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Adapting On Orbit: Conclusions of the STP-H6 Spacecraft Supercomputing for Image and Video Processing Experiment

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ABSTRACT

Spacecraft Supercomputing for Image and Video Processing (SSIVP) was a payload aboard the Department of Defense Space Test Program – Houston 6 pallet deployed on the International Space Station. SSIVP was designed and constructed by graduate students at the NSF Center for Space, High-Performance, and Resilient Computing (SHREC) at the University of Pittsburgh. The primary objective of this experiment was to evaluate resilient- and parallel-computing capabilities in a small-satellite form factor. Five flight computers, each combining radiation-tolerant and commercial-off-the-shelf technologies, were networked by high-speed interconnects, enabling a reliable space-supercomputing paradigm. Image-processing and computer-vision experiments were conducted on Earth-observation imagery acquired from two five-megapixel cameras. The system operated for 30 months, serving as an adaptable and reconfigurable platform to host academic and industry research. Despite on-orbit challenges with thermal constraints and operations, all mission objectives were completed successfully. SSIVP resulted in a dataset of nearly 20,000 images, radiation-effects data, and an increase in the technology-readiness level for two SHREC flight computers. Its designers and operators hope that SSIVP serves as a model for future reconfigurable and adaptable space computing platforms.

INTRODUCTION

The Space Test Program - Houston 6 - Spacecraft Supercomputing for Image and Video Processing (STP-H6-SSIVP) experiment served as a technology demonstration for novel space-computing hardware, software, and applications. It operated on the International Space Station (ISS) for 30 months from May 2019 to November 2021. The system was developed and operated by graduate students at the NSF Center for Space, High-Performance, and Resilient Computing (SHREC) at the University of Pittsburgh. The purpose of this mission was to demonstrate a reliable, scalable spacecraft supercomputing paradigm. The goals of this mission included the increase in technology-readiness level (TRL) of multiple new flight computer designs, collection of radiation-effects data as well as imagery, and demonstrations of SHREC student and member research executed onboard. To create a flexible platform that enabled this variety of research, the adaptability, reconfigurability, and autonomous operations of the system were crucial to mission success.

In orbit, the SSIVP mission encountered new challenges impacting operations. One example was unanticipated high temperatures, beyond the operational rating of the imagers, that required careful monitoring and further thermal modelling and analysis to implement additional safety requirements in operations. Entire mission functions and pipelines were updated as new flight applications and methods were developed and integrated. Despite on-orbit complications, all primary mission objectives were completed successfully. Additionally, the adaptable framework of the system allowed for continuous improvement to software and operations to meet new mission needs.

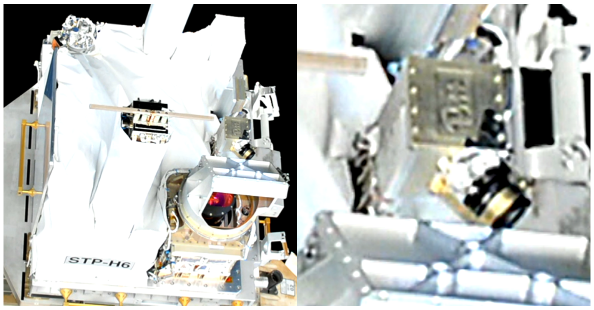

Figure 1: STP-H6-SSIVP Installed on EXPRESS Logistics Carrier 3 of the ISS

SSIVP made several key research contributions. A publicly accessible dataset of nearly 20,000 Earth-observation images was compiled, which includes several multi-frame bursts over landmasses. More than 10 device years of radiation-effects data were collected, and several radation-induced multi-bit upsets were observed. The successful upload of new research apps on orbit promoted versatility and continued research. The effectiveness of Gallium-Nitride (GaN) point-of-load (PoL) power converters was evaluated over the mission lifetime. SSIVP has demonstrated a flexible and incremental approach to the resolution of issues and expansion of mission capability on orbit. SSIVP served as a successful research concept for future reconfigurable and adaptable space-computing platforms.

This paper is structured as follows. The background section provides an overview of the SSIVP mission and relevant technologies. The approach section presents the issues encountered and overcome during operation as well as the experiments conducted onboard. The results section details the collected data and achievements of this mission. Finally, the conclusion section closes with a summary and details on future missions.

BACKGROUND

This background section introduces the STP-H6-SSIVP mission as well as a cursory overview of related missions and concepts. The CHREC Space Processor, both concept and original mission, serve as focal points. Earth-observation imagery, onboard processing, and radiation effects are also discussed.

CHREC Space Processor

SHREC was formally known as the NSF Center for High-performance and Resilient Computing (CHREC). This center achieved great success with one of the first hybrid space computer designs, the CHREC Space Processor (CSP). CSP began with the concept of enabling multifaceted hybrid space computing. The idea of hybrid design is highlighted in two ways. In one sense, the system is a hybrid in its combination of radiation-hardened (rad-hard) and radiation-tolerant (rad-tol) components along with commercial-off-the-shelf (COTS) parts. A COTS device is equipped with rad-hard monitoring and fault-mitigation systems as well as rad-tol nonvolatile memory. This allows for a significant increase in performance and affordability without compromising on reliability for a low-Earth orbit (LEO) use case. In another sense, the system is hybrid is its adoption of a Xilinx Zynq-7020 system-on-chip (SoC) featuring both an ARM Cortex-A9 processing system and a Artix 7-Series FPGA fabric. This enables capable conventional processing on the CPU as well as hardware acceleration in the FPGA.[1]

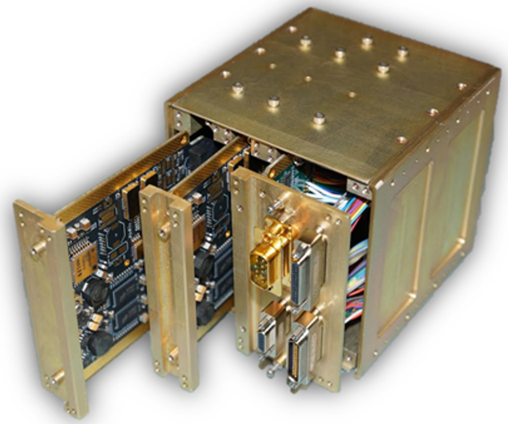

Figure 2: STP-H5-CSP as Configured for Integration into STP-H5-ISEM in Late 2016

STP-H5-CSP

STP-H5-CSP was a previous ISS payload developed and operated by CHREC that demonstrated two CSPs in their first flight test.[?] Both CSPs achieved great success over three years of mission operations from February 2017 to January of 2021. A photograph of the STP-H5-CSP hardware can be seen in Figure 2. FPGA configuration-memory scrubbers were deployed on both CSPs to monitor radiation-induced single-event upsets (SEUs) and to characterize the susceptibility of the Zynq-7020 SoC to radiation in the ISS orbit. A shared camera on STP-H5 also allowed STP-H5-CSP to capture over 12,000 Earth-observation images over its

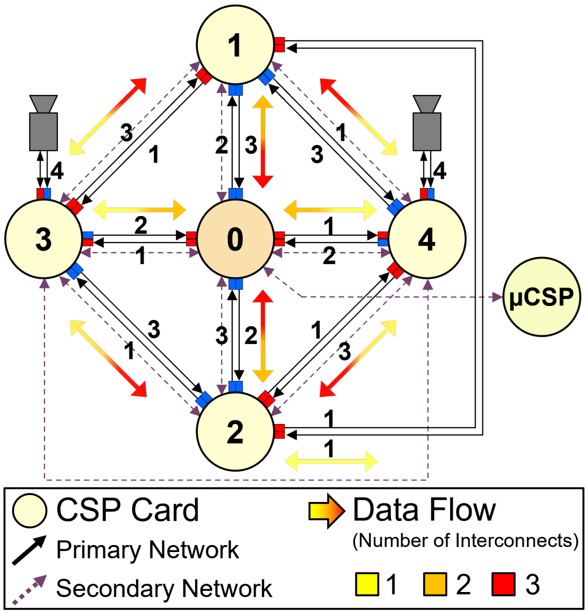

Figure 3: Network Topology of SSIVP

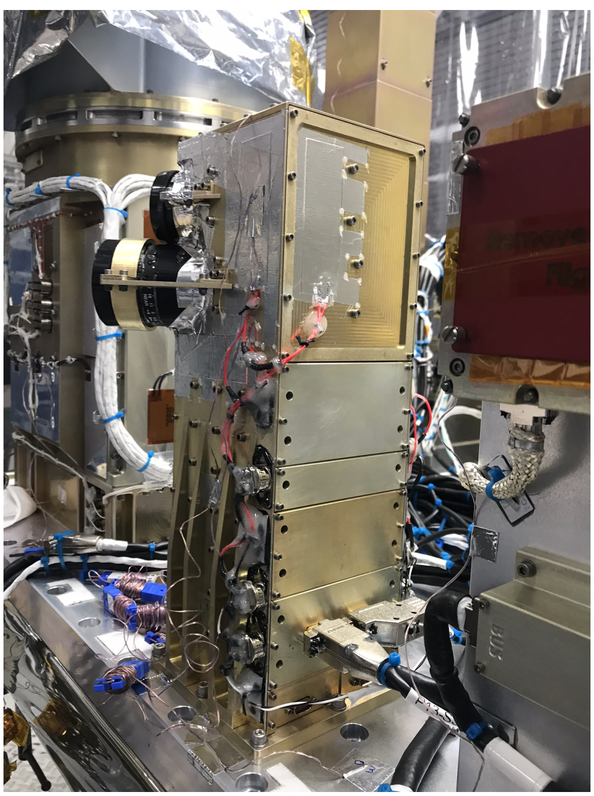

Figure 4: STP-H6-SSIVP as Configured for Integration with the STP-H6 Pallet in August 2018

lifetime. This aided in demonstrating onboard execution of image-processing and compression apps. STP-H5-CSP will remain operational on the ISS until mid-2022, but changes in the STP-H5-ISEM mission required communication with and operation of STP-H5-CSP to cease in 2021.

STP-H6-SSIVP

STP-H6-SSIVP was conceived as the next logical step for CSP qualification by scaling up with multiple space computers networked via high-bandwidth interconnects. The roughly 3U flight chassis included five CSPs and a µCSP Smart Module. Four of these CSPs were revision B units, the same as those flown and qualified in the STP-H5-CSP mission. One CSP was a new revision C unit that incorporated additional rad-hard memory voltage-regulation circuitry. The Smart Module served as the controller for a subexperiment to evaluate the performance of GaN PoL DC-to-DC power converters for use in LEO. This mission sought to raise the TRL of and establish flight heritage for each of these devices. The network topology of SSIVP is illustrated in Figure 3. A photograph of SSIVP as integrated into the STP-H6 pallet in August 2018 is shown in Figure 4.

The SSIVP flight software was designed with a separation of mechanism and policy to enable enhanced system adaptability for operations. Using this design principle, mechanisms that implemented software for essential system functions, such as image capturing, networking, and storage, exposed an interface to allow policies that implement user-defined apps and services to interact with these system resources. Furthermore, the software is designed to minimize the footprint of critical functions to reduce complexity in operations. The software is based on a modified Xilinx fork of the Linux kernel with a Busybox userspace, including a variety of standard Linux and student-developed apps and services. The core Flight System (cFS), developed by NASA Goddard Space Flight Center (GSFC), serves as the mission-critical flight software that manages command and data handling (C&DH), health and status, and other key functions as cFS apps.[2]

Earth-Observation Imagery

A variety of commercial and government satellites provide Earth-observation imagery at ever-increasing resolutions and frequencies. The Landsat program has been steadily providing visible-spectra imagery at 30-m ground-resolved distance (GRD), the ground distance between pixels in a digital image, since 1972. This imagery is still valuable, and its acquisition continues with the recently launched Landsat 9 in 2021.[3] Many modern platforms can provide imagery of significantly lower GRD. The Maxar and DigitalGlobe WorldView-3 satellite is capable of 0.31-m GRD panchromatic and 1.24-m GRD multispectral imaging at 1.2 million km^2 per day.[4] Expanding beyond single satellites, the Planet SkySat constellation can image 400,000 km^2 per day in five spectral bands at 0.5-m GRD.[5] The Maxar WorldView Legion constellation will generate 5 million km^2 per day of 0.3-m GRD imagery from six small satellites.[6] Pelican, the latest constellation developed by Planet, will deliver 0.3-m GRD imagery with up to 30 revisits per day from 32 satellites.[7] Small-satellite constellations can provide reduced revisit times, increased imaging capacity, and reduced cost and risk.

Despite vast differences in GRD, satellites with a wider field-of-view (FoV) and higher GRD can cover larger areas and enable more targeted tasking for other systems with narrow FoVs, higher resolutions, and lower GRD. While larger constellations can provide more rapid revisits of a previously imaged area and a larger volume of imagery, it is impossible to cover all visual fields simultaneously. Therefore, contributions of many satellites at all resolutions and GRDs, including STP-H6-SSIVP, are valuable to provide comprehensive coverage of the Earth.

Onboard Processing

Much can be done with the data generated by small Earth-observation satellites. The SpaceNet challenges seek algorithmic solutions to extracting key features, such as buildings or road networks, as well as assessing temporal change.[8] Techniques for climate studies from orbit via high-resolution, low-GRD satellite imagery have been demonstrated.[9] Rapid revisits by the most modern constellations can enable monitoring of conditions like traffic multiple times per day.[10]

The numerous satellites in orbit produce a vast quantity of high-resolution imagery. With ground-communication bandwidth at a premium, Earth-observation satellites need to be selective about what is transmitted to the surface. The capability to process raw data onboard and downlink the output results is important to maximize the science return of the mission. Lovelly demonstrates the significantly higher compute capability of the COTS processor and FPGA of the CSP compared to rad-hard space-processing solutions,[11] cementing the potential contribution of a scalable platform like SSIVP to this field. SSIVP also demonstrates that reliable COTS onboard-computing capability can be integrated in a small-satellite form factor.

Radiation Effects

Radiation poses numerous challenges for electronic devices in space. Radiation sources include galactic cosmic rays, solar particle events, and trapped particles in the geomagnetic field. Radiation effects on electronics are often categorized as cumulative effects or single-event effects (SEEs). Cumulative effects such as total ionizing dose and displacement damage dose cause long-term degradation due to absorption of ionizing and non-ionizing radiation, respectively. SEEs occur when a single particle strike induces some effect in the device. These effects can be destructive, such as latch-up or burnout, or non-destructive, in the case of an upset or transient.[?] To address these challenges in spacecraft development, NASA created the Radiation Hardness Assurance (RHA) program to provide guidance and improve mission dependability.[?]

APPROACH AND EXPERIMENTS

This section details the unique challenges encountered and experiments deployed on SSIVP. Initial diagnosis and recovery from unexpected thermal characteristics is first discussed. Beyond this, the experiments conducted during the operation of SSIVP are detailed.

Thermal Constraints

Upon initial post-launch checkouts, reported temperatures were higher than expected when compared to the thermal analysis performed during the system design. Due to the placement of the experiment on the ISS, SSIVP experienced higher sun exposure at negative solar beta angles, the angle between the ISS orbital plane and a vector originating from the sun, than at positive ones. This lead to temperatures high enough to be a concern for the imagers. As a result, the cameras could only be operated without risk for a brief period of the year when beta angles were optimal. To address this issue, a multi-phase plan to model, test, and adjust for the observed conditions was devised. Three approaches were taken to increase the operating window.

Because the temperature of the imagers was not directly measured on orbit, an interpolation from measured temperatures elsewhere on the payload was needed to determine the viable operating window. On-orbit thermal data was used to improve and correlate the thermal model resulting in reduced

Table 1: SSIVP Science Objectives

Category	Minimum Success	Comprehensive Success
Primary	• Collect science products for at least 30 days • Acquire profile of daytime and nighttime full-resolution images for analysis • Perform parallel computing algorithm experiments • Record upset rates for CSPv1 flight boards • Record upset rate for µCSP • Upload and reconfigure at least one CSP device • Upload and program at least one new parallel app	• Collect science products for over one year • Perform autonomous operation for algorithm correction based on observation conditions • Complete CSPv1 network protocol reprogramming • Complete functional tests of SHREC space middleware apps and suites • Perform integrated autonomous operations for camera configuration based on observational conditions
GaN PoL	• Collect science products for boards for at least 30 days during night cycles	• Collect science products for entire mission lifetime for all experiments

uncertainty in the interpolation, gaining back some margin.

Back in the lab, a spare camera identical to those flown on SSIVP was stress tested in a thermal chamber and qualified successful operation well above the manufacturer's specification. Through repeated cycling and long duration exposure, it was determined that the camera could be operated at temperatures 30 degrees Celsius above the listed maximum without significant risk.

Lastly, operation plans and automation scripts were adjusted so that the cameras could be swiftly powered on, configured, used, and then powered off again in short time intervals. These efforts reduced the powered-on time sufficiently to prevent the camera from reaching a steady state hot condition, and instead remained in the transient region at lower temperatures while operating. Additional safeguards were added to prevent autonomous operations from powering on the cameras above certain temperatures. Operations and automation were iteratively adjusted to maximize functionality while minimizing risk. The culmination of these three approaches allowed the system to be restored to viable function with a greatly increased window of operation.

Experiments

Once nominal function had been established, a series of software uploads were performed to add or enhance flight apps and capabilities. The first upload included additional imaging automation scripts, image-processing apps, and deep-learning classifiers. The suite of image-processing apps deployed onboard[12] was expanded with several more, including a new bilinear-downsampling thumbnailer and parallel Sobel edge detector.[13] A TensorFlow Lite framework for onboard classification[14] and prototype models for land-cover classification[?] were deployed onboard.

SSIVP also provided the initial test environment for the schedule manager. This system enabled timely task execution and hardware conflict mitigation.[15] SSIVP also served as a development target and testbed for the software baseline version of a CNN-JPEG deep-learning compression system.[16] The GaN PoL converter subexperiment also demonstrated positive results over several months of operation in the ISS orbit.[17]

Updates and new versions of the FPGA partial-reconfiguration system, Camera Link frame-grabber interface with the imagers, and radiation-monitoring system were completed for a second upload. These updates were thoroughly tested on the SSIVP flatsat and further demonstrate the capacity of SSIVP to adapt with the replacement of entire mission components. Unfortunately, the mission timeline did not support its deployment to SSIVP. Despite this, minor adjustments to automation scripts in orbit allowed for the system to capture bursts at sufficient rate for assembling large swaths of imagery. Many of these efforts, updates, and experiments were carried on to the successor of SSIVP, STP-H7-CASPR.[18,19]

RESULTS

This section details the data collected over the life of the experiment. Radiation-effects data and imagery are each explored. This section also revisits the

Table 2: Radiation Effects Data

CSP#	L1 Cache	L2 Cache	CRAM	BRAM
0			12	
1	5	5	6	
2	8	8	8	
3	1	1	3	
4	1	1	2	1

original goals of SSIVP to note the accomplishments of the platform.

Review of Mission Goals

The full list of science objectives established for SSIVP are listed in Table 1. All mission objectives were considered a success. However, the approach to a few of these objectives changed along with the mission. While CSP network protocol reprogramming was verified on the flatsat and could be conducted onboard, doing so would disturb the network structure and make running parallel apps difficult. To avoid loss of science, this goal was not directly pursued. Although SSIVP featured a reconfigurable framework that was capable of onboard partial reconfiguration (PR), the statically integrated direct memory access (DMA) controller used to interface with PR modules severely limited FPGA accelerators to stream-based architectures only and increased the difficulty of designing modules with optimal dataflows. However, lessons learned from this limitation have led to an improved design for future missions, such as on STP-H7-CASPR. The new design directly provides AXI interfaces to the PR region to support a variety of AXI-compatible FPGA cores and customized DMAs for dataflow-optimized accelerators. An updated frame grabber, radiation-effects monitor, and additional apps and scripts for new automation capabilities were incorporated into an additional upload. Unfortunately, changes to the ISS side of the upload framework as well as timing constraints related to STP-H7 development prevented the completion of this final upload. However, these objectives were pursued by other means. Automated camera reconfiguration through minor changes to existing tools improved burst capture capability. Existing scripts were modified to call specific apps based on preprocessing results, allowing for autonomous algorithm selection and correction based on changing observations. Another objective was the verification of upset count from the µCSP. However, since its SmartFusion2-based controller was immune to much of the radiation effects experienced, no µCSP upsets were detected over the life of the mission. This is still considered a success.

Table 3: Multi-Bit Upsets

CSP	Timestamp	LFA	PFA	Word	Bit
CSP0	1569779499	0000193E	00421318	7	3
		0000193F	00421319	7	3
CSP0	1599816094	00000770	00001B1C	78	4
		00000771	00001B1D	78	3
CSP0	1613692326	000012EA	0040209C	86	9
		000012EA	0040209C	86	10
CSP1	1595498931	0000141E	00420012	87	4
		0000141F	00420013	87	3
CSP2	1596177465	000005A6	000014A0	82	23
		000005A7	000014A1	82	24
CSP2	1599201045	000017F6	00420E86	35	14
		000017F9	00420E89	35	12
		000017FA	00420E8A	35	13
		000017FB	00420E8B	35	12
CSP2	1601314869	00000424	00000F1C	8	10
		00000424	00000F1C	8	11

Radiation Effects Data

With over 30 months of operation, the CSPs on SSIVP were exposed to a combined 12.5 device years of radiation in the ISS orbital environment with roughly 10 device years observed. For each CSP, SEUs were monitored in the L1/L2 caches of the ARM Cortex-A9 CPU and the configuration memory (CRAM) and block RAM (BRAM) of the Artix7-Series FPGA. A total of 47 SEUs distributed among these memories were observed, and these events are tabulated per CSP and memory in Table 2. Unfortunately, due to logging issues and unpredictable runtimes, some SEUs may have been missed, and the precise runtime for all CSPs is unknown. Therefore, reported data is likely to be overoptimistic, and it is expected the SEU rates are higher than observed.

Although SEUs are caused by a single particle strike, these events can manifest as either single-bit upsets (SBUs) or multi-bit upsets (MBUs). MBUs are interesting because the presence of multiple, simultaneous errors can overwhelm error-correction codes (ECC) and triple-modular redundancy designs. Seven of the observed CRAM SEUs manifested as MBUs, as shown in Table 3. Xilinx FPGAs use frame-interleaving for CRAM to distribute MBUs into SBUs across multiple frames, the latter of which can be corrected by single-bit ECC. Therefore, MBUs can easily be detected when multiple errors are observed at the same timestamp with adjacent frame address, word, and bit locations.

Sample Images

Over the mission lifetime, STP-H6-SSIVP captured nearly 20,000 Earth-observation images. These images have been used by students and members of SHREC for training classification and segmentation models. The full dataset has been cleared for public

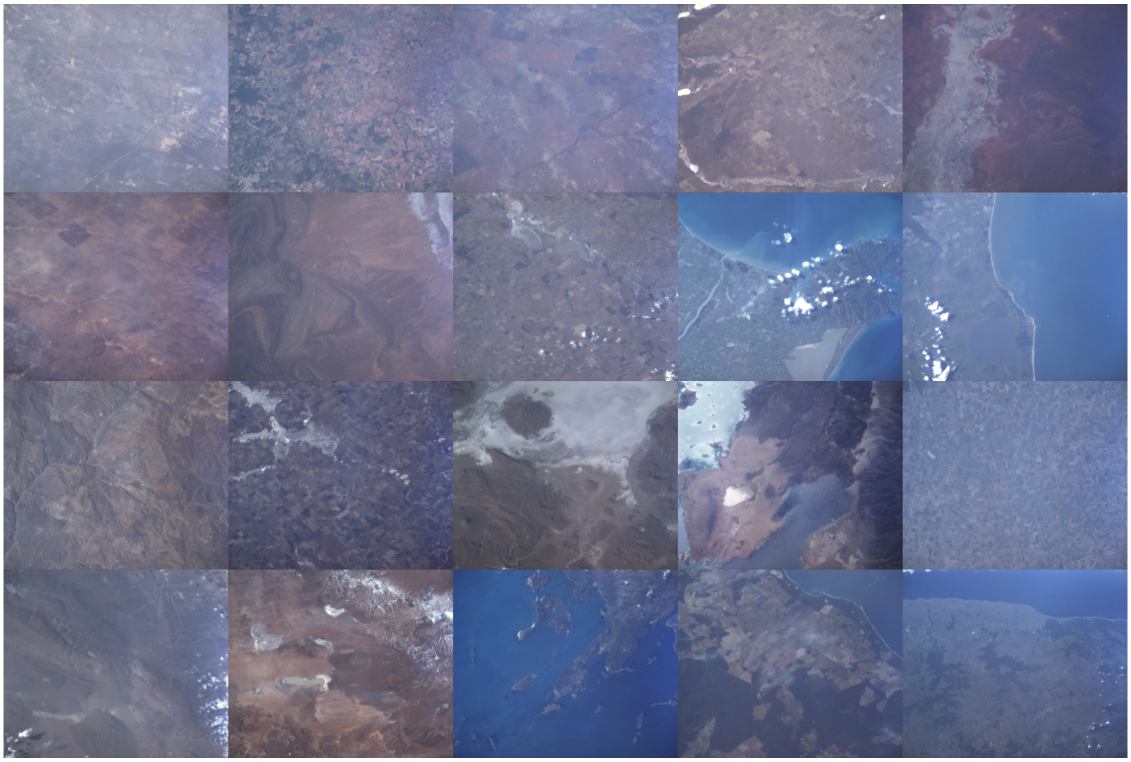

Figure 5: STP-H6-SSIVP Sample Images

release and can be acquired by contacting the authors. A number of sample images are included in Figure 5. These images represent a wide variety of the land cover types observed by SSIVP, including agriculture, rivers, coastlines, islands, and mountains.

Image Bursts

A new frame grabber was designed and developed for improved burst capture, but its upload was never completed. With adjustments made to the original frame-grabber and image-capture scripts in orbit, SSIVP was able to capture several multi-frame bursts. A sample burst is included in Figure 6. This burst was stitched together on the ground using 27 individual images. With the opportunity to extend the mission further, the process of stitching these images onboard prior to downlink was to be the next item under development.

Temporal Change

An area of high research interest in Earth observation is the analysis of temporal change. It is difficult to demonstrate change tracking with high-GRD imagery. However, the authors did manage to acquire some examples of temporal change at larger feature sizes. One such example is included as Figure 7. This image illustrates agriculture in northern Saudi Arabia. The SSIVP image, overlaid, with cooler color temperature, was captured on April 1st, 2021, while the Google Earth image was taken on December 23rd, 2020.[20] The more recent image depicts a significant increase of the agricultural land in the region over four months, with new growth near the top of the imaged area especially notable. Another goal that would have been pursued given a mission extension was the deployment of a image-contouring app that would allow features such as these to be counted and compared autonomously based on position, size, and other factors.

CONCLUSIONS

The STP-H6-SSIVP mission was a success not only in the research goals attained and the valuable data gathered, but also by its resilience through difficult conditions and changing operational constraints. All five CSP flight computers survived and operated nominally throughout the life of the mission. Radiation-effects data, GaN PoL converter data, and an Earth-observation dataset of nearly 20,000 images have aided the pursuits of SHREC center student and member goals. Numerous flight apps and automation

Figure 6: STP-H6-SSIVP Sample Burst with Stitching

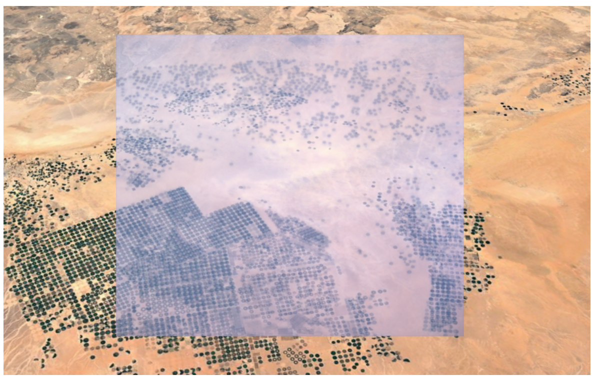

Figure 7: STP-H6-SSIVP Temporal Image Capture Overlay Sample[20]

techniques were deployed and tested on orbit. Many of these apps represent components of student thesis and dissertation research.

STP-H6-SSIVP was deorbited along with the Northrop Grumman Cygnus NG-16 resupply mission on November 20th, 2021. It functioned nominally in orbit from May 12th, 2019, to November 16th, 2021. This timeline was much longer than expected for a university mission. SSIVP has since been succeeded by the Configurable and Autonomous Sensor Processing Research (CASPR) mission aboard STP-H7. Lessons learned from SSIVP in design, software, and operations have been incorporated into STP-H7-CASPR. SSIVP thoroughly demonstrated adaptation to changing conditions and goals. The authors are pleased to declare the STP-H6-SSIVP mission a success.

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