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EDSN Development Lessons Learned

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ABSTRACT

The Edison Demonstration of Smallsat Networks (EDSN) is a technology demonstration mission that provides a proof of concept for a constellation or swarm of satellites performing coordinated activities. Networked swarms of small spacecraft will open new horizons in astronomy, Earth observations and solar physics. Their range of applications include the formation of synthetic aperture radars for Earth sensing systems, large aperture observatories for next generation telescopes and the collection of spatially distributed measurements of time varying systems, probing the Earth's magnetosphere, Earth-Sun interactions and the Earth's geopotential. EDSN is a swarm of eight 1.5U Cubesats with crosslink, downlink and science collection capabilities developed by the NASA Ames Research Center under the Small Spacecraft Technology Program (SSTP) within the NASA Space Technology Mission Directorate (STMD). This paper describes the concept of operations of the mission and planned scientific measurements. The development of the 8 satellites for EDSN necessitated the fabrication of prototypes, Flatsats and a total of 16 satellites to support the concurrent engineering and rapid development. This paper has a specific focus on the development, integration and testing of a large number of units including the lessons learned throughout the project development.

INTRODUCTION

Numerous applications have been identified for constellations or swarms of satellites working together. These swarms or constellations could include 10s, 100s or even 1000 satellites. Mission concepts include distributed Earth observation platforms, synthetic aperture radars and large array deep space telescopes[1,2&3]. Some of these mission concepts require complex inter-spatial coordination and cooperative interactions[1,2&3]. A near term application of these constellations or swarms is their use to perform time and spatially varying scientific measurements of coupled phenomena such as the interaction between solar-wind, magnetosphere, ionosphere, and thermosphere, and mesosphere on a planetary scale[1].

The Edison Demonstration of Smallsat Networks (EDSN) is a technology demonstration mission that provides a proof of concept for a constellation or swarm of satellites performing coordinated time varying multipoint observations with applications to space physics. EDSN provides a first step for a constellation of nano-satellites and includes numerous features applicable to near term and future mission concepts including: coordinated activities, inter-satellite communications, distributed data sharing, singular interaction with a ground station and distributed redundancy.

GOALS AND OBJECTIVES

The project goal is to demonstrate that a swarm of satellites is capable of collecting multi-point science data and transferring the data to the ground. This is achieved through the mission objectives:

1. Flight demonstrate one-way space-to-space data transfer whereby at least 2 satellites

transfer data to a third satellite, which then transfers the data to the ground

2. Flight demonstrate a system to collect multi-point science measurements, transfer science measurements to another satellite and transfer to the ground
3. Flight demonstrate a reaction wheel based pointing system.
4. Assess the viability of satellites built with Commercial Off The Shelf (COTS) components to operate for 60 days

The four objectives of the EDSN mission each provide advancement of the state of the art in small satellite constellations. To maximize the return from the technology demonstration mission, each of the objectives were decoupled and treated as their own technology demonstration. The benefit of this approach was that a failure in one objective would not impact the other objectives. The focus of the mission was to be a proof of concept and therefore the mission concept was developed to provide multiple opportunities for each objective rather than optimizing or maximizing the capability of the data/communications systems or attitude determination and control system.

MISSION OVERVIEW

The EDSN mission was designed to operate autonomously with minimal interaction from the ground, limited to collecting the technology demonstration and science data. This approach was taken to increase the number of opportunities to prove out the concept while reducing the complexity of the mission operations. Commanding of the satellites is limited to off-nominal satellite deactivation to prevent communication interference issue with other assets as required by the Federal Communications Commission (FCC).

The ORS Office, in partnership with Sandia National Laboratories, the University of Hawaii, the Pacific Missile Range Facility and the Aerojet Rocketdyne Corporation, is developing a low cost, small launch system known as Super Strypi. The University of Hawaii's HiakaSat will fly as the primary payload on the Integrated Payload Stack with an additional 12 CubeSats flying as secondary payloads. EDSN has eight identical 1.5U Cubesats that are deployed concurrently from this launch vehicle. The satellites remain inactive until 30 minutes after deployment. They charge until the battery voltage is >8 volts and then begin beaconing State of Health (SOH) data and start their de-tumble operations for 30 hours alternating between 30 minutes of magnetic alignment and 2 hours of charging. The satellites then perform a 60-minute magnetic alignment maneuver and acquire a GPS vector. The satellites use the GPS vector to propagate their orbit and autonomously plan their activities for the next minor cycle (a 25 hour period). Activities include: science measurements, crosslink sessions, downlink, pointing demonstration, the next GPS acquisition and the Planning and Scheduling for the next minor cycle. These minor cycles repeat and are referenced to a preprogrammed time and date determined by Coordinated Universal Time (UTC) with a 25 hour cadence. Activities are a mix of time referenced and/or position based with preprogrammed rules that govern their planning to ensure concurrent operations of coordinated activities including science measurements and crosslinking sessions.

The satellites are identical except for unique preprogrammed software parameters including satellite ID and beacon period offset. The satellites operate as either a Captain (Cpt) or Lieutenants (Lts). For each minor cycle (25 hr period) a single satellite operates as the Captain based on the unique ID and the UTC start time of the minor cycle. The other satellites operate as Lieutenants. The Cpt rotates to the next designated satellite in the constellation each minor cycle such that each satellite has multiple opportunities to be Cpt during the 60-day mission. A major cycle is defined as 8 minor cycles and is the time taken for a Cpt in the constellation to reassume the Cpt role.

All satellites perform science measurements, crosslink sessions, the next GPS acquisition and the Planning and Scheduling for the next minor cycle but only the Cpt performs a downlink and pointing demonstration. One downlink is schedule per minor cycle allowing each Cpt an opportunity to downlink the data collected from the Lts. The downlink is autonomously scheduled based on the stored location of the ground station and the longest communications window determined for the current minor cycle. The pointing demonstration satisfies Objective 3 by performing a 5-minute 3-axis stabilized sun pointing mode using the solar panels, magnetometer and rate gyros as sensors and 3 orthogonal DC motors as reaction wheel actuators. The reactions wheels are only used for the pointing demonstration all other maneuvers are accomplished by magnetic torque coils embedded in the solar arrays. Scheduler logic and the onboard orbit propagator prevent the pointing demo from being planned while the satellite is in eclipse.

The small power production of the satellites required efficient power use planning. To conserve power for power intensive activities, like downlink, the satellites use a low level power "Wait" state where the main processor and other satellite systems are deactivated. During "Wait" a low level processor controls the State-Of-Health (SOH) UHF beacon and when to turn back on the main processor determined by the start time of the next activity in the schedule. Fault management is implemented so that if the main processor has not been on in the past 10 hours the low level processor will wake the main processor and check status.

To meet Objective 2, science data is collected for two 10-minute periods at target locations of interest. The science team, from Montana State University (MSU), selected the Northern Hemisphere (Latitude 40 degrees North to 80 degrees North, Longitude -180 to 180 degrees) and the South Atlantic Anomaly (Latitude 10 degrees South to 50 degrees South, Longitude 10 degrees East to 120 degrees West). The scheduler uses logic to ensure that the science measurements occur as early as possible in the minor cycle given the satellites orbital path and the target locations. The benefits of this approach include reduced clock drift and orbital position errors from the recent GPS acquisition. The science data is returned to the ground via crosslinks in the constellation and then downlinked to the ground via the Cpt using an S-band transceiver. There is also a redundant method for science data return in case of communication issues with either the downlink or crosslink. The satellite beacon alternates between the last recorded science data packet and the SOH data packet every 60 seconds. Each satellite has a different beacon offset of 7.5 seconds so that all 8 satellites of the constellation can send beacons without interference with the others. Science data is stored in packets with additional data (satellite ID, time and position) for post processing on the ground. The science packets are passed through the constellation in a standard format using a store-and-forward methodology with the captain passing packets to ground without modification.

To meet Objective 1, the satellites perform four 47-minute crosslink sessions that are time referenced to the start of the minor cycle with a four hour cadence. The communications architecture is described in detail in Hanson, 2014[4]. During a crosslink session, the Lts turn on their UHF transceivers and listen. During the crosslink sessions the satellites are tumbling and use an omni-directional monopole antenna with ~120km range. However, there is still the possibility of missed crosslink communications since there are some nulls in the combined antenna patterns and based on orbit dynamics the satellites will drift out of range later in the mission. To increase the chance for data exchange, the Cpt satellite turns on the transceiver and sends 6 ‘ping’ packets, one every ten seconds and then switches to listen mode. The ‘ping’ packet header includes a ‘ping’ packet type and unique ID for the intended satellite. The ‘ping’ packet type acts as an instruction to send data. The Lts listen for the ‘ping’ packets and if they receive one, they process it and determine if it was intended for them as indicated by the unique ID. If it corresponds to their unique ID, the Lt waits for 60 seconds after receiving the first ‘ping’ and responds by transmitting a SOH packet and their stored science data for up to 4 minutes. Otherwise if not intended for them they continue to listen until either their unique ID is present or the 47-minute crosslink session window expires. The Cpt listens for the data from the Lt, stores it for future transmission to the ground and then moves on to send ‘ping’ packets to the next Lt and again switches to listen mode for the data from the target Lt. This ‘ping’ and response continues for all satellites throughout the constellation. The crosslink session methodology incorporates large time buffers of ~30 seconds between actions to account for any potential clock drifts between the satellites. If a satellite is out of range or it does not receive a ‘ping’ packet, it will continue to store the data (SOH & science) until it receives a ‘ping’ from a later crosslink session, another Cpt in the a future minor cycle, or it becomes Cpt and downlinks the data itself. Consequently, if the inter-satellite communications fail, the other mission objectives can still be met and science data is still returned for ground processing. In addition if downlink communications fail, redundant crosslink performance data is stored in the beacon SOH packets; including counters for the number of packets transmitted and received from the various unique satellite IDs so that Objective 1 can be partially achieved, demonstrating a key technology for future constellations and swarms.

Prior to a GPS acquisition and downlink the satellite performs a magnetic alignment activity. The satellite uses torque coils embedded in the solar panel printed circuit boards (PCBs) to align with the Earth’s magnetic field and provide 2-axis stabilization. A GPS acquisition is scheduled towards the end of each minor cycle and is immediately followed by the scheduling and planning of the activities for the next minor cycle. If at any point in the mission the satellites fail to acquire a GPS vector the satellite continues to perform a GPS acquisition activity until a vector is obtained or the battery reaches low voltage and the satellite goes into charge state where it provides SOH including last known time and orbit state on a UHF beacon. If satellites have an anomaly or issue resulting in a reset of the onboard processors, upon reboot they check to see they still have a valid time and schedule. If so they proceed on with the next activity in normal operation; otherwise they will acquire a new GPS vector and plan activities for the following minor cycle.

All satellites switch to the new minor cycle based on the UTC reference for that date which varies by 1 hour each day due to the 25 hr minor cycle cadence. The next satellite in the constellation is promoted to Cpt and previous Cpt is demoted to a Lt. There is only one Cpt per minor cycle and the rotation is preprogrammed prior to launch. Whether a satellite is a Captain or Lt is also indicated in the satellite SOH data. The EDSN mission has a planned duration of 60 days to meet Objective 4. Satellite data parameters are also available in both the downlink and beacon SOH packets to understand satellite activities including reset counters for processors, battery voltage and coarse position/attitude data. The satellites have a predicted on orbit life of ~500 days and will continue to perform autonomous operations provided there are ground station contacts until re-entry and burning up in the atmosphere.

During mission operations Santa Clara University (SCU) is used as the ground station with S and UHF band receivers. SCU tracks the satellites and receives data from the S-band downlink and the UHF beacons. To downlink the data the S-band transceivers onboard the satellite and at the ground station perform a hand shake and once a lock is the established the Cpt satellite autonomously transmits the data from the constellation in a preprogrammed manner to allow for data return from all satellites. The Cpt satellite will continue transmitting the data and if it reaches the end of the data buffer will repeat, retransmitting the data as long as there is a lock with the ground station. Once the S-band downlink is completed the satellite deletes only the data it has transmitted. If there is data that was not transmitted in the buffer the satellite stores this data for downlinking at the next opportunity in a future minor cycle. The raw data is stored at SCU then decoded and processed into values and engineering units. The data is distributed between mission partners SCU, NASA Ames Research Center (ARC) and Montana State University (MSU) as appropriate. The science data is combined with satellite data for position and time measurements and post processed by MSU for further scientific analysis. Both SCU and NASA ARC perform additional post processing of satellite data to provide mission status and analyze satellite operations and condition.

SATELLITE OVERVIEW

The eight EDSN satellites are identical 1.5U Cubesats measuring 10 x 10 x 17 cms and weighing ~1.73kg. In order to support extension to larger swarm mission architectures, the EDSN spacecraft was designed to leverage low cost consumer grade commercial-of-the-shelf (COTS) components and inherited many design elements from the PhoneSat 2.0 architecture. NASA Ames Research Center (ARC) under the Small Spacecraft Technology Program (SSTP) within the NASA Space Technology Mission Directorate (STMD) developed the satellites. The satellites have crosslink, downlink and science collection capabilities. Two satellite exteriors are shown in Figure 1 and the internal and key components are shown in Figure 2.

The main processor, a Samsung Nexus S smartphone, manages onboard activity scheduling and execution while data is routed through a Parallax P8X32A Propeller chip for distribution to the transceivers and distributed processors. Two ATMega2560 chips control the GPS receiver, science payload, and attitude control subsystem (ACS) while two ATMega328P chips control sensors and electronic relays. The availability of development boards for these components made it easy for software engineers to build prototypes and perform early testing of flight software code.

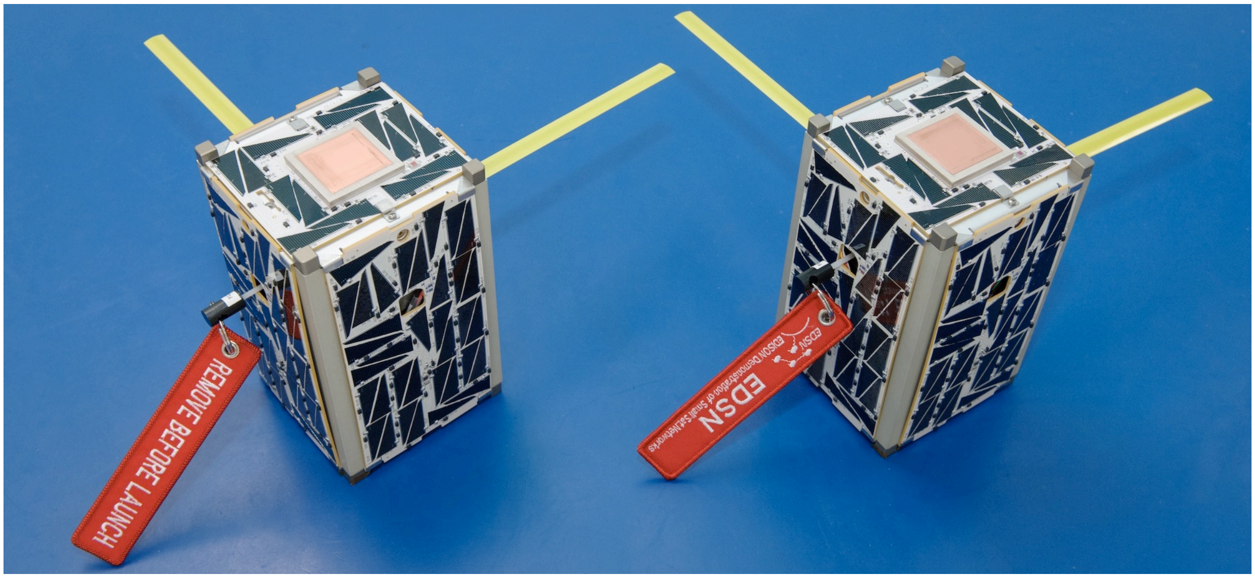

Figure 1: Two EDSN satellites with the S-band patch and UHF monopoles shown.

A MicroHard MHX2420 transceiver is used for S-band downlink, an AstroDev Lithium 1 UHF transceiver is used for crosslink sessions, and a StenSat UHF transmitter is used for the beacon. The ACS consists of three orthogonal brushless motor reaction wheels and torque coils embedded in the solar panel printed circuit boards (PCBs). Attitude determination uses the smartphone gyro and magnetometer sensors combined with currents from the solar panels.

Orbit average power of ~1 watt is provided by 6 solar panels that use Triangular Advanced Solar Cells (TASC) from Spectrolab. The solar panels are mounted directly to a 1.5U solid Pumpkin chassis. A GPS and an S-band patch antenna are mounted to the 1U ends of the structure while two UHF monopole antennas extend off the 1.5U faces.

Four lithium ion 18650 batteries in a COTS holder are used for combined energy storage of 5.2 Ah and bus voltage regulation. However, because a COTS battery holder provides over-charge protection for the battery, a Zener diode is needed to provide over-voltage protection for the bus. Additional voltage regulation is done at the board level to keep the system modular. The 8 PCB subassemblies and battery holder are electrically inter-connected through a single backplane PCB.

System level power management is relatively simple. If a low voltage limit of 7 volts is reached, all components (excluding the low level processor) turn off. If the system is booting up or restarting, a threshold of 8 volts must be reached before the main processor can be operated and activities can be executed.

The science payload is the Energetic Particle Integrating Space Environment Monitor (EPISEM) developed by MSU to characterize the radiation environment in low-earth orbit (LEO). The payload uses a thin-walled Geiger-Müeller tube that detects penetrating beta/gamma radiation from energetic particles above a certain energy threshold[5]. The science payload and scheduled downlink activities rely on a Novatel OEMV-1 GPS receiver for position and time knowledge.

The flight software leverages previous developments from the PhoneSat 2.0 architecture including the use of the Android operating system, custom libraries and Arduino code for the distributed processors. The software was enhanced to include; payload and GPS receiver interfaces, a more robust router, additional transceivers, augmented Executive and Scheduler, onboard orbit propagation and reinforced fault management. The system uses watchdogs for the majority of processors and an ack/nack protocol for critical satellite bus data. These features reduce the risk of processor hangs and data loss or lock up in high-traffic situations.

DEVELOPMENT

In August 2013 the project went through a rebaseline and was scoped to the mission goals and objectives presented in the earlier section[6]. The satellite development went from concept to completion in 8 months. The Flight satellites were completed in March of 2014 and are currently in long-term storage until launch in late 2014.

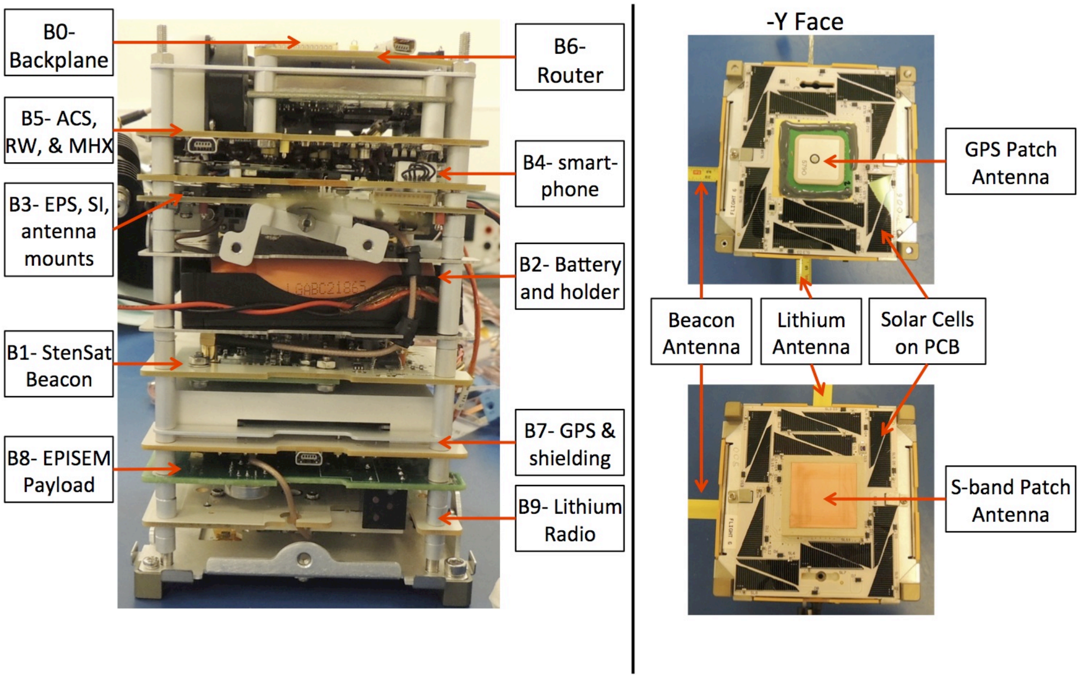

Figure 2: The elements of the EDSN satellites highlight the major components and subassemblies.

The EDSN mission it unique in that it has a technology demonstration that includes multiple satellites using low cost consumer grade COTS components with some custom parts needed to increase performance or due to packaging constraints. The EDSN mission uses a risk posture comprised of decoupled objectives, multiple attempts at technology demonstration, redundancy through number of units and the focus on systematic failures versus any and all failures. Consequently the constellation was designed to operate even with the loss of a single or multiple satellites without affecting mission success. Examples of this approach include multiple data paths for science and SOH data, the ability to miss ground station contacts and designing the inter-satellite data transfer architecture where the goals was to demonstrate the ability rather than focus on high performance or efficiency.

The EDSN project used concurrent engineering, multiple development paths, additional processes and increased number of Engineering Development Units (EDUs) to reduce the development time over a traditional CubeSat flight project. To achieve the development of the 8 final Flight units, a total of 12 Flight units, 4 EDUs, 2 Flatsats, 2 DevSats and spare components/subassemblies were produced. The multitude of units allowed for concurrent developments in all areas including hardware, software, procedures, integration and testing. The EDSN project also took some development risks including reduced design analysis versus early testing, postponing the majority of environmental testing to the system level and single batch fabrication of printed circuit boards PCB rather than the traditional multiple spins. Lessons learned from this projects approach are discussed in the next section.

Processes adopted by EDSN to facilitate the production, tracking and testing of the components and subassemblies for each of the Flight, EDU and Flatsat units included; procuring units in large (>20) quantities with spares, major components/subassemblies having individual travellers, assignment of components based on performance, inventory tracking and a process flow that was available to all team members and continuously updated daily. To manage the amount of units and staff a detailed schedule was developed and updated daily with conflicts addressed in 15 minute daily tag ups or handled in real time by the Systems Engineering and Management team. The Systems Engineering and Management team reviewed the schedule daily for both short and long term milestones addressing long lead, facility or resource conflicts early before impact to the daily project progress. Leads for key areas: communications, electrical, software, mechanical, systems engineering, Ground Support Equipment (GSE) and Integration & Testing (I&T) were responsible and accountable for their areas, tasks and staff. All leads provided notification of possible impacts to their work and new resource needs in the daily tags with a weekly meeting used to address upcoming tasks and milestones. Late task or impacts had to be negotiated with affected areas/team members and a recovery plan identified and implemented with Management and Systems Engineering concurrence. While issues still arose throughout the project due to conflicts, anomalies or unanticipated tasks, these processes were effective at reducing their impact to the project schedule.

The multitude of units and concurrent development paths required a flexible staff loading where part time labor was leveraged from other work areas at NASA Ames Research Center. An example of this was the increase in staff during the PCB testing. Each satellite consists of 6 solar panel PCBs and 9 internal PCBs that are mated to other components, such as the radios and reaction wheels, to make up 10 subassemblies. For the development of the Flight Units, EDUs, Flatsats and spares a total of 24 or more boards were fabricated for each of the 15 different PCBs resulting in more than 360 boards that were each individually inspected and tested. To facilitate testing on this scale for spaceflight, procedures were developed and GSE acquired to allow testing by multiple teams concurrently.

The EDSN satellite uses a variety of readily available consumer grade COTS processors combined with a Nexus S phone. During development the project was able to buy low cost developer kits for each processor that could be quickly wired together similarly to the satellites. These units were called Development Satellites (DevSats) and an example is shown in Figure 3. DevSats provided opportunities for early Flight Software (FSW) prototyping, development and testing prior to EDU or Flight units being available. Since the same processor set and interfaces were being used, the amount of modifications to the FSW was extremely limited when switching to the actual hardware configuration.

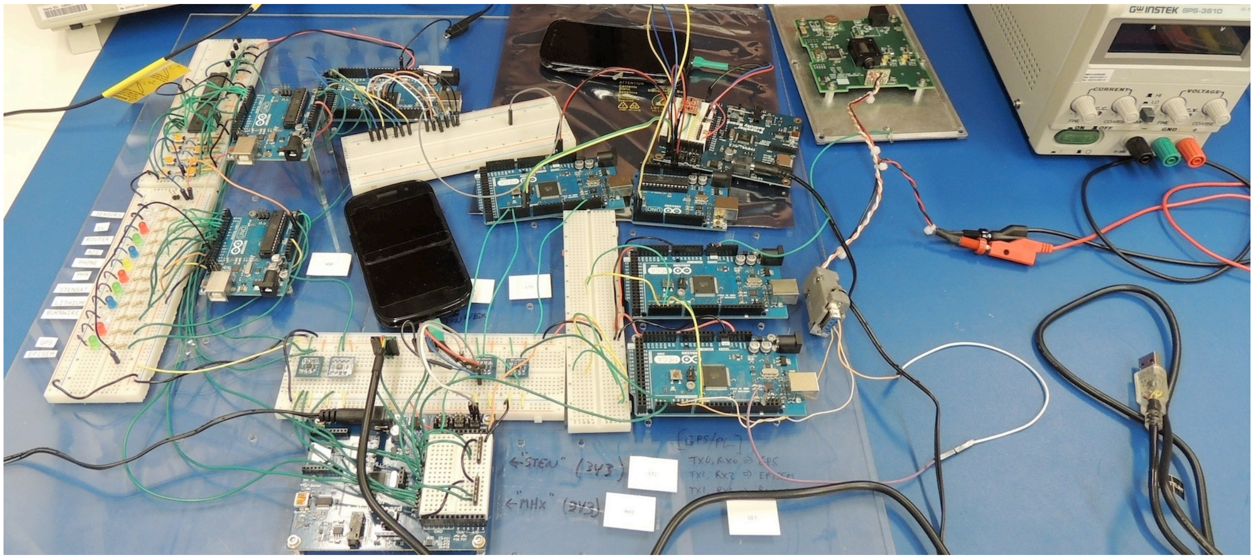

Figure 3: The EDSN DevSat during early flight software development and testing. Note the Nexus S phone and consumer grade developer boards.

During the EDSN development, the PCBs were limited to one production run which meant that all boards were identical excluding minor tracked revisions. This meant that the boards in the Flight units were the same as the EDUs and Flatsats. This approach added risk to the development but also provided a benefit to the EDUs and Flatsats ensuring a consistent configuration and operation when performing hardware, software and functional testing.

Flatsats were developed to test the large amount of boards and enable probing of the data lines that would normally be inaccessible in the densely integrated EDUs or Flight units. The satellite backplane PCB was replaced with a custom Flatsat PCB that enables connection of PCB and subassemblies using the same data paths, the large green PCB shown in Figure 4. In addition data and power can be enabled, disabled and probed for electrical and software testing. The Flatsats were instrumental in FSW testing including anomaly resolution, off-nominal conditions and regression testing for FSW releases. The Flatsats also allowed for detailed electrical checkouts and proof/over testing of one set of PCBs prior to Flight unit integration. An example was a quick swap of payload boards that allowed the team to troubleshoot bad command timing issues with the EPISEM interface.

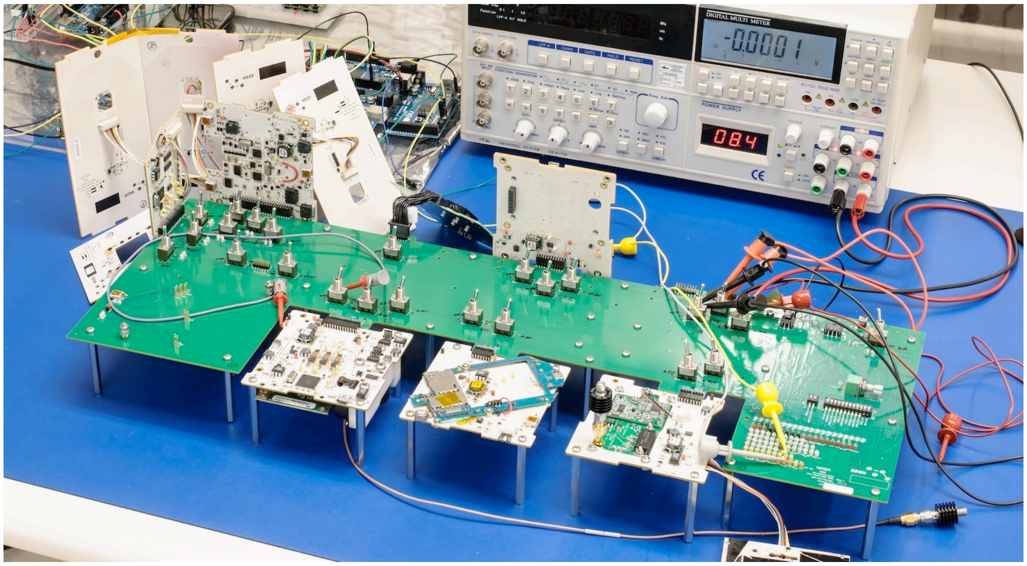

Figure 4: The EDSN FlatSat interfaced to numerous EDSN PCBs used during electrical checkout and flight software testing. A partial EDSN DevSat is also shown in the rear left.

The Engineering Development Units (EDUs) are almost identical to the Flight units excluding minor configuration revisions. EDUs 1&2 also lacked antennas and instead used RF cabling and attenuators to enable direct connections to the transceivers for radio frequency (RF) testing. The EDUs served multiple purposes during the project development including fit check, early system testing, test procedure maturation for Flight units, GSE interface, system checks and early mission simulations while the Flight units were undergoing integration and testing. Early in the project numerous competing resources were identified especially related to the EDUs. Consequently, the number of EDUs was increased to 4 units. The EDUs underwent early fit checks, interface checkout and environmental testing with issues addressed prior to the integration of the Flight unit subassemblies. In addition the EDUs provide a method for testing flight software releases and mission simulation operation prior to FSW releases and integration with the Flight units.

The Flight units incorporated minor revisions based on the lessons learned from the development of the Flatsats and EDUs. Twelve Flight units were developed to provide flight spares and allowed the selection of the highest performing units for flight. Although identical, very minor production and workmanship effects resulted in slight increases in performance for transceivers, power generation and the attitude control system. Originally the later EDUs were to be used as qualification units but as issues and anomalies were identified there were increased needs for additional EDUs. Flight units 1 & 2 were developed first and performed qualification testing prior to the completion of Flight units 3 through 12.

LESSONS LEARNED

The unique and compressed development of EDSN resulted in many lessons learned including things to avoid and items that can be beneficial to future projects. Procedures provided both of these attributes. With a large team involved and substantial part time labor, procedures were required to perform testing of PCBs, subassemblies and integrated satellites. However, the time and consequently cost required to develop the procedure sometimes caused delays to the project. Procedures for key tests were essential, especially for functional and environmental testing. However, procedure writing needs to be balanced against the amount of effort to perform the test or integration task. Procedures were used heavily for Flight units but there were numerous tests of engineering units that were outlined, performed and documented with a test report. In the case of EDSN often the designer was not able to perform testing of all the components. This required greater procedural detail than if the designer was performing the test themselves. Review at the system level of the procedures also provided benefits as missed verification items and tasks needed for other technical areas were caught before the tests were conducted, reducing the amount of retest. Future projects with this many components and units should consider implementing automated testing processes as there is a large potential benefit from the reduction of time and consistency in test results.

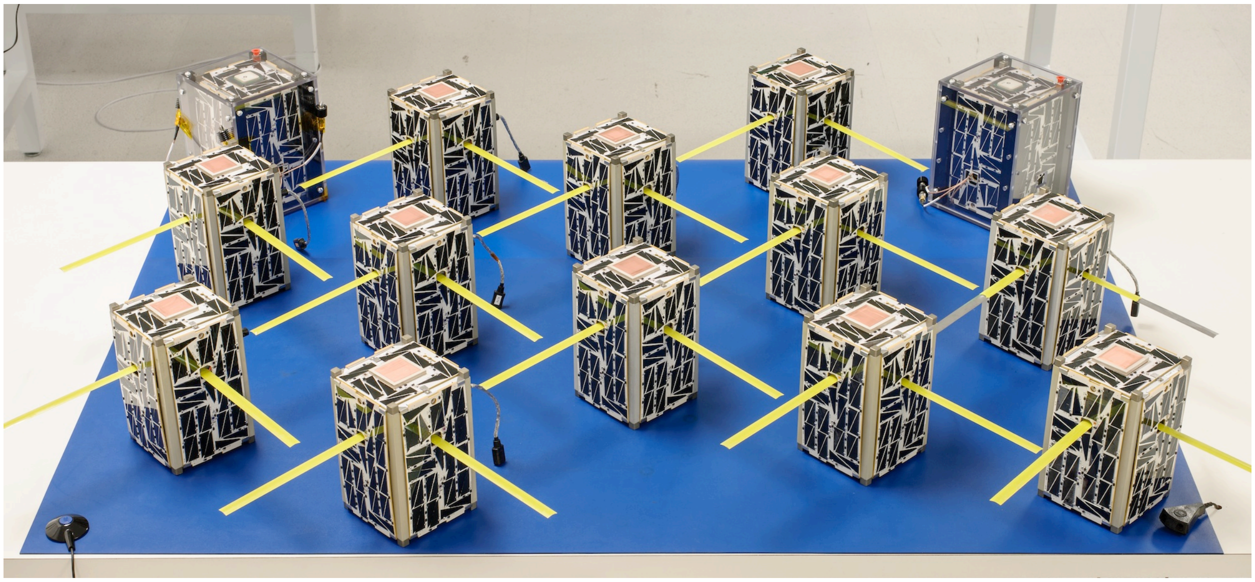

Figure 5: The 8 EDSN Flight units combined with flight spares and Engineering Development Units (EDUs).

To track the large amount of components, subassemblies and units, travellers were used for all major elements and incorporated into the higher level traveller at the various integration steps. The travellers included information on tasks, date performed, task executor, firmware/software loads, if any issues arose during testing or anomalies and workmanship problems were identified. The travellers were extremely useful for tracking the hardware elements especially when selecting elements for the Flight units. Travellers were documented on paper and were difficult to track at the system level. A configuration matrix was used for checking in and out items and process flow checklist were used to ensure steps in the I&T process were not missed. Future projects should consider using an electronic inventory system that provides more real time data without additional manual data entry overhead. Systems to consider include barcodes, Quick Response (QR) code, Radio Frequency Identification (RFID) tags and/or future automatic identification and data capture (AIDC) technologies.

During project development, multiple descope options were evaluated throughout the project cycle and communicated with stakeholders prior to implementation. Examples of descopes considered for EDSN include; reducing the number of spare units, flying EDUs, tailoring of the test plan, early environmental tests versus detailed design analysis, limited environmental testing at the component and subassembly levels, single tests for an EDU versus all units, reduced performance, elimination of objectives, reduction in minimum success criteria and elimination/re-ordering of development tasks. Not all these descopes were implemented but having a detailed schedule as a daily tool and these options enabled the management and Systems Engineering team to make tough decisions based on current and accurate data. Descopes that were implemented include; tailoring of the test plan, early environmental tests versus detailed design analysis, limited environmental testing at the component and subassembly levels, single tests for an EDU versus all units and re-ordering of activities such as the first Flight units becoming qualification units for environmental testing. It is highly recommended that projects identify credible descopes and engage stakeholders for input early in the project before they are required so when issues arise the project can recover and there are no surprises for stakeholders.

Updating documentation in real time was difficult due to the fast project pace. This required other communication efforts and a large amount of time from systems and interface personnel to ensure team members were on same page. This sometimes resulted in missed or misinterpreted information and repeated discussion on the same topic. The project addressed these issues as they developed by co-location of the team, positioning engineering and testing facilities together and providing area leads with responsibility to communicate changes or issues to their sub-teams.

During the project there was a significant need for Ground Support Equipment (GSE) used for integration and testing of the many units. Standard test equipment such as multi-meters and power supplies were in high demand throughout the project. Rather than buy a large amount of equipment for short durations, it was more economical to rent, especially in the case of the complex test equipment such as signal analyzers that are expensive but only needed for short periods of time. In addition emphasis should be placed on planning for GSE cables, computes, connectors, software licenses and other minor items. For these inexpensive items, it is recommended that projects buy with margin in many cases twice as much as you think you will need as the lost time far exceeds the small procurement costs. Many of these items can also be repurposed for future projects.

To reduce the development schedule to 8 months, the EDSN project borrowed heavily from the design architecture of the Phonesat project. This had the benefit of reducing the amount of needed design time but it also inherited the design issues and introduced new issues from extending the architecture not originally intended for the more complex mission and satellite interactions. In addition, the functional decomposition and requirements development process was abbreviated and incomplete resulting in difficulties during test planning, verification and validation. The project focused on functional testing and relied heavily on the mission simulations that occurred late in the project development for verification and performance evaluation. Software maturation issues combined with late testing anomalies resulted in a late FSW build after the completion of environmental testing. FSW regression testing and an additional long duration (~12 day) mission simulation test were conducted on the Flight units to ensure verification and performance and reduce the risk of new errors introduced by the late flight software changes. During development some lower level tests were never linked to higher-level requirements, and as a result, we collected test data that was not useful. An example of this is that a lot of the battery pack test procedure was not helpful in evaluating the actual battery performance and additional retests had to be performed later in the project. Future projects should focus on collecting data linked to higher level requirements to further streamline the integration and test process.

A key component to a fast paced and compressed duration project is to ensure all stakeholders are well informed, consulted and able to assist with resources if needed. EDSN used an inchstone schedule, with weekly milestones, that were reported currently to stakeholders at a single weekly meeting. The weekly meetings included: a schedule overview, major accomplishments, weekly progress of milestones, next week milestones, resolution of any missed milestones and identification of any higher level issues. A combined weekly meeting with stakeholders ensured information, decisions and issues could be coordinated and addressed without the delaying of communicating with multiple parties. This ensured efficient and timely decision making and also reduced the over project reporting requirements.

Early in the development multiple competing critical paths were identified including the flight software and PCB developments. To reduce the schedule several items were implemented including leveraging the Phonesat architecture, multiple EDUs, Flatsats and a risk posture of a single production run of the PCBs without the usual multiple board spins. PCB production had each type of board fabricated in a single lot then one of the boards was fully assembled and inspected prior to assembly of the remaining boards. The PCB's designers took this risk into account and reviewed the designs prior to fabrication and also provided descope opportunities in the design where areas or functionality in the circuits could be reduced or eliminated by the removal of simple components without requiring a new PCB production or cutting of traces. This worked effectively when combined with early Flatsat and EDU testing to identify issues and perform configuration revision prior to Flight unit builds. However, the rework and revisions required to the flight boards consumed significant resources of the project and delayed integration and testing activities. Although this single production run approach reduced the schedule in comparison to multiple board productions, it was not optimal and some non-critical functionality was lost. Other issues required work-arounds in software or accepting known issues. Future projects should evaluate the test and rebuild trade-off early in the project planning phase.

It is recommended that future projects plan for functional and environmental testing early in process including interfaces and functionality that is required on the satellite for I&T but not necessary for flight. The EDSN project had incorporated many aspects in the design for testing including LEDs for visualization, test points, and FSW that enabled interfacing with the various processors and the ability to change firmware if necessary. However, an oversight in environmental testing meant there was not an easy way to electrically deactivate the satellite during thermal vacuum testing. This resulted in a late design kludge before the production of the Flight units and required additional GSE workarounds that caused an impact to the project schedule. Another example was that GSE software was necessary to perform integration and testing activities but the FSW became the project critical path and so the resources intended to develop GSE software were consumed with FSW development tasks. A consequence of this was that numerous anomalies were observed during testing that had to be investigated and resolved with several of them related to GSE software operations that were not exhaustively tested prior to hardware testing.

ANOMALIES AND RESOLUTIONS

During any project there are always issues and anomalies that occur and EDSN was no exception. Several EDSN anomalies and resolutions are presented here to advise future projects and raise awareness for future Cubesat and multiple satellite missions.

With hardware based projects there is the possibility of workmanship issues that can arise during fabrication and integration. EDSN had a few issues including incorrect part placement, polarity switches and cable shorts. EDSN took a proactive approach to the workmanship processes and included a quality and mission assurance program including training, review before production, receipt inspections of components, functional tests at multiple steps of the test flow, procurement of spare/replacement components, use of procedures and a two person system for testing of Flight units. These actions meant that issues were identified early in process and could be rectified before satellite integration or environmental testing where they would cause major schedule impacts to the project. The spare parts also enabled failed components to be swapped out with minor impact.

EDSN made use of a large amount of low cost consumer grade COTS components to enable rapid and cost effective development but this also caused its own type of issues. A particular example on EDSN was the issues relating to the male and female connector used between the PCB, cables and backplane. The connectors sometimes had intermittent contact or alignment issues that required rework. Future projects should consider using higher-grade (automotive or industrial) components that undergo more rigorous testing and batch inspection. Although there is an increased cost per component and in sometimes lead-time these are offset by the high cost of schedule impacts that can potentially be incurred due to team down time. Another process used by EDSN that was successful was full testing/screening of critical components/subassemblies prior to integration at the system level.

The EDSN satellites use a diagnostic port that allows for data interface and battery charging during I&T activities. The port is cycled numerous times during the test flow and during the EDU test program it was identified that one of the ports was beginning to separate the mechanical ground connectors from the PCB. To alleviate these issues and protect the access port, a strain relief connector saver was implemented for the Flight units to significantly reduce the number of mate/demate cycles for the diagnostic port. With the compact nature of Cubesats it is not always possible to implement connector savers but future project should consider their implementation for external access ports.

During the testing of PCBs the project was having issues with MOSFETs that were used for switching of power and data lines. During testing we were finding several failures >1% where we would normally expect failures in the parts per million. These component failures were so prevalent in the design and a systematic issue that a decision was made to replace these component with a different part from a known reliable vendor with internal ESD protection. The root cause was never determined and no further issues were observed after the change in component. Future projects should be careful to ensure the components meet requirements including worst case specifications, include ESD protection or other similar attributes and most importantly are sourced from reputable known vendor that has previous flight heritage.

During the rapid development of the design some assumptions were made on the hardware that were not communicated to the FSW team that resulted in unused connections and/or undefined inputs/outputs. EDSN resolved this issue by eliminating unnecessary connections and ensuring that there were no floating or undefined values in the software. Future projects should ensure that hardware designs and software implementation assumptions are communicated and where appropriate reviewed by an engineer with both software and hardware experience. This is especially true if the project is inheriting an existing software or hardware architecture.

Similar to any software project bugs and unintended features were encountered during testing. EDSN concurrently developed the hardware and software and used several processes successfully to reduce the impact of FSW bugs and unintended features. JIRA was used by the FSW development team for tasks, bug tracking and included custom fields for unit and system testing. In addition, static analysis tools and peer reviews were performed on flight software against the requirements to identify poor coding practices and ensure system functionality. Early prototyping and testing on relevant hardware including the DevSats, Flatsats and EDUs also reduced the instances of bugs and development time. A central repository with subversion tracking and virtual machines were used to ensure consistent and concurrent software development. As new software releases became available processes for loading, verifying and tracking the versions became necessary. EDSN successfully used travellers and procedures to accomplish these processes. In addition at set of regression test tied to low-level functional requirements were used to ensure the performance prior to a software release.

During the development, a Zener diode was implemented to prevent an over voltage condition to the bus. To charge the satellite a diagnostic port is used that feeds power through the Zener diode that clamps at a set voltage and dissipates excess energy when the battery is full. During TVAC testing the satellites used external power supplies in combination with batteries as there was not a system available to provide solar flux and therefore power through the solar panels. The Zener diode was not accounted for during TVAC test planning and during test operations there was an additional thermal load that was being provided by the Zener diode. EDSN had used test predicted values and observations of the key components to enable early identification of problems during the test and were able to provide a work around in real time rather than having to rerun the test. Future projects should ensure for key tests that predicted performance is known before the test commences, accounts for GSE interactions and that late design changes are considered for impact not only to the flight system but also testing.

CONCLUSION

The Edison Demonstration of Smallsat Networks (EDSN) is a technology demonstration mission that provides a proof of concept for a constellation or swarm of satellites performing coordinated activities. By decoupling mission objectives and focusing on multiple attempts at the technology demonstrations the mission provides a pathfinder for more complex future applications of swarms and constellations. These applications include the formation of synthetic aperture radars for Earth sensing systems, large aperture observatories for next generation telescopes and the collection of spatially distributed measurements of time varying systems, probing the Earth's magnetosphere, Earth-Sun interactions and the Earth's geopotential. EDSN is also a space physics mission, performing coordinated time varying multipoint observations of space weather by measuring penetrating beta/gamma radiation from energetic particles. The EDSN mission also provided a unique learning experience for the production and interaction of multiple nanosatellites. The project demonstrated the ability to reduce the traditional development time of small satellite missions. Benefits were gained from a tailored risk posture, additional processes, techniques and new skills required for this type of project. Several lessons were learned both good and bad that can be useful for future project including the use of a large amount of sparing, multiple units, concurrent developments, descope planning, and the careful consideration of design decisions that affect project implementation.

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