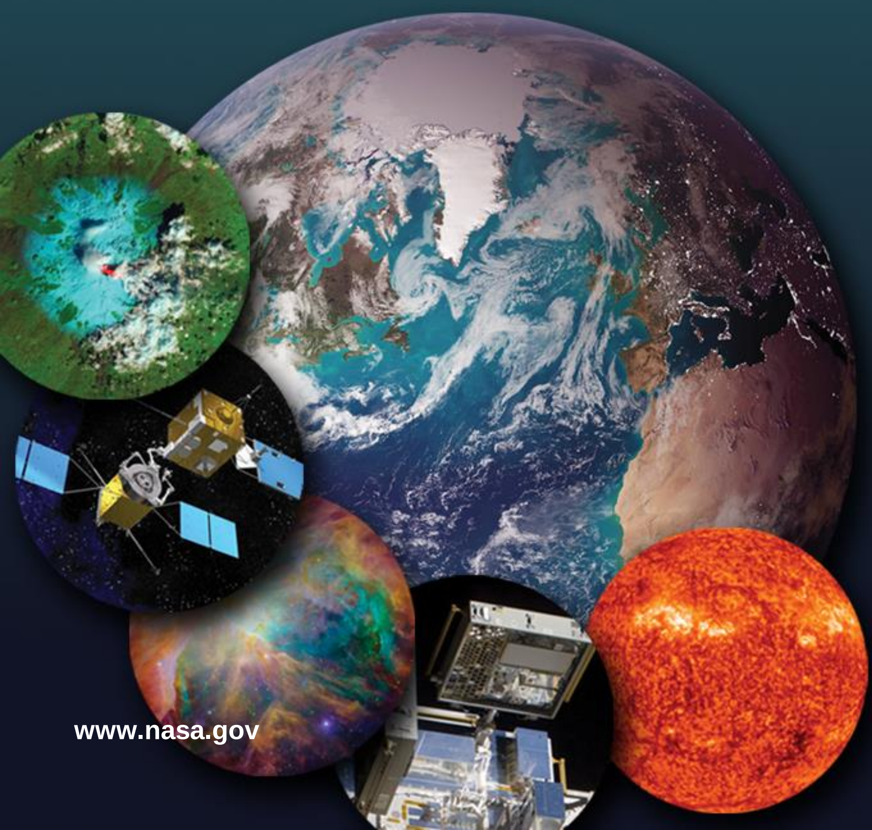
National Aeronautics and Space Administration

SpaceCube: A Family Of Reconfigurable Hybrid On-Board Science Data Processors

SpaceCube



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2014 International Conference on Reconfigurable Computing and FPGAs
Cancún, Mexico December 8-10, 2014

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)

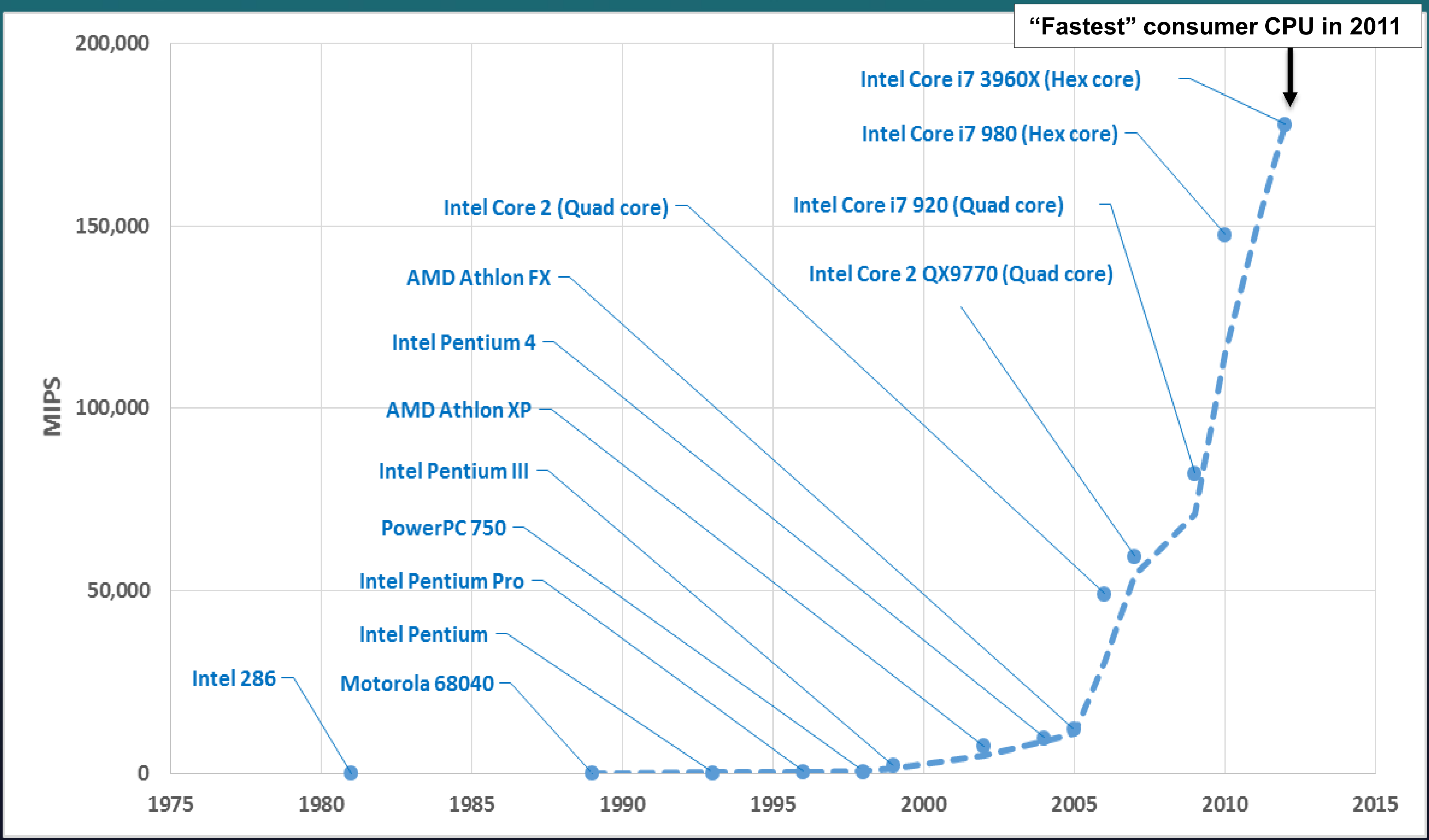
Our Solution

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

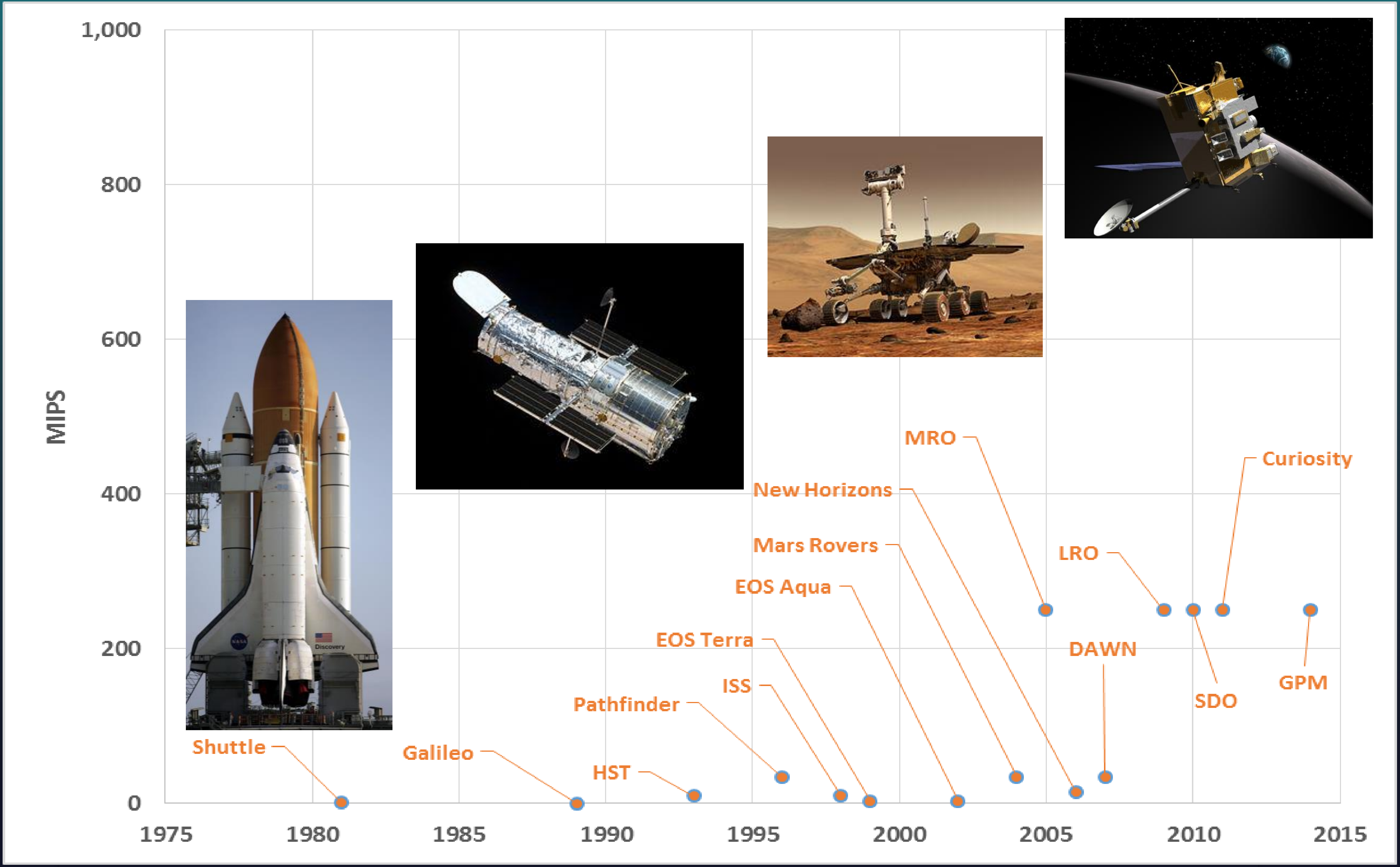
- **Hybrid processing … CPU, DSP and FPGA logic**
- **Integrated "radiation upset mitigation" techniques**
- **SpaceCube "core software" infrastructure**
- **Small "critical function" manager/watchdog**
- **Standard interfaces**

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

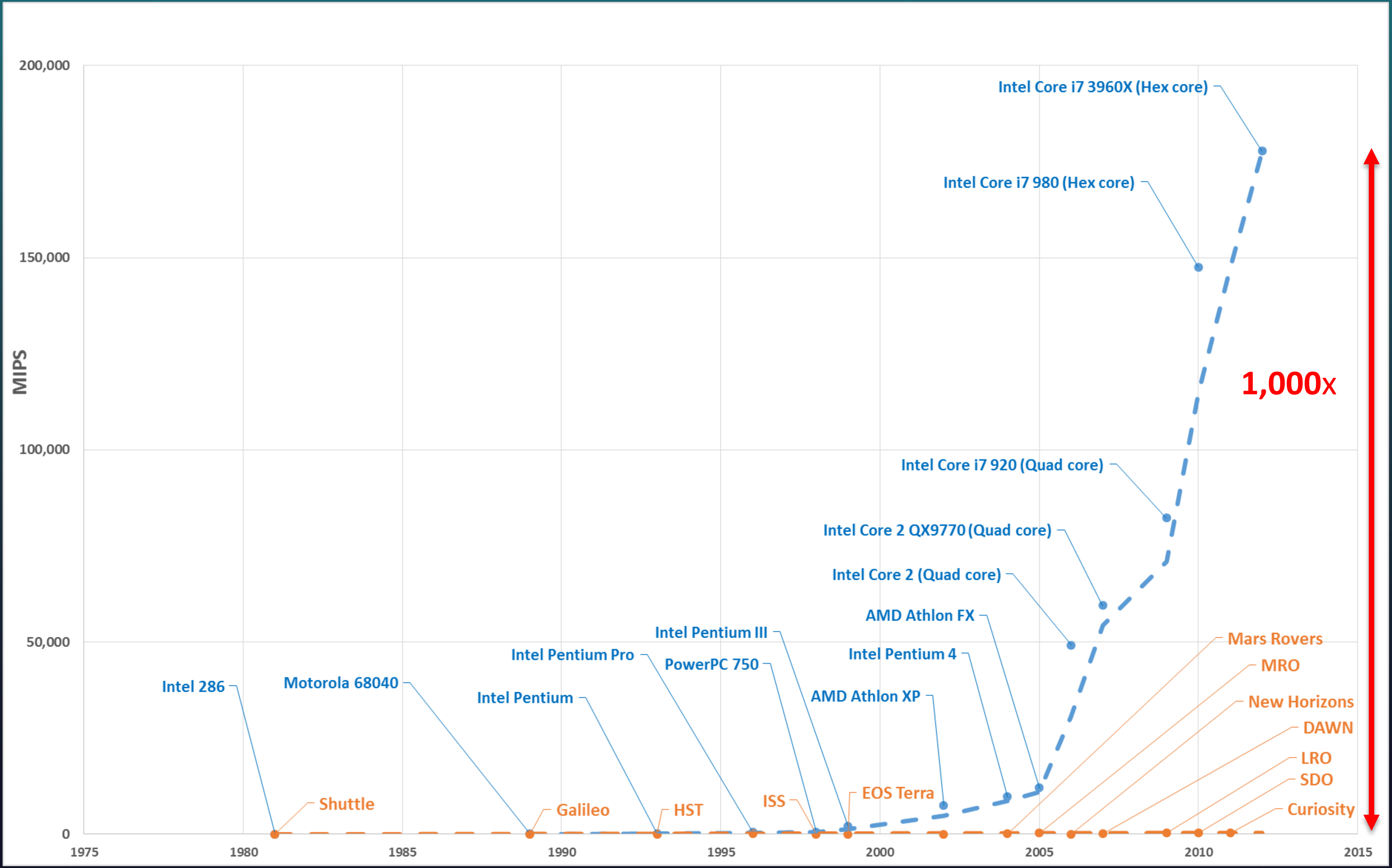
Commercial Processor Trend



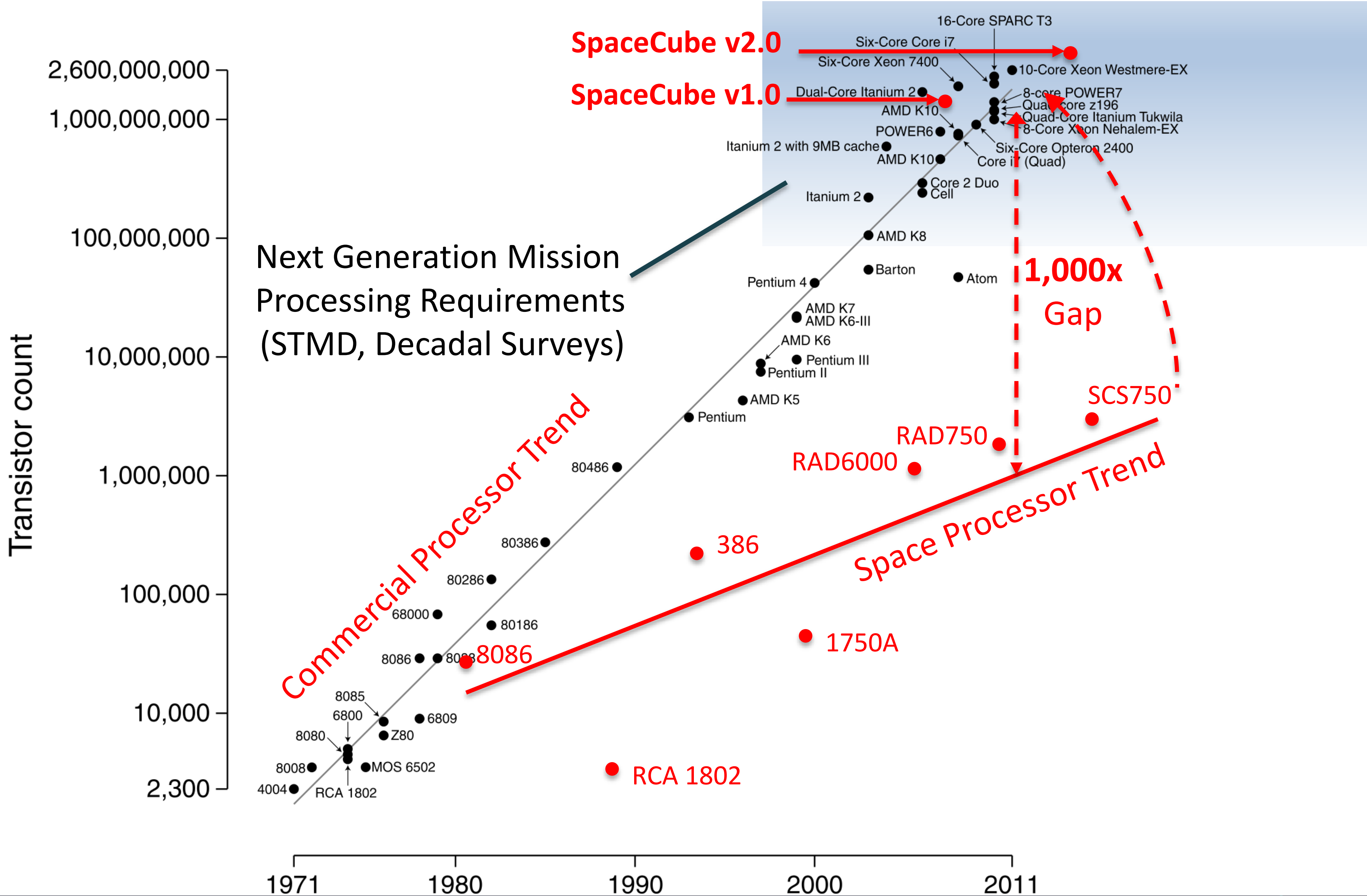
Space Processor Trend



Processor Trend Comparison



SpaceCube Closes the Gap



Processor Comparison

Processor	MIPS	Power	MIPS/W
MIL-STD-1750A	3	15W	0.2
RAD6000	35	15W	2.33
RAD750	300	15W	20
LEON 3FT	75	5W	15
LEON3FT Dual-Core	250	10W	25
BRE440 (PPC)	230	5W	46
Maxwell SCS750	1200	25W	48
SpaceCube 1.0	3000	7.5W	400
SpaceCube 2.0	6000	10W	600
SpaceCube Mini	3000	5W	600

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 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 2.0 is 4x to 20x more capable than these earlier systems**

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 algorithm updates**
- **Adaptive processing modes**

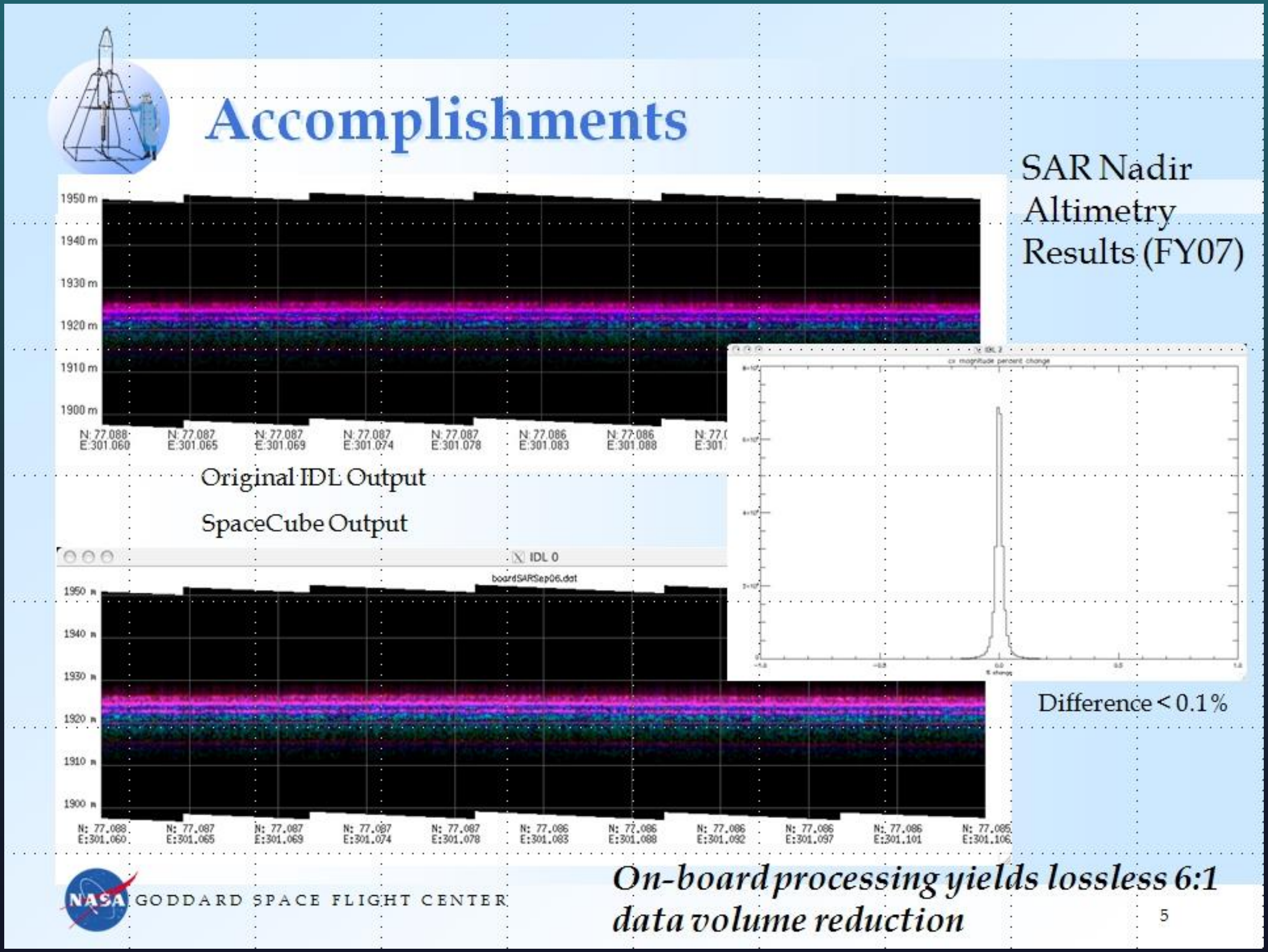
From mission to mission

- **Avionics reconfigured for new mission**

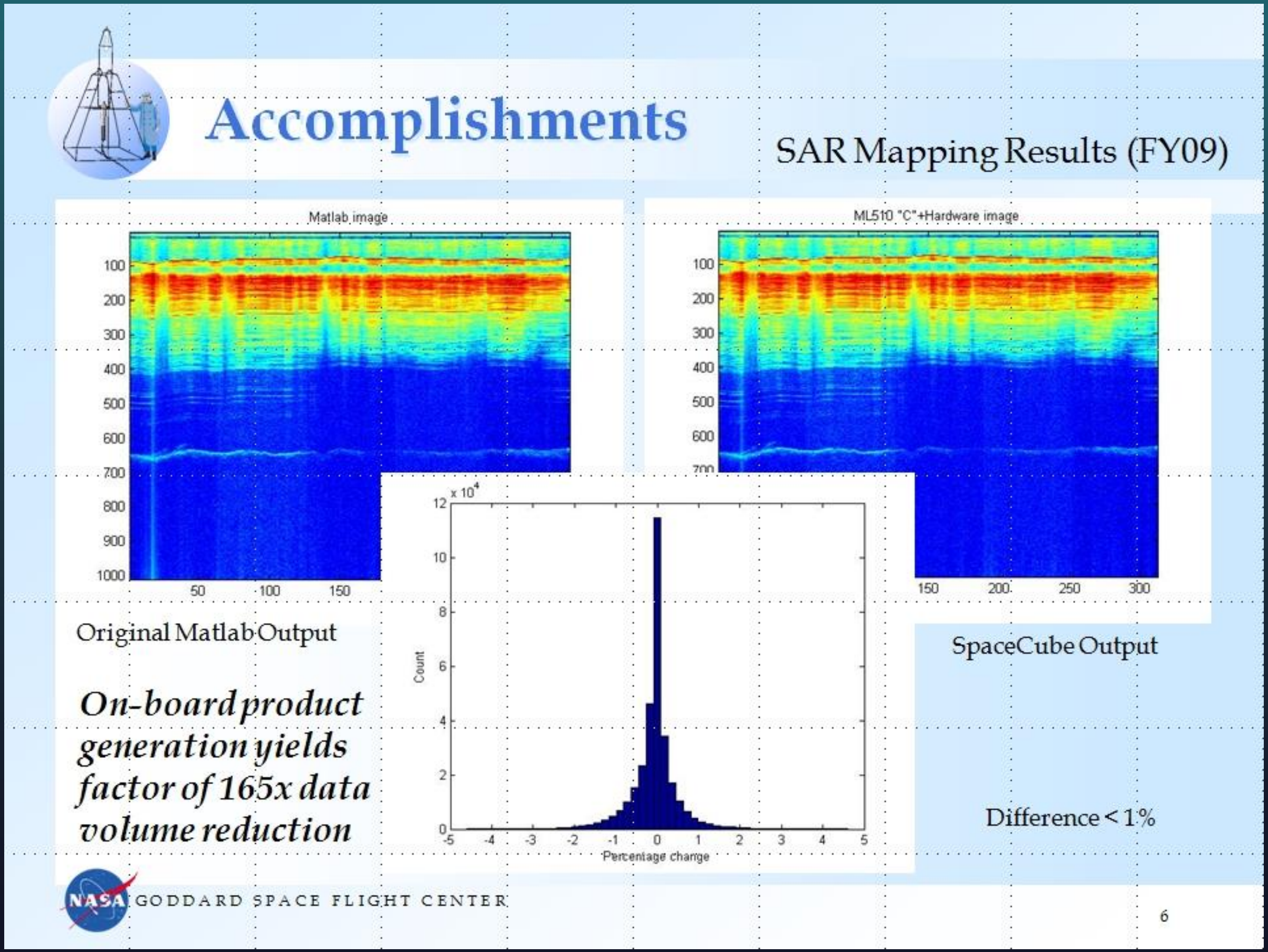
Past Research / Missions

2006 - 2012

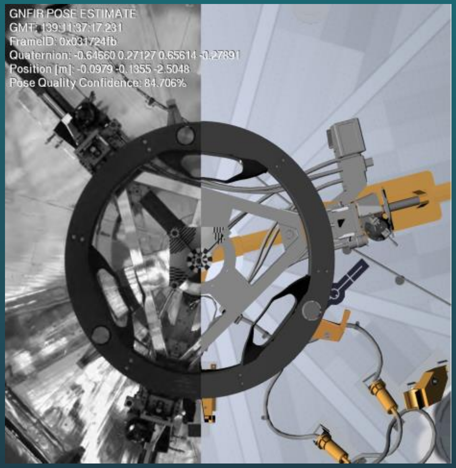
On-Board Data Reduction

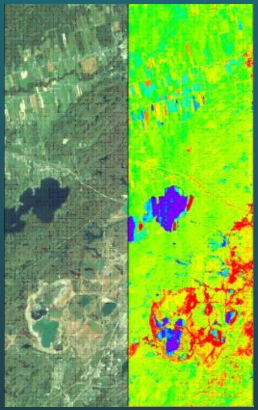


On-Board Data Reduction (cont.)

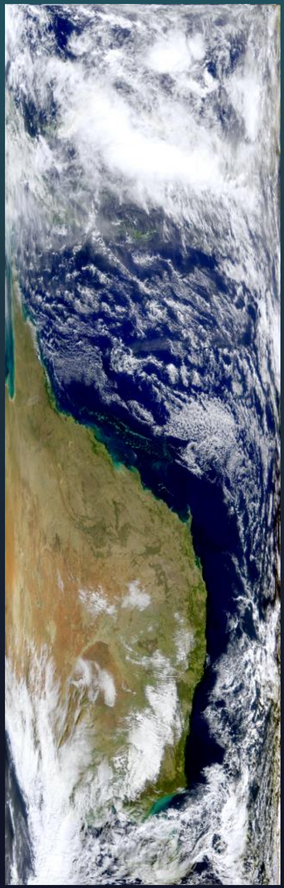


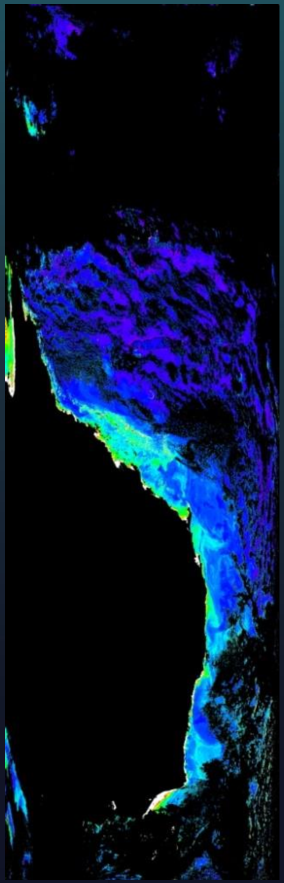
On-Board Product Generation

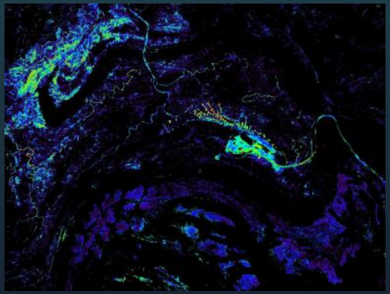


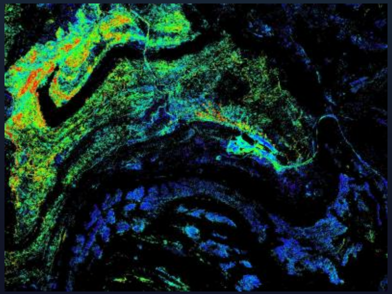


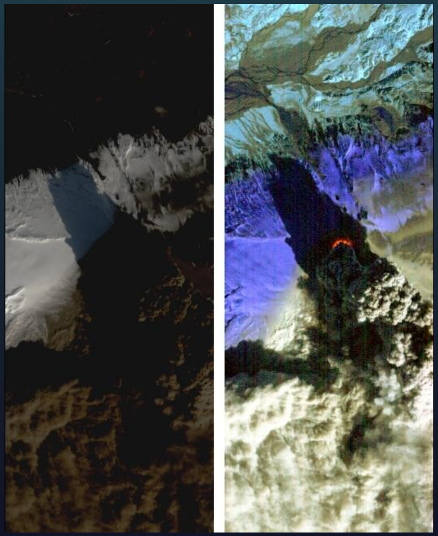
- Classification
- Product Generation
- Event Detection
- Atmospheric Correction

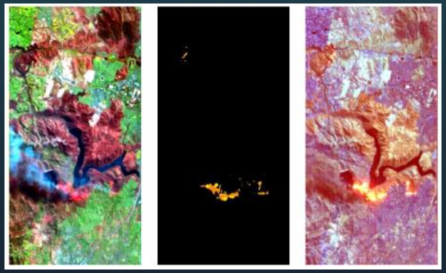


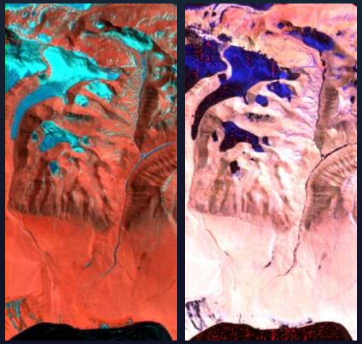






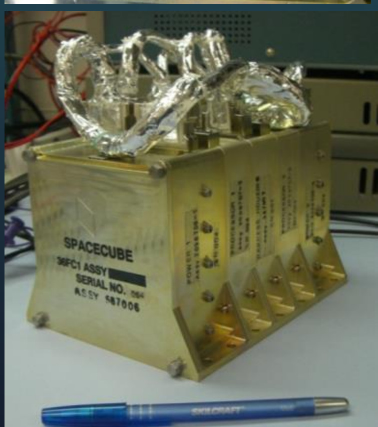






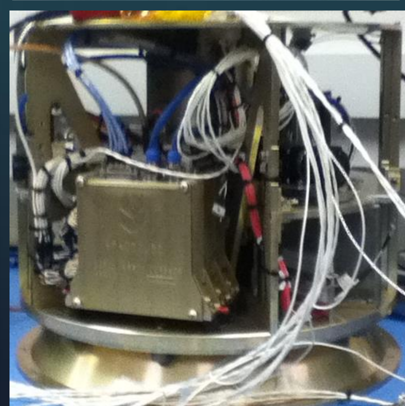
SpaceCube Family Overview

v1.0



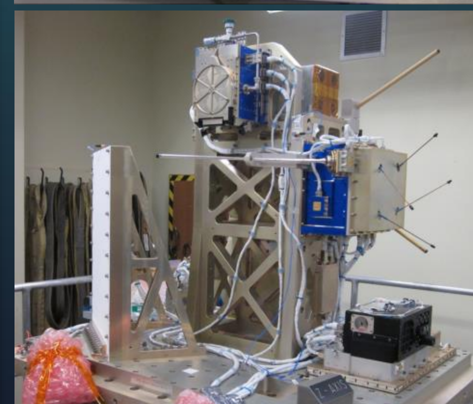
2009 STS-125
2009 MISSE-7
2013 STP-H4
2016 STP-H5

v1.5



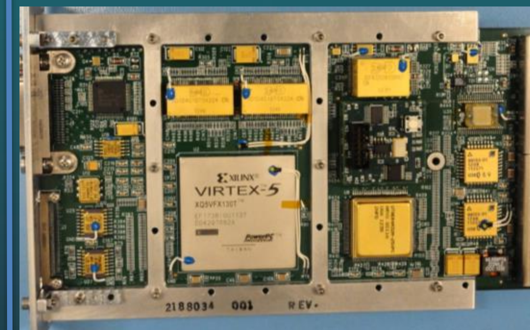
2012 SMART

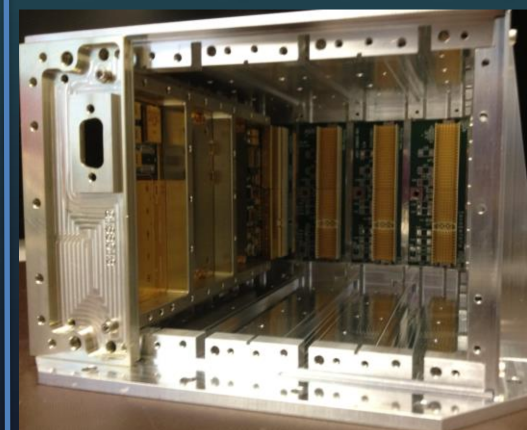
v2.0-EM



2013 STP-H4
2016 STP-H5

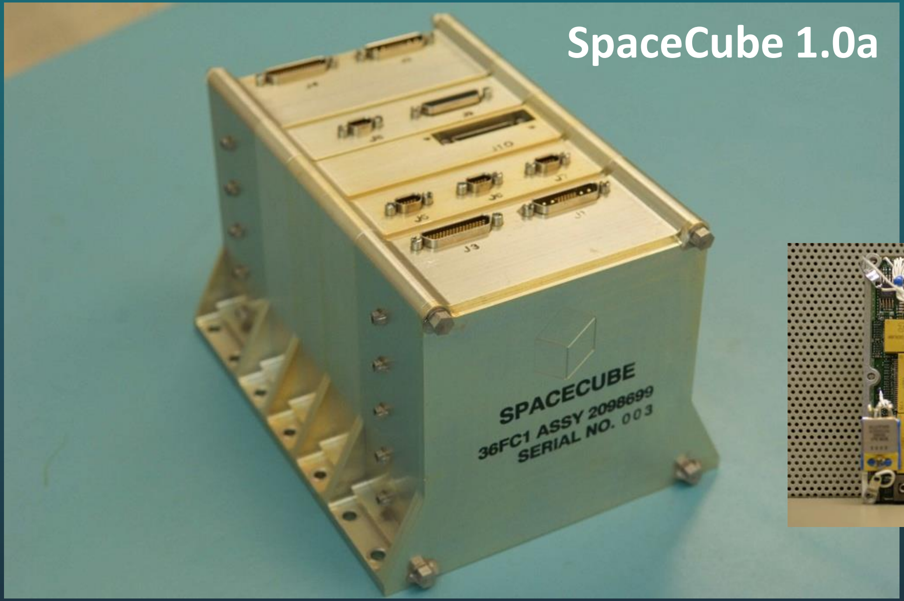
v2.0-FLT



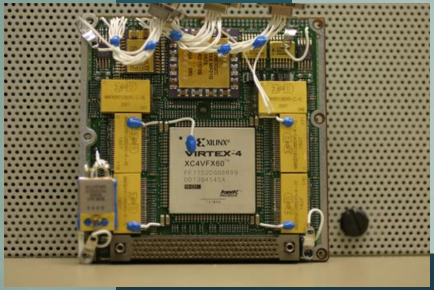


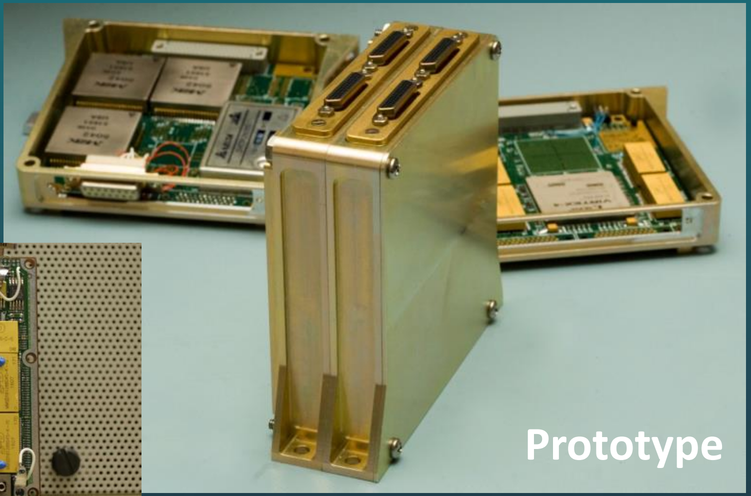
2015 GPS Demo
- Robotic Servicing
- Numerous proposals for Earth/Space/Helio

"First Generation" Systems



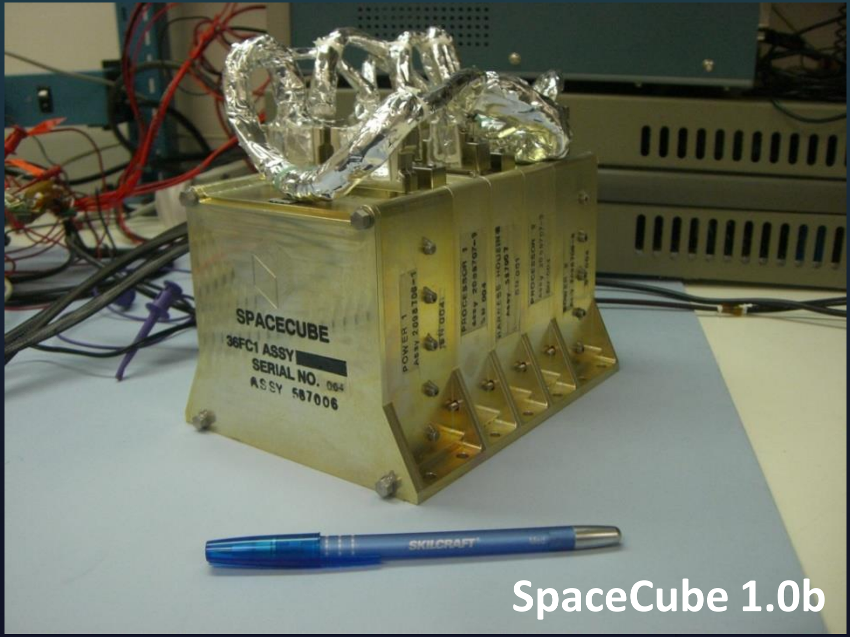
SpaceCube 1.0a





Prototype

SpaceCube 1.5



SpaceCube 1.0b

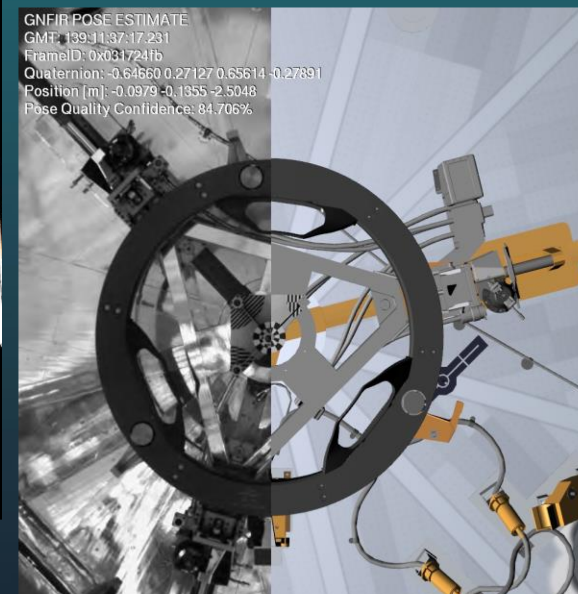
On-Board Image Processing

STS-125 Payload Bay

Long Range Camera on Rendezvous

Flight Image RNS Tracking Solution

Short Range Camera on Deploy



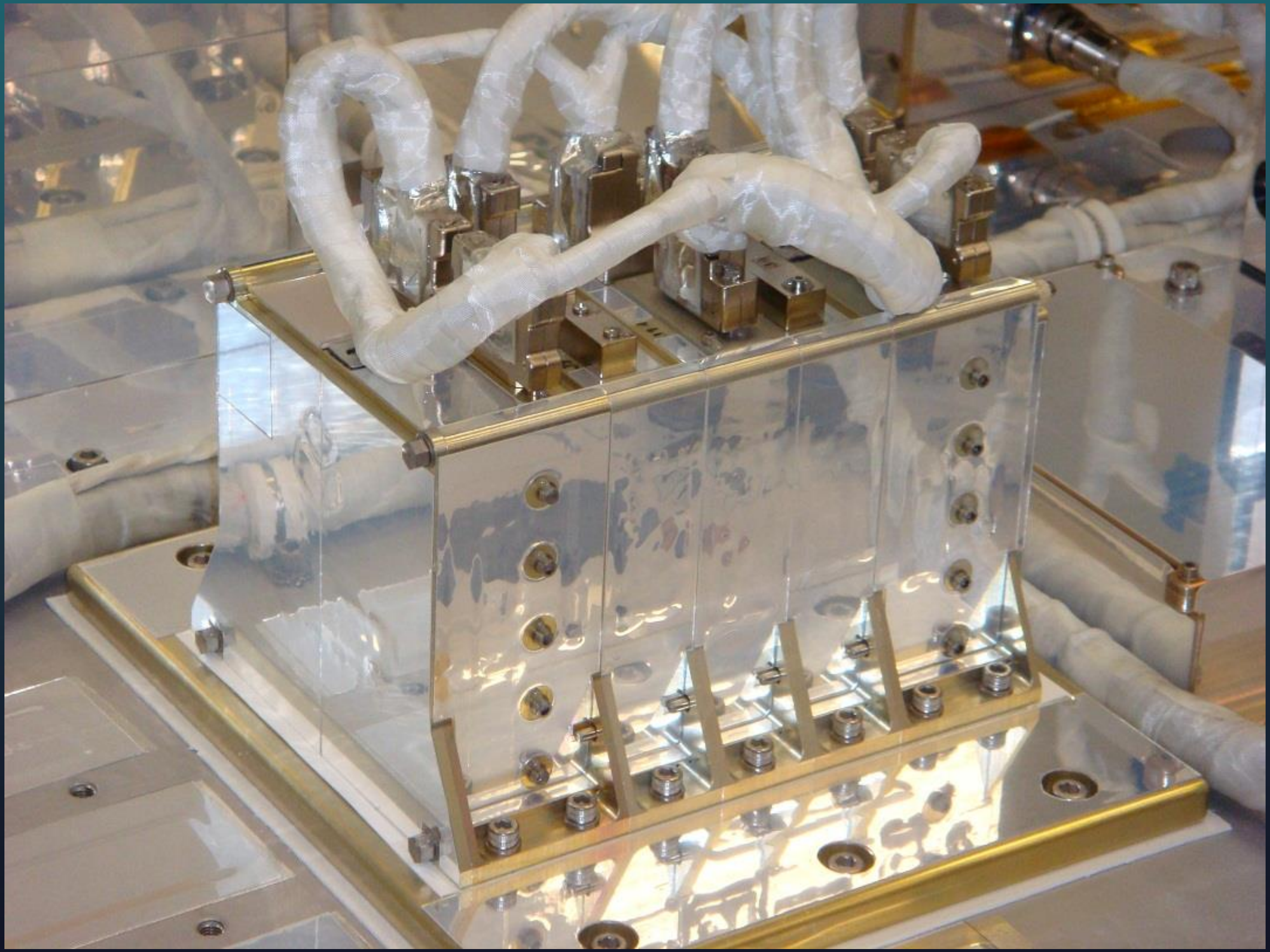
Flight Image RNS Tracking Solution

HST-SM4

GSFC SpaceCube 1.0a - Hubble SM 4 (May 2009):

- Autonomous Rendezvous and Docking Experiment
- Hosted camera AGC and two Pose algorithms

MISSE7/8 SpaceCube

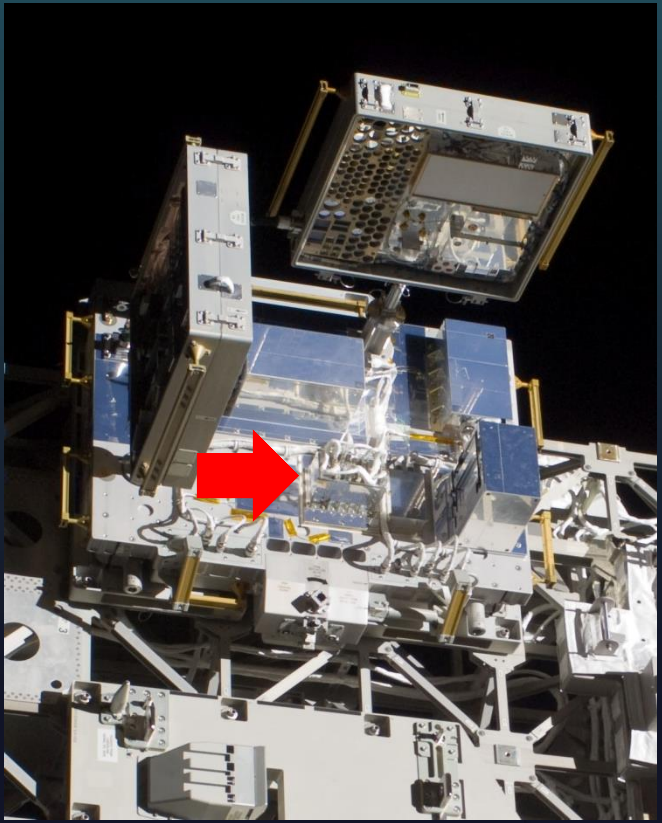


SpaceCube Upset Mitigation

Orbit	ISS
Days in orbit	1800+
Total SEUs detected & corrected	200+
Total SEU-induced resets	6
Total SEU-induced reset downtime	30 min
Total processor availability	99.99%

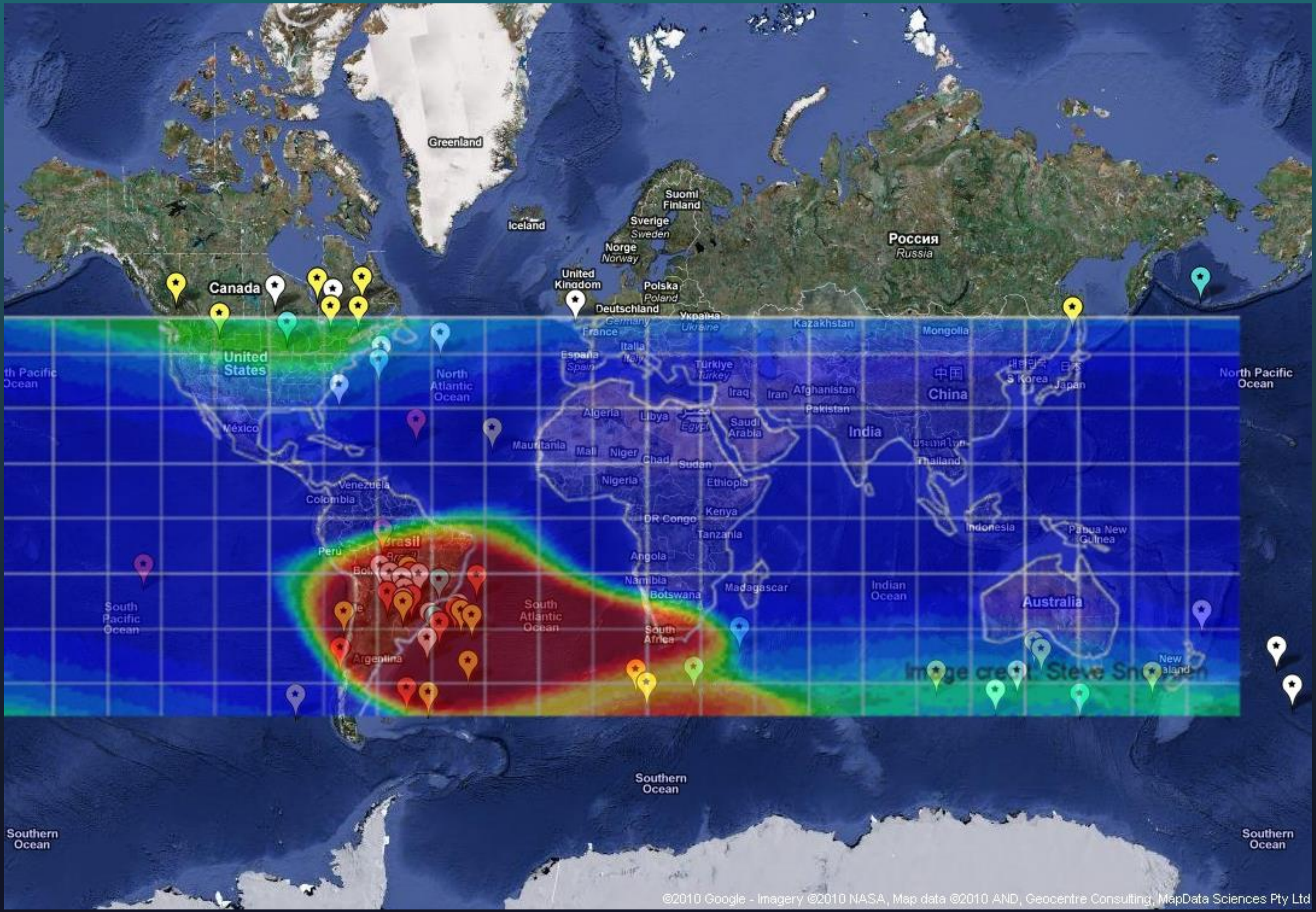
GSFC SpaceCube 1.0b (Nov 2009):

- "Radiation Hardened by Software" Experiment (RHBS)
- Autonomous Landing Application
- Collaboration with NRL and the DoD Space Test Program (STP)

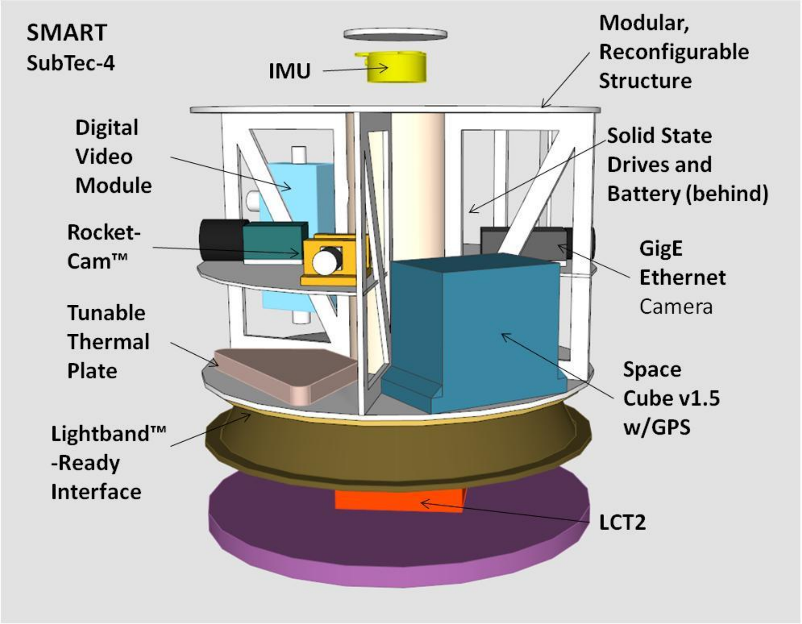


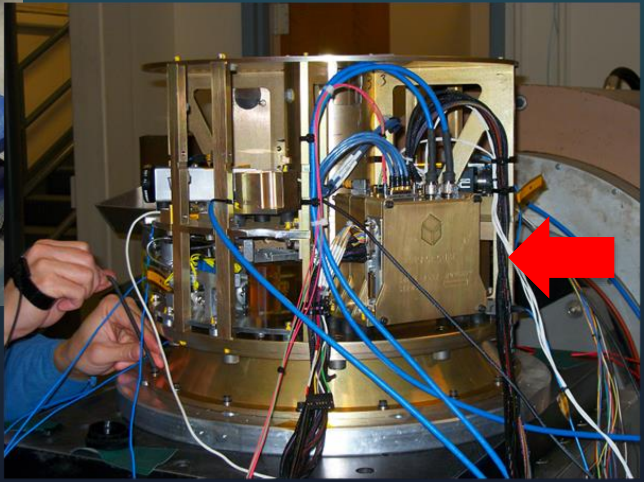
On-Orbit Upset Locations

On-Orbit Upset Locations



SMART Sounding Rocket Experiment





SpaceCube 1.5 on the SMART sounding rocket payload (SubTec-5, launched June 2011):

- **Multi-function avionics**
- **Collaboration with ORS**

SMART Video

SpaceCube 1.5 - SMART GigE Camera Clip
NASA Wallops Flight Facility - June 10, 2011

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

Current Research / Missions

2013 - 2014

ISS SpaceCube Experiment 2.0

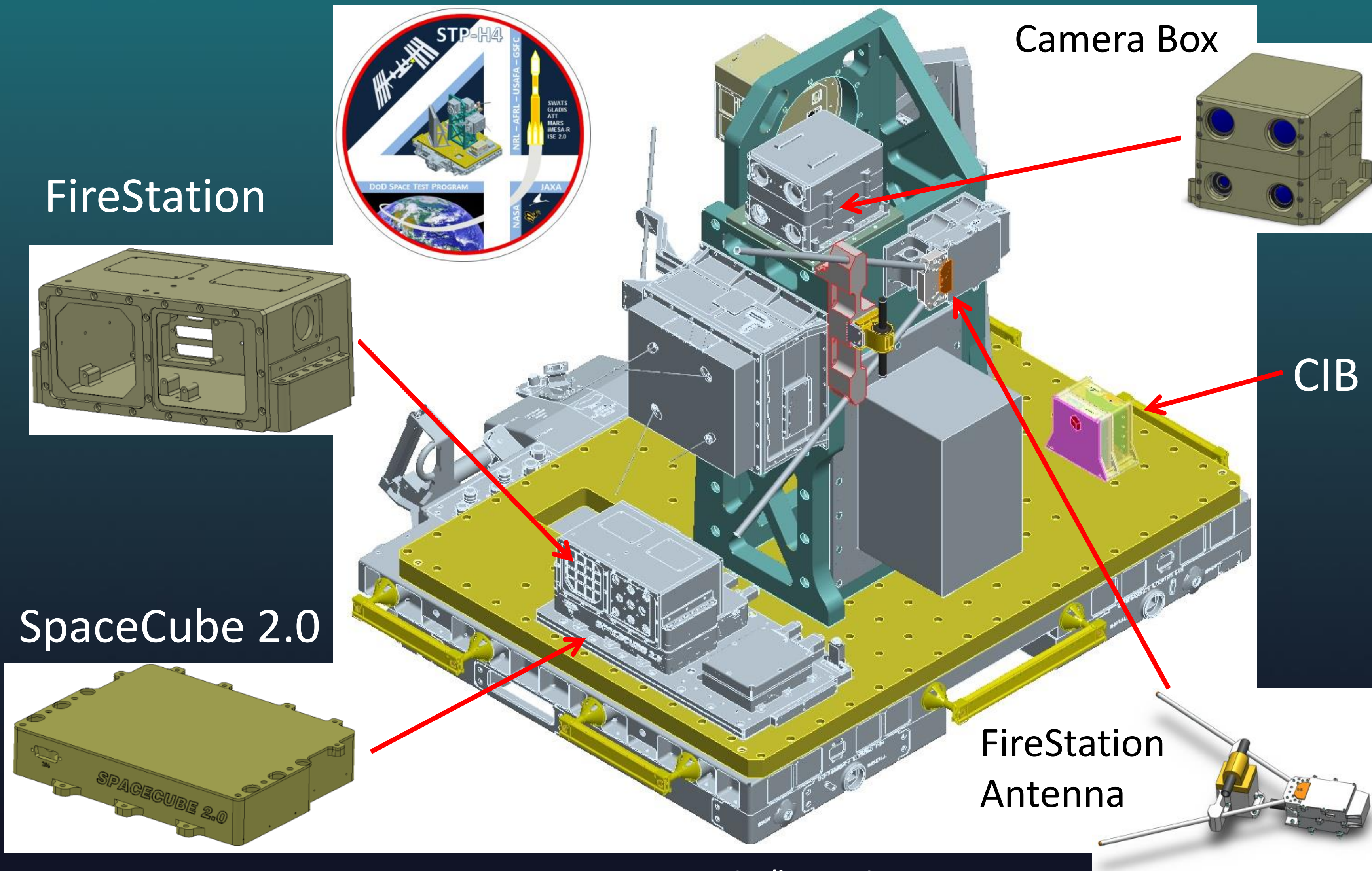
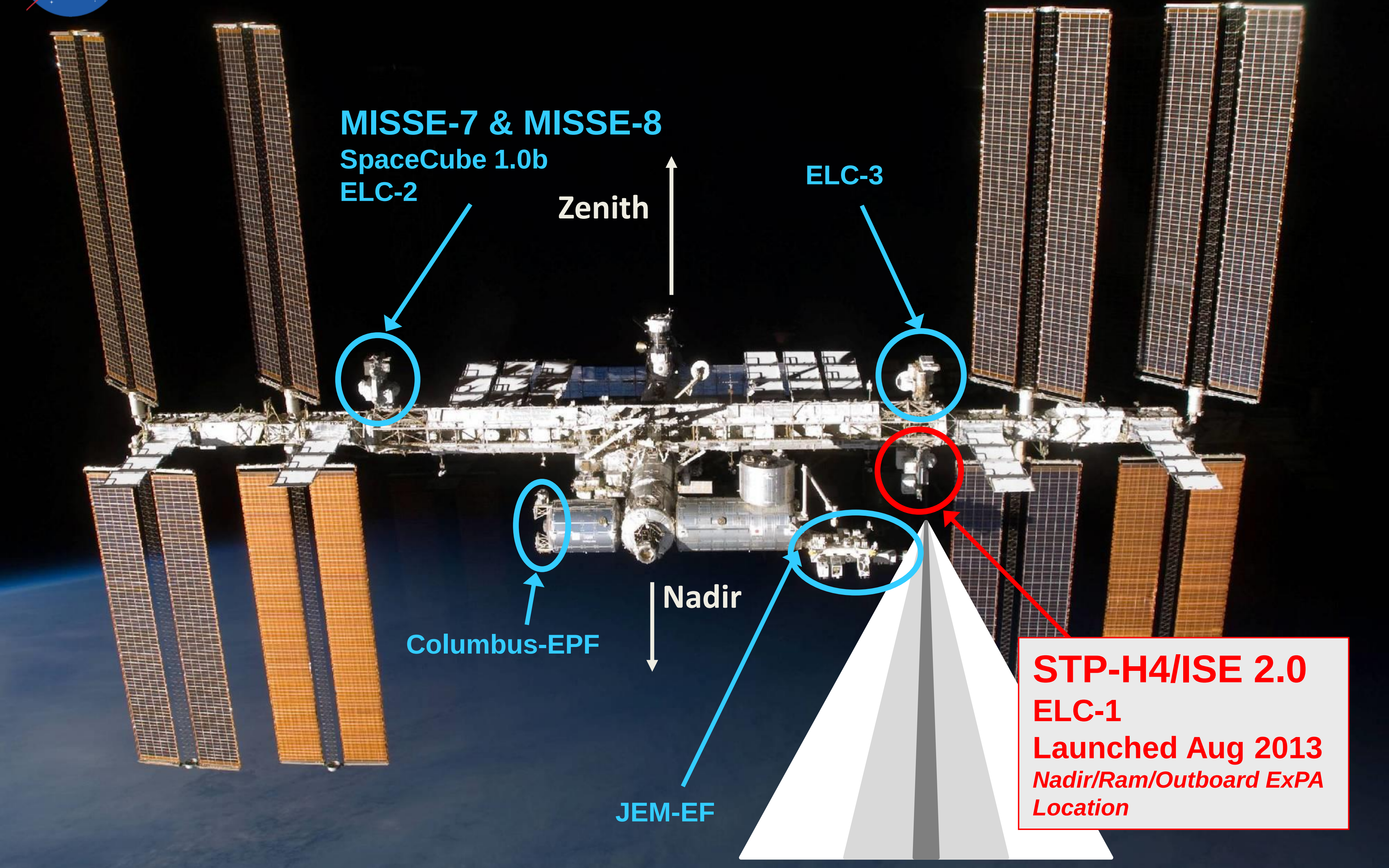


Image Credit: DoD Space Test Program

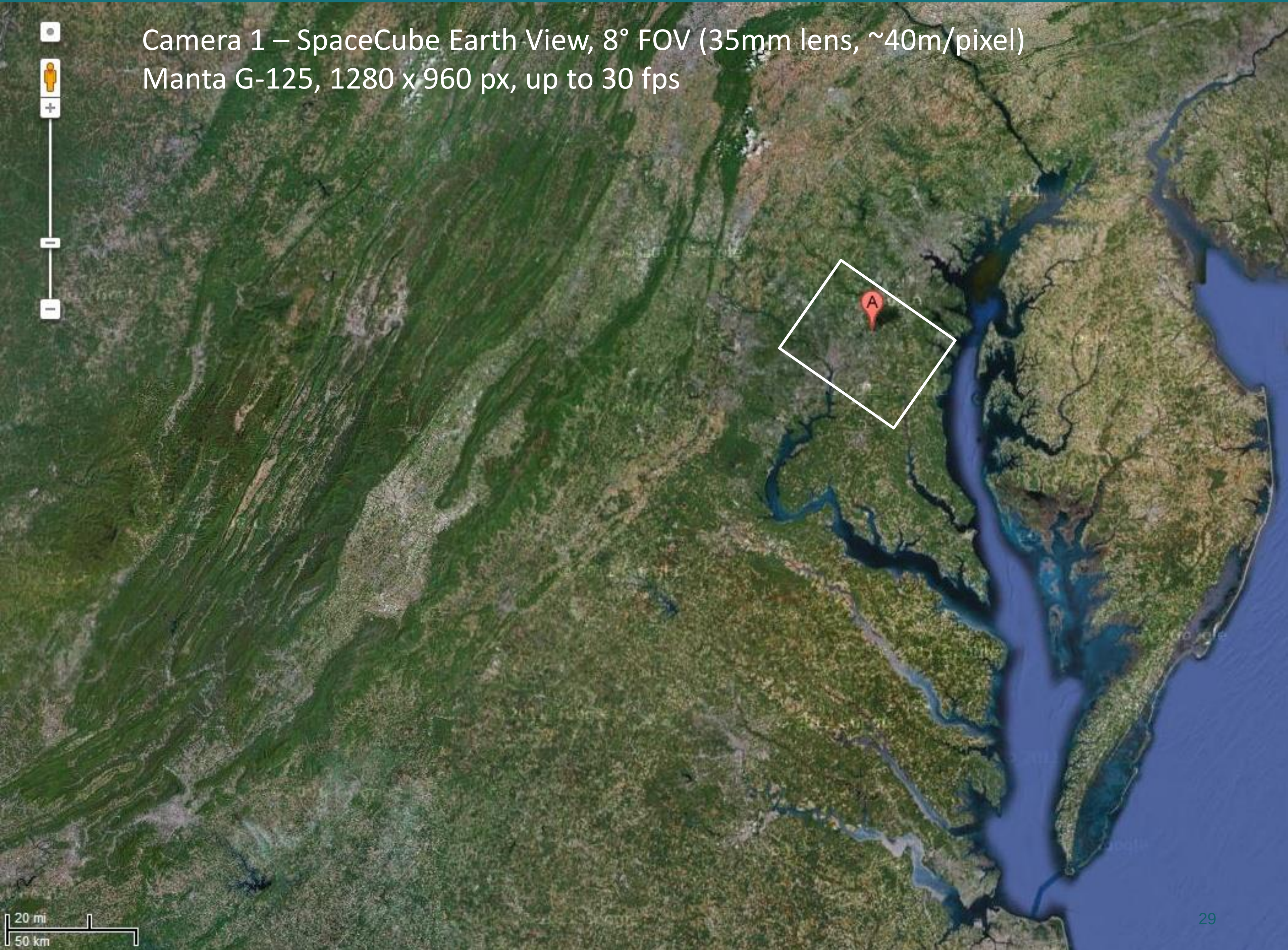
STP-H4 / ISE 2.0 Location & FOV



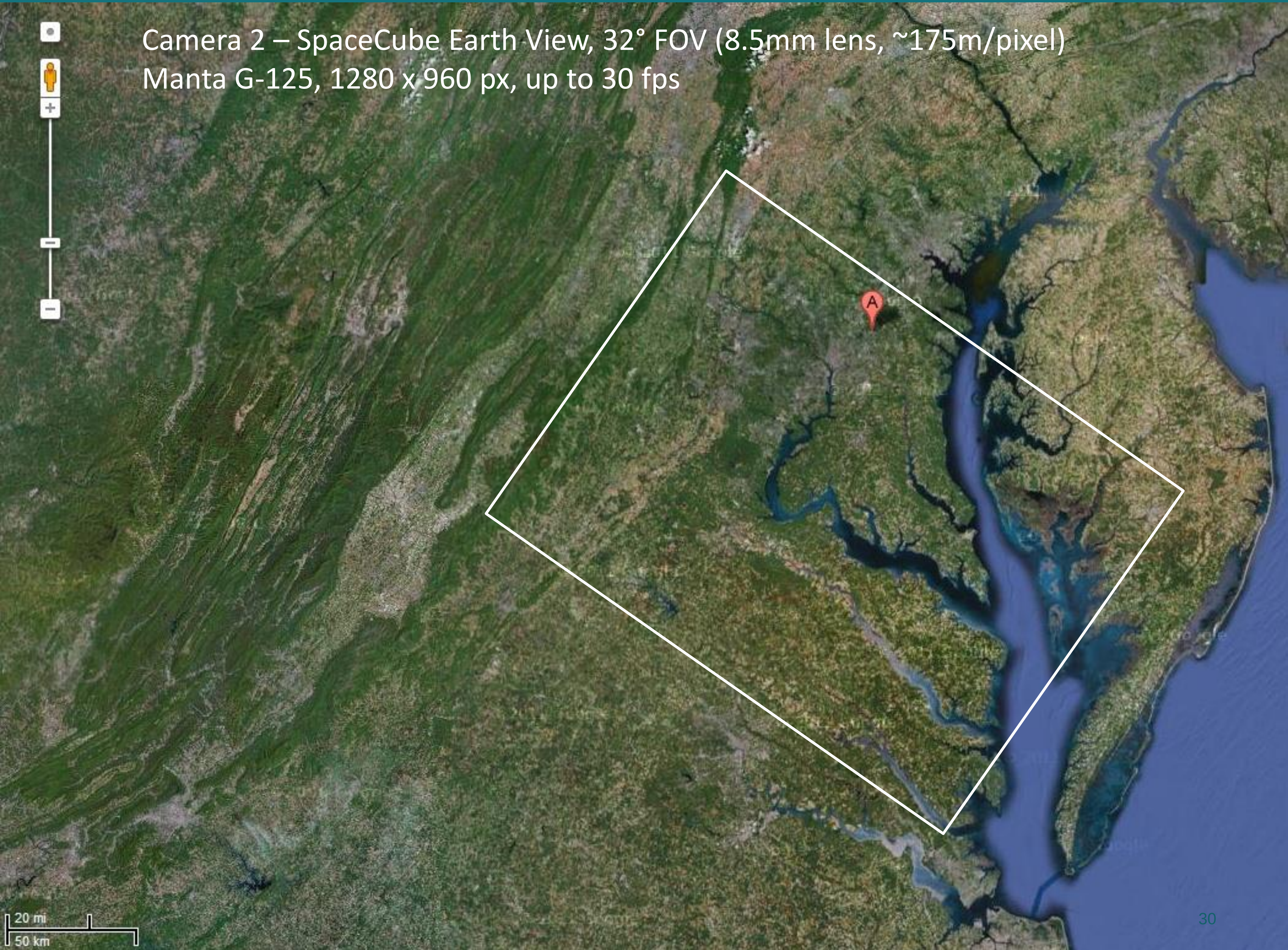
ISS Flying Towards You

Image Credit: DoD Space Test Program

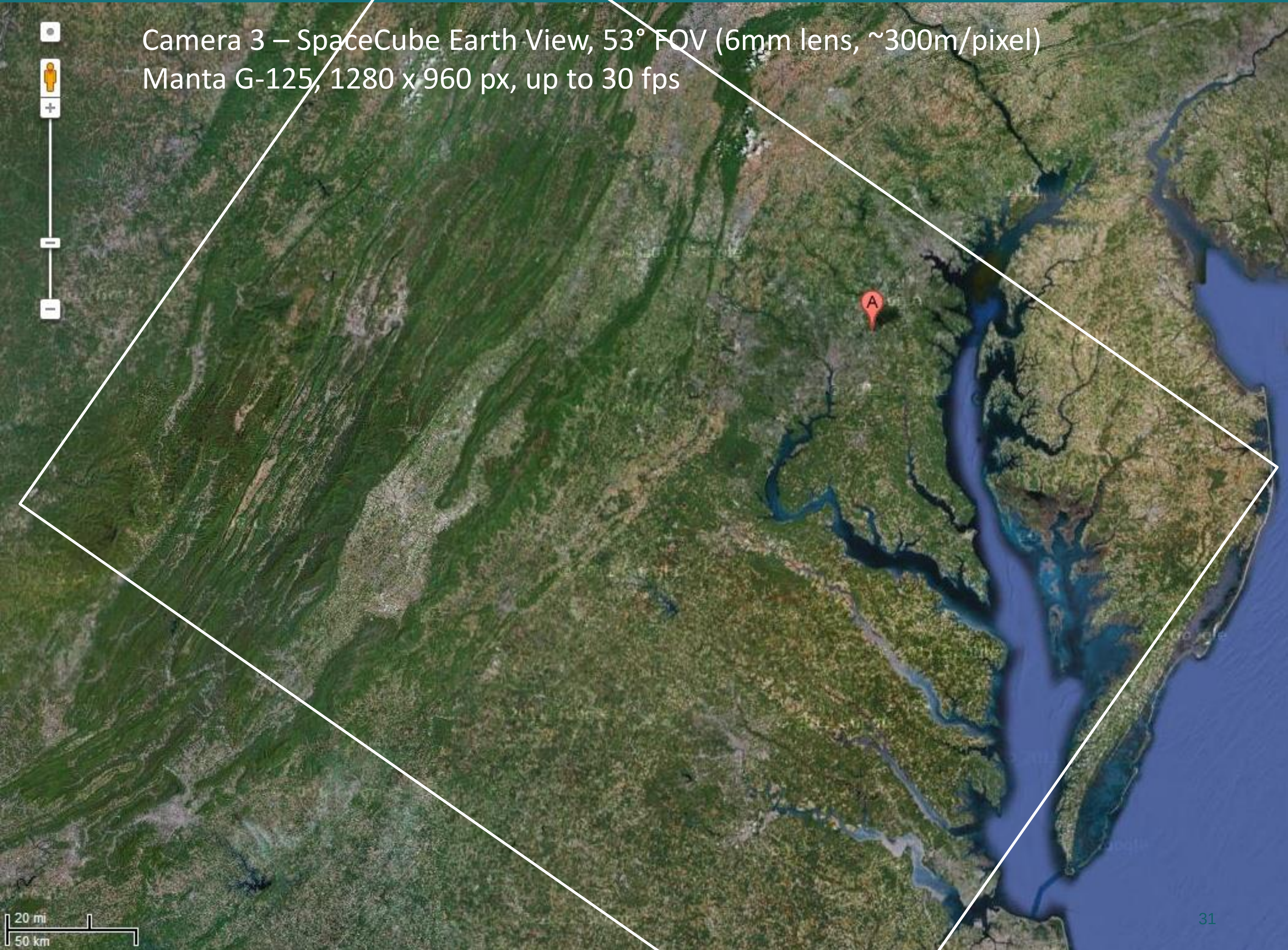
Camera 1 – SpaceCube Earth View, 8° FOV (35mm lens, ~40m/pixel)
Manta G-125, 1280 x 960 px, up to 30 fps



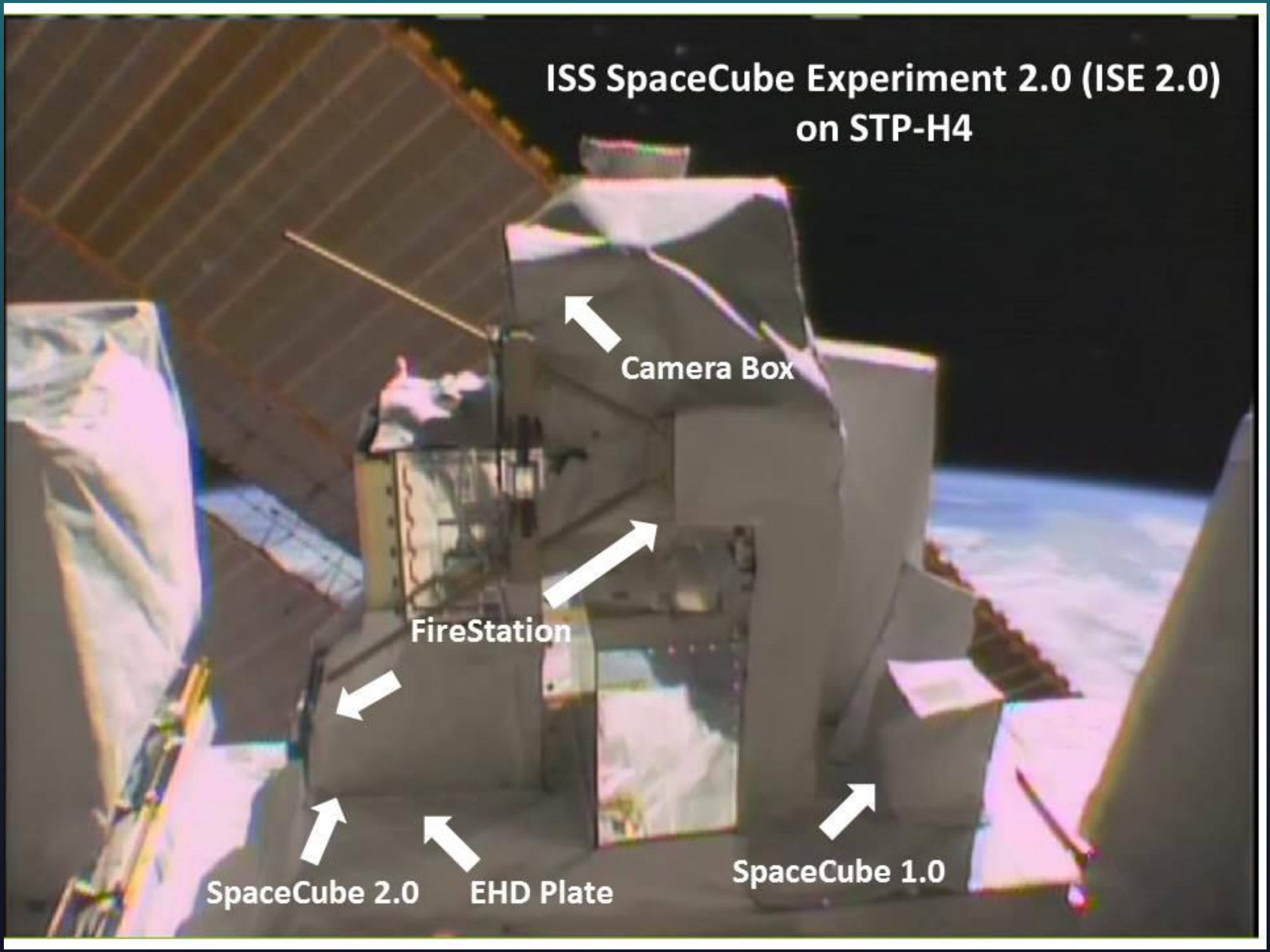
Camera 2 – SpaceCube Earth View, 32° FOV (8.5mm lens, ~175m/pixel)
Manta G-125, 1280 x 960 px, up to 30 fps



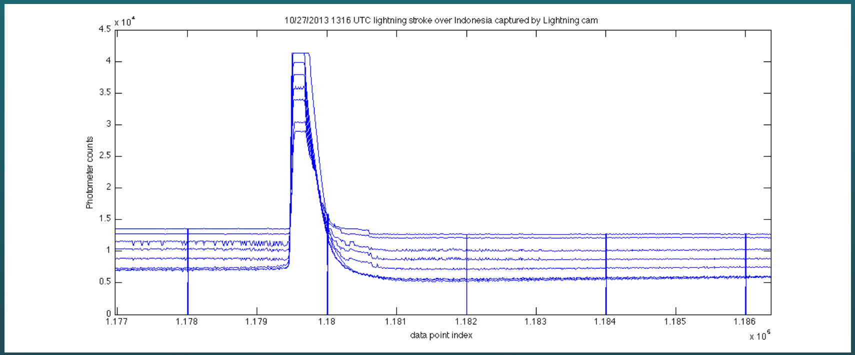
Camera 3 – SpaceCube Earth View, 53° FOV (6mm lens, ~300m/pixel)
Manta G-125, 1280 x 960 px, up to 30 fps

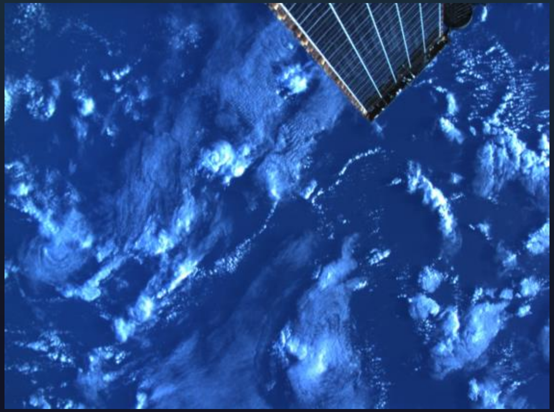


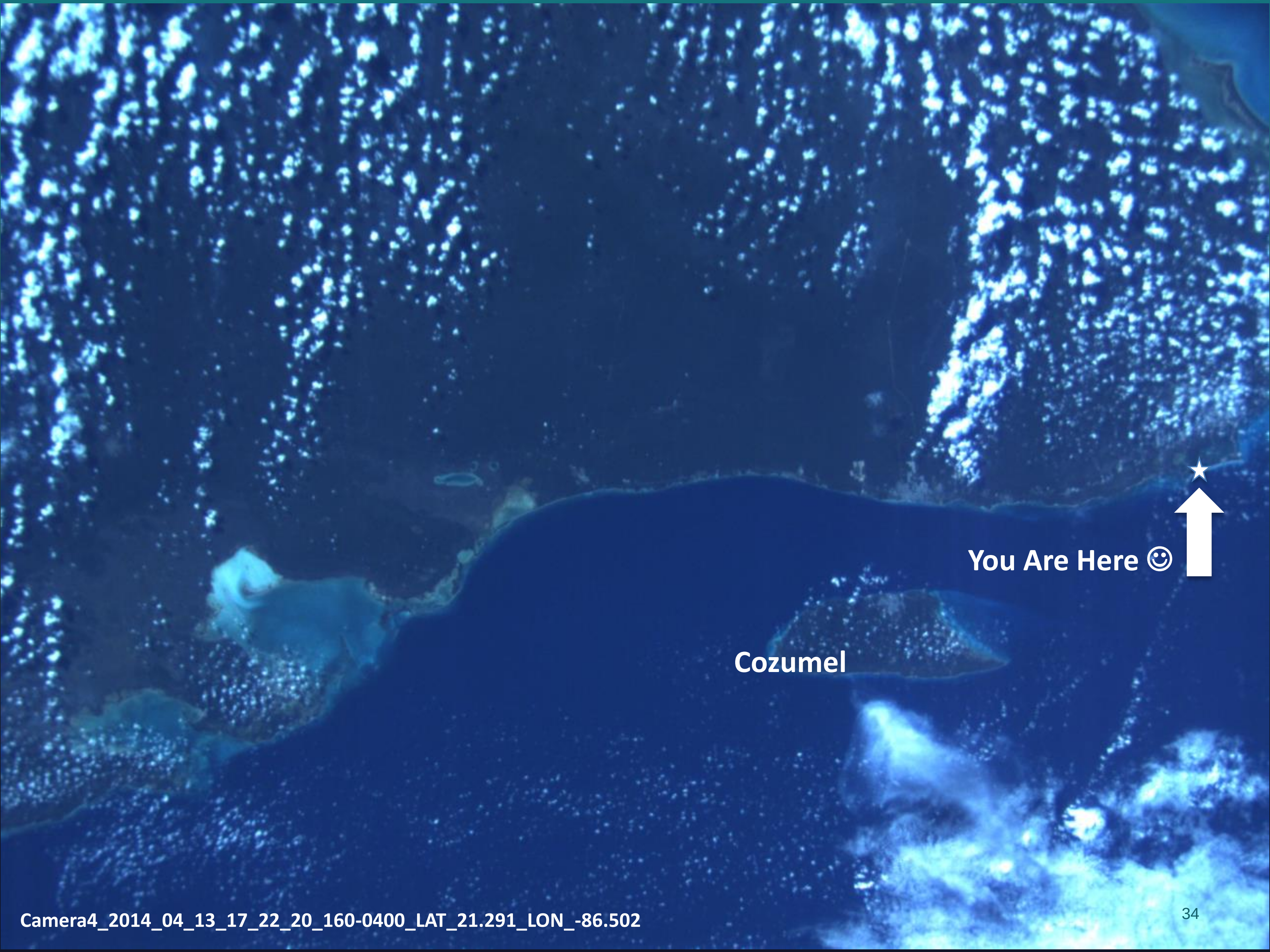
ISE 2.0 on ISS – August 2013



ISE 2.0 Sample Data & Images






You Are Here ☺
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STP-H5 On-Orbit Location

ISS SpaceCube Experiment – Mini (ISEM)

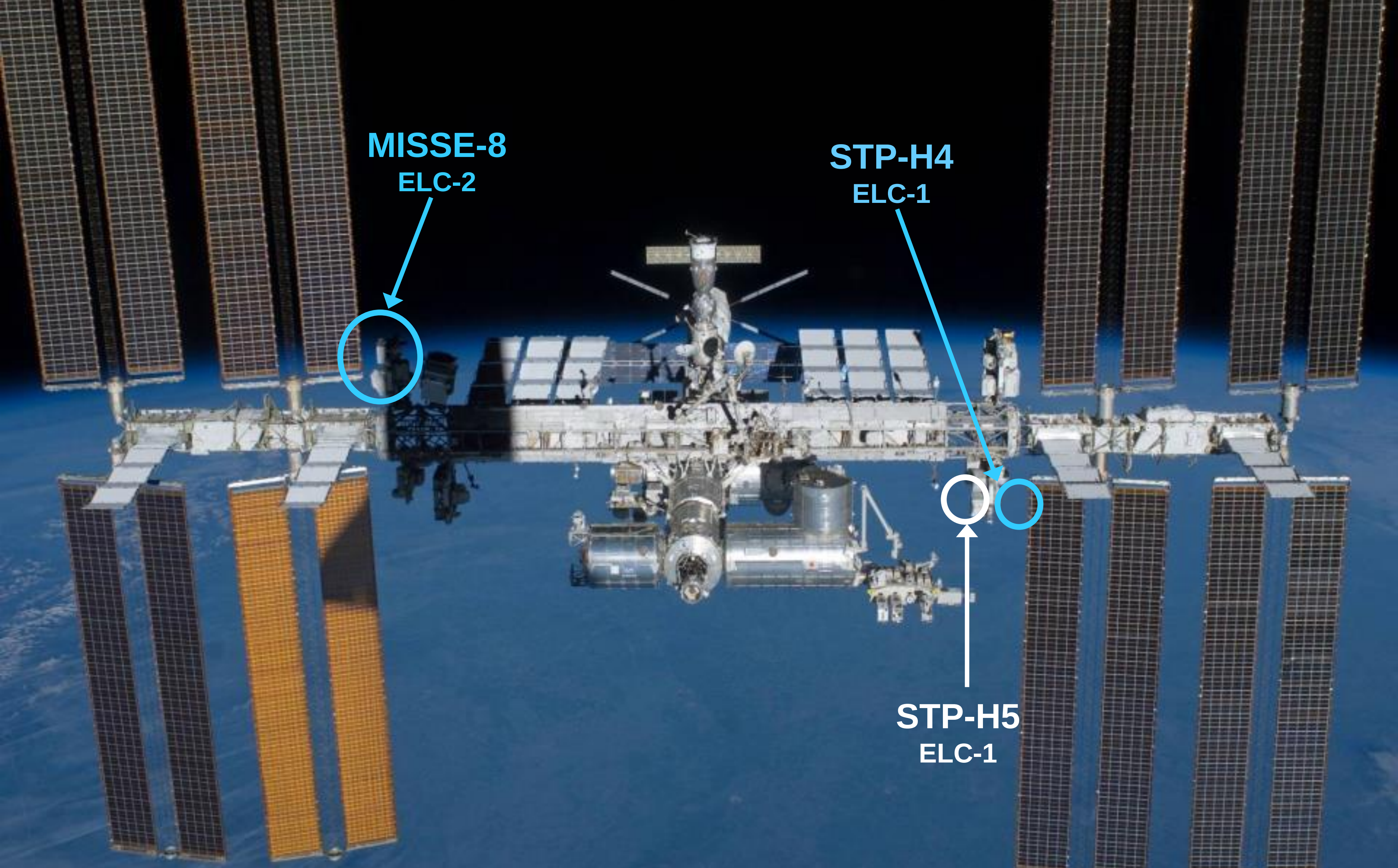
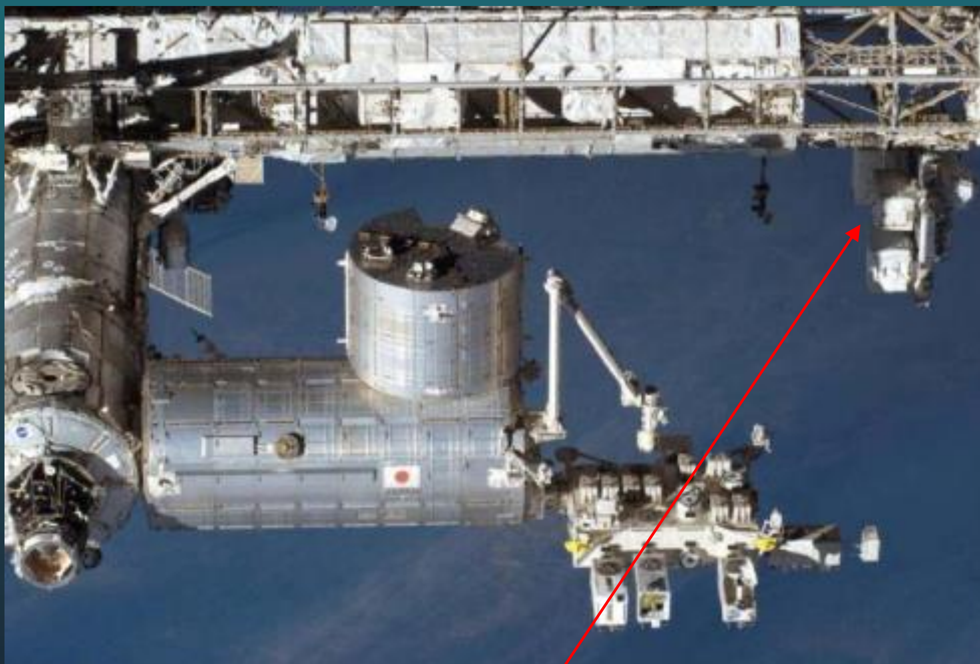
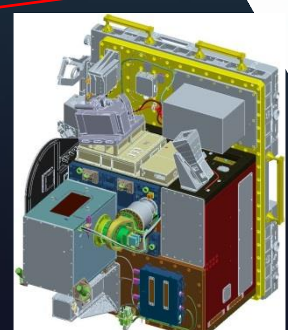


Image Credit: DoD Space Test Program

STP-H5 Location on ELC1



STP-H5 to be
installed at this location



STP-H5

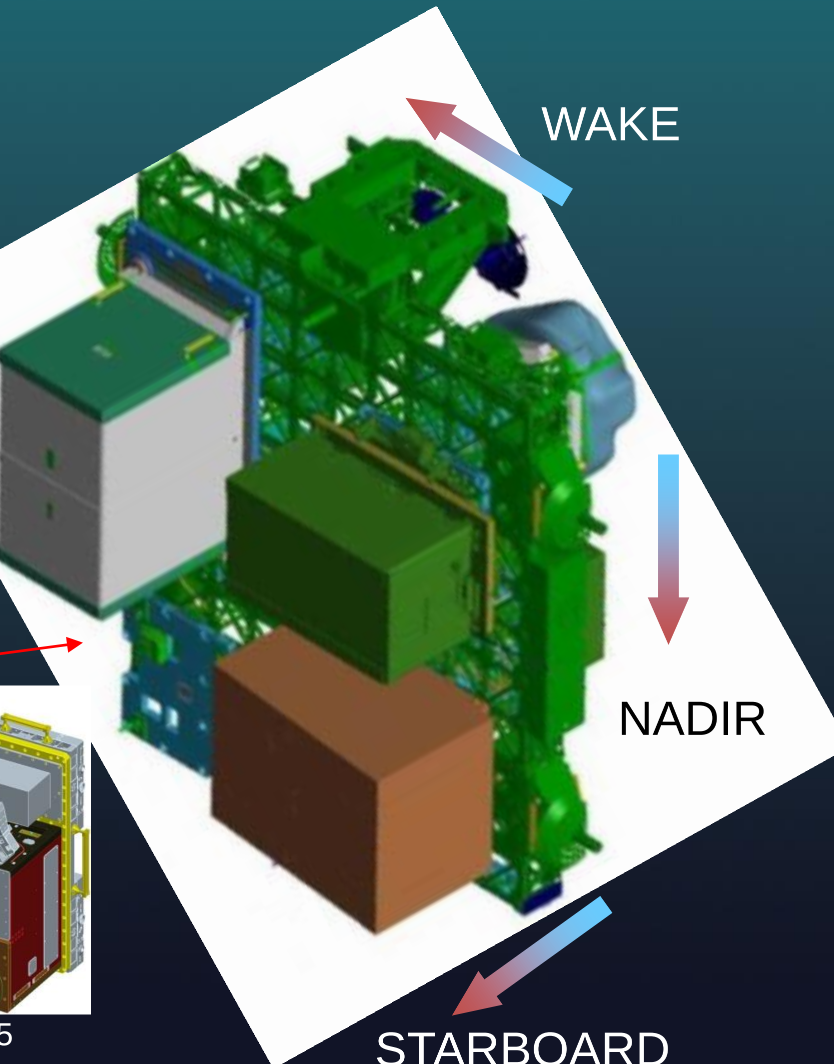
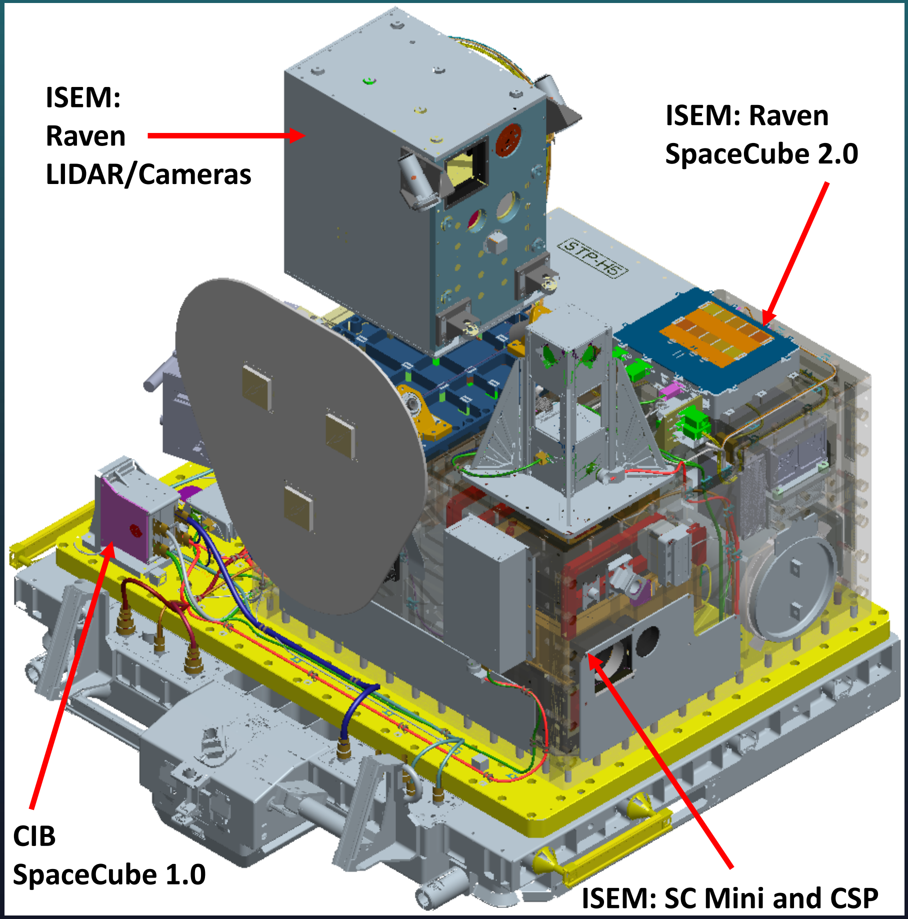


Image Credit: DoD Space Test Program

STP-H5 Pallet Layout



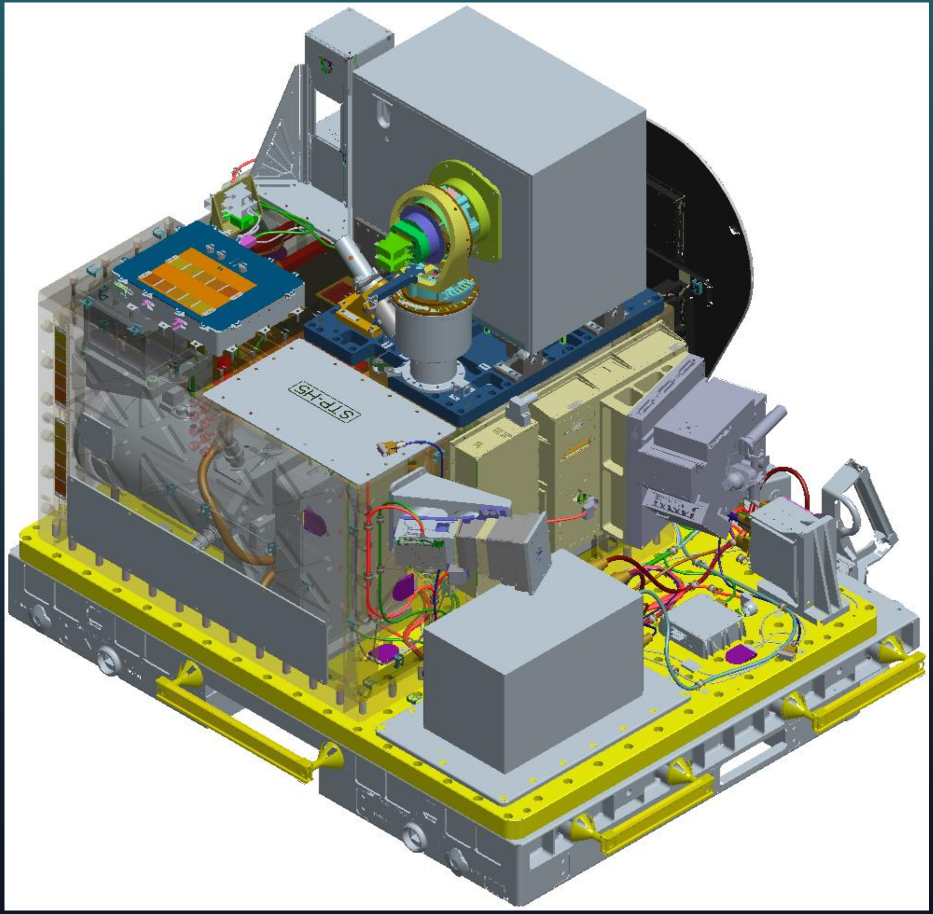
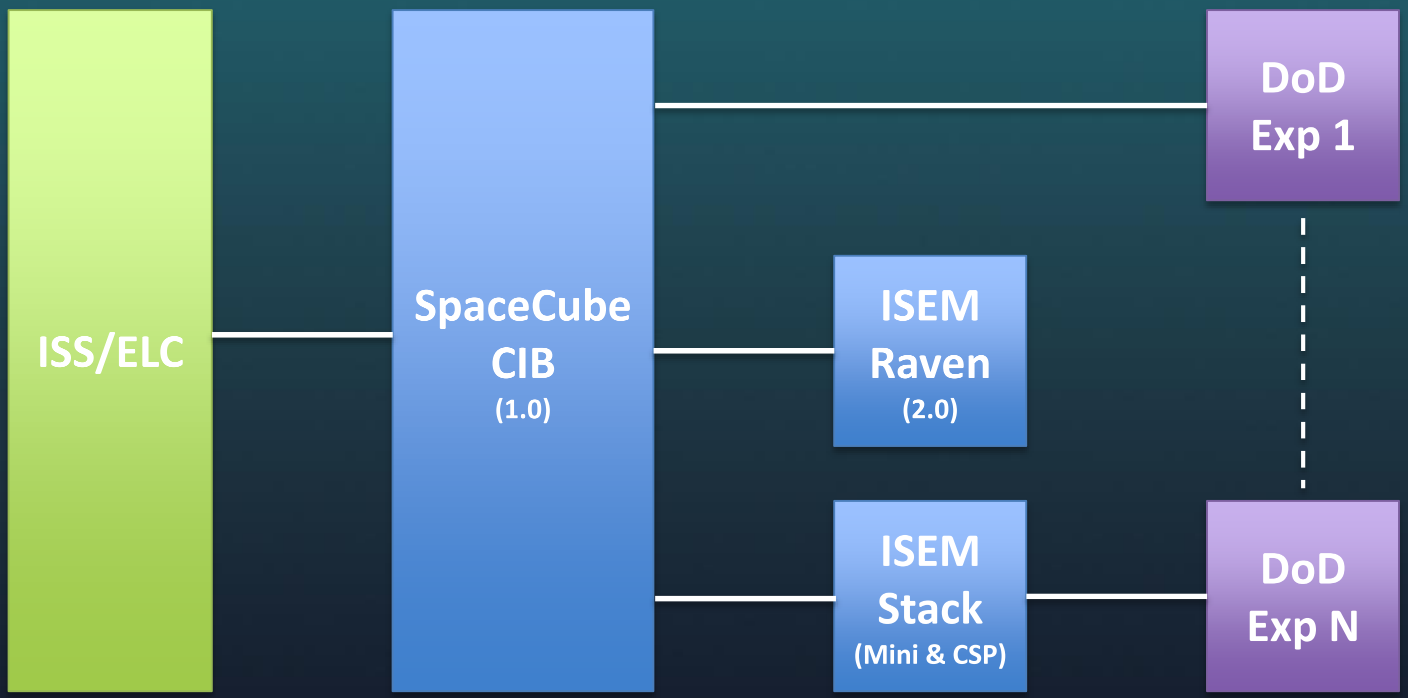
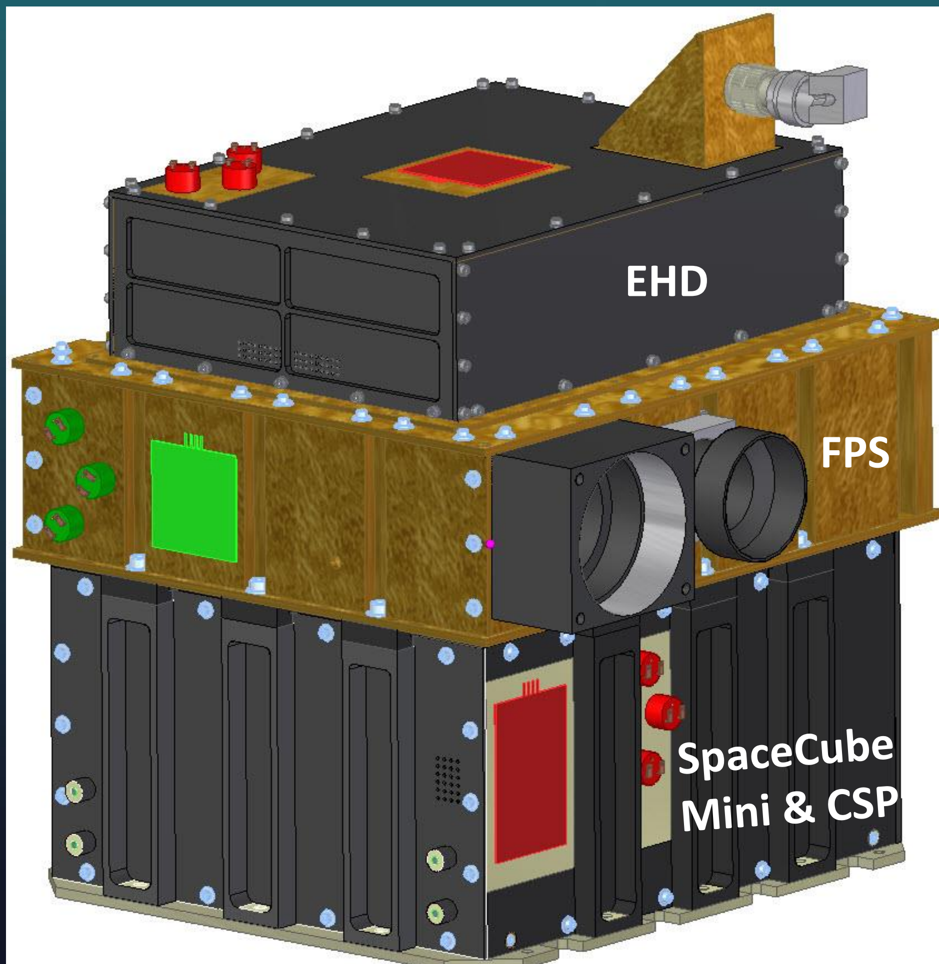


Image Credit: DoD Space Test Program

STP-H5 Configuration Overview



ISEM Experiment Overview

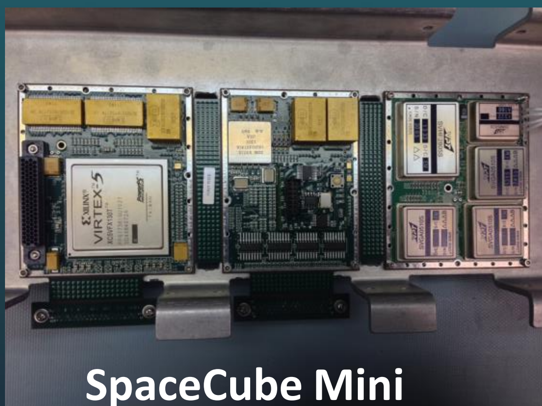


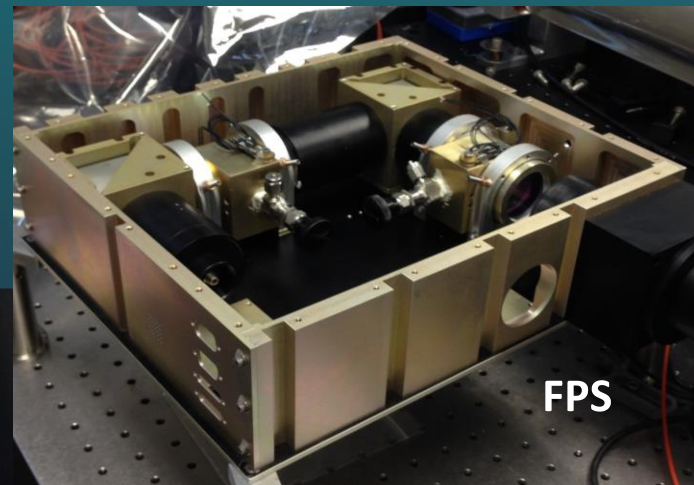
ISEM Stack

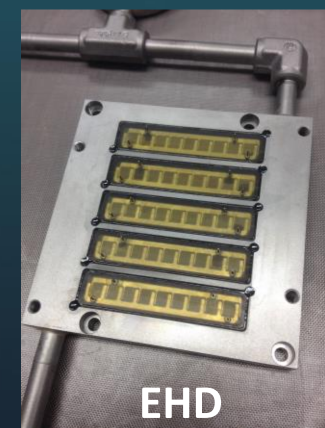
- Electro-Hydro Dynamic (EHD) thermal fluid pump experiment
- Fabry-Perot Spectrometer (FPS) for atmospheric methane
- SpaceCube Mini (Virtex 5) science data processor
- CHREC* Space Processor (CSP) and visible camera (Zynq)

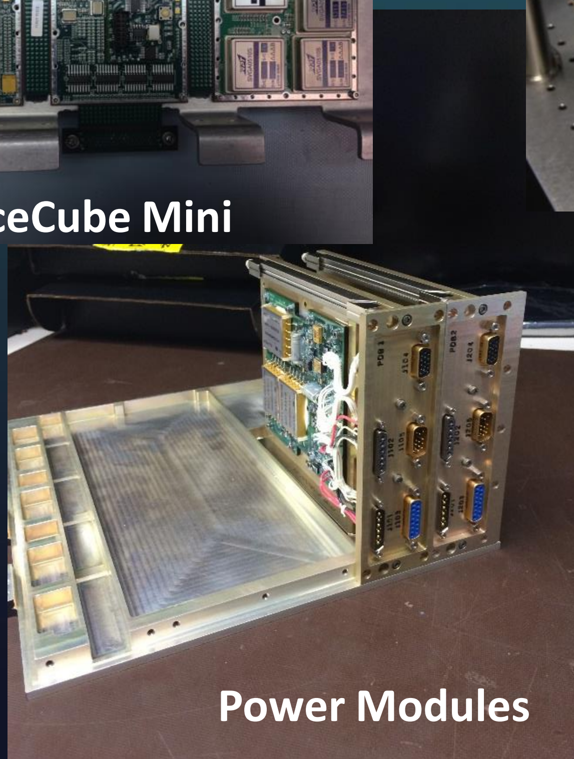
*CHREC – National Science Foundation Center for High-performance Reconfigurable Computing (www.chrec.org)

ISEM Stack Components



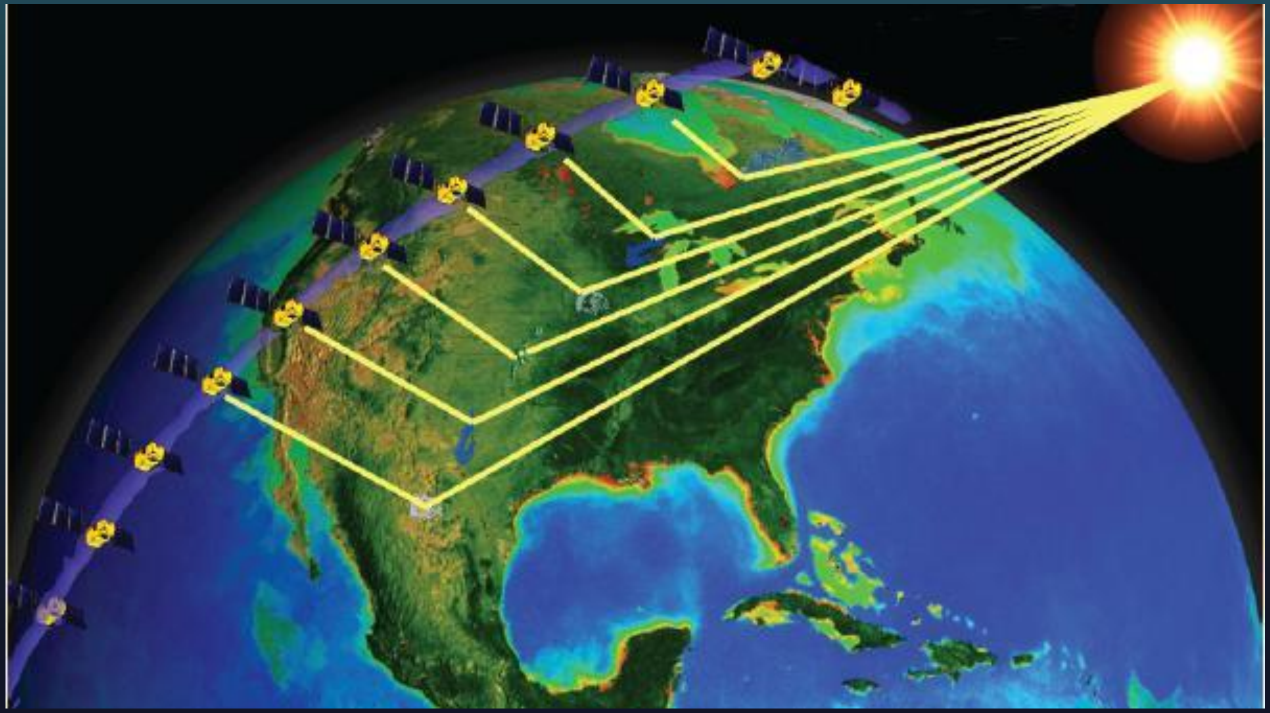


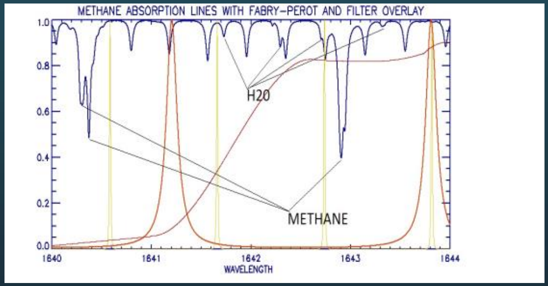


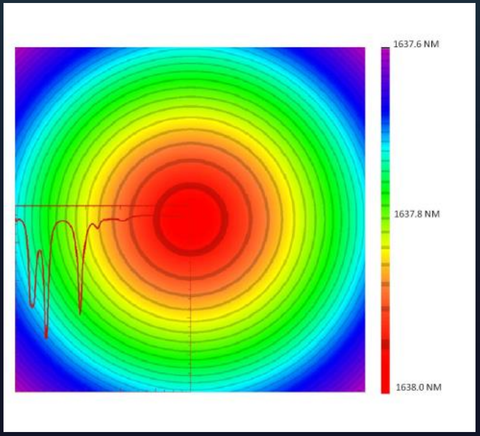


ISEM FPS Science

Fabry-perot Spectrometer Measures Absorption By Atmospheric Gases In Sunlight Reflected Off The Earth







Raven Experiment Overview

Raven is a technology development experiment to the ISS with the objective to

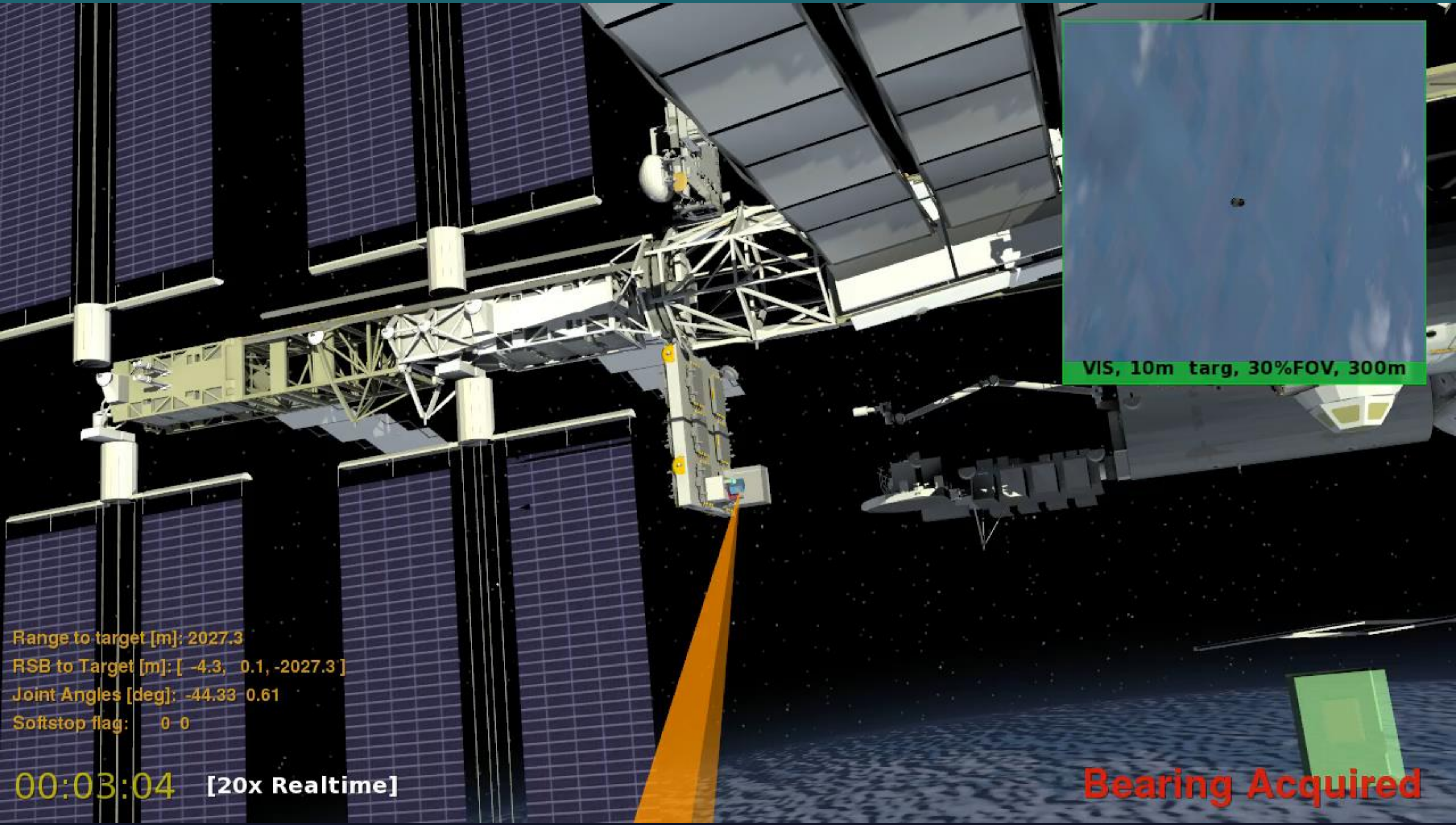
- Demonstrate cooperative and non-cooperative rendezvous can be accomplished with ***similar*** hardware suite
- Provide an orbital ***testbed*** for servicing–related relative navigation algorithms and software
- Demonstrate an ***independent*** visiting vehicle (VV) monitoring capability

Raven utilizes a complex, but compact, complement of hardware to accomplish these goals:

- Two-axis gimbal provides sensor pointing
- Relative navigation sensors provide tracking in three bands—visible, SWIR, and LWIR
- High-performance SpaceCube avionics provide efficient, reliable, and reconfigurable computing environment
- State-of-the-art pose and navigation algorithms provide non-cooperative operations

Raven tracking representative visiting vehicle

Raven Movie

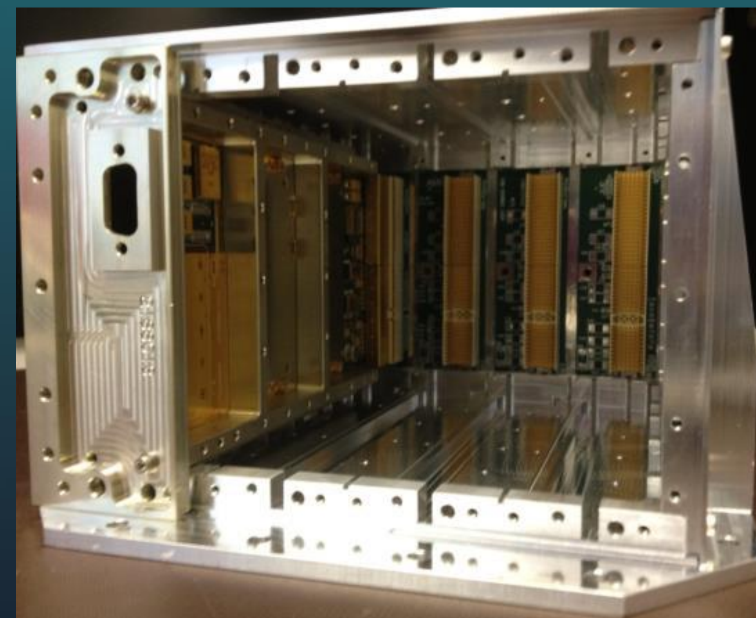

VIS, 10m targ, 30%FOV, 300m
Range to target [m]: 2027.3
RSB to Target [m]: [-4.3, 0.1, -2027.3]
Joint Angles [deg]: -44.33 0.61
Softstop flag: 0 0
00:03:04 [20x Realtime]
Bearing Acquired

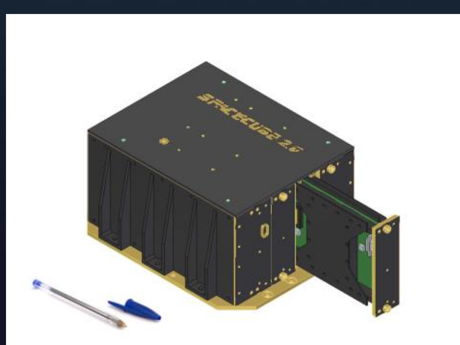
Future Research / Missions?

2014 – 20??

SpaceCube 2.0 Flight Unit

SpaceCube 2.0 Flight Processor





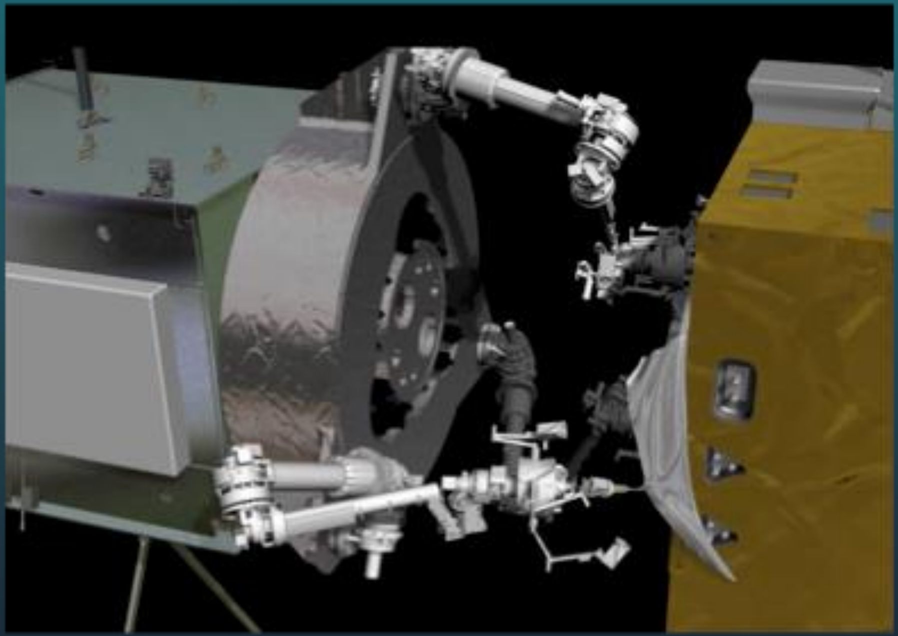
Mentor Graphics TLA Technology Leadership Awards 2014

Four Card Flight Unit

- **Dimensions: 5 x 7 x 9 inches**
- **Weight: 5.8 kg**
- **Power: 20 watts (typical)**

Robotic Satellite Servicing

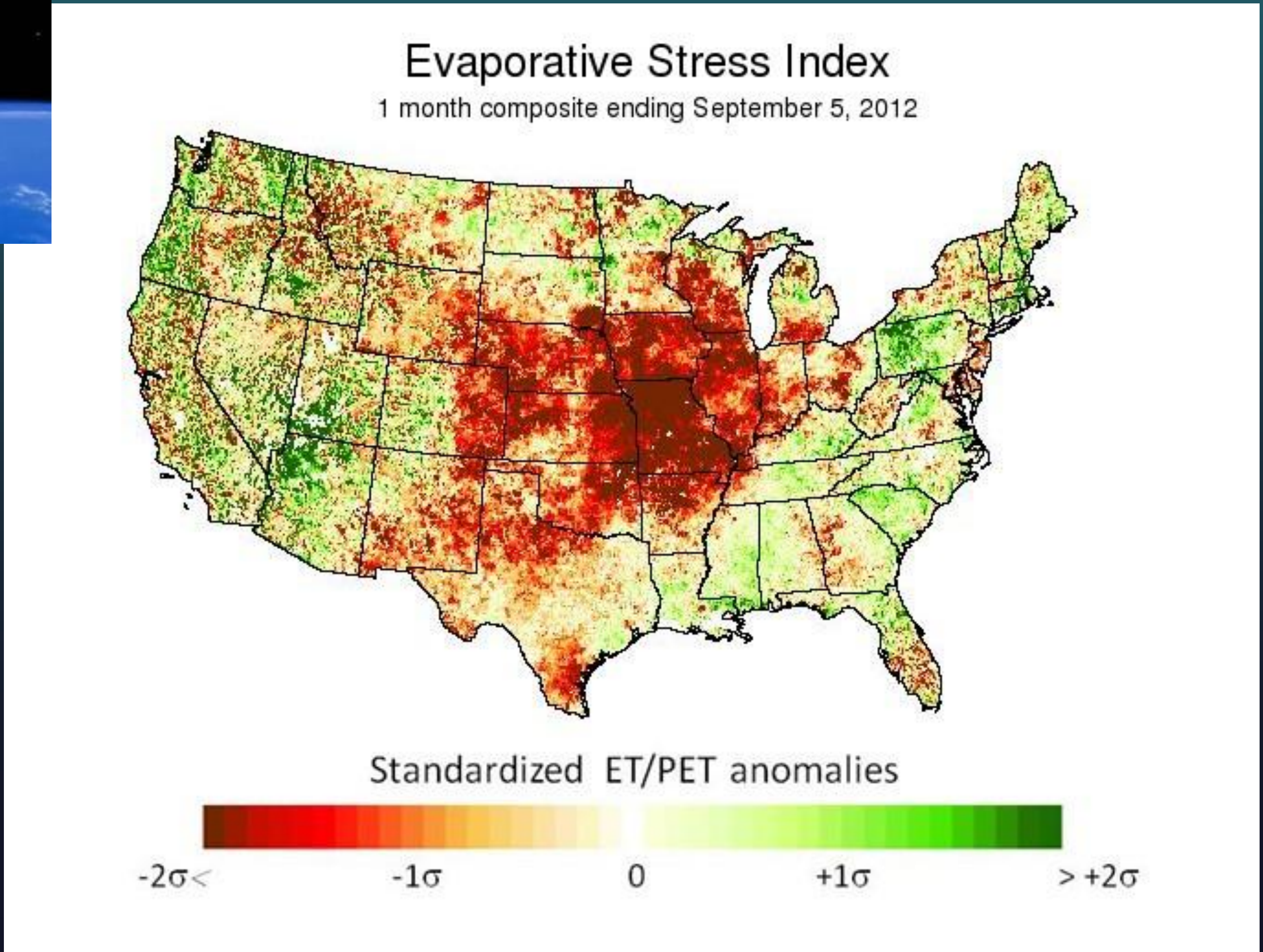
- Autonomous rendezvous & docking
- Robotic servicing



- Inspect
- Refuel
- Repair
- Replace
- Relocate

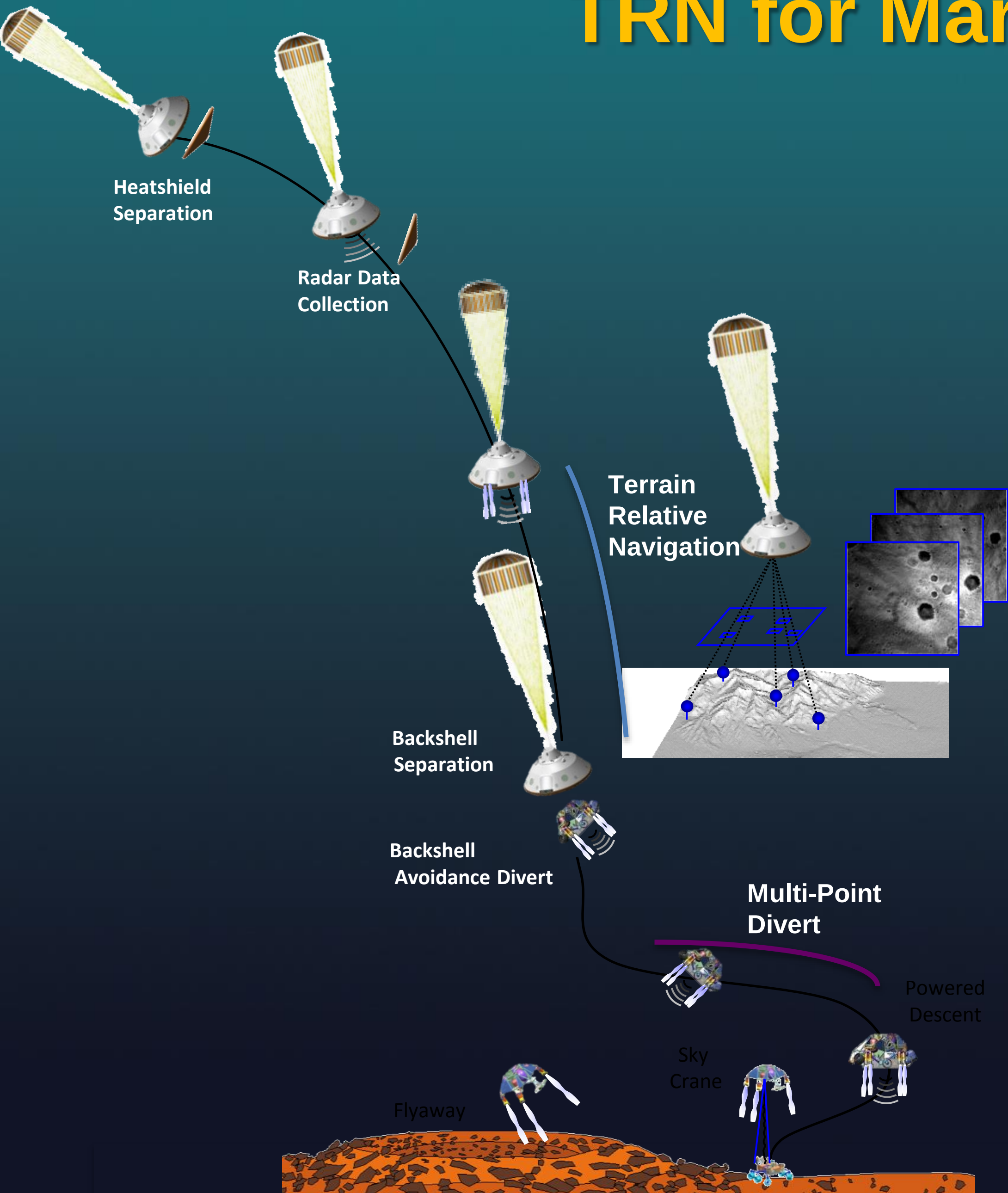
Imaging Spectrometers

Image Credit: HyspIRI Mission Concept Team



- Direct broadcast
- Real-time products
- Data volume reduction
- Adaptive processing
- Sensor webs

TRN for Mars Missions



Terrain Relative Navigation (TRN)

- **Works by taking images during parachute descent and matching them to an onboard map**
  - **Uses a dedicated compute element and camera**
  - **Yields a position solution**
- **Performs terrain relative navigation while the spacecraft is priming the descent engines**
- **Executed by the Lander Vision System (LVS)**

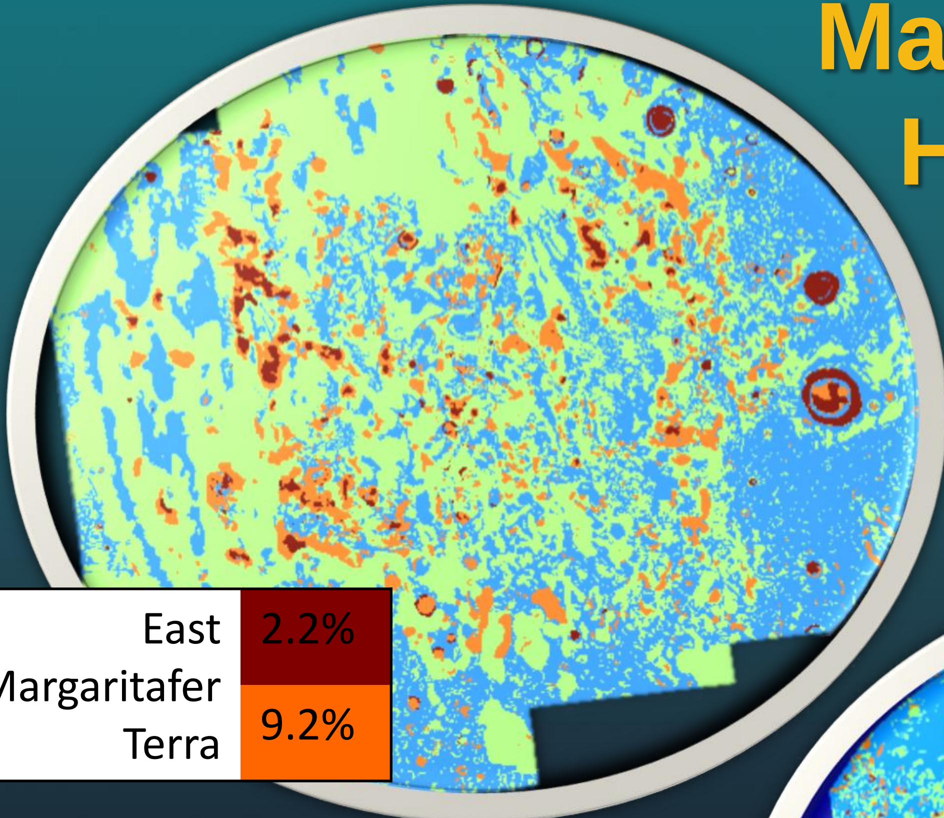
Multi-Point Divert

- **Uses position solution and list of safe landing locations to select a landing target**
- **Augments original MSL backshell avoidance divert (requires slightly higher backshell separation altitude)**
- **Lives within MSL fuel and control authority constraints**

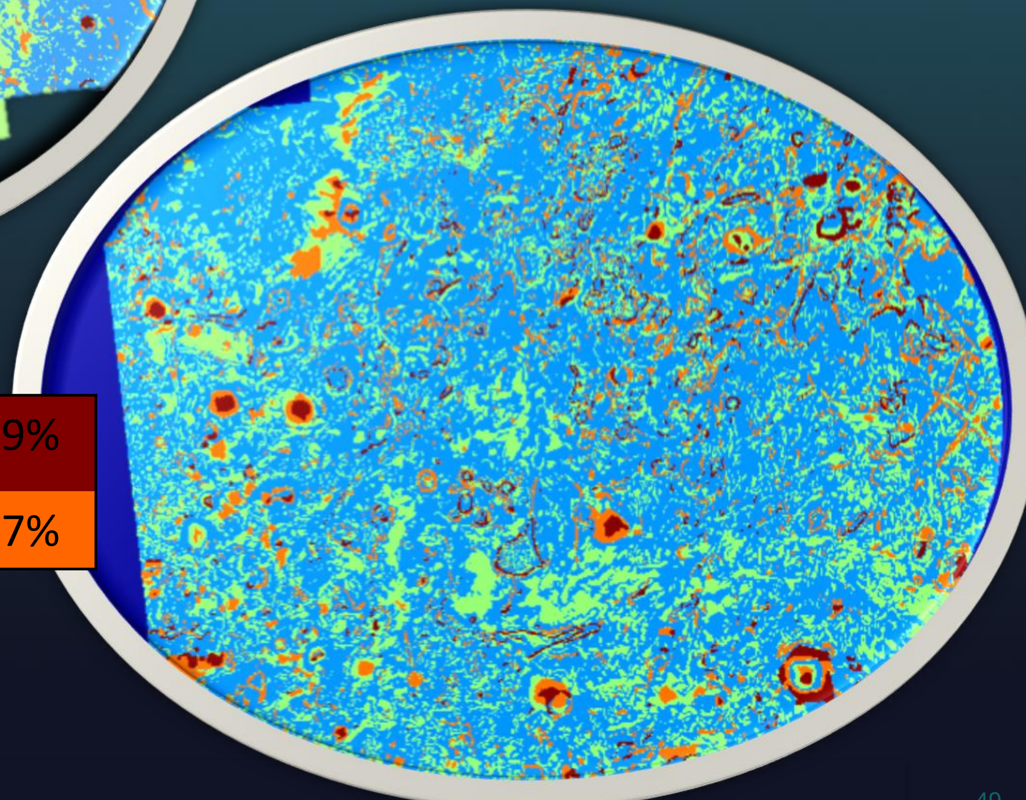
Credit: JPL Mars EDL Team

Mars Sample Caching High Priority Sites

- TRN Enables Landing at NE Syrtis and E Margaritifer
- **MSL could not land at these sites**



East Margaritafer Terra	2.2%
	9.2%



Northeast Syrtis	2.9%
	8.7%

- End of mission hazard
- Not end of mission, but hard to drive
- Landing hazards, but OK to land on
- No landing hazards

Credit: JPL Mars EDL Team

Real-time Mars Terrain Analysis

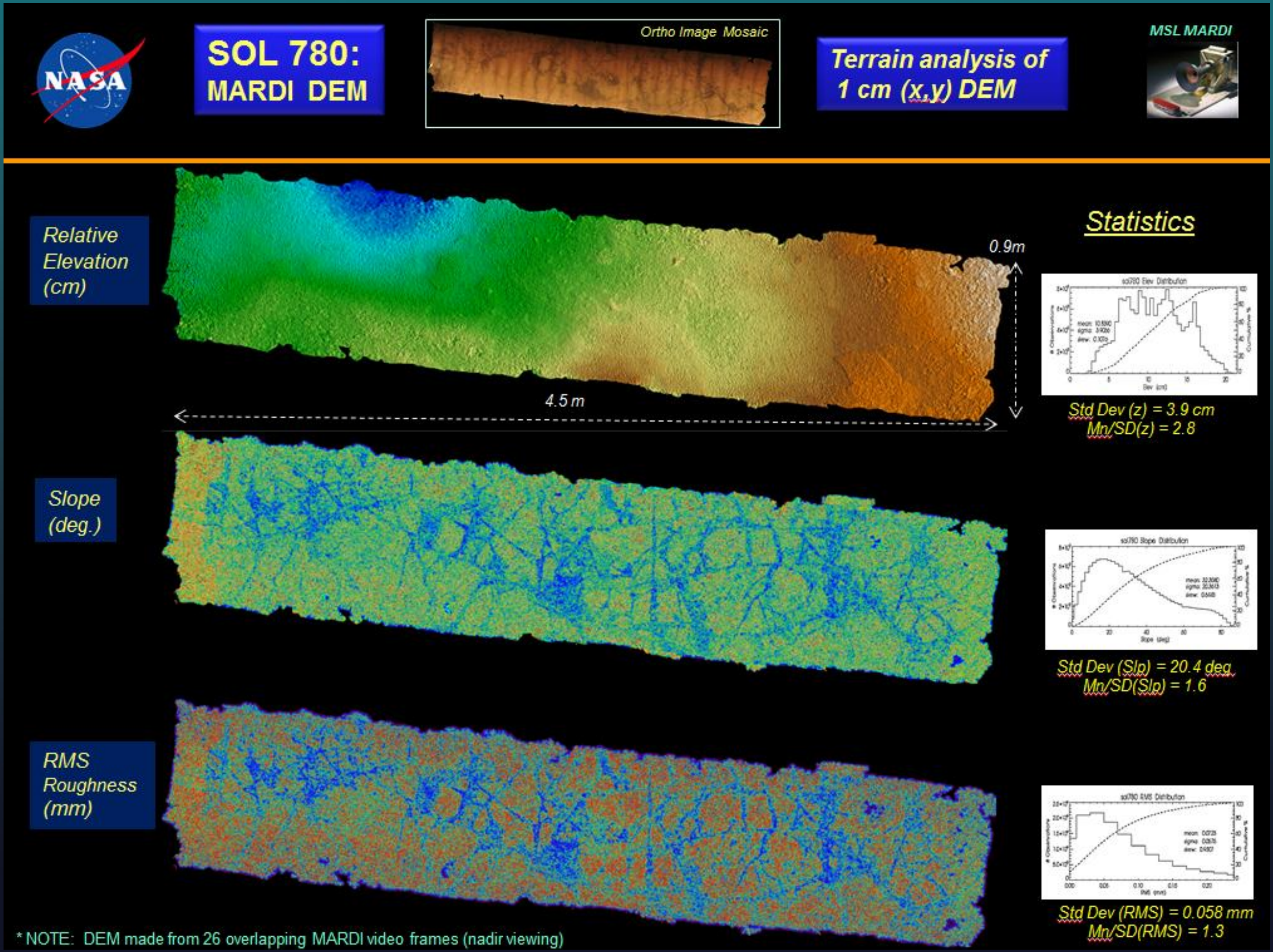


Figure by Garvin for MSL Science team: MARDI-based DEM derived from sidewalk video imaging mode data collection on the 22 m drive to “Book Cliffs” illustrating the power of fixed-nadir video imaging for terrain analysis of Mars in support of engineering (geotechnical) assessments.

More Rover Applications?

Fast traverse

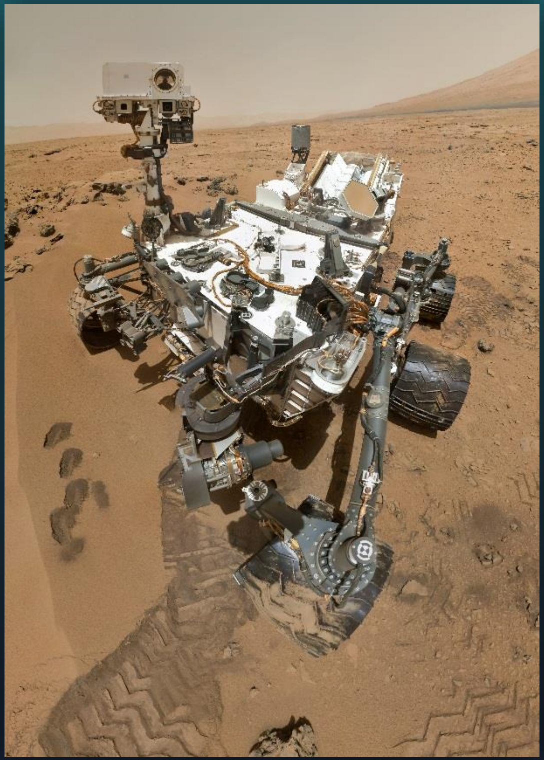
Terrain mapping (while driving)

Background science (while driving)

Entry/Descent/Landing documentation (video)

- Landing
- Parachute release
- Sky Crane

On-board processing for efficient use of downlink



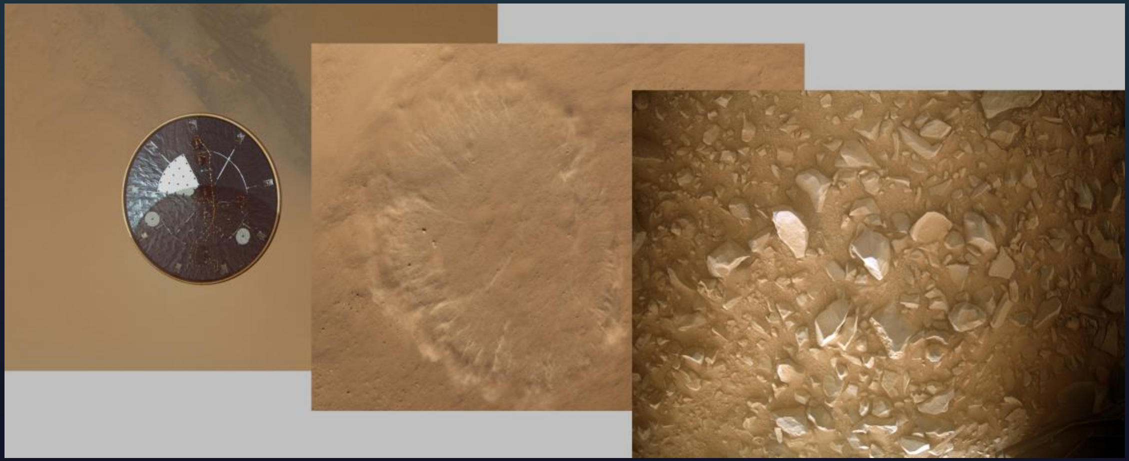


Image Credit: JPL / MSSS MARDI Team

SpaceCube "Next"

- Xilinx Zynq?
- Multi-core / Many-core?
- GPU?
- Other devices (Altera, etc.)?

Information Sciences Institute
USC Viterbi School of Engineering

Future Collaborations?

- NASA Centers
- DoD Space Test Program
- CHREC (Florida, BYU)
- CubeSats
- Commercialization
- Universities / Industry
- You?

Conclusions

SpaceCube is a MISSION ENABLING technology

- **Delivers 10x to 100x on-board computing power**
- **Cross-cutting (Earth/Space/Planetary/Exploration)**
- **Being reconfigurable equals BIG SAVINGS**
- **Past research / missions have proven viability**
- **Ready for infusion into operational missions**

The SpaceCube Team

Thanks you! Questions?

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Special thanks to our sponsors: NASA/GSFC IR&D, NASA Satellite Servicing Capabilities Office (SSCO), NASA Earth Science Technology Office (ESTO) , DoD Space Test Program (STP), DoD Operationally Responsive Space (ORS)