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NANOSATELLITE AND PLUG-AND-PLAY ARCHITECTURE II (NAPA II) UPDATE

James C. Lyke, et al.

12 August 2019

Interim Report

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
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14. ABSTRACT
Under a second $12M program agreement (PA) between US and Sweden (PA-TRDP-US-SW-AF-13-01), AFRL and FMV developed concepts from the previous NAPA program (e.g.a common "plug and play" technology) with four focus areas: (1) missions, (2) mission studies, (3) "i-Missions", and (4) technology development. The core "mission" activity involved development of a 6U-format Space Plug-and-play Architecture (SPA) Research Cubesat (SPARC). SPARC-1 (first and only pursued under this PA) demonstrates rapidly composable and service oriented spacecraft networks. In the mission studies focus area, the US/Sweden collaborative team explores concepts as diverse as mesh communication networks, synthetic aperture radar, combat search and rescue, blue force tracking, space situation awareness, and potentially other militarily relevant roles. SPARC-1 launched 4 May 2019. The "i-Missions" focus area studies the kinetics of rapid mission development. The methodology involves interchangeable blackbox (self-describing) components, software (middleware and applications), advanced pushbutton tools supporting accelerated design flows, and elements of ground systems architecture capable of working fluidly with networks of potentially hundreds of these platforms. The technologies focus area develops miniature spacecraft components and subsystems. This program is on-going (projected complete in Spring 2020), and this interim report summarizes a snapshot, as of August 2019.

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1.0 SUMMARY

Under a second $12M program agreement (PA) between US and Sweden, the US Air Force Research Laboratory (AFRL) and Swedish Defense Material Establishment (FMV) developed concepts from the previous Nanosatellite and Plug-and-play Architecture (NAPA) program (e.g., a common “plug and play” technology) with four focus areas: (1) missions, (2) mission studies, (3) "i-Missions", and (4) technology development. The core "mission" activity involved development of a six unit (6U)-format Space Plug-and-play Architecture (SPA) Research Cubesat (SPARC). SPARC-1 (first and only pursued under this PA) demonstrates rapidly composable and service oriented spacecraft networks. In the mission studies focus area, the US/Sweden collaborative team explores concepts as diverse as mesh communication networks, synthetic aperture radar, combat search and rescue, blue force tracking, space situation awareness, and potentially other militarily relevant roles. The "i-Missions" focus area studies the kinetics of rapid mission development. Consistent with the plug-and-play model of the personal computer, the aspiration of the SPARC series (and the broader umbrella of research being done between the US and Sweden in the Nanosatellite And Plug-and-play Architecture or "NAPA" program) is to pioneer a methodology for creating mission capable 6U spacecraft. The methodology involves interchangeable blackbox (self-describing) components, software (middleware and applications), advanced pushbutton tools supporting accelerated design flows, and elements of ground systems architecture capable of working fluidly with networks of potentially hundreds of these platforms. The technologies focus area develops miniature spacecraft components and subsystems. This program is on-going (projected complete in Spring 2020), and this interim report summarizes a snapshot, as of August 2019, and is an update of a previous report covering the period 12 January 2014-12 January 2016.

Since the last report, the primary emphasis of NAPA has been on the development, assembly, integration, test, launch, and initial on-orbit test and evaluation of the SPARC-1 spacecraft. This SPARC-1 (Space Plug-and-play Architecture Research Cubesat-1) is the first joint US/Sweden military research nanosatellite (6U cubesat), representing culmination of a research activity spanning more than a decade. The spacecraft design encompasses a blending of technologies and components developed by both countries, with primary payloads of direct interest to each nation. The US payload, referred to as an Agile Space Radio (ASR) is an on-orbit reconfigurable transceiver, intended to support live experimentation with different waveforms and protocols useful to communications missions. The Swedish payload is a visible camera optimized for the study of space situational awareness (SSA) concepts.

SPARC-1 integration and test was completed by Spring 2018. The flight readiness review was conducted October 2018, and the spacecraft was transferred to Rocket Labs in March 2019 (Huntington Beach, CA) for transfer to the Rocket Lab launch site in New Zealand. SPARC-1 was launched as part of a group of three spacecraft on 4 May 2019. Initial contact was established 12 May 2019, with an almost full extraction of telemetry. The telemetry revealed much of the key functionality of SPARC-1 worked as expected, but the spacecraft power charging was compromised due to an error in the sun sensor that resulted in a pointing error, keeping SPARC-1 from fully charging. Three more confirmed contacts were made with SPARC-1 from two locations (Albuquerque, NM USA and Dongara, AUS), the last being in June 2019. At the time of this writing, the work to re-establish contact with SPARC-1 continues.

2.0 INTRODUCTION

Nanosatellites have grown in popularity with the advent of the cube satellite, cannisterized dispensers, and the availability of launch opportunities. In this paper, we chronicle the completion of a so-called “6U” cubesat, referred to as the Space Plug-and-play Architecture Research Cubesat-1 (SPARC-1), which at the time of its inception (~2010) represented a fusion of novel hardware, software, and protocol concepts. It was a joint venture between the US and Swedish military establishments, reinforced by an international program agreement (PA) with a primary aim of demonstrating rapidly-developed missions that would be realized as scalable constellations created using innovative design flows and implemented with modular plug-and-play architecture technologies. The work relating to the early design concepts of SPARC-1, as well as the modularity and design tool flow concepts have been described in previous technical publications [1-2]. In the present paper, we describe the final implementation of the SPARC-1 system, which departed in some respects from the previously described embodiment [1]. Much of the physical realization remains in the form and spirit of that previous description (Figure 1).

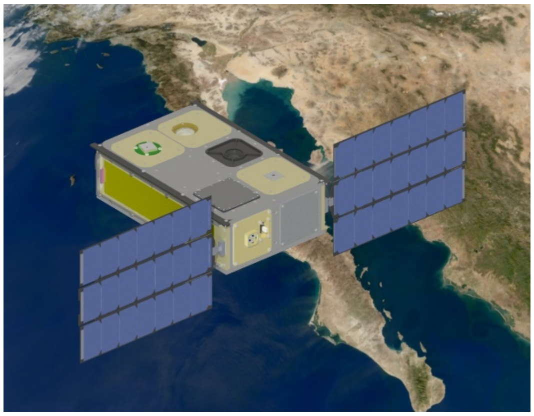


Figure 1. Artist Depiction of the US//Sweden 6U Cube Satellite, SPARC-1

The most significant differences in the interior architecture of the present-day SPARC-1 design when compared to the previous paper are in the avionics. Today, a single Beagle Bone Black [3] computer with Ethernet and serial port interfaces replaces a network of three Spacewire-equipped processing cards. A back-up send only radio provides an ability to send terse Tweet-like messages to earth through the Globalstar satellite network. The original notions of plug-and-play middleware were replaced with a simpler traditional software design that embodied much of the spirit and intent of the sweeping work in plug-and-play software developed by AFRL.

3.0 BACKGROUND

Since 2006, the US Air Force Research Laboratory (AFRL) and the Swedish Defense Material Administration (FMV) have collaborated in nanosatellite technologies that emphasize modularity and the miniaturization of high-performance components. Following a FMV visit to AFRL (March 2006), it was apparent that both countries had considered analogous approaches to modularity, plug-and-play architectures, and miniaturization. As such, the prospects for a technological collaboration seemed sensible, especially at a time of optimism on the prospects of an Operationally Responsive Space (ORS) program that would be a likely future sponsor of the collaborative work. The ORS Office was formed soon thereafter (in May 2007, at the same physical site, Kirtland Air Force Base, NM, USA). Subsequently, ORS pursued its own internationalization campaign through the creation of a multinational Memorandum of Understanding (MOU). MOUs in research are important as they establish an umbrella mechanism for creating collaborative projects. In 2018, ORS was renamed as the Space Rapid Capability Office (Space RCO).

The AFRL work with Sweden evolved as a series of three projects, the first being a grant to Sweden to study an innovative thermal management concept, funded under the notion that it could be used in a broad suite of modular technologies for creating miniature spacecraft. The next two collaborations were program agreements (PAs), the first spanning 2009-2011 and the second spanning 2013-2020. These PAs, referred to as Nanosatellite and Plug-and-play architecture (NAPA), were intended to explore common protocols, testbeds, components, and eventually entire spacecraft, based on modular plug-and-play concepts, such as the Space Plug-and-play Architecture (SPA) pioneered by AFRL in support of ORS and rapid developments. The reader is referred to previous papers for descriptions of these plug-and-play concepts [4].

The NAPA collaboration has been considered successful on several levels. First, it provided a means to harmonize otherwise disparate concepts in modular hardware and software. It also provided a way to think about missions, as will be discussed in the next section, as being an overall capability realized by constellations of simple nanosatellites, scalable in quantity.

4.0 SPACECRAFT MISSION

A single space experiment (such as SPARC-1) can test new ideas or serve as a pathfinder for new technologies. In the NAPA concepts of mission, capabilities would be identified, such as combat search and rescue (CSAR), blue force tracking (BFT), space situational awareness (SSA), and other missions involving communications or earth surveillance methods. A modular architecture, combined with the right “wizard” design tool flow concepts, would allow the rapid specification and implementation of scaled constellations in a cradle-to-grave sense in which the development, launch, an on-orbit operation could be carried out within a single arc activity.

SPARC-1 is a single spacecraft of an intended series of missions that would explore technologies, design approaches, and operations concepts. SPARC-1, as a compact 6U cubesat, packs together two different mission roles, along with a set of advanced bus technologies.

The missions of SPARC-1, by circumstance rather than intent, were cleanly separated by the interests of the research groups of both countries. We briefly outline these mission concepts in this section.

The SPARC-1 satellite is a testbed for testing reconfigurable software defined radio capability. The ASR is paired with a pair of ANT-S/S antennas to provide a full duplex S-Band transceiver platform. The dual antennas provide all aspect communications with the ground so communications can be maintained at all times. The antenna control is performed by the ASR radio system. The ASR is used for command and control of the SPARC-1 satellite while on orbit. The ASR radio system also hosts alternative waveforms developed by third parties and are uploaded to the ASR radio for characterization while in orbit. The basis of the ASR, referred to as “LPR-SDR-S/S” was developed for small form factor cubesats, which due to expense rely on communication using existing ground infrastructure. One of the SPARC-1 experiment objectives is to demonstrate the waveform flexibility of software defined radios on the fly. The ASR in SPARC is a high performance radio capable of 4W output RF transmission power. When paired with the two (ANT-S/S) antennas, ASR is capable of covering the entire Unified S-Band (USB) frequency range as well as all vehicle aspect orientations (i.e., the radio is approximately omni-directional).

SPARC-1 is compatible with a wide range of ground sites allowing the Air Force to control it from a variety of orbits. Command and control is the default mode of the LPR radio. When enabled, a variety of other experimental waveforms can be uploaded and tested. This capability will allow a wide range of communication experiments to be conducted on orbit. This capability allows for rapid development and testing of waveforms.

Cubesat communications have advanced considerably since their inception in the late 1990s. This enabling capability allows them to fly while using existing ground infrastructure and thus integrate them with larger missions. Software defined radios are an enabling capability for the small satellites. The challenges of developing these types of radios are the small size, high performance, survival of extreme environments and reliability. The ASR provides all of these features as well as the primary mission of communications.

5.0 SATELLITE COMPONENTS

Shown below (Figure 2) is the satellite with the key components identified.

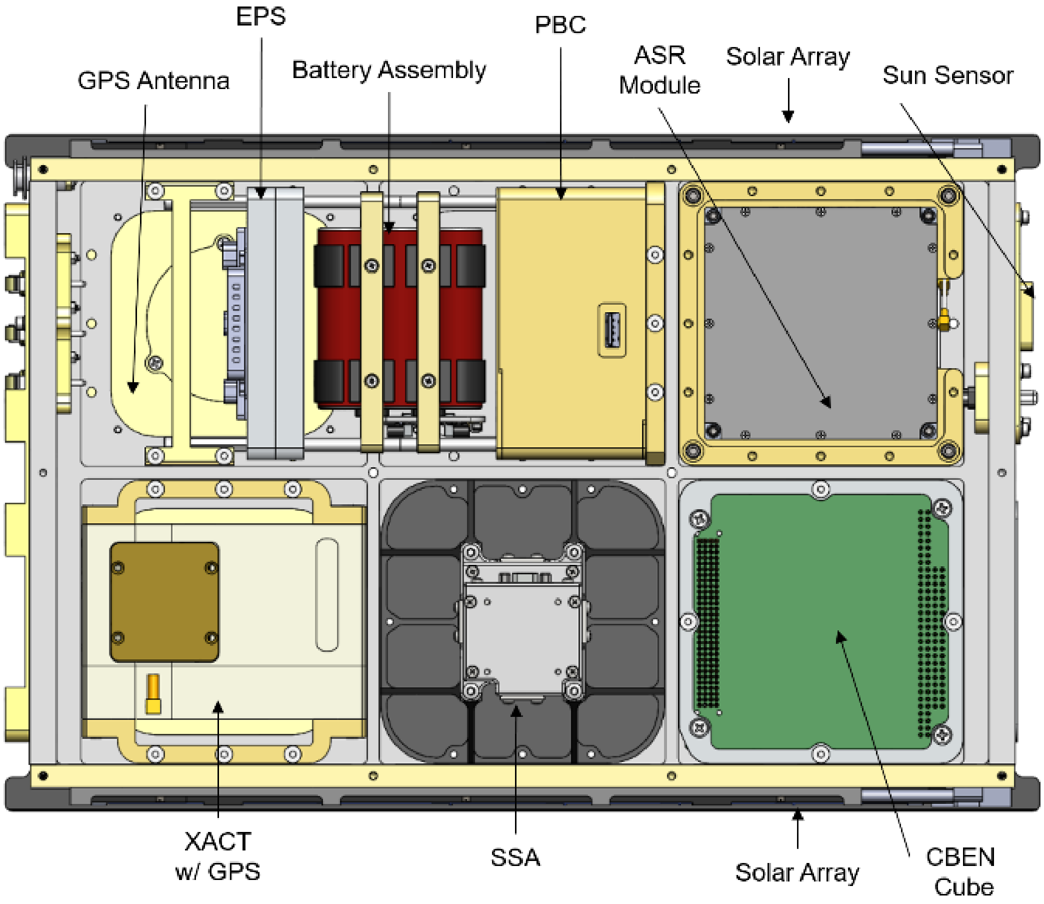


Figure 2. **SPARC-1 Layout**

5.1 Command and Data Handler (C&DH)

The C&DH consists of a Beagle Bone Black (BBB) single board processor and a custom interface board built by Vulcan Wireless together referred to as the Plan B Computer (PBC). AFRL has previously performed radiation testing on three BBB units and found it acceptable for low earth orbit missions with failures occurring above 15 kRad. The custom interface card provides four TTL RS-422, one TTL RS-485, a 12v DC to 5v DC converter to power the BBB, and a watchdog timer.

5.2 Flight Software (FSW)

The Flight Software System runs on the Plan B Computer (PBC) Beagle Bone Black. The software is based upon a modular open system architecture approach developed for the AFRL Plug and Play Satellite (PnPSat). Since there is a single processor in SPARC-1, we chose to implement the Adaptive Sensor Interface Modules (ASIMs) as individual modules called soft ASIM (sASIM). Each hardware component has a specific sASIM providing interfaces. The FSW architecture is shown below (Figure 3).

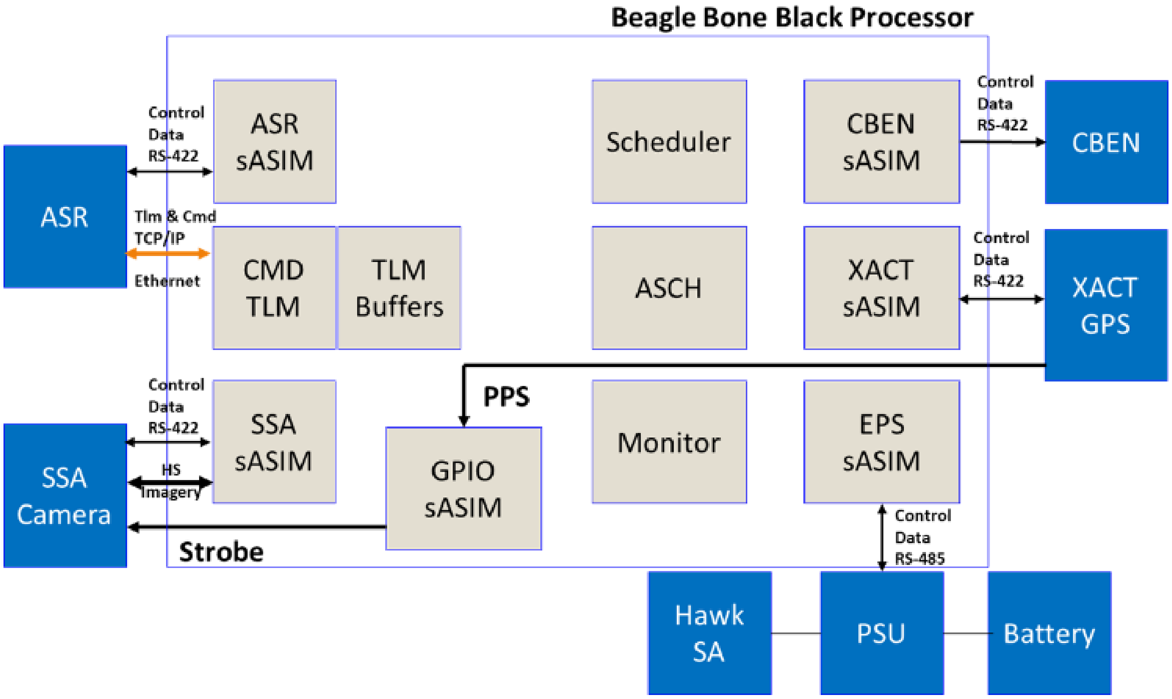


Figure 3. **Flight Sotware (FSW) Architecture**

For example, the ASR and XACT soft-ASIMs provide interfaces to the SPARC-1 Messaging Interface and manage the serial RS-422 interfaces to the hardware components. The XACT sASIM provides the interface to the XACT ADCS handling ground commands, attitude and position data, housekeeping data, and telemetry. In addition, the XACT timing is used to provide the general purpose inputs and outputs time interface a message with the time of the next pulse per second (PPS) signal which is used to synchronize the time for the computer and SSA camera strobe.

The ASR sASIM accepts commands from the SPARC-1 Messaging Interface, formats them for the ASR hardware using the Radio Control Interface protocol, and manages the ASR RS-422 serial control interface. Command responses are sent to the Telemetry and Command Application for formatting and relay to the ground. The sASIM also requests the telemetry data block from the ASR at a 1Hz rate and sends them to the data telemetry buffer for downlink.

The Scheduler accepts commands from the ground and at the appropriate time, releases them to the specific applications. It also manages the command queues allowing individual or group removal based upon ground command. Commands that have become stale are automatically removed.

The Autonomous Spacecraft Handler (ASCH) provides spacecraft control during initial startup and when in Safe Mode (SC_SAFE). It is responsible to capture initial tip off rates (DETUMBLE), deploy the Hawk solar arrays (DEPLOY), check the current battery voltage (CHECKBATTERY), and then transition to Normal Mode (SC_NORMAL). Once the spacecraft has transitioned to normal mode the ASCH monitors the bus voltage and temperature sensors and will transition back to Safe Mode. The ASCH can be commanded from the ground to enter either SAFE or NORMAL mode, bypassing its internal processing. The ASCH is the critical routine that is responsible for initial spacecraft commissioning and managing Safe Mode.

The Command and Telemetry application accepts telemetry messages including data, command response, and image types. Separate buffers are maintained for each telemetry type. The CMD/TLM provides a TCP/IP interface to the ASR radio. The ASR connects to this interface whenever there is good contact with the ground and closing the connection when that contact is lost. The CMD/TLM also interacts with the SPARC-1 ground station software to maintain a list of telemetry messages that have been correctly received on the ground. Messages that have been sent but not properly received are retransmitted insuring that all data is correctly processed.

5.3 Electrical Power System (EPS)

The EPS consists of the power supply unit (PSU), the battery pack and the solar array. All three systems were developed by different vendors and then integrated into a cohesive system. The PSU and battery pack are shown below (Figure 4).

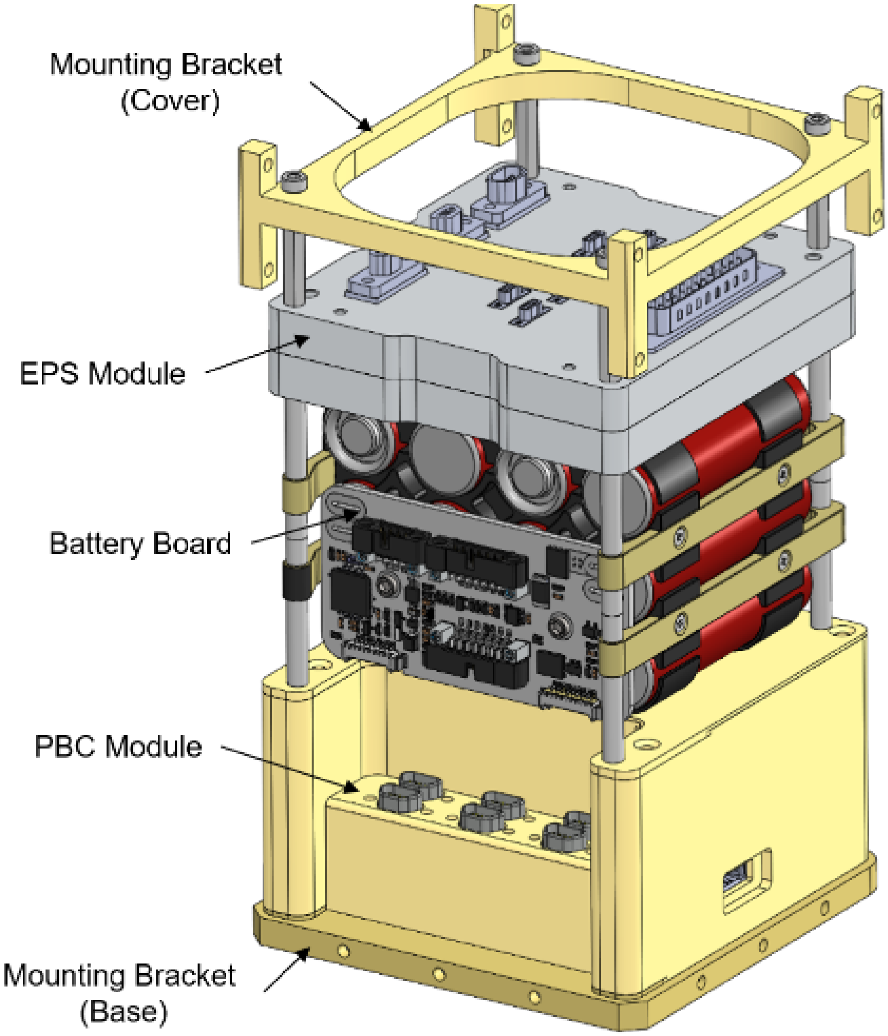


Figure 4. **Power Supply Unit and Battery Pack**

For example, the ASR and XACT soft-ASIMs provide interfaces to the SPARC-1 Messaging Interface and manage the serial RS-422 interfaces to the hardware components. The XACT sASIM provides the interface to the XACT ADCS handling ground commands, attitude and position data, housekeeping data, and telemetry. In addition, the XACT timing is used to provide the general purpose inputs and outputs time interface a message with the time of the next pulse per second (PPS) signal which is used to synchronize the time for the computer and SSA camera strobe.

The PSU Control Unit is powered on upon separation from the launch vehicle. A one-time, 30-minute timer enables the PBC and the ASR radio. For all other subsystems, the PSU Control Unit must receive a command to activate the power. During normal operation, the EPS is commanded from the PBC over a RS485 serial command interface.

The solar array is the High Watts per Kilogram (HaWK) system. The HaWK has three panels of solar arrays per wing and two wings. It has a mass of approximately 276 grams and utilizes Spectrolab solar cells. At beginning of life, it can provide 36 watts at seventy degrees Celsius.

5.4 Structure and Thermal

SPARC-1 is based on the SUPERNOVA 6U structure modified to support the ASR S-band antennas. SPARC-1 orientation is shown deployed below (Figure 5). The original design was based on using the Planetary Systems Corporation's Canisterized Satellite Dispenser (CSD) which is preload tab based design providing a modellable load path and securing the satellite so it cannot jiggle during launch. However, the current dispenser is a modified Nanoracks 6U rail based model that is also compatible with the SPARC-1 design.

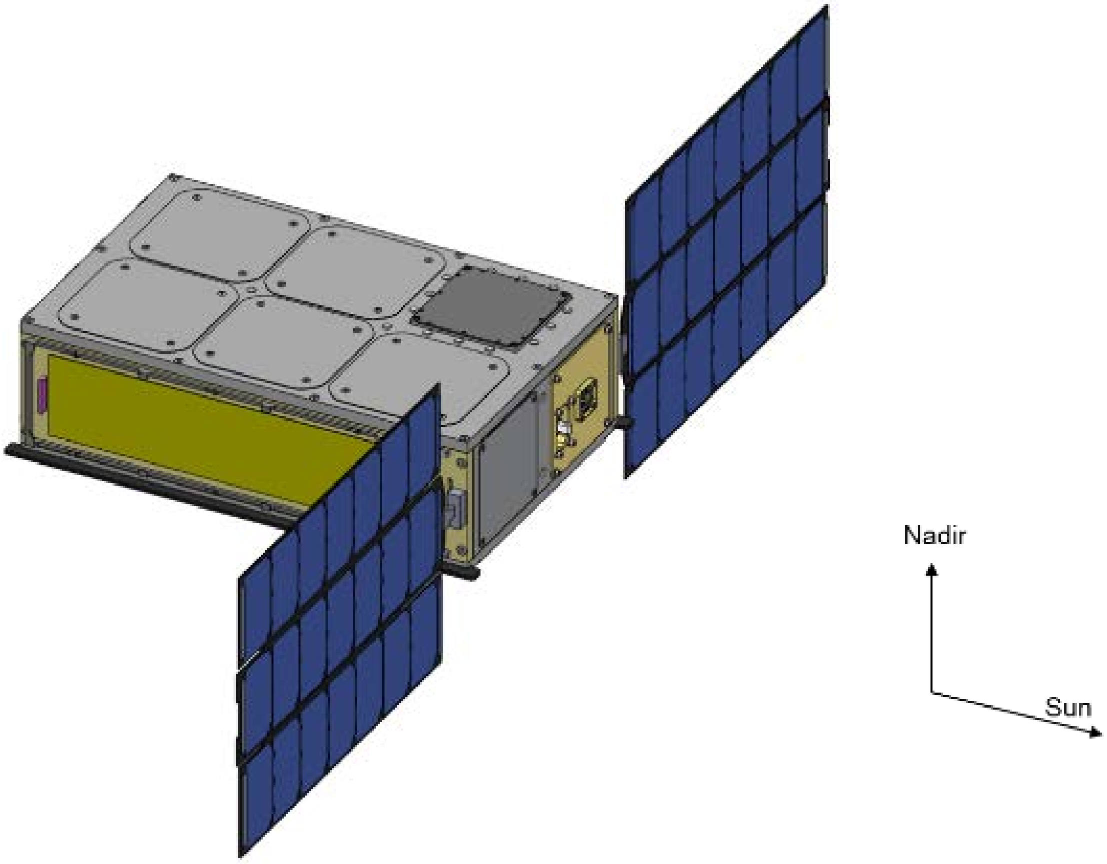


Figure 5. **SPARC-1 Orientation**

A simple bulk thermal model has been used to estimate the on-orbit temperatures for the solar arrays and body. These are shown below (Figure 6). In addition, eight temperature sensors are mounted inside the body and that data will be compared to these estimates.

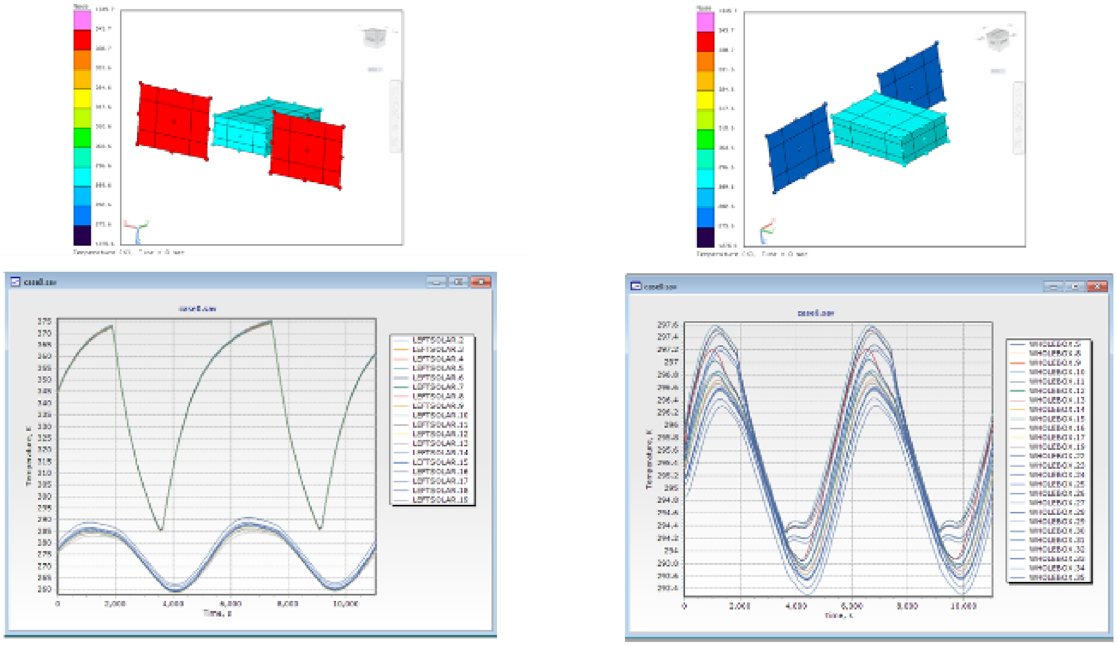


Figure 6. **Temperature Estimates for Solar Array and Body**

5.5 Communications

There are multiple communications capabilities on the spacecraft including the Vulcan Wireless software radio *(ASR)* and the Globalstar Simplex modem.

Figure 7. **Vulcan agile software radio (ASR)**

Shown above (Figure 7) is the Vulcan Wireless software radio. It is a full duplex flight model complete with integrated diplex filter and antenna switch. Extensive signal analysis and processing of other software radios has been accomplished on previous missions [7-12, 14] through similar hardware as utilized in the ASR.

The Globalstar Simplex unit provides routine housekeeping data to the ground operations team. Based on past performance, it is believed that most spacecraft in the future should include a system such as the Globalstar to ensure access to available spacecraft health from the minute the satellite deploys until the end of life (24 hours a day).

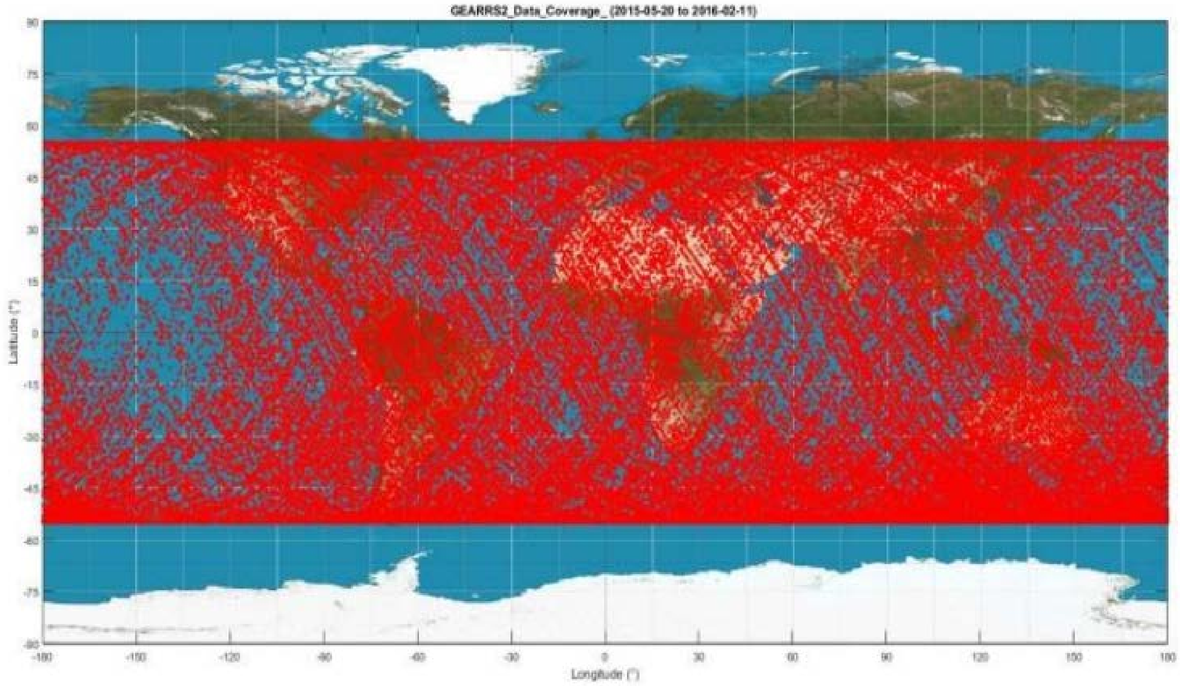


Figure 8. **GEARRS2 Communications Coverage**

Some GEARRS2 Simplex raw data before projection and sampling Normalization is shown above (Figure 8). As can be seen, this type of coverage capability provides a satellite operations team with near real-time access of spacecraft information anywhere on orbit [19]. Degrading hardware can be quickly identified and tracked for trends and possible resolution.

Figure 9. **COSMIAC 3-Meter Dish**

For ground operations, the team will utilize the three-meter s-band dish at the COSMIAC Research Center (Figure 9) at the University of New Mexico (UNM). The dish system was installed and is maintained by students and faculty from UNM. Full design information is available upon request. The system transmit utilizes the Amergent software radio with a final amplification section of 30 watts of power being applied to the feed assembly. On the receive path, the dish provides approximately 30dB of gain which is then passed through a low noise amplifier for an additional 28dB of gain. Both signals are then passed approximately 200 feet through LMR-400-UF which contributes 7dB of loss.

5.6 Attitude Determination and Control (ADACS)

Blue Canyon Technologies developed the fleXible Attitude Control Technology (XACT) attitude control system to provide reliable high-performance attitude control, compatible with a variety of CubeSat configurations [6].

5.7 SSA Payload

The SSA sensor is a Hyperion Technologies IM400 Imaging Star Tracker (Figure 10) able to take images of point source objects with a resolution of 88 µrad/pixel. Much of what has been accomplished in this payload builds on previous SSA flights [5, 13, 15-18]. On SPARC-1, the camera has a limiting star magnitude of 6.9 for a 100msec exposure. Images are taken based upon a strobe from the GPIO which is in-turn triggered by the GPS based 1 PPS. To maximize pointing precision and simplify implementation, images are taken on whole seconds. Camera operating parameters such as exposure time, gain, etc. can be commanded from the ground and implemented via the SSA sAIM. The 2048x1944 pixel images take approximately 14 minutes to transfer from the camera to the sASIM and then 1 minute to download by the ASR.

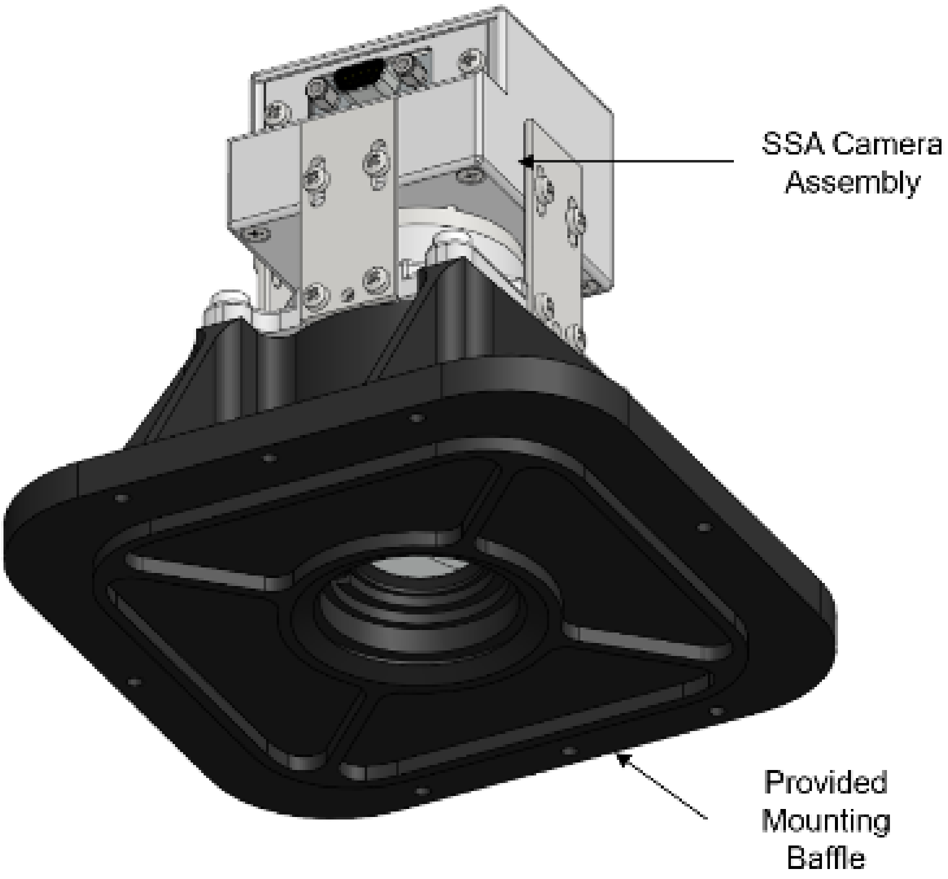


Figure 10. Swedish Space Situational Awareness **(SSA) Payload**

5.8 CBEN Payload

The CBEN cube (Figure 11) can send messages depending on the ground requests using a Globalstar send-only radio [19]. The messages of the CBEN repertoire include adjusting camera exposure, color correction settings, capturing an image, performing Raspberry Pi software updates, etc. Each time one of these actions is performed, an acknowledgement message packet is queued for transmission, permitting ground verification of whether the request is successful or not. If successful, certain required outputs are contained within the message. When an image is captured, the image itself does not get sent back over the radio, but rather, the file size of the captured image is reported.

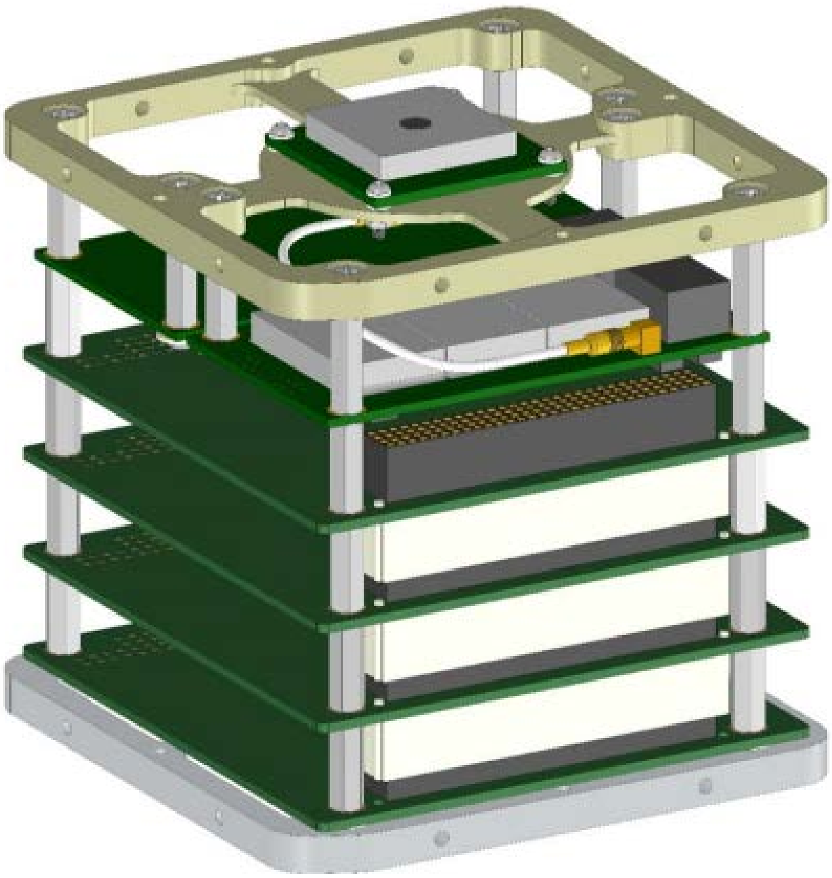


Figure 11. CBEN Payload

6.0 INTEGRATION AND LAUNCH OF SPARC-1

Following several annual briefings of the U.S. Department of Defense's Space Experiment Review Board (SERB), SPARC-1 secured support for launch in low earth orbit from the DoD Space Test Program.

The impetus for SPARC-1 itself dates back to approximately September 2013, not long after the approval of the latest bilateral program agreement for the NAPA program. The SPARC-1 program took approximately two years to go from critical design review to completion. While the development program experienced some setbacks, such as the redesign of the computer system, much of the delay was driven by available launch dates and frequency licensing. As of September 2018, all radio frequency licensing was completed.

SPARC-1 integration and test was completed by Spring 2018. The flight readiness review was conducted October 2018, and the spacecraft was transferred to Rocket Labs in March 2019 (Huntington Beach, CA) for transfer to the Rocket Lab launch site in New Zealand. Figure 12 shows the SPARC-1 configuration test fit into a standardized 6U dispenser.

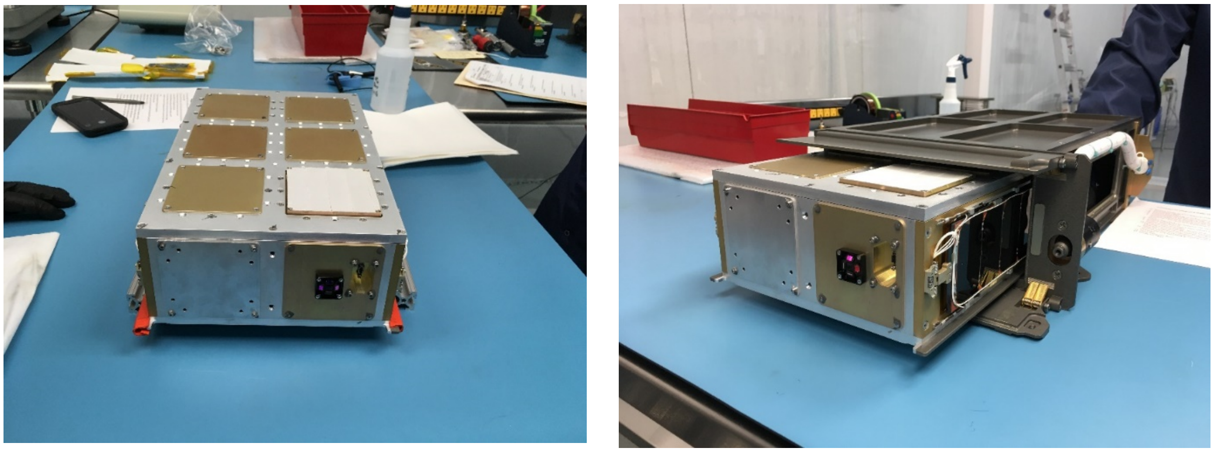


Figure 12. SPARC-1 in stowed (left) configuration, integrated into 6U dispenser (right)

SPARC-1 was launched as part of a group of three spacecraft on 4 May 2019 (Figure 13). Initial contact was established 12 May 2019, with an almost full extraction of telemetry. The telemetry revealed much of the key functionality of SPARC-1 worked as expected, but the spacecraft power charging was compromised due to an error in the sun sensor that resulted in a pointing error, keeping SPARC-1 from fully charging. Three more confirmed contacts were made with SPARC-1 from two locations (Albuquerque, NM USA and Dongara, AUS), the last being in June 2019. At the time of this writing, the work to re-establish contact with SPARC-1 continues.

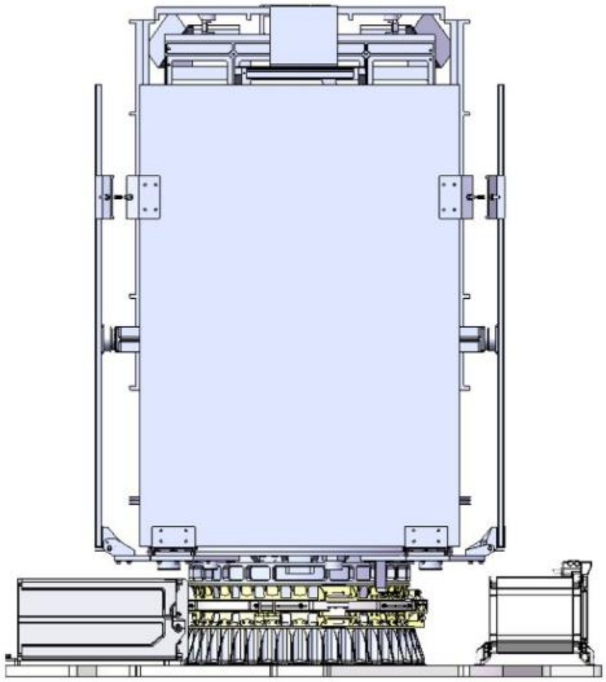
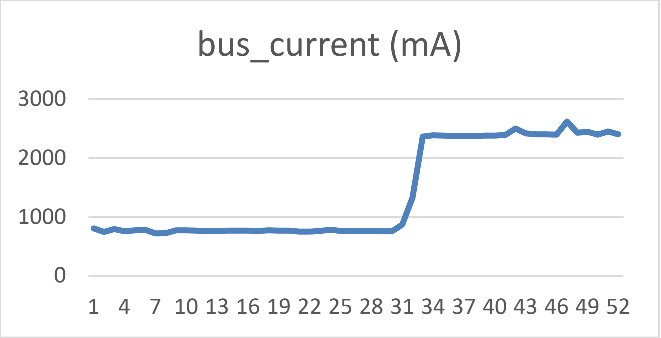


Figure 13. Depiction of how three spacecraft were integrated onto the Rocket Labs Electron launch vehicle. SPARC-1 is the small spacecraft to the left on the launch ring.

Four contacts were made with SPARC-1, two of which successfully collected telemetry. Typical telemetry from the first contact is shown in Figure 14. At the time of this writing, the telemetry is still being analyzed, and more details may be provided in a future report.



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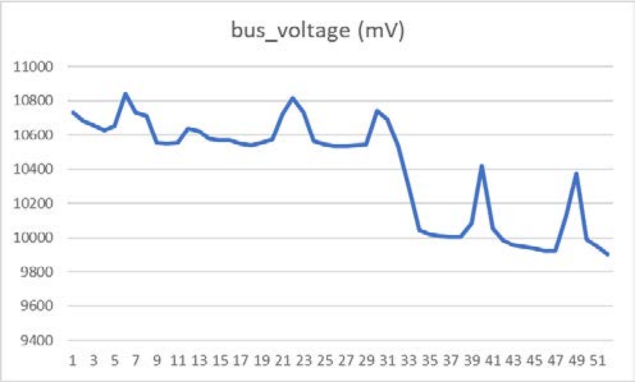

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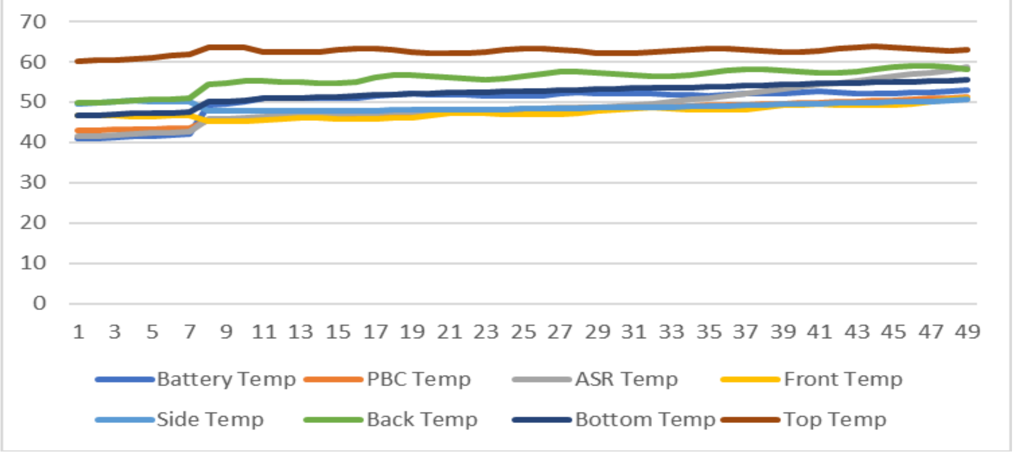

(c)

Figure 14. Representative telemetry from SPARC-1 during first telemetry collection. (a) Bus current consumption. (b) Bus voltage. (c) Some thermometry from eight temperature sensors. All horizontal units are time (1 = 10 seconds).

In the original plan, it was expected that SPARC-1 would be considered operational (mission ready) following a two-week checkout. Instead, four months (at the time of this writing) have been spent attempting to make contacts and correct the software in the guidance subsystem to compensate for what appears to be a mis-oriented sun sensor. Since the spacecraft will be in orbit for at least two years, it is still possible to recover the spacecraft. In this event, SPARC-1 will be mission capable.

A mission capable SPARC-1 will provide opportunities for the science teams of US and Sweden to conduct experiments. Swedish researchers will provide information on desired SSA experiments, while in the US, the AFRL team will identify a series of cognitive radio experiments to examine a variety of use cases pertaining to meshed communications, combat search and rescue, and blue force tracking with traditional and experiment waveform concepts. CBEN can be configured to test experimental neuromorphic concepts. Failing this, we can fall back on primary SSA data for studying the same machine-learning algorithms.

7.0 CONCLUSIONS

The SPARC-1 spacecraft represents the culmination of a long and fruitful collaboration between the US and Swedish military organizations. It reflects the hopes to not only fly a spacecraft, but also to enable the creation of scaled missions that can be implemented rapidly. The program of collaboration started well over a decade ago, a time over which the ambitious napkin sketches became expressed through the SPARC-1 project. Of course, the world did not stand still, and many of the ideas we outlined were also outlined and implemented by others. In fact, several of the technologies (the solar panels, radio, and some of the avionics) developed through support of NAPA also transitioned into other flight projects, which helped reduce the risk for SPARC-1.

Even though at the time of this writing, SPARC-1 is not mission capable, to even receive a single telemetry message means that most of SPARC-1 works according to its intended design. While we remain hopeful of recovering SPARC-1 for its full mission functionality, even making orbit and establishing contact is a significant result of the NAPA partnership.

REFERENCES

[1] J. Lyke, et al., "SPARC-1: A joint US/Sweden multi-mission modular nanosatellite platform," 2016 IEEE Aerospace Conference, Big Sky, MT, 2016, pp. 1-16.

[2] J. Lyke, J. Freden, F. Bruhn, M. Ahlberg, and J. Preble, "Architectural Framework and Toolflow Concepts for Rapidly Composable Wireless Spacecraft," NATO Applied Vehicle Technology AVT-257-RSM-041 Specialists Panel, Avila, Spain, 26 September 2016.

[3] "Beagleboard," Wikipedia article, https://en.wikipedia.org/wiki/BeagleBoard, retrieved 1 October 2018.

[4] James Lyke, Quinn Young, Jacob Christensen, and David Anderson, "Lessons Learned: Our Decade in Plug-and-play for Spacecraft," Proceedings of the 28th Annual AIAA Conference on Small Satellites, Logan, UT, 2014.

[5] Pirada Techavijit, Sorawat Chivapreecha, Polkit Sukchalerm, and Aniwat Plodpai, “CubeSat image transmission in JPEG compression: An experiment on high altitude platform,” 2016 8th International Conference on Knowledge and Smart Technology (KST), Thailand.

[6] Matthew Baumgart, Michael Ferenc, Daniel Hegel, Bryan Rogler, and Devon Sanders, “GNC Implementations for Small Interplanetary and Lunar Spacecraft,” AAS 18-041.

[7] Emre Baceski, Serhan Gökçebağ, Ahmet Erdem, Caban Gökhan Erbay, Mücahit Akyol, Kamil Arslankoz, İsmail Arslan, Muhammed Akif Ağca, Yusuf Burak Aydın, Alim Rüstem Aslan, and Osman Ceylan, “HAVELSAT: A software defined radio experimentation CubeSat,” 2015 7th International Conference on Recent Advances in Space Technologies (RAST), Istanbul.

[8] Alessio Fanfani, Sara Jayousi, Simone Morosi, Luca Simone Ronga, Enrico Del Re, and Luca Rossettini, “Feasibility Study of an Alert Messaging System by Means of CubeSat,” SDR and Web Service Technologies GLOBECOM 2017, 2017 IEEE Global Communications Conference, Singapore.

[9] Mamatha Ramapura Maheshwarappa, Mark D. J. Bowyer, and Christopher P. Bridges, “Improvements in CPU & amp; FPGA Performance for Small Satellite SDR Applications,” 2017 IEEE Transactions on Aerospace and Electronic Systems, Volume 53, Issue 1, pp. 310-322.

[10] Mamatha R. Maheshwarappa, Mark Bowyer, and Christopher P. Bridges, “Software Defined Radio (SDR) architecture to support multi-satellite communications,” 2015 IEEE Aerospace Conference, pp. 1-10.

[11] Jennifer L. Alvarez, Mark Rice, John R. Samson, and Michael A. Koets, “Increasing the capability of CubeSat-based software-defined radio applications,” 2016 IEEE Aerospace Conference, pp. 1-10.

[12] "Vulcan Wireless SDR Products," Available from http://www.vulcanwireless.com/products/, April 2011.

[13] R. Sandau, K. Brieß, and M. D'Errico, "Small satellites for global coverage: Potential and limits," ISPRS Journal of Photogrammetry and Remote Sensing, vol. 65, pp. 492-504, 2010.

[14] M. R. Maheshwarappa and C. P. Bridges, "Software defined radios for small satellites," Adaptive Hardware and Systems (AHS) 2014 NASA/ESA Conference, pp. 172-179.

[15] A. Mehta, "USAF Focuses on Space Debris Other Threats," Defense News, 24 May 2014

[16] V. Hernandez, P. Gankidi, A. Chandra, A. Miller, P. Scowen, H. Barnaby, E. Adamson, E. Asphaug, and J. Thangavelautham, "8220; SWIMSat: Space Weather and Meteor Impact Monitoring using a Low-Cost 6U CubeSat," Proc. 30th Annual AIAA/USU Conference on Small Satellites, 2016.

[17] Jordyn Stoddard, David Messinger, and John Kerekes, “Effects of CubeSat design parameters on image quality and feature extraction for 3D reconstruction,” 2014 IEEE Geoscience and Remote Sensing Symposium.

[18] D. J. Walvoord, A. J. Rossi, B. D. Paul, B. B. Brower, and M. F. Pellechia, "Geoaccurate three-dimensional reconstruction via image-based geometry," in Proc. SPIE Defense, Security, and Sensing, Vol. 8747, 2013.

[19] Globalstar Link: From Reentry Altitude and Beyond,
http://mstl.atl.calpoly.edu/~bklofas/Presentations/SummerWorkshop2016/3_HankVoss.pdf.

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ASIM	applique sensor interface module
ASR	Agile space radio
CCSDS	Consultative Committee for Spacecraft Data Systems
CSD	cannisterized satellite dispenser
DHS	Data handling system
EDAC	error detection and correction
FPGA	field programmable gate array
HBNR	High Bandwidth Nanosat Radio
JAXA	Japanese space agency
MOC	Mission operating center
Mbps	millions of bits per second
NAPA	Nanosatellite and plug-and-play architecture
NRZ-L	non return to zero low (protocol)
OBC-S	on-board computer
OIS	Open internet standard
ORS	Operationally Responsive Space
PBTF	Push button toolflow
PL1	Payload 1
PL2	Payload 2
POC	Payload operating center
PPOD	poly-picosatellite orbital dispenser
REST	Representational State Transfer
RMAP	remote memory access protocol
RTEMS	Real-time executive for military systems
SPA	Space Plug-and-play Architecture
SPA-1	I2C based SPA standard interface
SPARC	SPA Research Cubesat
SPA-S	spacewire-based SPA standard interface
SpW	spacewire
SSA	Space Situational Awareness
TCM	telecommand module
TMR	triple modular redundancy
TT&C	timing, telemetry, and control
UART	universal asynchronous receiver transmitter
VC	virtual channel
XML	extensible markup language
xTEDS	XML-based transducer electronic datasheet

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