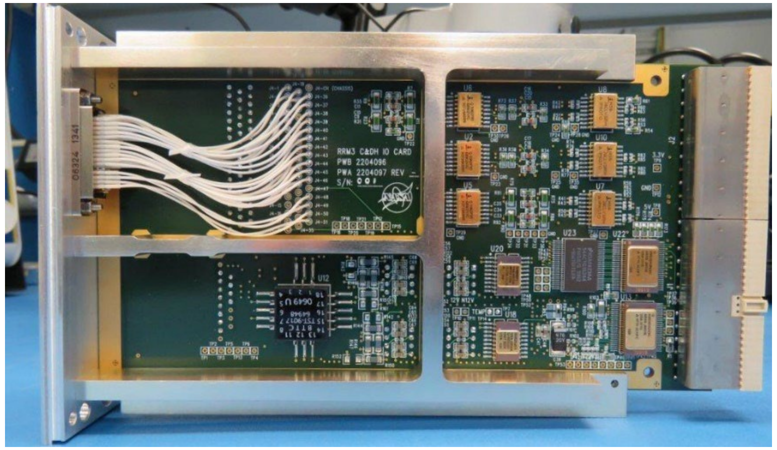
High Level Requirements

- Interface with ISS and RRM3 instruments:
  - Cameras, thermal imager, motors
- Monitor/Control cryo-cooler and fuel transfer
- Stream video data
- Motor control of robotic tools
- Host Wireless Access Point

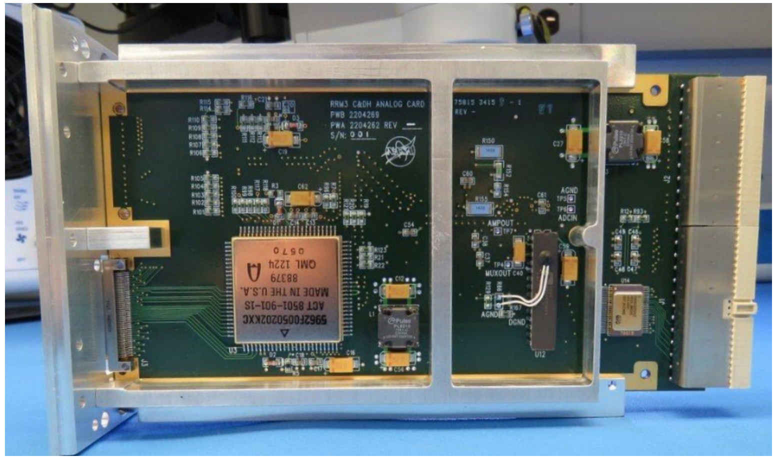
Robotic Refueling Mission 3 SpaceCube



1553/Ethernet/Digital Card



Analog Card



Accomplishments and Key Highlights: SpaceCube Mini-Z

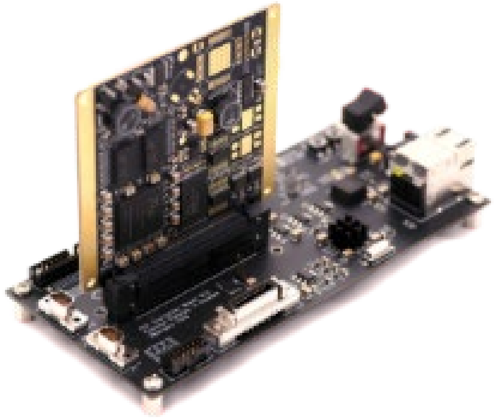
Overview of SpaceCube Mini-Z

- Collaborative development with **NSF CHREC** at University of Florida for Zynq-based 1U Board
  - Selective population scheme between commercial and rad-hard components
  - Rapid deployment prototyping
  - Convenient pre-built software packages with cFS
- **Re-Envisioned** to support quality-of-life upgrades and enable specific NASA mission needs

Missions and Heritage

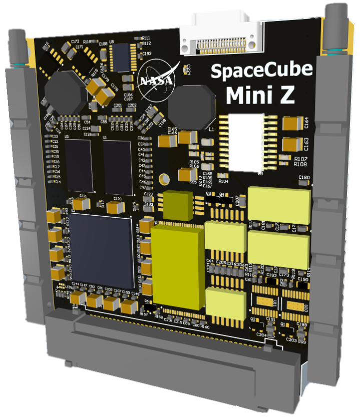
98% COTS Parts

- Launched Feb 2017 to ISS on STP-H5/CSP featuring 2 CSPv1 cards performing image processing
- Launched May 2019 to ISS on STP-H6/SSIVP featuring 5 CSPv1 for massive parallel computing
- Featured on many more…

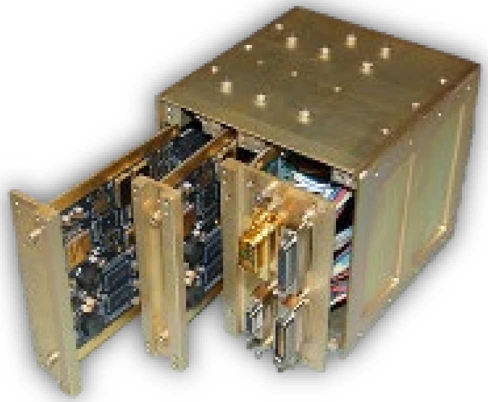


CSPv1 Development Board

Original CSPv1



NASA SpaceCube Mini-Z



STP-H5/CSP Flight Unit

Goddard Space Flight Center

Time-on-orbit

Project	Version	Part Req	BOM Count	COTS %	COTS Months
RNS	v1.0	2+	3700	1%	12
MISSE-7	v1.0	N/A	3100	2%	22320
SMART	v1.5	N/A	1000	95%	32
STP-H4 CIB	v1.0	N/A	1500	1%	900
STP-H4 ISE2.0	v2.0-EM	N/A	1250	99%	111375
STP-H5 CIB	v1.0	N/A	1500	1%	1101
STP-H5 ISEM	v2.0 Mini	N/A	1000	98%	35966
STP-H5 Raven	v2.0-EM	N/A	1500	99%	136249
RRM3	v2.0	N/A	1429	95%	41498
STP-H6 CIB	v1.0	N/A	1500	1%	295
STP-H6 GPS	v2.0	N/A	1157	99%	22527
Restore-L Lidar	v2.0	3	2000	0%	N/A
STPSat6	v2.0 Mini	N/A	1500	98%	N/A

Totals	Units Flown	11
	Xilinx FPGAs	26
	Xilinx Device-Years	66.64
	Part Years	141575
	COTS Part Years	31050

All Xilinxs flown have been unscreened

Failures:
- **Commercial Ethernet Hub on ISE2.0, 1-yr into mission**
- **No known EEE part failures in orbit**

Also to note: We flew many COTS components on some of these projects:
- **ISE2.0, SMART, and ISEM all flew COTS cameras that were ruggedized. SMART flew COTS SATA drives.**
- **Raven flew a $5 USB interface card to an IR sensor**
- **STP-H5 and -H6 have CHREC Space Processors (CSPs) that were 95% COTS components. See references for more info on CSP results (no failures to date)**
- **RRM3 suffered a failure that may be related to a specific COTS part, but the part was used in a stressing condition that any grade part would eventually fail.**
- **NavCube Commercial vendor populated PWBs**

Lessons

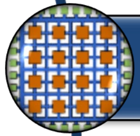
- The likelihood of other issues is much greater than a part issue
  - Workmanship, solder shorts, thermal design, cold solder joint, design deficiency, incompatible connectors, improper derating, worst case analysis deficiency, etc.
  - Lots of “parts issues” that truly were not parts issues
- Do not need to strictly satisfy long-standing practices or views
- Robust design and test philosophy injects more confidence in end-product than what parts levels are inside the box. Part tolerance issues are flushed out of a good design and test program.
- High number of EDUs increases the sample size, and the likelihood of finding a design/part issue

Conclusion

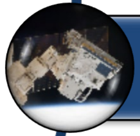
SpaceCube is a MISSION ENABLING technology

- Delivers exceptional computing power in number of form factors

- Cross-cutting technology for Comm/Nav, Earth and Space Science, Planetary, and Exploration missions

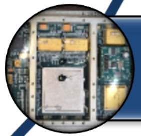


- Being reconfigurable equals BIG SAVINGS



- Past research / missions have proven viability

- Designs support AI applications for autonomy and analysis onboard



- Successful technology transfer to industry through commercialization

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Publications

SpaceCube Publications

- A. Geist, C. Brewer, M. Davis, N. Franconi, S. Heyward, T. Wise G. Crum, D. Petrick, R. Ripley, C. Wilson, and T. Flatley, “SpaceCube v3.0 NASA Next-Generation High-Performance Processor for Science Applications,” 33rd Annual AIAA/USU Conf. on Small Satellites, SSC19-XII-02, Logan, UT, August 3-8, 2019.
- A. Schmidt, M. French, and T. Flatley, “Radiation hardening by software techniques on FPGAs: Flight experiment evaluation and results,” IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2017.
- A. Schmidt, G. Weisz, M. French, T. Flatley, C. Villalpando, “SpaceCubeX: A framework for evaluating hybrid multi-core CPU/FPGA/DSP architectures,” IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2017.
- D. Petrick, N. Gill, M. Hassouneh R. Stone, L. Winternitz, L. Thomas, M. Davis, P. Sparacino, and T. Flatley, “Adapting the SpaceCube v2.0 data processing system for mission-unique application requirements,” IEEE Aerospace Conference, Big Sky, MT, June 15-18, 2015.
- T. Flatley, “Keynote 2 — SpaceCube — A family of reconfigurable hybrid on-board science data processors,” International Conference on ReConFigurable Computing and FPGAs (ReConFig14), Cancun, Mexico, Dec 8-10, 2014.
- D. Petrick, A. Geist, D. Albaijes, M. Davis, P. Sparacino, G. Crum, R. Ripley, J. Boblitt, and T. Flatley, “SpaceCube v2.0 space flight hybrid reconfigurable data processing system,” IEEE Aerospace Conference, Big Sky, MT, March 1-8, 2014.
- D. Petrick, D. Espinosa, R. Ripley, G. Crum, A. Geist, and T. Flatley, “Adapting the reconfigurable spacecube processing system for multiple mission applications,” IEEE Aerospace Conference, Big Sky, MT, March 1-8, 2014.
- T. Flatley, “Keynote address I: SpaceCube: A family of reconfigurable hybrid on-board science data processors,” NASA/ESA Conference on Adaptive Hardware and Systems (AHS), June 25-28, 2012.
- M. Lin, T. Flatley, A. Geist, and D. Petrick, “NASA GSFC Development of the SpaceCube Mini,” 25th Annual AIAA/USU Conf. on Small Satellites, SSC11-X-11, Logan, UT, August 8-11, 2011.
- J. Esper, T. Flatley, and J. Bull, “Small Rocket/Spacecraft Technology (SMART) Platform,” ,” 25th Annual AIAA/USU Conf. on Small Satellites, SSC11-VII-6, Logan, UT, August 8-11, 2011.

SmallSat / CubeSat Publications

- S. G. Kanekal L. Blum E. R. Christian G. Crum M. Desai J. Dumonthier A. Evans A. D. Greeley S. Guerro S. Livi K. LLera J. Lucas J. MacKinnon J. Mukherjee K. Ogasawara N. Paschalidis D. Patel E. Pollack S. Riall Q. Schiller G. Suarez E. J. Summerlin, M. Desai, S. Livi, K. Llera, J. Mukherjee, and K. Ogasawara, “CeREs: The Compact Radiation belt Explorer,” 32nd Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug 4-9, 2018.

- S. Sabogal, P. Gauvin, B. Shea, D. Sabogal, A. Gillette, C. Wilson, A. D. George, G. Crum, and T. Flatley, “Spacecraft Supercomputing Experiment for STP-H6,” 31st Annual AIAA/USU Conf. on Small Satellites, SSC17-XIII-02, Logan, UT, Aug 5-10, 2017.

- C. Wilson, J. MacKinnon, P. Gauvin, S. Sabogal, A. D. George, G. Crum, T. Flatley, “µCSP: A Diminutive, Hybrid, Space Processor for Smart Modules and CubeSats,” 30th Annual AIAA/USU Conf. on Small Satellites, SSC16-X-4, Logan, UT, August 6-11, 2016.

- C. Wilson, J. Stewart, P. Gauvin, J. MacKinnon, J. Coole, J. Urriste, A. D. George, G. Crum, A. Wilson, and M. Wirthlin, “CSP Hybrid Space Computing for STP-H5/ISEM on ISS,” 29th Annual AIAA/USU Conf. on Small Satellites, SSC15-III-10, Logan, UT, August 8-13, 2015.

- B. LaMeres, S. Harkness, M. Handley, P. Moholt, C. Julien, T. Kaiser, D. Klumpar, K. Mashburn, L. Springer, G. Crum, “RadSat – Radiation Tolerant SmallSat Computer System, “29th Annual AIAA/USU Conf. on Small Satellites, SSC15-X-8, Logan, UT, August 8-13, 2015.

- S. Altunc, O. Kegege, S. Bundick, H. Shaw, S. Schaire, G. Bussey, G. Crum, J. Burke, S. Palo, D. O’Conor, “X-band CubeSat Communication System Demonstration,” 29th Annual AIAA/USU Conf. on Small Satellites, SSC15-IV-8, Logan, UT, August 8-13, 2015

- D. Rudolph, C. Wilson, J. Stewart, P. Gauvin, G. Crum, A. D. George, M. Wirthlin, H. Lam, “CSP: A Multifaceted Hybrid System for Space Computing,” Proc. of 28th Annual AIAA/USU Conference on Small Satellites, SSC14-III-3, Logan, UT, August 2-7, 2014.

- S. Palo, D. O’Connor, E. DeVito, R. Kohnert, G. Crum, S. Altune, “Expanding CubeSat Capabilities with a Low Cost Transceiver,” Proc. of 28th Annual AIAA/USU Conference on Small Satellites, SSC14-IX-1, Logan, UT, August 2-7, 2014.