PHONESAT IN-FLIGHT EXPERIENCE RESULTS

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ABSTRACT

Over the last decade, consumer technology has vastly improved its performances, become more affordable and reduced its size. Modern day smartphones offer capabilities that enable us to figure out where we are, which way we are pointing, observe the world around us, and store and transmit this information to wherever we want. These capabilities are remarkably similar to those required for multi-million dollar satellites. The PhoneSat project at NASA Ames Research Center is building a series of CubeSat-size spacecrafts using an off-the-shelf smartphone as its on-board computer with the goal of showing just how simple and cheap space can be.

Since the PhoneSat project started, different suborbital and orbital flight activities have proven the viability of this revolutionary approach. In early 2013, the PhoneSat project launched the first triage of PhoneSats into LEO. In the five day orbital life time, the nano-satellites flew the first functioning smartphone-based satellites (using the Nexus One and Nexus S phones), the cheapest satellite (a total parts cost below $3,500) and one of the fastest on-board processors (CPU speed of 1GHz). In this paper, an overview of the PhoneSat project as well as a summary of the in-flight experimental results is presented.

1 CONSUMER TECHNOLOGY FOR SPACE APPLICATIONS: THE SMARTPHONE

Start with the smartphone, a device that enables command and data handling, position and attitude determination, observation, and wireless communication – a set of subsystems remarkably similar to a conventional multi-million dollar satellite at a fraction the cost. From here, the PhoneSat Project has expanded to explore leveraging the investment of any consumer industry to build space systems. The root objectives of the project are to reduce cost whilst increasing capability.

The method of repurposing consumer technology has brought along different mindsets from which to look at space. For PhoneSat, a new approach to space development has been adopted - release early, release often. This agile space development approach is far more suited to low cost, un-manned space applications than the traditional systems engineering methods.

The PhoneSat project consists of the development of a series of nano-satellites that use an off-the-shelf smartphone as their on-board computer. By doing so, PhoneSat takes advantage of the high computational capability, large memory as well as ultra-tiny sensors such as high-resolution cameras and navigation devices that smartphones offer. In addition, having the option of using the Open Source Android Operating System provides a large variety of existing libraries, as well as a modular software approach which enables fast iteration time-frames and an ease of crowd sourced applications. Space has shifted paradigm from a hardware problem to a software problem.

The full potential of removing cost as a barrier to entry in space is still being realized and explored by the global community. Two predominant applications being pursued by companies around the Silicon Valley Bay Area are Earth observation at unprecedented update rates and space-based educational platforms. For science, low cost platforms enable a larger number of experiments to be tested, in addition to experiments previously not possible – expanding our knowledge base.

To date, the PhoneSat Project has flown four satellites demonstrating the feasibility and economic advantage of supplementing and augmenting space industry technologies with consumer technologies. The focus of this report is around the PhoneSat project and the Antares flight, on which two PhoneSat 1.0's and a beta version of PhoneSat 2.0 were manifested. An overview of the project goals will be presented first, followed by the architecture of each satellite version and the flight concept of operations. Next, the flight data from the Antares launch will be detailed. Finally, future objectives of the project will be presented.

2 THE PHONESAT PROJECT

2.1 Long term goal

The PhoneSat project aims to democratize space by making it accessible to more people. The PhoneSat approach to lowering the cost of access to space consist of using off–the-shelf consumer technology, building and testing a spacecraft in a rapid way and validating the design mainly through testing. PhoneSat's role in the space industry consists of exploring ways to do things in a non-traditional manner that enables new breakthroughs by providing a platform in space for experimentation and testing.

2.2 Origin and evolution

The PhoneSat project has been developed at NASA Ames Research Center since its inception in 2009 after the summer session of ISU (International Space University). The PhoneSat project believes in the effectiveness and quick response of small teams and as such, the team has always been composed of about half a dozen students and young engineers.

From the very beginning, the project has adopted an iterative approach for the development of the spacecraft. The idea is to frequently release a new iteration of the design that improves the current work in order to quickly arrive at a functioning unit - an approach known as "release early, release often" that aligns with the local culture in the Silicon Valley.

From a very early stage, the project realized the potential of smartphones as the main computational core for satellites. Given the level of performances and integration smartphones offer, the PhoneSat team conducted some additional testing on the ground in order to validate their adaptability for space applications. After the success of this preliminary testing, the project decided to develop a spacecraft around the smartphone. The first version of the satellite was called PhoneSat 1.0 and took the shape of the standard 1U size CubeSat with the main goal of determining whether or not a smartphone could survive in a space environment. Upon completing PhoneSat 1.0, the team naturally moved to the design of PhoneSat 2.0 with the objective of developing a complete satellite bus. In April 2013, the first three PhoneSat satellites were sent to space and successfully accomplishing their mission of staying alive. Figure 1 shows a project time line of the events that have taken place in the PhoneSat project.

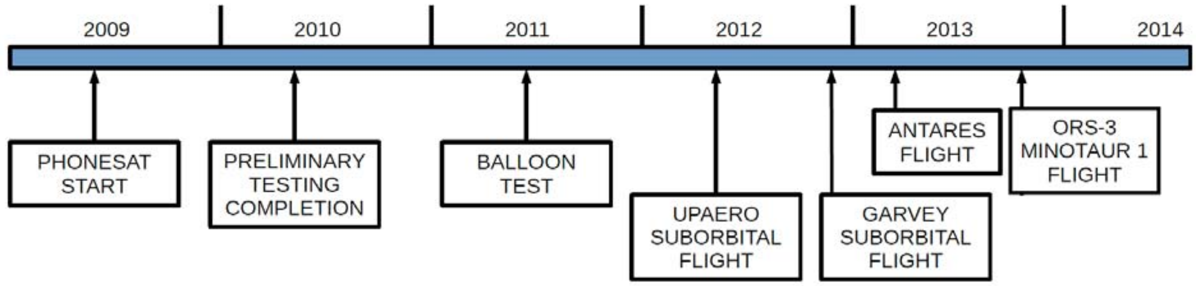

Figure 1. PhoneSat project timeline

3 PRELIMINARY TESTING

In order to validate the survivability of the smartphone in a space environment, a set of tests were conducted using a HTC Nexus One phone. The first test exposed the phone to a vacuum level of 2E-6 Torr and thermal extremes of -35C and +60C. Under these conditions, no anomalies in the performances of the smartphone were observed. Along with the smartphone, an Arduino board was tested and showed no evidence of deterioration.

As a next step in the testing process, a smartphone was flown as a payload in a sounding rocket that reached 10km altitude. The payload was also equipped with an Inertial Measurement Unit (IMU). During the flight, accelerometer and magnetometer data from the phone and IMU were collected and stored in the phone's SD-card. Other than the accelerometer saturating at about 2G, the test was successful since the smartphone was proven to survive launch environment conditions.

Finally, the smartphone passed vibration and shock tests according to GEVS standards.

4 PHONESAT 1.0

4.1 Description

Based on the success of the preliminary testing, the PhoneSat team started the design of the first spacecraft of the PhoneSat family. PhoneSat 1.0's goal was to prove that a smartphone can actually work in space. The design was kept as simple as possible. PhoneSat 1.0 consisted of a Nexus One smartphone that was used as a main flight computer, Li-Ion batteries to increase the operational life time of the satellite, an external beacon radio to downlink data from the spacecraft to a ground station and a small watchdog to monitor the health of the smartphone and reboot it if any anomaly in its performance was observed. Figure 2 shows a photo of PhoneSat 1.0 with some batteries removed so the smartphone can be seen from the outside of the spacecraft. The total cost in parts of PhoneSat 1.0 is $3,500 and it has probably the fastest processor (CPU of 1GHz) that has ever been to space.

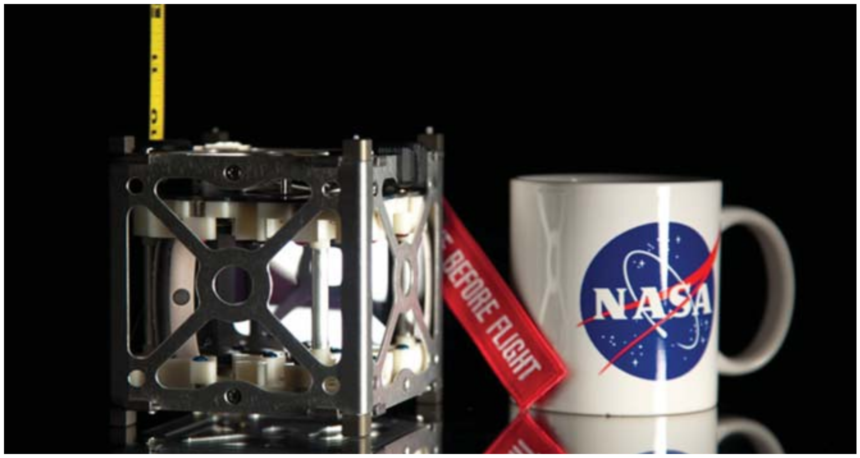

Figure 2: PhoneSat 1.0

4.2 Mission objectives

Demonstrate that a phone can 1) function in space, and 2) can provide a useful computing platform in space, by performing one highly complex computing task (advanced image processing) and radioing evidence to the ground.

4.3 Hardware architecture

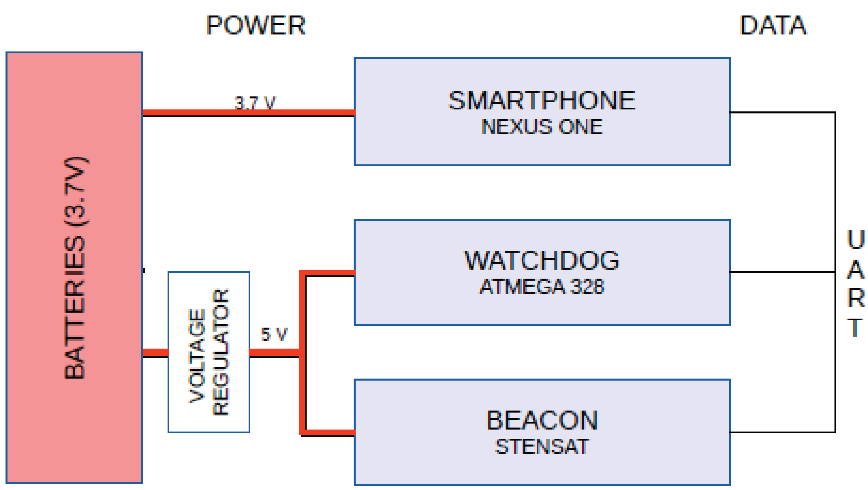

Figure 3: PhoneSat 1.0 hardware architecture

Figure 3 shows an overview of the hardware architecture of PhoneSat 1.0. The Nexus One phone is embedded in the satellite with its battery removed. In place of the battery is a set of 12 Li-Ion batteries mounted in a 3D printed battery holder and connected in parallel to provide power to the spacecraft for about 10 days of operations. The phone interfaces to the Atmel ATmega 328 that runs Arduino software (used as a the watchdog) and the StenSat beacon radio via the phone USB connector converted to a serial port. The watchdog is in charge of making sure that the phone functions properly and reboots it if misbehaviour is detected.

PhoneSat uses a StenSat beacon radio, a commercial-off-the-shelf radio in the amateur band, to downlink data to the ground. The StenSat beacon transmits packets of data at 1200bps AFSK at an RF output power of 1W. PhoneSat 1.0 uses this radio at a frequency of 437.425MHz with a piece of tape measure trimmed at the right length as an antenna.

PhoneSat 1.0 collects data from the accelerometer and magnetometer sensors built into the phone and from two additional temperature sensors located in two different locations in the spacecraft. This data is stored in the phone's memory. The phone camera is also used to take pictures of its surroundings. Figure 3 shows a diagram of the PhoneSat 1.0 hardware architecture.

4.4 Software architecture

The software of PhoneSat 1.0 is built on top of the Android 2.2 framework. The app developed consists of a few activities and modules that are interconnected as shown in Figure 4.

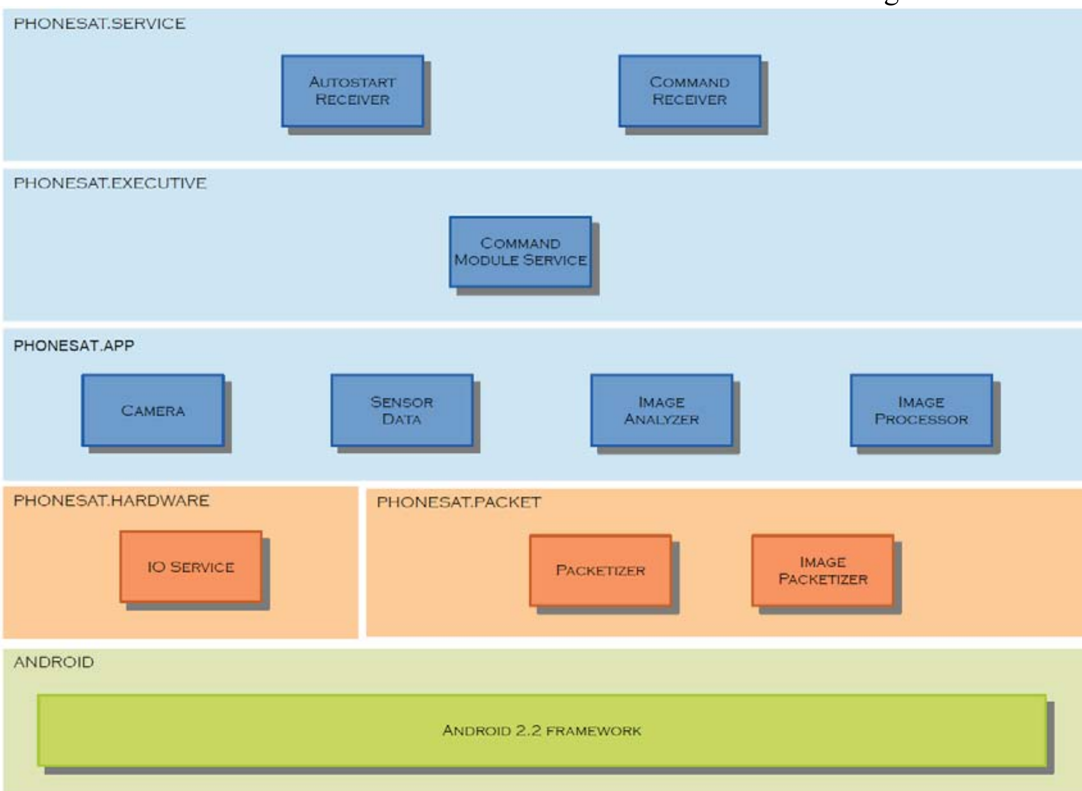

Figure 4: PhoneSat 1.0 software architecture

The package *phonesat.service* is in charge of handling the Android execution flow of the app. It has two classes: the *autostart receiver* that is responsible for starting the app and the *command receiver* that is in charge of calling the *phonesat.executive*. *Phonesat.executive* contains the *command module service* that acts as a scheduler.

There are four activities that can be run: (1) the *camera activity* takes 1 picture every time it's called, (2) the *sensor data service* collects sensor data from the phone and the external sensors, (3) the *image analyzer* is in charge of selecting the best image among the pictures taken according to a pre-defined criteria and (4) the *image processor* is responsible for analyzing and decomposing into tiles the picture selected.

At the *phonesat.hardware* level, the IO service contains all of the hardware drivers. The *phonesat.packet* module is responsible for packetizing both the sensor data and the images so they can be sent through the beacon radio.

The smartphone chooses the best picture over the 100 selected. The best picture in PhoneSat 1.0 is defined as the one that has a higher edginess, which means that their pixels are more different from the contiguous pixels within the same picture. Once the best picture has been selected, the software decomposes it into tiles of three different resolutions (background, medium and high). Every tile is contained in an image packet. For each resolution, the number of tiles in which the picture is divided is shown below.

- Background: 1 packet
- Medium resolution: 64 packets
- High resolution: 256 packets

The probability of sending any of this packets depends on the day of the mission (given priority to the low resolution packets during the first days and to the higher resolution during the rest of the mission) and on the relevance of information on the picture

4.5 Concept of operations

Initialization

Immediately after the spacecraft has been ejected from the launch vehicle, the watchdog powers on. The smartphone is turned on by the watchdog 45 minutes after deployment.

Phase 1

After the initialization phase, the phone is in phase 1 in which it performs a health check. During this phase, each sensor and subsystem is checked and data is compiled into a standard health packet, stored in the smartphone's SD card and transmitted over the beacon radio at a regular interval of 30 seconds. The last 10 health packets are stored in the SD card. After every 10 packets sent, the beacon radio is rebooted. This phase happens during the first 24 hours of the mission. The mission time is kept in the phone throughout the mission so that a system reboot during this phase does not reset the 24 hour countdown A health packet consists of: *Satellite_ID, restart counter, reboot counter, Phase 1 count, Phase 2 count, time, battery voltage, temp 1, temp 2, accel X, accle Y, accel Z, Mag X, Mag Y, Mag Z, text "hello from he avcs"*

Phase 2

This phase starts once a full system health check has been performed. During this phase, image packets and health packets are sent to Earth through the beacon radio. A health packet is sent once for every 9 image packets downlink.

This phase can be divided in 3 sub-phases

- Health Data Measurements: Health data is measured and the 10 most recent samples are stored in the SD card.

- Health Data Downlink: Once 9 packets have been sent through the beacon containing image information, the 10th one is reserved for a health packet.

- Image Sequence: One picture is taken every minute until 100 pictures are taken and stored to the SD card. Pictures are then analyzed and the top image is selected. This image is packetized and compiled into standard image packets. These image packets are transmitted over the beacon radio coupled with health packets in the ratio explained above.

Safe Mode

If the watchdog detects that the phone is not sending any data to the radio for a certain period of time, the spacecraft functionality is reduced to the bare minimum. In this condition, the spacecraft only transmits health data containing the last 10 sensor data values stored in the SD card prior to failure. This mode lasts for 90 minutes. After this period, the spacecraft resumes its normal operations. A safe mode packet consists of: *Satellite_ID, last 10 voltage values, last 10 temperature sensor 1 values, last 10 temperature sensor 2 values, text "SAFEMODE"*

4.6 Testing

In order to validate the design, PhoneSat 1.0 went through an extensive series of testing. A radio range test was conducted over 37km straight line-of-sight distance in order to validate the communications link. This showed that the link was strong enough to receive data from the satellite if it were placed in a 500km altitude orbit. Next, the spacecraft passed a week-long test to prove the robustness of the system and the stability of the software. To prove the flight readiness of the system and the team, PhoneSat 1.0 was lifted in a balloon up to 30km altitude while doing the operations described in the previous section. This test served to expose PhoneSat 1.0 to temperature extremes (during the test, temperatures below -5C were recorded) and to test the communications system in a more dynamic manner. The analysis of the test results showed that the system performed as expected.

Subsequently, PhoneSat 1.0 underwent environmental qualification and acceptance testing at NASA ARC. PhoneSat 1.0 was first placed into a bell jar Thermal Vacuum chamber and successfully underwent days of Day in the Life test to simulate on orbit operations. To help qualify the satellite for severe and harsh launch environment, the satellite then underwent Random Vibration and Mechanical Shock testing to launch provider-prescribed levels. After satisfying these requirements, the satellite was placed into the Bell Jar again for Thermal Vacuum Bakeout for 60°C over 6 hours in order to outgas all parts.

After successfully qualifying PhoneSat 1.0, multiple units were assembled, baked out in a vacuum chamber and thermally cycled in an oven between -5°C and 45°C for approximately 12 hours. Then, two PhoneSat 1.0s were selected to be combined with a PhoneSat 2.0 beta in a flight-like ISIPOD for acceptance vibration testing.

5 PHONESAT 2.0

5.1 Description

PhoneSat 2.0 is an extension of PhoneSat 1.0; building on and supplementing it's capabilities to form a low cost satellite bus. Bus subsystems for PhoneSat 2.0 were designed to include: command & data handling, electric and power system, two-way communications, and attitude control and determination system. The agile space development methodologies were continued in an effort to minimize project cost and focus on the technology whilst eliminating un-necessary overhead. The PhoneSat 2 series of satellites have been built as flight units in multiple instantiations. PhoneSat 2.0 Beta was baselined with the available capabilities of C&DH, EPS and minimal ACS in order to leverage a delayed launch of the PhoneSat 1.0 manifest. PhoneSat 2.4 was baselined for the ELaNa 4 flight manifested on ORS-3. PhoneSat 2.5 was baselined for the ELaNa 5 manifest on SpaceX CRS-3. Flight data from the PhoneSat 2.0 Beta baseline is presented later in this report, whilst PhoneSat 2.4 data will be presented in a future report and PhoneSat 2.5 is currently sitting on the launch pad. The following section describes PhoneSat 2. **Error! Reference source not found.** depcits that PhoneSat 2.5 spacecraft – part of the PhoneSat 2.0 series of Spacecraft.

Figure 5. PhoneSat 2.5

5.2 Mission objectives

Demonstrate bus functionality for parts cost of less than $10k. Defined objectives were (1) command and data handling on a smartphone (2) power generation (3) rate control of the satellite. In addition, a focus was given to monitoring longevity of the smartphone and peripheral microprocessors in the LEO radiation environment.

5.3 Hardware architecture

PhoneSat 2.0 is more complex from a hardware point of view than PhoneSat 1.0; focusing on providing more subsystems for bus functionality whilst maintaining the 1U form factor. The hardware architecture supports; a new Electric Power System (EPS) architecture, second radio for two-way communication, an attitude determination and control system (ADCS), a distributed network of sensors throughout the spacecraft and a new smartphone model as well as data interface architecture.

PhoneSat 2.0 has a new electric power system (EPS) architecture, a second radio that provides two-way communications, an attitude determination and control system (ADCS), a distributed network of sensors throughout the spacecraft and a new smartphone model as well as data interface architecture.

In terms of the EPS, the system uses high efficiency multi-junction TASC solar cells that populate all six external faces of the spacecraft. These solar cells are used to charge 4 Li-Ion batteries similar to the ones used in PhoneSat 1.0, the battery arrangement is two batteries in series and two in parallel that provide a 7.4 nominal bus voltage. The unregulated power from the batteries is down converted for each subsystem as needed. PhoneSat 2.0 retains the ATmega 328 microcontroler that PhoneSat 1.0 uses as a watchdog; with the added functionality power management.

For the communications subsystem, PhoneSat 2.0 keeps the same Stensat beacon radio and the tape measure antenna as PhoneSat 1.0. Additionally, the Microhard MHX-2420 radio operateing on 2.4GHz ISM band at 1W output power, is used for two-way communications. A patch antenna designed by Astronautical Development, LLC is used for this radio.

The attitude determination utilizes the Nexus S smartphone built-in magnetometer and gyro as well as current sensors for the solar panel as a coarse sun sensor. For attitude control, PhoneSat 2.0 has magnetic coils on all six faces of the CubeSat and three brushless DC motors that are used as reactions wheels to orient the spacecraft.

PhoneSat has a set of sensors across the satellite that measure current and temperature as well as monitor the state of the battery. This data is used primarily for sate of health monitoring.

The data architecture of PhoneSat 2.0 is centred around the serial converted USB port of the smartphone and a serial router. This architecture enables multiple devices to talk to each other as well as the smartphone.. Figure 6 and Figure **7** show a power and data diagram respectively of the PhoneSat 2.0 bus.

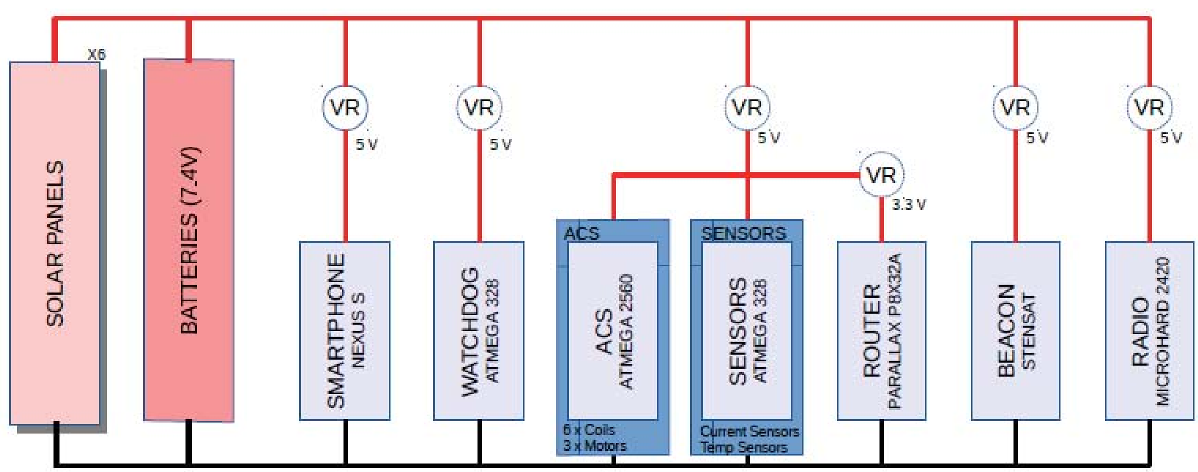

Figure 6: PhoneSat 2.0 power distribution architecture

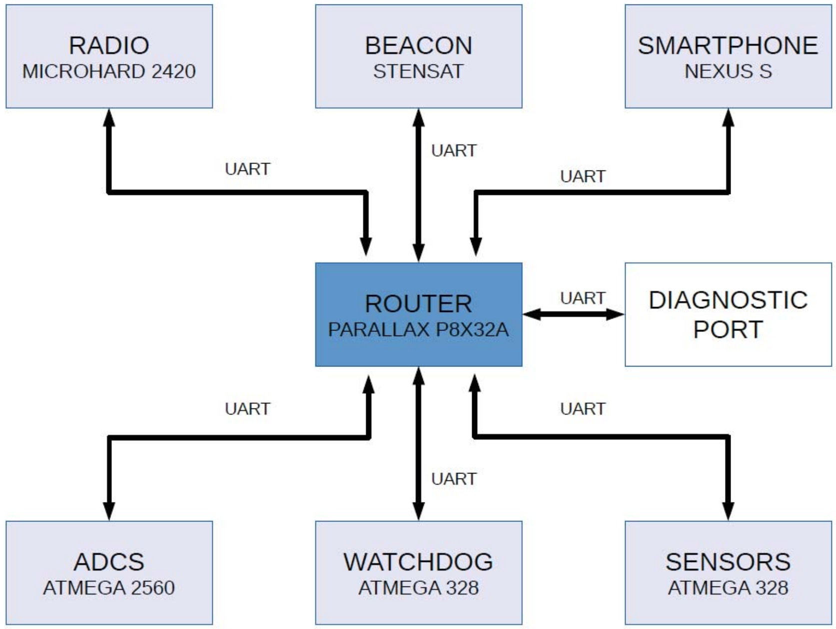

Figure 7: PhoneSat 2.0 data distribution architecture

5.4 Software architecure

In following the expansion from a single smartphone in Space for PhoneSat 1.0 to a capable bus for PhoneSat 2.0, the Software Architecture expanded and made use of a more modular design. The software is organized in different layers that interface with the android framework. Figure 8 shows a diagram of the software
architecture, followed by a detailed description of each section.

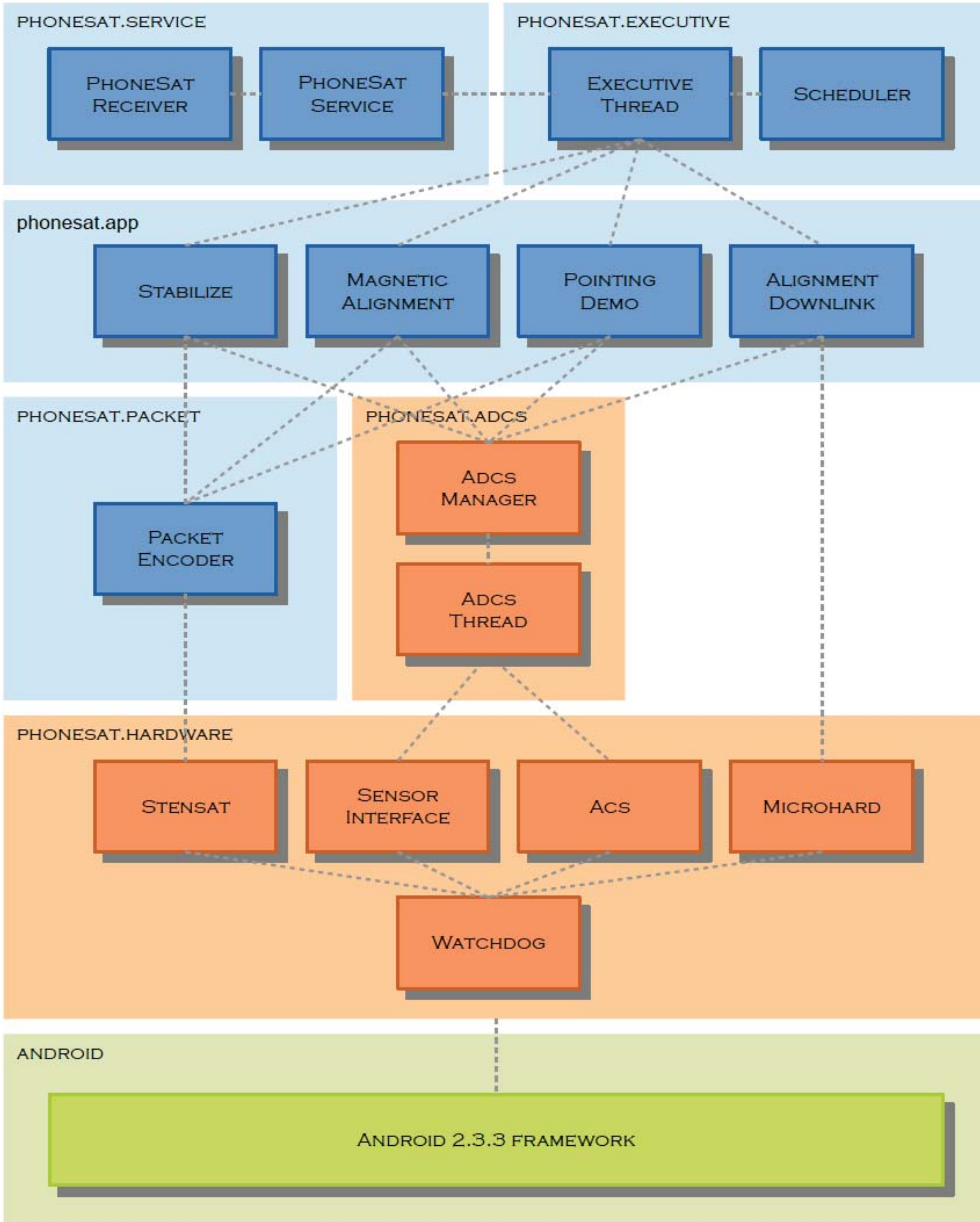

Figure 8: PhoneSat 2.0 software architecture

phonesat.app: this software package contains the applicative. It handles the execution of the concept of operations.

- Stabilize: this activity is run after the deployment of the spacecraft to stabilize it. This is performed by using magnetic coils.
- MagneticAlignment: this activity is a variant of Stabilize. It also uses the magnetic coils to stabilize the spacecraft, but also apply a constant magnetic field in order to align one

specific axis of the spacecraft to the magnetic field of the Earth. This activity is run prior to a ground communication.

- PointingDemo: this activity is controlling the reaction wheels of the spacecraft to point to a designated target. It is either used to take picture of the moon or to align the S-band antenna to the ground station.
- AlignmentDownlink: this activity is running the same ADCS algorithm than MagneticAlignment, plus turns the S-band radio ON to establish a ground to space communication. The magnetic alignment allows a better communication link by aligning the S-band antenna.

phonesat.service: this package contains the code needed to handle the Android execution flow of the App.

- PhoneSatService: this is the generic Android service managing the flight application. It handles the initialization of the system.
- PhoneSatReceiver: this is a generic Android broadcast receiver. It receives various phone internal events from Android and passes them to the flight application.

phonesat.adcs: this package contains the ADCS algorithms.

- AdcsManager: this class is running the ADCS algorithms in a dedicated low-latency thread. It listens for activities (phonesat.app) to determine which algorithms to use, executes these algorithms and controls the magnetic coils and reaction wheels.

phonesat.executive: this package contains the code to schedule and execute the mission activities.

- ExecutiveThread: this class holds a single thread of execution where the mission activities are posted. This is a simple queue (first in – first out) of pending activities.
- Scheduler: the activities to execute are written in a text file on the phone file system. This file contains the start time and the name of the activities to execute. This file is written by the ground station every time a link is established. The Scheduler class is responsible to read this file and push the pending activities to the ExecutiveThread.

phonesat.packet: this package contains the code to encode beacon packets.

- PacketEncoder: this class encodes the beacon packets.

phonesat.hardware: this package contains the device drivers for the PhoneSat hardware.

- Watchdog: this class is the driver for the Watchdog device.
- SensorInterface: this class is the driver for the sensor interface. It receives the sensor data which is external to the phone, like temperature sensors and current sensors.
- Acs: this class is the driver for the ACS device. The ACS device controls the magnetic coils and the reaction wheels.
- Stensat: this class is the driver for the Stensat beacon radio.
- Microhard: this class is the driver for the Microhard radio.

5.5 Concept of operation

Because PhoneSat 2.0 does not have an onboard GPS, the mission schedule is determined on the ground and uploaded to the spacecraft. The possible activities that can be programmed are described in the software architecture (package phonesat.app).

When no schedule has been uploaded yet or when the current schedule has been fully executed, the spacecraft enters a ground listening mode described below.

Initialization - Deployment sequence
Once PhoneSat 2.0 is deployed from the launch vehicle, the watchdog turns on and starts a counter. After 50 minutes, the smartphone starts the Stabilize activity for 5 hours in order to detumble the spacecraft. Once this activity is completed, it starts the MagneticAlignment activity for 1 hour.

Ground listening mode
When in this mode, the smartphone will aligns the spacecraft to the Earth's magnetic field and listen for ground commands over the Michrohard radio.
The chances of establishing a ground link depends on the duration to charge the batteries; the shortest the better.

Scheduler mode
When the phone has a valid time and a schedule file with one or more pending activities to execute, it will wake-up to execute these activities. The phone will be sleeping the rest of the time, keeping the maximum battery power for the scheduled activities.

Sleeping mode
In this mode the phone is off, the only microcontroller powered on is the watchdog which transmits a health packet every 2.5 minutes.

5.6 Testing

Similar to PhoneSat 1.0, all instantations of PhoneSat 2.0 (PhoneSat 2.0β, PhoneSat 2.4, and PhoneSat 2.5) were extensively tested. PhoneSat 2.0β, the trailblazer for PhoneSat 2.4 and PhoneSat 2.5, tested successfully in two suborbital flights, UpAero's SL6 launch in April 2012 and Garvey Spacecraft Corporation's (GSC) P-19 rocket in December, 2012. The UpAero launch exposed the satellite hardware to extreme environments up to 117 km, providing confidence that the satellite hardware could survive a harsh and severe orbital launch. The GSC launch verified the on board radios' ability to close the link to a ground station.

Following the successful completion of these suborbital flights, PhoneSat 2.0β underwent qualification testing. First, the satellite was baked out at 50°C for 12 hours in the bell jar. Then the satellite was power tested under vacuum between 12°C and -20°C for more than 18 hours. Finally, the satellite was performing on orbit operations while thermally cycled under vacuum to between on orbit predicted temperatures. PhoneSat 2.0β then successfully passed the Mechanical Shock test at launch provider-prescribed levels. The satellite was then tested at qualification Random Vibration levels.
After this unit was qualified, PhoneSat 2.4 and PhoneSat 2.5 were subjected to similar tests with levels adjusted to meet each launch provider's requirements.

6 IN-FLIGHT TEST RESULTS FROM THE ANTARES MAIDEN FLIGHT

6.1 Payloads

The first PhoneSat on orbit was delivered by the Antares maiden flight on April 21, 2013. On board this launch system there were three PhoneSat units. Two copies of the PhoneSat 1.0 and one beta release of the PhoneSat 2.0 with preliminary baselined capabilities. The PhoneSats were named "Alexander", "Graham" and "Bell" in honor of Alexander Graham Bell the inventor of the first practical phone. Graham and Bell were two full PhoneSat 1.0 vesions, Alexander was the PhoneSat

2.0 Beta which included the power and data architecture of PhoneSat 2.0. All three spacecraft achieved more than 100% of the mission objectives. Figure **9** shows the spacecraft before integration in the dispenser.

Figure 9. From left to right: PhoneSat 2.0 beta (Alexander), PhoneSat 1.0 (Graham) and PhoneSat 1.0 (Bell)

6.2 Mission overview

The three PhoneSats were deployed into a 260km x 240km altitude orbit at 51.6 degrees inclination. Since the satellites were deployed in such a low orbit - their orbital life time was very short, approximately 5 days - the radio amateur community support became a key element in order to receive a greater number of packets from the satellite. A website was setup where the radio amateurs could store and share packets received from the satellites. The response from the radio amateur community was great with more than 100 amateur operators consistently tracking PhoneSat all around the world. Figure 10 gives an idea of the distribution of radio amateurs that registered on this website (www.phonesat.org).

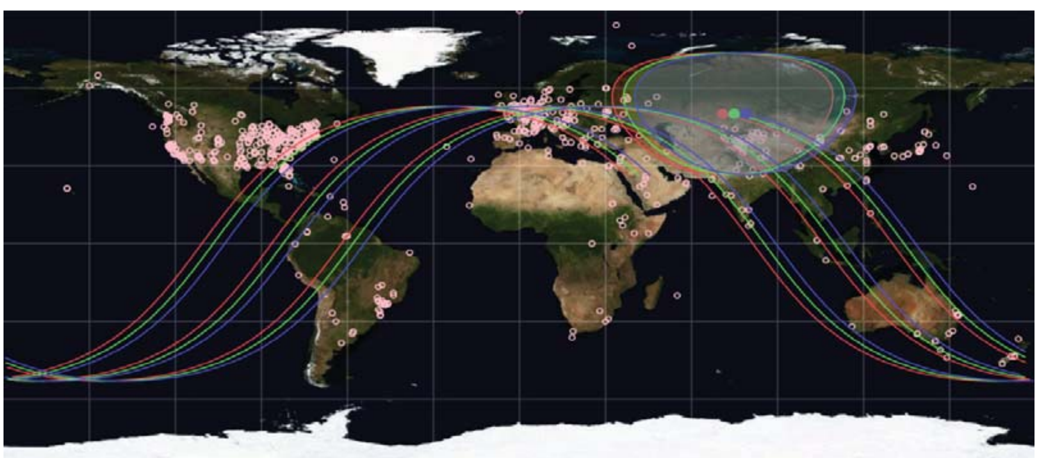

Figure 10. Radio amateurs registered on www.phonesat.org

6.3 In-flight results

PhoneSat 1.0 health data

Graham and Bell collected battery voltage data, accelerometer and magnetometer data from the sensors built into the smartphone and temperature from two external sensors placed in different locations of the spacecraft. Figure 11shows the battery voltage over time for both spacecraft. As it can be observed, both PhoneSat 1.0 units depleted their batteries at a similar rate.

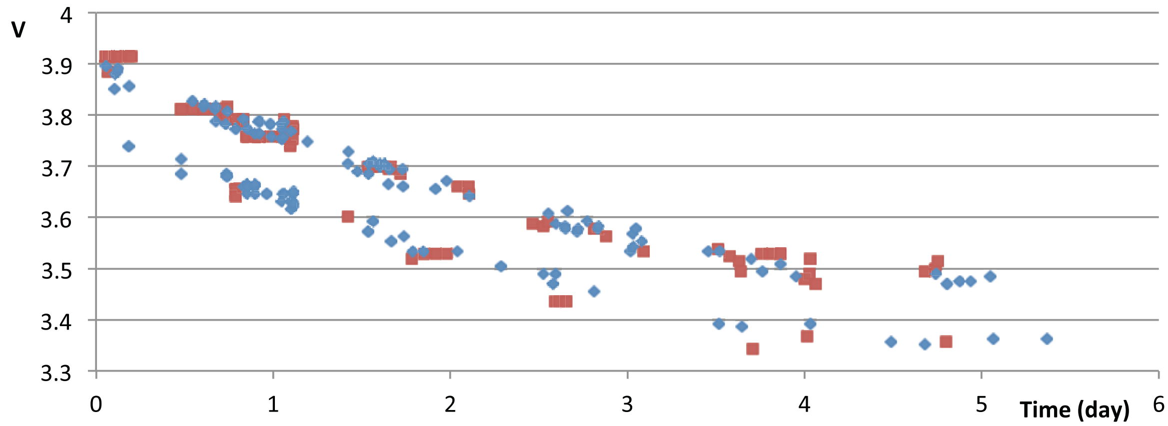

Figure 11. Battery voltage evolution over time. ■ represents data from Graham, ◆ represents data from Bell.

Figure 12 and Figure 13 show the accelerometer and magnetometer data from Graham. Similar data was received from Bell, this data is no shown in this paper to keep it more concise. This acceleration is a product of noise, no flight calibration and the sensor being located away from the center of mass. The magnetometer data shows a value of a magnetic field module is time variant and greater than the field for this orbit due to parasitic magnetic field in the satellite.

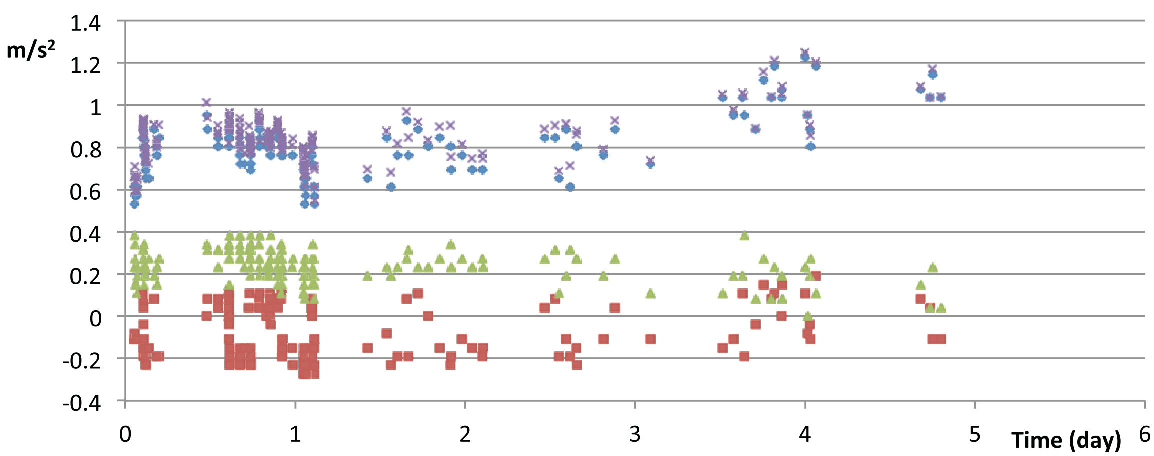

Figure 12. Accelerometer data from Graham**.** ■: acceleration X axis, ◆: acceleration Y axis, ▲: acceleration Z axis, ×: acceleration module.

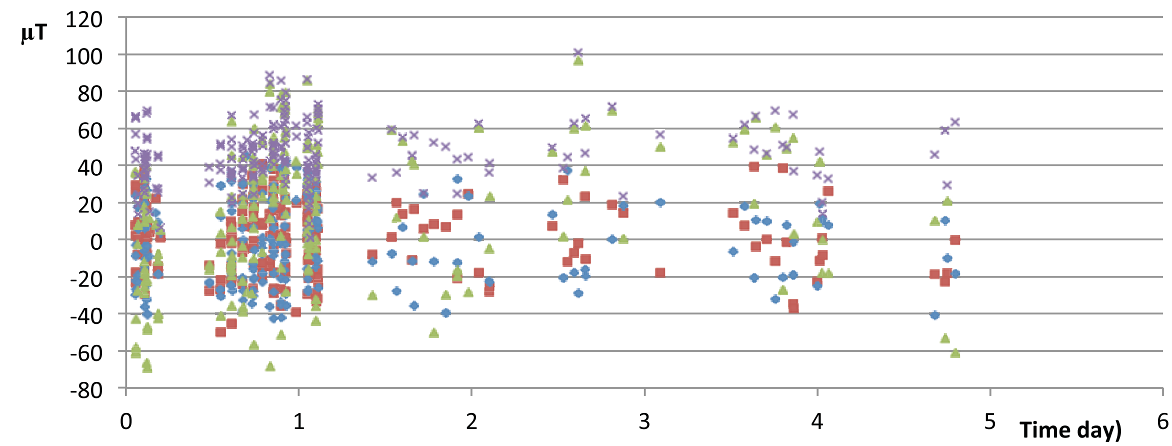

Figure 13. Magnetometer data from Graham. ■: magnetic field X axis, ◆: magnetic field Y axis, ▲: magnetic field Z axis, ×: magnetic field module.

Finally, Figure **14** shows the temperature recorded by the sensors for both spacecrafts, as it can be seen, it ranged from -10C to +30C approximately.

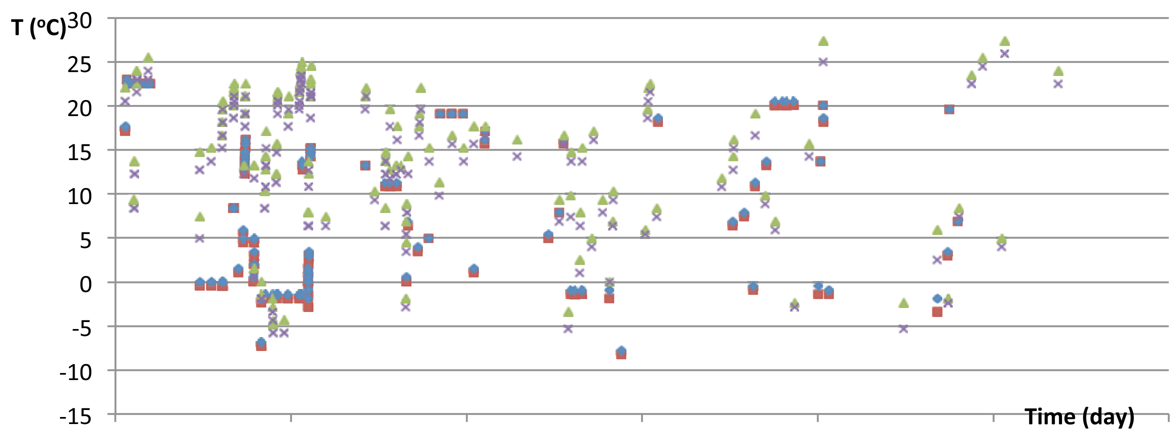

Figure 14. Temperature data from Graham and Bell. ■: temperature sensor 1 - Graham, ◆: temperature sensor 2 - Graham, ▲: temperature sensor 1 - Bell, ×: temperature sensor 2 - Bell.

Figure **15** shows a transition from eclipse to sun light and how the satellite increasingly warms up from -3C to 14C.

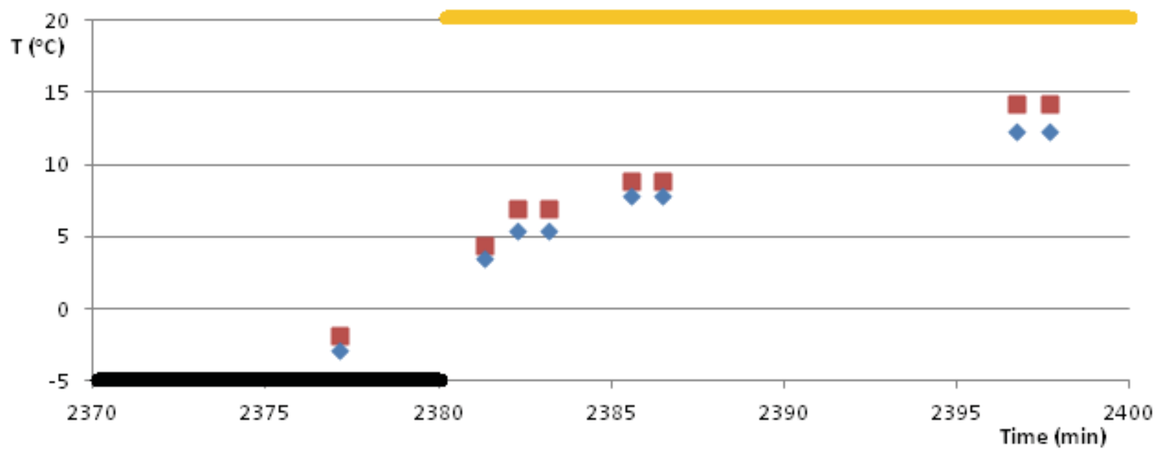

Figure 15. Temperature variation on the PhoneSat 1.0 while transitioning from eclipse to sun light. . ■: temperature sensor 1 - Graham, ◆: temperature sensor 2 – Graham. The orange line represents the time under sunlight and the black line the time in eclipse.

In terms of the phone survivalability to the space environment, one phone reboot was observed in Grahan and four in Bell during the five day mission. In terms of radio signal strength, the packets were decoded consistently from both spacecraft.

PhoneSat 1.0 imaging

On the second day of the mission, the spacecraft started downloading the pictures that had been taken. Over the course of the remaining days of the mission, the picture packets were assembled as a jigsaw puzzle. The image was stored in low, medium and high resolution, each packetized into lengths appropriate for the beacon transmitter. Priority was assigned to the low resolution packets in order to ensure a complete image to some resolution was received. By the end of the orbital lifetime, high resolution packets had begun to be transmitted. Figure **16** shows the images taken of Earth by each smartphone camera from Space.

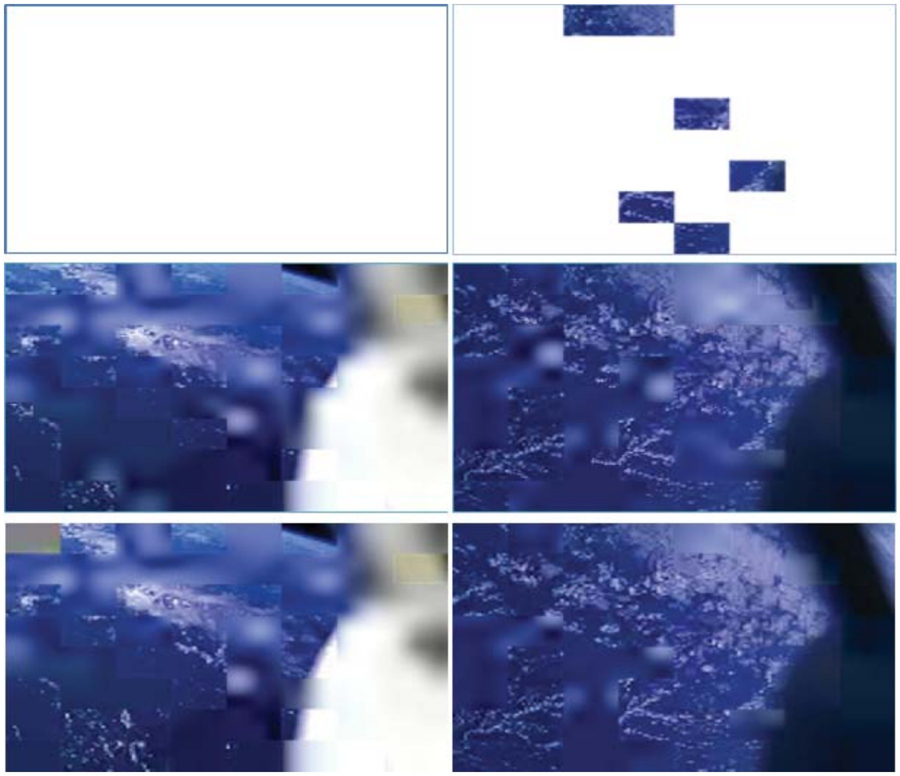

Figure 16. PhoneSat 1.0 pictures. Left: Bell pictures. Right: Graham pictures. The top pictures correspond to the second day of the mission, the middle pictures are from the third day of the mission and the bottom ones are the last ones obtained.

Table 1 shows the number and percentage of each picture packet type that were received.

Table 1. Picture packets received for each satellite

	Graham		Bell	
Background image	1	100%	1	100%
Medium resolution image	53	83%	40	63%
High resolution image	109	43%	61	24%

PhoneSat 2.0 beta data

Phone 2.0 beta collected smartphone sensor data including compass, gyro and accelerometer. In addition, subsystem current consumption as well as solar panel current generation were measured. The satellite also recorded temperature on eleven different locations of the spacecraft. The temperatures recorded ranged between -1C and 27C for the interior of the spacecraft and -20C and +40C for the exterior. Counters on the smartphone and arduino's all showed zero reboots. The obtained gyroscope data from the smartphone is shown in Figure **17** below. A waiver was obtained with the LSP to allow no burn-wire for the deployable tape measure antenna. Subsequently, the antenna deployed against the ejection module, creating a high initial spin rate of the spacecraft.

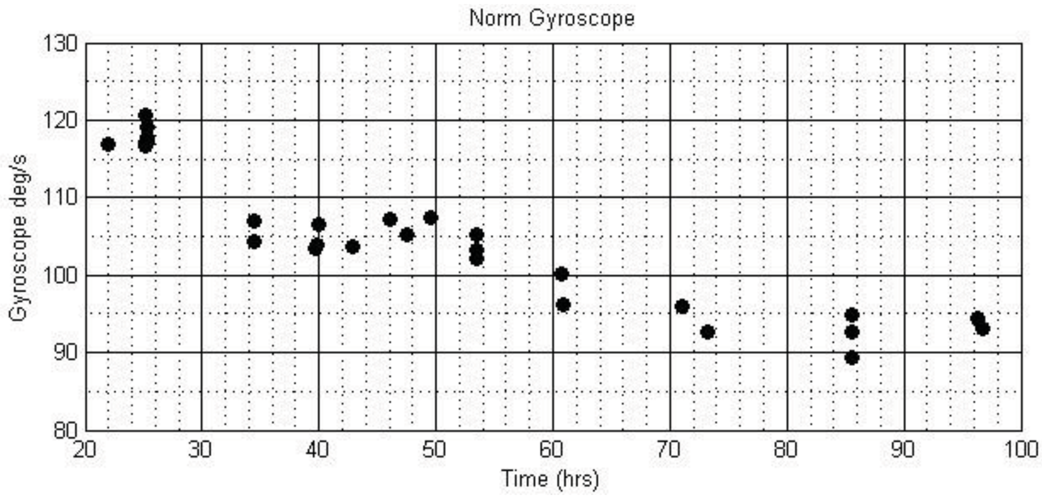

Figure 17 - PhoneSat 2.0 Beta Smartphone Gyroscope

7 PHONESAT CONTINUOUS EFFORT

PhoneSat is an iterative effort that has continued post flight of the Antares. Two PhoneSat 2.0 version of the satellite were delivered for the ORS-3 Minatour 1 and SpaceX CRS-3 flight. The satellite (PhoneSat 2.4) manifested on ORS-3 launched in November 2013 and successfully accomplish the mission. Additionally, two PhoneSat 2.5's will launch on the SpaceX CRS-3; the second as the bus for KickSat.

EDSN, a swarm of 8 satellites designed a NASA Ames Research Center, is an extension of the PhoneSat 2.0 bus designed for space communication networks. The EDSN mission is schedule to launch at the end of 2014. The PhoneSat team is currently working on new concepts for PhoneSat 3.0 and beyond.

8 CONCLUSION AND ACKNOWLEDGEMENTS

The PhoneSat Project has successfully demonstrated the use of consumer technology, namely the smartphone to supplement traditional space hardware to drastically reduce cost. In addition, agile development has been successfully employed in order to maximise technological advancement over time. With satellite bus functionality now possible for consumer technology prices, a substantial number of missions for science, education technology and commercial applications are now economically viable. A large thank you to the innovative c0-PIs that formed the foundation for this project: Chris Boshuizen and Will Marshall, in addition to the team that gave this projects its initial success.

9 REFERENCES

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