

# Advanced Hybrid On-Board Science Data Processor - SpaceCube 2.0

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**Abstract - Many of the missions proposed in the Earth Science Decadal Survey (ESDS) will require “next generation” on-board processing capabilities to meet their specified mission goals. Advanced laser altimeter, radar, lidar and hyper-spectral instruments are proposed for at least ten of the Decadal Survey missions, and all of these instrument systems will require advanced on-board processing capabilities to facilitate the timely conversion of Earth Science data into Earth Science information. Both an “order of magnitude” increase in processing power and the ability to “reconfigure on the fly” are required to implement algorithms that detect and react to events, to produce data products on-board for applications such as direct downlink, quick look, and “first responder” real-time awareness, to enable “sensor web” multi-platform collaboration, and to perform on-board “lossless” data reduction by migrating typical ground-based processing functions on-board, thus reducing on-board storage and downlink requirements. The convergence of technology collaborations between the Goddard Space Flight Center (NASA/GSFC), the U.S. Air Force and the Naval Research Lab (NRL) is being leveraged to produce a SpaceCube 2.0 on-board data processing system that will meet the on-board processing needs of the ESDS missions. SpaceCube 2.0 technology can directly support ACE, GEO-CAPE, HypIRI, ICESat-II, LIST, SCLP, SMAP, SWOT, PATH and 3D-Winds.**

## I. INTRODUCTION

SpaceCube is a Field Programmable Gate Array (FPGA) based on-board science data processing system developed at the NASA Goddard Space Flight Center (GSFC). The goal of the SpaceCube program is to provide 10x to 100x improvements in on-board computing power while lowering relative power consumption and cost. The SpaceCube design strategy incorporates commercial rad-tolerant<sup>1</sup> FPGA technology and couples it with an upset mitigation software architecture to provide “order of magnitude” improvements in computing power over traditional rad-hard flight systems (see TABLE 1).

SpaceCube is based on the Xilinx Virtex family of FPGA processors, which include CPU, FPGA and DSP resources. These processing elements are leveraged to produce a hybrid science data processing platform that accelerates the execution of science data processing algorithms by distributing computational functions among the elements, allowing each type of processor to do “what it’s good at”. This approach enables the implementation of complex on-

board functions that were previously limited to ground based systems, such as on-board product generation, data

TABLE 1 - PROCESSOR COMPARISON

	MIPS	Power	MIPS/ W
<b>MIL-STD-1750A</b>	3	15W	0.2
<b>RAD6000</b>	35	10-20W	2.33 <sup>1</sup>
<b>RAD750</b>	300	10-20W	20 <sup>2</sup>
<b>SPARC V8</b>	86	1W <sup>3</sup>	86 <sup>3</sup>
<b>LEON 3FT</b>	60	3-5W <sup>3</sup>	15 <sup>3</sup>
<b>SpaceCube 1.0</b>	3000	5-15W	400 <sup>4</sup>
<b>SpaceCube 2.0</b>	5000	10-20W	500 <sup>5</sup>

Notes:  
 1 – typical, 35 MIPS at 15 watts  
 2 – typical, 300 MIPS at 15 watts  
 3 – processor device only, total board power TBD  
 4 – 3000 MIPS at 7.5 watts (measured)  
 5 – 5000 MIPS at 10 watts (calculated)

reduction, calibration, classification, event/feature detection and real-time autonomous operations. The system also is fully reconfigurable in flight, through either ground commanding or autonomously in response to detected events/features in the instrument data stream.

## II. SPACECUBE EVOLUTION

The SpaceCube 1.0 system is based on the Xilinx Virtex 4 (FX60) FPGA technology and first flew as part of the Relative Navigation Sensors (RNS) experiment during Hubble Servicing Mission 4 in May 2009. The Hubble unit (SpaceCube 1.0a) interfaced with three cameras and ran autonomous rendezvous and docking algorithms to simulate a robotic servicing capture and release. The system operated on-orbit for approximately 60 hours, and met all RNS experiment goals. The second SpaceCube experiment (SpaceCube 1.0b) flew as part of the Naval Research Lab (NRL) Materials on the International Space Station Experiment 7 (MISSE7) payload and was installed on the Space Station in November 2009. The purpose of the MISSE7 SpaceCube experiment is to test and validate our “radiation hardened by software” (RHBS) mitigation techniques. The RHBS strategy involves a combination of traditional “memory scrubber” functions and a “program execution error detection and correction” software architecture that runs in the background to find and fix single and multi-bit radiation induced upsets. The goal of

<sup>1</sup> susceptible to radiation induced upsets, but not to destructive failures

RHBS is to enable the reliable use of commercial rad-tolerant processing elements in space and to “asymptotically



FIG 1- MISSE7 BEING INSTALLED ON STATION

approach” the reliability of true rad-hard systems while providing more computing power for less cost. The MISSE7 SpaceCube experiment will remain on the Station for the next 2-5 years and will serve as an on-orbit testbed for current and future RHBS technology development efforts. Early upset detection/correction results from the MISSE7 SpaceCube experiment are shown in FIG 2. To date, the MISSE7 SpaceCube has operated continuously on orbit for over 18 months and has experienced over 100 upsets (total upsets in four FPGAs), but all of the upsets have been successfully mitigated and no functional errors have occurred. A new set of experiments are currently being uploaded to the MISSE7 SpaceCube and testing will continue as the payload transitions to MISSE8.



FIG 2 - SPACECUBE UPSET DETECTION & CORRECTION

SpaceCube 1.5 is being designed to support a quick-turnaround sounding rocket flight and serves as a stepping stone to the next generation SpaceCube 2.0 system currently being developed under funding from the Earth Science Technology Office (ESTO). SpaceCube 1.5 moves from

the Virtex 4 to the Virtex 5 family of FPGAs and adds several industry standard plug-and-play interfaces such as Gigabit Ethernet and SATA-II. The SpaceCube 1.5 system is scheduled to launch in June 2011 and is the first in a series of sounding rocket technology demonstration flights in collaboration with the Department of Defense (DoD) Operationally Responsive Space (ORS) program.

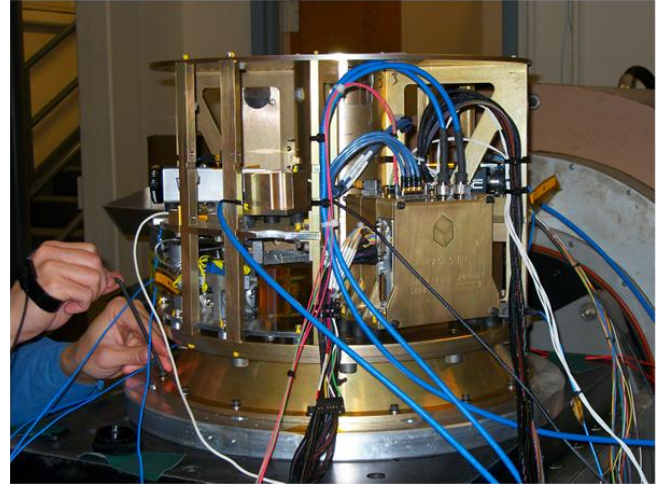
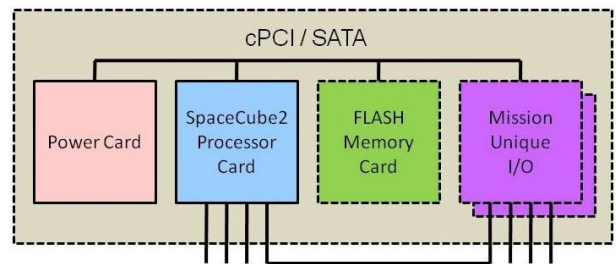


FIG 3 - SPACECUBE 1.5 SOUNDING ROCKET PAYLOAD

ESTO is currently funding the development of the SpaceCube 2.0 system under their Advanced Information Systems Technology (AIST) program, to provide advanced on-board science data processing capabilities to the upcoming series of Earth Science Decadal Survey (ESDS) missions. The SpaceCube 2.0 system is based on Xilinx Virtex 5 technology and adds Spacewire and cPCI interfaces, in addition to the Gigabit Ethernet and SATA-II interfaces developed for the SpaceCube 1.5 system. SpaceCube 2.0 also moves from custom packaging that was used on SpaceCube 1.0 and 1.5 to an industry standard 3U form factor, and is fully scalable to support a wide variety of mission requirements (See FIG 4).



Standard 3U Card Form Factor  
Nominal Box Level Parameters:  
Size 5"x5"x7", Weight 10-15 lbs, Power 10-20 watts

FIG 4 - SPACECUBE 2.0 BLOCK DIAGRAM

The SpaceCube 2.0 breadboard will be flown as an experiment on the International Space Station (ISS) through a collaboration with the U.S. Air Force as part of their Space Test Payload – H4 (STP-H4) payload. The ISS SpaceCube Experiment 2.0 (ISE 2.0) will couple the SpaceCube 2.0 breadboard with a camera system, gamma ray detector, photometer, antenna and thermal plate experiment, with the primary goals of extending SpaceCube RHBS research, developing Earth Science “event detection” algorithms and studying gamma ray bursts from terrestrial lightening/thunderstorms. ISE 2.0 is scheduled for delivery to the Air Force in 2012, with a launch to the ISS in 2013 (See FIG 5).

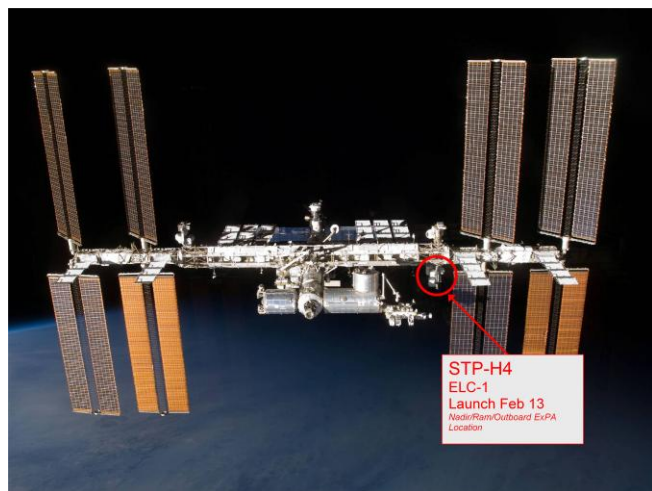


FIG 5 – ISE 2.0 EXPERIMENT LOCATION

A SpaceCube 2M (SpaceCube 2.0 Mini) system is also being developed to support CubeSat, Unmanned Aerial Vehicle (UAV), in-situ/embedded sensor and robotic/rover applications, and will incorporate a significant subset of the full SpaceCube 2.0 features and functions in a small package (See FIG 6). The first SpaceCube Mini will fly as part of the Intelligent Payload Experiment (IPEX) CubeSat that will demonstrate advanced on-board processing capabilities for missions such as HypsIRI. Additional SpaceCube Mini systems are baselined for GSFC Technology Demonstration CubeSats (TechCube) and the collaborative sounding rocket experiments with DoD/ORS.

The SpaceCube 2.0 and SpaceCube 2M processor cards are being designed to accommodate either the commercial Virtex 5 FX130T part (with embedded PowerPCs) for “high-performance” applications or the radiation hardened Virtex-5QV FX130 SIRF part (developed by the Air Force Research Lab, implemented without embedded PowerPCs) for “high-reliability” applications. In addition to the ESDS mission applications the SpaceCube 2.0 system is also being baselined by the Satellite Servicing Capabilities Program for use as a high performance autonomous rendezvous and docking processor for a number of their technology demonstration missions.



FIG 6 - SPACECUBE MINI

### III. SPACECUBE APPLICATIONS

A number of SpaceCube on-board science data processing applications have been developed and demonstrated under NASA/GSFC Internal Research and Development (IRAD) funding during the past five years. This includes applications such as Synthetic Aperture Radar (SAR) processing and hyper-spectral data product generation. The general approach for developing SpaceCube applications involves obtaining algorithms (usually in Matlab or IDL) and sample data sets from science team collaborators, converting the algorithms to ‘C’, testing and validating results on the Virtex CPUs (PowerPCs), benchmarking the compute intensive functions, and then implementing a variety of Virtual Hardware Description Language (VHDL) and other library functions to accelerate the processing. Typical “hybrid processing” results have yielded a 25x to 50x speed-up in compute intensive functions vs. CPU-only performance.

One of the key mission enabling capabilities provided by the SpaceCube is the computing power to perform on-orbit data reduction, which allows science instruments to collect significantly more data without increasing on-board storage or downlink bandwidth requirements. Dramatic data volume reductions can be achieved by moving typical ground-based processing functions on-board, without the use of compression or other “lossy” techniques. Our SAR “Nadir Altimetry” application achieved a 6:1 data volume reduction by simply moving the first stage ground processing functions on-board (see FIG 7), and our SAR “Delay-Doppler Mapping” application achieved a 165:1 data volume reduction by producing the image products directly on-board (see FIG 8). These results can enable an instrument to run for hours rather than minutes or continuously (respectively), and provide data products to the users in real-time.

Similar results have been achieved processing hyper-spectral data. Fire detection/characterization, cryospheric classification and ocean color (chlorophyll) applications have demonstrated on-board product generation capabilities that can be used by Earth Science data customers such as emergency first responders and researchers in the field who would benefit from real-time direct broadcast data products (see FIG 9).

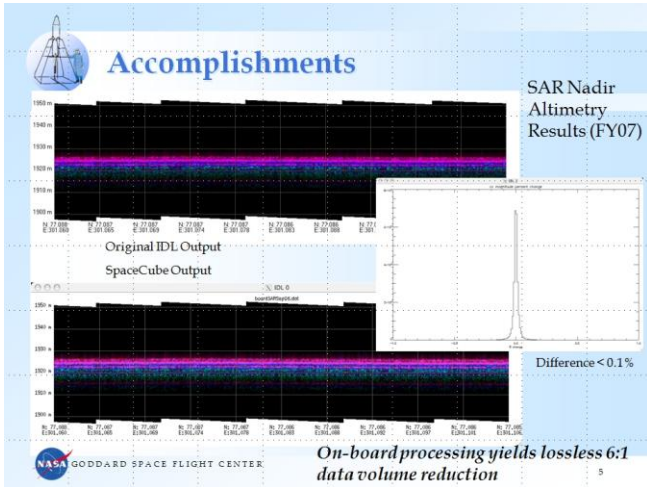


FIG 7 - SAR NADIR ALTIMETRY RESULTS

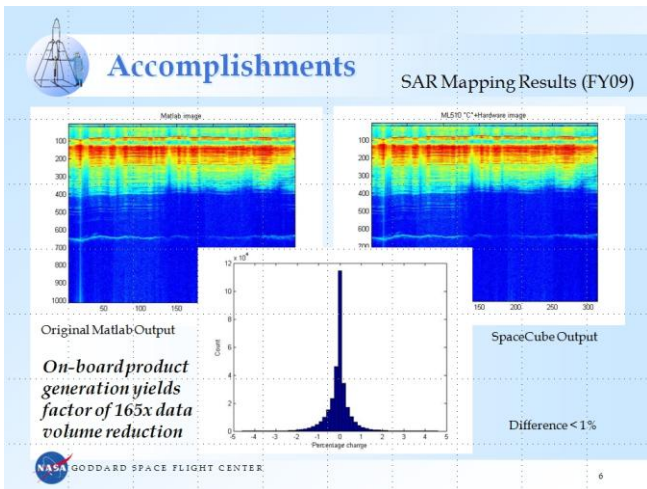


FIG 8 - SAR DELAY-DOPPLER MAPPING RESULTS

On-board product generation can also be leveraged to autonomously detect and react to events, such as changing data collection modes when storms/hazards are detected, or changing observation targets when planned targets are obscured by cloud cover. Algorithms to process a variety of events/targets (wildfire, volcano, hurricane, flood, algal bloom, oil spill, etc) can be stored in SpaceCube FLASH



## On-Board "VSWIR" Products

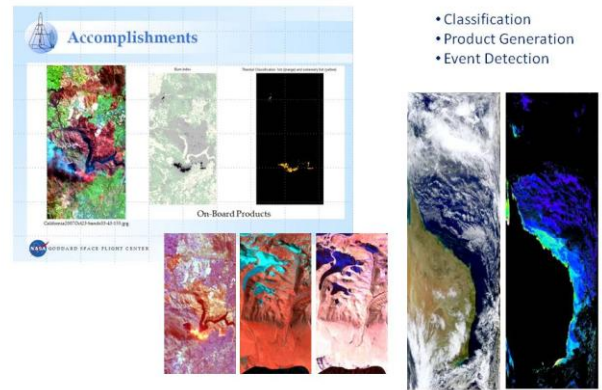


FIG 9 - HYPER-SPECTRAL PRODUCT GENERATION

memory and the "active" algorithms can be reconfigured in real-time to process the current event.

### IV. CONCLUSION

Many of the missions proposed in the Earth Science Decadal Survey will require "next generation" on-board processing capabilities to meet their specified mission goals. Advanced laser altimeter, radar, lidar and hyper-spectral instruments are proposed for at least ten of the Decadal Survey missions, and all of these instrument systems will require advanced on-board processing capabilities to facilitate the timely conversion of Earth Science data into Earth Science information. Both an "order of magnitude" increase in processing power and the ability to "reconfigure on the fly" are required to implement algorithms that autonomously detect and react to events, to produce data products on-board for applications such as direct broadcast, quick look, and "first responder" real-time awareness, to enable "sensor web" multi-platform collaboration, and to perform on-board "lossless" data reduction by migrating typical ground-based processing functions on-board, reducing on-board storage and downlink requirements. SpaceCube 2.0 promises to deliver a 10x to 100x improvement in on-board processing power to enable the next generation of Earth Science missions, and an active, collaborative program of technology development and flight demonstrations is rapidly moving this technology forward.

### V. REFERENCES

- <http://en.wikipedia.org/wiki/SpaceCube>
- <http://gsfctechnology.gsfc.nasa.gov/SpaceCube.htm>