A Baptism of Fire: The STRaND-1 Nanosatellite

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ABSTRACT

The CubeSat standard has inspired a new wave of engineers, researchers, and scientists – all aiming to utilise ‘commercial off-the-shelf’ (COTS) subsystems to build nanosatellite systems. For this same reason, students and staff at Surrey have been designing a 3U CubeSat with the intention of providing low-level design, build and test experience for early career engineers, provide on-orbit demonstration of key technologies in attitude and orbit control systems (AOCS), and finally assess smart-phone components for future spacecraft applications. The modern smart-phone is the latest in a consumer driven and start-of-the-art electronics market which the STRaND-1 mission aims to exploit; assessing hardware components and exploring software towards new methods in designing and operating new satellites. The ‘Surrey Training, Research and Nanosatellite Demonstrator’ is the first in a line of ambitious missions which aims to strengthen the ties between Surrey Space Centre (SSC) and Surrey Satellite Technology Ltd (SSTL). The project began in April 2010 where STRaND-1 was designed in the team’s free time but the major build work began in mid-October 2012. Launched on 25 February 2013, the assembly, integration and test (AIT) phase took approximately 4 months to complete. This paper discusses this phase and the typical-CubeSat subsystems and non-PC/104 AOCS and computing payloads in a custom payload bay. In-orbit results of the new nanosatellite power, attitude and orbit control system are presented. With many new capabilities to demonstrate on STRaND-1 when in-orbit, exploiting the latest consumer electronics and software with real training and mission utility was disruptive. We evaluate the ground-based operational processes during commissioning.

THE STRAND PROGRAMME

STRaND-1 is the first in a series of Surrey Satellite Technology Ltd. (SSTL)-Surrey Space Centre (SSC) collaborative satellites designed for the purpose of technology path finding for future commercial operations. The aims of the STRaND (Surrey Training, Research and Nanosatellite Development) programme are:

- To challenge the current industry standard development process and to discover new ways of designing, manufacturing and testing space hardware,
- To demonstrate novel space technologies and the use of existing modern terrestrial commercial-off-the-shelf (COTS) technologies in space, and
- To provide a rapid hands-on training experience for less experienced engineers and academics in designing and building new satellite technologies.

The STRaND programme is the first time Surrey has entered the CubeSat field and differs from most CubeSats in that the payload is a modern commercial off-the-shelf (COTS) Android smartphone as a payload, along with a suite of advanced attitude and orbit technologies developed by the University of Surrey and the CubeSense AOCS board [1] from the University of Stellenbosch in South Africa. STRaND-1 was built and tested by a team of young engineer volunteers in their
own free time, supported in the final stages by experienced staff. STRaND-1 was also different in that anyone (not just from the space engineering or space science community) was eligible to fly their “app” in space, for free. Further information on STRaND-1 and the design can be found in [2-4] but this paper aims to focus on the assembly, integration and test phase of the mission as well as launch and early operations (LEOP) at SSTL and SSC (Figure 1).

![Figure 1: STRaND-1 Avionics in AIT](image)

The paper is divided further into 5 sections. Section 2 describes the assembly, integration and test phase of COTS and custom CubeSat subsystems, Section 3 describes launch and early operations, Section 4 presents the current results from orbit, and Section 5 concludes. The payload module is also discussed in detail. As such, a critical review of these systems is provided and their implementations discussed. Future recommendations and developments are also provided for current and future CubeSat teams.

1. STRaND-1 DESIGN, BUILD & TEST

STRaND-1 is a 3.5 kg 3-Unit CubeSat. Its physical configuration is split into an avionics core block and a payload bay. It has two deployable solar panels and two body mounted panels with thermal control surfaces on the chassis. The payload occupied approximately two thirds of the entire spacecraft volume.

The avionics core consists of the GomSpace on-board computer (OBC), SSTL/SSC volunteer designed radio, ClydeSpace electrical power system (EPS), and SSC volunteer designed power switches. As with any satellite, this primary core is essential to the operation of STRaND-1.

1.1. Onboard Computer (OBC)

The on-board computer selected for the mission was the GomSpace A712 commercial device [5]. It runs FreeRTOS [6] with the NewLib C library and GomSpace-developed CubeSat Protocol (CSP) API which interfaces to on-board magnetometers and magnetorquer drivers, and master-mode off-chip I2C bus. The standard program consists of three threads which provide an ftp server for uploading new images to RAM/ROM as well as a command line interface and stdio interface for online debugging. An additional thread contained all the STRaND-1 functionality called ‘StrandMind’. It interfaced with other I2C subsystems, and provided a hardware abstraction layer using lower-level accesses for memory allocation and the I2C bus from the API. The decision to operate within a single task was made to keep our implementation of timing requirements simple - assuming that existing tasks would not interfere. Within the StrandMind task, there is a core round-robin scheduler and installer that calls out to various ‘modules’ which have to act cooperatively and within 100 ms. It is, in principle, possible to replace, augment, and remove any of these modules in flight, without turning the on-board computer off and without ceasing any on-board operations. As the modules are loaded into volatile random access memory they will be lost if the power is cycled and the system will revert back to its launch state. There are caveats: uploaded modules (as opposed to those flashed before launch) cannot make any external function calls and must have a single entry point.

**Existing Hardware & Software:** Notably missing are direct memory access (DMA) controllers and free universal asynchronous receiver/transmitters (UARTs) which may have allowed code to be loaded into the memory of a non-running system in orbit, i.e. cold upload and boot of a complete new operating system post-launch. The system has two banks of FLASH memory, one of which holds the code that always boots upon power-on, and the other is left writeable by the GomSpace software layer for flashing through the debug port with a running OBC; use of the flashed image then requires manual changing of physical onboard jumpers. Not having immediate access to the GomSpace source code meant that initial designs did not seek to exploit the potential of the second flash bank, and when the source did become available effort had to be focussed on the stability of StrandMind code rather than exploring and debugging existing code.

If using GomSpace OBC again the FLASH bank jumpers would be wired to control lines on the radio microcontroller to allow for uplink of new code. Operating the radio system as an I2C master is recommended.

**StrandMind Installer:** On the ground, an entire onboard operating system is compiled with the new
module in place. Executable and linking format files are then inspected to determine exactly where in the new binary object the new module is located. These functions are then extracted from the full binary and placed together in an upload binary, wherein they are preceded by two 32-bit offset values which give the position in the upload binary of the two functions' entry points.

The upload binary is then transmitted to the on-board computer using Strandatoga, a simpler derivative of Saratoga – a UDP-based transport layer protocol [7], to ensure complete and correct reception of the entire image. The binary is stored into some dynamically allocated area of random-access memory. The StrandMind will call the function at the intrinsically indicated offset which installs the new module. The offset of the module's step function's own entry point is passed as an argument to this initialization function. That function can insert this offset into StrandMind's round-robin list, and then the new module is effectively installed and running. Bearing in mind that the installation routine is given access to all running system variables, it can in fact do much more than this.

The simple use-case described above has been demonstrated both on a PC-based (x86) build of the operating system, and on the GomSpace OBC itself in ground-tests. This was a labour-intensive manual process. Both these situations present their own problems: a PC requires execute permission to be arranged on the memory allocated to hold the new code, and the ARM-7 demands that modules are loaded on a four-byte boundary as the function call. While it may seem limited to running single monoblocks of code, ingenuity could be used to overcome this through use of explicit function pointers and jumps. This is facilitated by the fact that uploaded installers can, in fact, do anything with the live system. It would be a formidable task, however, to actually replace a part of the core system, if such proves buggy, due to the complexity and size of the code or code modules involved.

1.2. STRaNdceiver Radio

The STRaNdceiver communications module was a key development in the mission. The high level concept was to develop a modular based system with analogue radio circuitry on one board and the demodulation and data handling on another board (interface being at the baseband stage). This would allow for flexibility on future STRaNd missions by only needing to redevelop the analogue front-end for different frequency radio systems.

This initial version was a modular VHF-uplink / UHF-downlink data transceiver. Both uplink and downlink were 9K6 baud HDLC frames, with James Miller data scrambling and CCITT-16 CRC. A modular deployment system was employed for both whip antennas, housed on the analogue RF board.

The digital board makes use of modern integrated modulation/demodulation modem ICs that also handle HDLC framing and CRC integrity checks, reducing the burden on the processor that receives and transmits the data. It contains a PIC24 microprocessor that handles baseband data communications, control logic for the transceiver, power amplifier, I2C bus comms, and IF circuitry. The RF board comprised all the RF, power-switching and antenna deployment circuitry. An S-band daughter module and RF amplifier chain was designed and tested, including a deployable dipole antenna, but due to time constraints was not included on the final flown hardware.

The RF modchip had a fixed intermediate frequency band ~400 to 450 MHz, therefore the VHF uplink was passed through an upconverter. Using a fixed LO, mixer stage and RF amplifier chain the 145 MHz signal was converted to the 430 MHz band before being passed to the receiver modem chip. This upconverter chain was custom-designed for the STRaNdceiver using COTS parts. The data-stream for uplink was stored in a buffer in the digital section microprocessor until requested by the OBC, as the I2C master. The OBC needed to poll the receiver regularly, and this enabled the STRaNdceiver microcontroller to also act as a watchdog for the OBC, and if it did not receive regular polling requests from the OBC the STRaNdceiver would be able to autonomously initiate a beacon if/when the OBC suffered a single event, and allow ground control to initiate a power reboot, bypassing the I2C master control of the OBC.

UHF downlink was achieved by a single-stage power amplifier driven directly by the transmitter-side modem chip, which then processed this data into HDLC frames and passed the completed frames to the transmitter modem chip for broadcast. A solid-state power control switch, commanded by the microcontroller, enabled or disabled the UHF power amplifier. Downlink output power was assessed using an HP power meter – the single-stage power amp analogue gain was tuned to produce 31.5 dBm; after allowing for feed and antenna losses the transmitter produced an EIRP of approximately 30 dBm as shown in Figure 2.

Uplink sensitivity was estimated from modem-chip values and front-end gain to be better than -90 dBm. Modulation envelope measurements from the UHF power amp were found to have minimal in-band distortion and clean roll-off.
It is appropriate to say that the radio system on STRaND-1 has the most operation in orbit, and a number of lessons learnt from this initial version of the STRaNDceiver will be folded into a second-generation STRaNDceiver on future missions:

- On the analogue board, the input and output IF lines should be separated further to improve signal isolation
- General filtering and improved matching to the antennas, and use of RF shields on the PCB
- Use of a higher gain LNA (or possibly two-stage cross-strapped)
- Use of a phase-lock loop controller with a redundant crystal for the local oscillator
- Moving the currently integrated antenna deployment assembly off the analogue board and externally mounted, connecting the antennas to the analogue board using coaxial cable
- Improved power switching system, introducing a hot-redundant functionality and greater radiation tolerance
- A two-stage power amplifier for downlink with cross-strapping for redundancy purposes.

Due to time constraints some software functionality was not included that will be included in a second generation STRaNDceiver:

- Local hardware for housekeeping telemetry such as voltage, current and temperature to be included in the watchdog beacon data set
- Accessing telemetry points on the modulator / demodulator chip including RSSI, status of the receive signal lock, and status of the automatic frequency compensating function
- More sophisticated “back door” functionality allowing the STRaNDceiver to take full control of the I2C bus in the event of an OBC single event, allowing ground control to inject I2C commands directly on to the bus
- CW-functionality to enable interleaving of robust Morse-code downlink and modulated data downlink
- Direct access to the SPI interface of the downlink modulator chip, allowing for in-orbit reconfiguration of the downlink signal (e.g. different modulation schemes, changes to transmit bit rate, frequency changes, etc.)

1.3. Electrical Power & Distribution

STRaND-1 used a standard 3U EPS [8] from ClydeSpace, with a ClydeSpace 20 Whr battery [9]. Integration and use of this subsystem was generally straightforward although the communication protocol used by the power system on top of the I2C bus was non-standard when compared to the OBC and other systems. Some support was required from both GomSpace and ClydeSpace to successfully enable communication between the two units.

The spacecraft had 4 solar panels. Two body-mounted panels and two “wing” deployable solar panels. In stowed configuration, the spacecraft was power safe in tumble. When the battery voltage dropped to 7.5 V, the AOCS system would control the spacecraft to point at the Sun, the wings would be deployed and the power generation maximised.

All solar panels used triple junction cells and were placed on an FR4 substrate, bonded with a space-rated epoxy resin. The difference in coefficient of thermal elasticity between the cells and substrate was considered acceptable and a thicker layer of epoxy was used to ensure strain relaxation. Thermal cycling of the panels showed the panels to be robust over large temperature range.

Due to a large number of experimental payloads on STRaND-1, the power budget did not enable all payloads to be permanently powered and so a new power switch distribution module was developed to provide power switch functionality. The only available volume in the stack for this switch module was above the CubeSense attitude determination module, and the large cameras mounted to the CubeSense board meant that the switch module had to be designed on a novel H-shaped PCB. Despite the fact that the board had a thin cross beam instead of a near-square layout, the stresses induced under vibration testing did not cause the PCB to fail structurally.

The power distribution board consisted of 8 current limited switches and two lines for the arm and fire of the panel deployment circuits. The current trip setting...
and trip time for the switches was software selectable with a resolution of 0.5 ms and proved to be very useful feature given the dynamic nature of the STRaND-1 where different combinations of payloads had to be switched than it was originally planned and switches were reused.

Due to the routine polling for these parameters requiring higher priority, I2C communication occasionally had timing errors. This was rectified using several safeguards such as maximum ON time for the switches, communication watchdogs and timeouts and a command acknowledgement protocol. The current measurement had a small non linearity at low current measurements which meant that current measurements below 20 mA had a significant deviation from the calibration equation. In the linear calibrated region of the current sensing the largest deviation over a range of 1.5 A was only 2.93 mA.

The power distribution board was tested thoroughly and performed as expected in all ground tests. During flight, there was not enough time to demonstrate the complete functionality of the unit to compare against ground tests. Telemetry was part of the standard beacon data and the behaviour was nominal. The panel deployment arm telecommand was sent, and the power distribution board telemetry returned that the arm switch in the “armed state” and confirmed at least basic operation of the power distribution unit in orbit.

1.4. Payload Block

The payload block consisted of non-PC/104 conforming boards in a separate structure to house the smart-phone, Digi-Wi9C, pulsed plasma thrusters (PPTs), attitude and orbit components, and water-alcohol resistojet propulsion (WARP) system. Much of the payload design is described in [10] and includes the intended operations, software architecture, and hardware design.

Smart-phone Payload: A Google Nexus-One [11] was integrated together with a Digi-Wi9C [12] connected to a custom motherboard which interfaces over I2C. During assembly, the wires necessary to connect to other systems were particularly small at 0.7 mm kynar wire. The power button itself is a 2-pole / 4-pin switch was very sensitive to impedance matching - causing it to occasionally and unintentionally power on. This was controlled with a digital switch upon construction but a FET-based switch circuit would be best used in the future. The wiring and switch can be seen in Figure 3.

Further to the total ionising dose experiments [10], proton and neutron tests are essentially for future development of space systems derived from mobile phone technologies.

Connecting the smart-phone with Digi-Wi9C was achieved using a hard-wired and RTV’ed USB 8 cm cable. The Wi9C was operated using a standard Linux 2.6 platform which ensured it was easy to modify given internal experience with Linux 2.6 and with numerous existing open-source tools used to talk over I2C and over USB to higher layers within the smart-phone. This is described in depth in [10]; a design approach was adopted similar to that of gnuradio, using existing or bespoke developed C applications for processes which are timing critical, with data processing and flow management handled by Python scripting. A motherboard was then designed and built to provide and I2C slave interface and further power switches and regulation. The Wi9C as a Linux platform does not operate in I2C slave-mode so a PIC24 with 256 KB was used to provide a shared interface between the GomSpace OBC and the Wi9C. Custom C-code was written to arbitrate I2C bus access, using GPIO interrupts for signalling.

During assembly, the existing C328A camera [13] was replaced by a stripped down Linux-compatible USB
webcam for ease of physical and software interfacing. An example image can be found in Figure 4.

Figure 4: Inside view of USB webcam to smartphone

Testing the complete unit created a unique problem whereby the Wi9C would fail to correctly execute the startup boot sequence; the only indication of this was a slowly flashing Ethernet LED. This problem was eventually traced to an incorrect start-up of the processor due to the in-rush current of interfaces powering on simultaneously exceeding the capabilities of the interface board. This is documented for other ARM-based processors, such as the Raspberry Pi [14] and required significant debugging. In the future, a simpler and smaller single board computer (SBC) such as the NXP mBed [15] could be utilised; this could achieve the core packet exchange requirements needed with the smartphone at substantially lower power requirements, with the loss of some flexibility. For example, using the Wi9C Linux platform made smartphone file management and file transfer very simple. This functionality would therefore need to be implemented on the smartphone itself.

Pulsed Plasma Thruster Payload: The Pulsed Plasma thruster experiment was one of the major system design drivers for the mission. The need to maximise the distance of the thrusters from the CoM (to maximise the applied torque) led to physical configuration design decisions and caused other subsystems to find more complex assembly solutions. The design of the PPT units (two banks of 4 discharge chambers and a control and charging unit) did not accommodate the standard PC/104 alignment bars and this greatly complicated the order in which units were integrated during AIT.

Testing of the unit highlighted some unexpected behaviour in that the squiggle motor assemblies were susceptible to the interference caused by a PPT discharge and so after every firing an alignment routine would have to be conducted over the entire thruster bank. This was possibly due to EM interference affecting the piezoelectric crystals - but this requires further investigation.

Induced transient voltages were detected during test firings, however the introduction of high frequency filters on the power circuitry of the thruster experiment reduced the ripple effect on the power lines, and further protection was added by applying copper tape to the outsides of the each discharge chamber which reduced EMI to acceptable levels.

Attitude & Orbit Control System: This system includes CubeSense, magnetorquer rods, wheels, and butane thruster. During mechanical review, it was decided to reinforce the support for the relatively large cameras integrated on the CubeSense board. These cameras comprised of standard webcam detectors with glass fish-eye lenses to maximise the field of view for the Earth and sun-sensing cameras. Due to the rapid timescales of the build, the decision was taken to 3D print supportive “chins” for the lenses out of ABS polymer – shown in Figure 5.

Figure 5: CubeSense 3D Printed ‘Chins’

Research on the outgassing properties of ABS showed that a number of ABS materials are listed in the NASA material database all with acceptable levels of volatile mass loss and so the material was considered acceptable [16]. Focusing the lenses was easy to achieve with these mechanical parts.

Under testing CubeSense with the OBC and power systems, the I2C bus would often fail due to node dropout or the bus being pulled down. Hot plugging of I2C systems during integration and test created varying bus impedances and was difficult to manage for numerous I2C devices. This was solved by adding a
level converter circuit for a 3.3 V in/out system for a known bus impedance and isolation circuit. CubeSense was not the only unit to suffer from this problem but as one of the first units available to test encountered this first. Having equipment to automatically decode I2C traffic like in Figure 6 was essential for our testing.

Figure 6: Oscilloscope with I2C Debugging
The structure rods were replaced for brass rods due to magnetic interference. The torque rod firing time was 700 ms and magnetometer measurements were delayed by 300 ms to allow for unaffected telemetry collection. However in flight, it appeared that the magnetometer readings were interfered with leading to undetermined control states – as shown in the telemetry.

The second propulsion system on the spacecraft was originally designed as a more conventional resistojet solution. This subsystem saw significant design evolution over the course of the design and build phase.

The initial intent was to build a butane-based propulsion system drawing from SSTL heritage propulsion systems. Indeed the thruster assembly itself changed very little over the design phase. Novelty in design was intended to be the use of a square-profile, 3D-printed aluminium propulsion tank with embedded fill and drain valve and propellant filter. Finite element analysis indicated that even at the small scale of nanosatellites and the modest pressures of liquid butane, the level of deforming on the tank would be unacceptable. The design was iterated to a cylindrical (but with flat cap) geometry and prototypes built. Test sections of the 3d printed aluminium structure were electron-beam welded to investigate the quality of the bond. Analysis showed that the heat affected zone had an unacceptable level of inclusions and cavities. It is hypothesised that this is due to small amounts of polymer residue left behind from the aluminium powder mix originally used in the 3D printing process. As a result, a more traditional machined version of the tank was manufactured with a standard electron beam weld bond on the cap.

Future experiments would focus on investigating the use of heat treatment (either before or after welding) to reduce the level of porosity of 3D printed Aluminium components as shown in Figure 7.

Figure 7: Electron beam welding test sample of 3D-printed aluminium, with porosity in the weld area
Complications in the shipping process and adherence to CubeSat standards on pressure vessels and for the sake of simplicity for the launch agency meant that a change of propellant was necessary. The decision was taken to move to a water propellant as this requires no pressured filling equipment at launch site, 1-bar absolute tank pressure (and so not considered pressure vessel), plus the fact that a greater mass of propellant could be stored. Thermodynamic analysis of the resistojet thruster showed that the new propellant could still be vapourised even with the greater specific heat capacity. The mix was 50%-50% de-ionised water and isopropanol, to ensure the propellant did not freeze when the spacecraft was at -20°C.

1.5. Qualification: Thermal Vacuum & Vibration
Existing facilities at SSTL in Sevenoaks were used to complete thermal vacuum (TVAC) and vibration tests between 18-21 Dec 2013. The thermal vacuum tests aimed to demonstrate functionality in a vacuum and to satisfy launch agency requirements. 3 cycles from -10 to 50 °C were seen at 2 x 10⁻⁵ Torr; totalling 56 hours in vacuum. The test setup and temperatures achieved can be seen in Figure 8.
Vibration tests include low level sine test from 10 – 2000 Hz, combined sine/quasi-static tests and qualification random vibrations for 180 s at varying amplitudes based on the PSLV launcher. Control signals were fixed to the baseplate for which ±3 dB alarms could be used. As shown in Figure 9, the tests were completed successfully with no visual evidence of damage.

2. LAUNCH & EARLY OPERATIONS (LEOP)

The Launch at ISRO in Shriharikota, India: The launch integration process was very straightforward. The working relationship with the launch agency was very positive and straightforward. An initial fit check at ISRO facilities using the Flight Model ISIPOD and a dummy mass representing the spacecraft de-risked the final integration process.

The spacecraft itself was integrated with the ISIPOD at SSTL facilities in Guildford, UK, and shipped out to the launch site as a single assembly which was then mounted in due course to the launch vehicle using a simple aluminium interface plate. The ISIPOD dispenser was itself simple to use, simple to interface to the launch vehicle, and from the fact that STRaND-1 was successfully deployed in orbit, reliable. We would like to thanks the ISIS team in supporting the initial fit check operations at ISRO facilities.

The Groundstation at SSC in Guildford, UK: The satellite successfully separated from the Indian PSLV C-20 launcher in low Earth orbit after its launch on 25th February 2013, and first contact with STRaND-1 was made on its second pass over the Guildford ground station. During commissioning, it was found that there were problems with the ground segment operated from the Surrey Space Centre’s ground station at the University of Surrey. The groundstation was developed under the GENSO project in 2007 [17] and has been used for reception of satellite signals only and given the short time-scale of the project, was not tested sufficiently with the STRaND-1 flight model. As a consequence, our uplink was not optimal during the first two weeks. The key factors in the uplink being received by STRaND-1 were the chosen software and old desktop PCs and better TLEs.

The computers used were particularly old and were quickly replaced. The software used was also replaced to a lighter solution which did not load the PC as heavily – now using Orbitron [18] which has worked effectively for numerous CubeSats since Feb 2013. Additionally, the frequency has to be increased by 2.215 kHz as per the ICOM910 manual on packet data.
An assessment of the antennas revealed some of the common problems with the siting on campus – problems with line of sight, reflection, and metal in the near-field. Initially, we experienced interference from air conditioning units. Plate metal in the near-field of the VHF antenna showed under simulation that the Uda-Yagi antenna with a conductor in the vicinity sends the main beam off course. Figure 10 shows some comparative far field patterns with and without the offending conductor.

![Figure 10: CST Simulations of VHF Antenna Pattern without (top) & with (bottom) near-field metal](image)

Operationally this meant that small VHF packets < 16 B would be received but not larger packets used for sending 'hole-maps' of the Strandatoga protocol. The message for starting a file transfer was small but we were missing transaction timeouts, meaning we could start file downloads but not stop them. Not being able to transmit hole-maps and a lack of transaction timeouts meant time was spent debugging the groundstation.

Another key issue here was the delivery of adequate decoding tools to the amateur community. A spreadsheet was released showing the format of the packets being transmitted but no decoding software was released. As such, the amateur community utilised a number of existing and new tools from avid supporters (ZL2BX, GW6KZZ, VK5HI, EA1JM, G3VZV, JH4XSY/1, W7KKE, N8MH, VK6MJ, DK3WN, ST2NH, PE0SAT, WA6FWF, PA3WEG).

Range testing of the groundstation to other hams in Surrey showed that with little/no pointing and no high power amplifier (HPA), all packet sizes could be received over 12 miles. Given this and further ground testing with the engineering model (EM), similar on-orbit behaviors were found when the VHF uplink antenna was only partially deployed.

In future groundstation operations, a freely available decoder is necessary for ease of use with existing systems. Moving from AX.25 standards requires further groundstation work and must be considered if amateur support is requested. As groundstation operations continued, the use of software defined radios (e.g. Funcube Dongle [19]) and software tools like gnuradio [20] were essential to our operations.

**Day-to-Day Operations:** Due to the dawn-dusk orbit, high, long duration pass opportunities occurred in batches of three centred around 6 AM and 6 PM each day. During LEOP this meant that operators were effectively resident at the university ground station to catch the 04.30 passes. Despite a full write-up for the operations, a natural rhythm to how a pass was managed very quickly came about. Due to the ground station set up several roles naturally evolved:

- **Data Operator(s):** Interacted with the spacecraft in real time on a Linux-PC during the pass and monitoring the real-time telemetry stream. Ultimately responsible for the safety of the spacecraft, and reporting on the health.

- **Tracking Operator(s):** Responsible for operating and monitoring the automatic tracking of the ground antenna and radios on a Windows-PC. This means ensuring appropriate TLEs were fed to the both control systems to ensure optimal azimuth, elevation and Doppler compensation. Responsible also for reporting on signal strength and the carrier detection.

The passes were observed by SSTL/SSC staff and students at the university, some of whom were not even involved with the STRaND mission. Being able to observe a live spacecraft operational pass is an invaluable experience and each pass provided an excellent teaching opportunity, for many whom this was their first mission experience – learning from experienced staff. The process for a nominal pass was as followed:

- Analysis of telemetry from previous passes used as input to brainstorm meeting of what the goals of the next pass should be
- Flowchart of pass activities that could be conducted, dependent upon real-time telemetry and agreed by the operations and systems teams.
- Pre-pass briefing by lead spacecraft operator 10 minutes before pass - this briefing was open to all...
SSC and SSTL staff and was an excellent training tool.

- Operations team conduct pass as per the agreed flowchart.
- Post-pass briefing by lead spacecraft operator, summarising what route through the flowchart was taken.

SSTL and SSC will continue to operate the groundstation using these new tools in radio communications. SSC will work with the local Electronics & Radio Society (EARS) here to operate an S-band dish in the coming years. For general operations both the spacecraft and groundstation need interleaving and forward error correction (FEC) codes are essential for next generation spacecraft along with timeouts for all large transactions. These were missing due to lack of time for software development.

3. CURRENT STRaND-1 RESULTS & STATUS

STRaND-1 started out as a voluntary mission in 2010. Because of this, when the launch opportunity was announced in the late summer of 2012, the mission was at CDR level. Therefore the STRaND-1 team effectively manufactured, integrated and tested a 3U CubeSat with a significant amount of new technologies without flight heritage, to flight readiness within 4 months. This is a significant achievement and a testament to the dedication of the team. Such a rapid build and test phase is only possible with a collocated team with extensive in-house test-facilities.

The STRaND-1 signal was reported after the first orbit as being clear, with an average of 22 dB from amateur sources. As shown in Figure 11, the averaged received signal from SSC is shown as 22 dB also.

Figure 11: Noise floor & STRaND-1 signal using gnuradio at SSC

The telecommands (TCs) to restart the beacon timers and initiate further downlinking of important telemetry were transmitted for the battery voltages, solar array currents, magnetometer readings, and switches. One pass allowed for amateurs in the region to downlink 995 packets, with SSC receiving over 1000 packets/pass on 18 March 2013.

As the OBC had been running fully for over 27 consecutive days and satisfied that debugging the groundstation would be an on-going issue to work through, it was unfortunate that a geomagnetic storm arrived at Earth and caused STRaND-1 to stop communicating \[21\]. It was briefly recovered after transmitting reset commands but went silent after 24 hours. The last three days of STRaND-1 are shown in Figures 12 a-c.

Figure 12: a) Battery voltage, b) Array current, c) Magnetometer readings.

All three plots indicated no serious problem. The battery voltage is shown to drop and was still far above safety limits. The solar array currents showed that we were still in the stowed configuration. And finally the magnetometer readings showed there was still an...
operational AOCS with (interfering) magnetorquer firings.

The total data downloaded was approximately 274 KB over 65 K packets. AMSAT and ham-radio members contributed greatly, especially during commissioning and although 43 KB of data was decoded, an estimated 55 KB in 13.9 K packets was not time-stamped for display in Figure 13.

![Figure 13: Total Data Downloaded](image)

This totals to 372 KB in 5 weeks and 1 day. It can be seen also in March when the new PCs and software were installed – the greatest contributor towards optimal groundstation uplink operations.

Current Status: We have had no communication from STRaND-1 since 31 March due, we believe, to radiation or charging effects during a geomagnetic storm. The team have been tirelessly working to understand what has happened but there is insufficient information to explain what occurred. We will continue to listen and transmit to the satellite and are now holding out for a large eclipse season in November 2013 to cause hard power resets of all spacecraft systems.

4. SUMMARY

This paper has aimed to give an insight into an intense program where volunteers were able to learn together on how design, build, test, and operate a CubeSat. Throughout the programme hardware, software and interfacing problems were encountered, and many valuable lessons were learned in solving these problems. From its inception as a small volunteer project in 2010, to a decision to complete the build and test of the spacecraft in September 2012 to meet an imminent launch, the programme gained more and more interest and support both internally and externally. The AIT phase was incredibly intense and it is a testament to the dedication of the team and the invaluable support from experienced SSTL engineers that the volunteer design was built, tested and ready for the ISRO PSLV C-20 launch. One of the main technical sacrifices that resulted from this intense schedule was that of the system testing. Whilst it was always planned to have a long period of system level testing, the reality was that this phase was significantly compressed as unit and software schedules slipped to the right for a variety of reasons. As a result, very limited system end to end testing could be performed. Results were presented to show that the STRaNdceiver worked at 22 dB and over 372 KB of data was downloaded in just over 5 weeks with AMSAT support despite problems getting the new SSC groundstation fully commissioned. The rapid nature of this mission showed how dynamic teams can operate, how fast engineering problems are solved, and how ‘plug-and-play’ existing CubeSat technology is - when given the chance. The STRaNd programme will continue, using CubeSat lessons learnt, experience and staff from STRaNd-1 as a baseline.

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