

USING CUBESAT/MICRO-SATELLITE TECHNOLOGY TO DEMONSTRATE THE AUTONOMOUS ASSEMBLY OF A RECONFIGURABLE SPACE TELESCOPE (AAREST)

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Future space telescopes with diameter over 20 m will require new approaches: either high-precision formation flying or in-orbit assembly. We believe the latter holds promise at a potentially lower cost and more practical solution in the near term, provided much of the assembly can be carried out autonomously. To gain experience, and to provide risk reduction, we propose a combined micro/nano-satellite demonstration mission that will focus on the required optical technology (adaptive mirrors, phase-sensitive detectors) and autonomous rendezvous and docking technology (inter-satellite links, relative position sensing, automated docking mechanisms). The mission will involve two "3U" CubeSat-like nanosatellites ("MirrorSats") each carrying an electrically actuated adaptive mirror, and each capable of autonomous un-docking and re-docking with a small central "15U" class micro/nano-satellite core, which houses two fixed mirrors and a boom-deployed focal plane assembly. All three spacecraft will be launched as a single ~40kg micro-satellite package. The spacecraft busses are based on heritage from Surrey's SNAP-1 and STRaND-1 missions (launched in 2000 and 2013 respectively), whilst the optics, imaging sensors and shape adjusting adaptive mirrors (with their associated adjustment mechanisms) are provided by CalTech/JPL. The spacecraft busses provide precise orbit and attitude control, with inter-satellite links and optical navigation to mediate the docking process. The docking system itself is based on the electromagnetic docking system being developed at the Surrey Space Centre (SSC), together with rendezvous sensing technology developed for STRaND-2. On orbit, the mission profile will firstly establish the imaging capability of the compound spacecraft before undocking, and then autonomously re-docking a single MirrorSat. This will test the docking system, autonomous navigation and system identification technology. If successful, the next stage will see the two MirrorSat spacecraft undock and re-dock to the core spacecraft in a linear formation to represent a large (but sparse) aperture for high resolution imaging. The imaging of stars is the primary objective, but other celestial and terrestrial targets are being considered. Teams at CalTech and SSC are currently working on the mission planning and development of space hardware. The autonomous rendezvous and docking system is currently under test on a 2D air-bearing table at SSC, and the propulsion and precision attitude control system is currently in development. Launch is planned for 2016. This paper details the mission concept, technology involved and progress to date, focussing on the spacecraft busses.

Keywords: CubeSat, Rendezvous, Docking, Telescope, Adaptive Optics

I. INTRODUCTION

In recent years, there has been a desire to develop space-based optical telescopes with large primary apertures. The current state-of-the-art in terms of development is the James Webb Space Telescope (JWST), which has a primary aperture diameter of 6.6m [1]. JWST represents a major advance in space telescope design due to its use of mechanically deployable (hinged) elements for its primary mirror. However, there is a limit to how large an aperture can be constructed in this way, given the limitations

imposed by the diameter of the launch vehicle. One method to overcome this limitation is to autonomously assemble, in orbit, mirror elements fixed to small independent spacecraft (Fig.1). In doing so, a telescope with a large, segmented primary mirror can be constructed. Furthermore, if each of these mirrors is manufactured to have an identical initial shape (and then adjusted upon assembly), a substantial reduction in manufacturing costs can be realized. We believe that autonomous assembly of such elements is a key enabler for a lower cost

approach to the orbital deployment of large telescopes with aperture diameters of 10m or more.

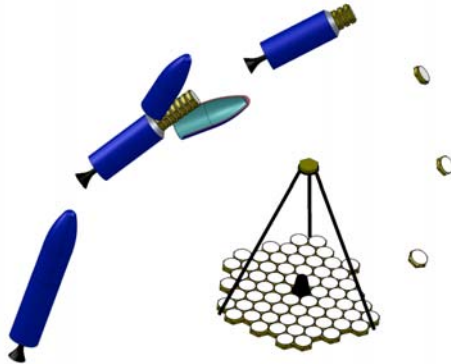


Fig. 1: On orbit assembly of a large space telescope from small autonomous "MirrorSat" elements

In order to prove the feasibility of such a concept, a collaborative effort has been set up between the California Institute of Technology (CalTech) and the University of Surrey – Surrey Space Centre (SSC), with the top-level objectives of developing a low-cost, small satellite mission to demonstrate all key technological aspects of *autonomous assembly* and *reconfiguration* of a space telescope based on an optical focal plane assembly (*camera*) and *multiple* mirror elements synthesizing a single coherent aperture, and to demonstrate the capability of providing *high-quality* images using a such a telescope. The project, which has been running since 2009, is known as "AAReST" – for the "Autonomous Assembly of a Reconfigurable Space Telescope". The aim is to be ready for launch in 2016.

II. MISSION CONCEPT

From the top level mission objectives, a series of more detailed system design requirements follow:

- The mission must involve *multiple* spacecraft elements.
- All spacecraft elements must be *self-supporting* and "*intelligent*" and must cooperate to provide systems *autonomy* – this implies they must be each capable of independent free-flight and have an Inter-Satellite Link (ISL) capability.
- Spacecraft elements must be *agile* and *manoeuvrable* and be able to *separate* and *re-connect* in different configurations – this implies an effective Attitude and Orbit Control System (AOCS), and Rendezvous & Docking (RDV&D) capability (sensors and actuators).
- All Spacecraft elements must lock together *rigidly* and *precisely* and provide a *stable* platform for imaging – this implies a precision docking adapter and precision Attitude Determination and Control System (ADCS).

- The mirror elements must be capable of independent motion and/or shape adjustment and wavefront sensing in order to synthesize a single coherent aperture.

These requirements have resulted in the composite spacecraft concept shown in Fig. 2.

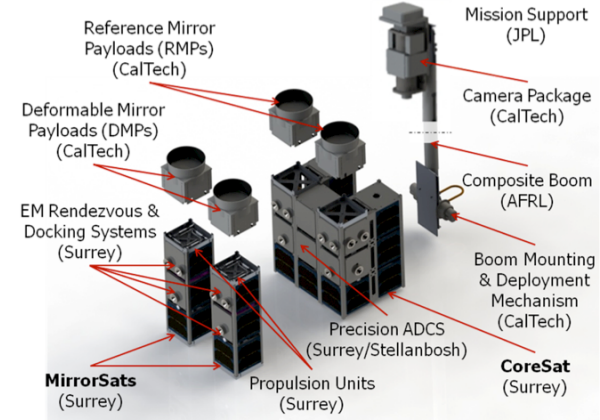


Fig. 2: AAReST spacecraft elements

The spacecraft bus, ISL, AOCS, precision ADCS, propulsion and RDV&D systems are largely the responsibility of the Surrey team, with support from the University of Stellenbosch. The optical systems (mirrors, cameras, wavefront sensors, mirror selection system), aperture synthesis, and deployable boom are largely the responsibility of CalTech, with support from the Air Force Research Laboratory (AFRL) and NASA Jet Propulsion Laboratory (JPL).

The AAReST mission will involve two "nanosatellite" class vehicles based on 3U CubeSat-type structures ("MirrorSats"), which each carry a Deformable Mirror Payload (DMP) and a central "15U" microsatellite ("CoreSat"), which houses two rigid Reference Mirror Payloads (RMPs) and a "Camera Package" mounted on a deployable carbon-fiber composite boom.

All three spacecraft will be launched as a single ~40kg microsatellite package with a stowed volume of 0.4m by 0.4m by 0.6m (Fig. 3).



Fig. 3: AAReST launch configuration

During launch, the MirrorSats, Camera Package and Boom are held rigidly onto the CoreSat via Frangibolts and burn-wires. However, once in orbit, the boom will be released to deploy the Camera Package to form a prime focus telescope of 1.2 m focal length, and 0.3° field-of-view, where the primary mirror is divided into a sparse aperture consisting of an arrangement of four 10cm diameter circular mirrors (2 RMPs and 2 DMPs).

Once initial imaging has been carried out using bright stellar targets, the Moon, and possibly terrestrial targets, the reconfiguration aspect of the mission will be tested. The Frangibolts holding the MirrorSats will be fired, and the MirrorSats are then just held magnetically onto the CoreSat via small permanent magnets in the docking system. The docking system is electro-magnetic with switchable polarities, and thus can overcome the magnetic latching to allow the MirrorSats to separate and re-attach in the different configurations (Compact or Wide) for more imaging – see Fig.4.



Fig. 4: AAReST concept demonstrating the launch configuration (left), initial imaging configuration (middle) and secondary imaging configuration (right)

The 3-point extended Electro-Magnetic Docking Systems (EMDSs) use a Kelvin Clamp arrangement to ensure rigid and repeatable alignment of the MirrorSat and CoreSat spacecraft. This provides the mechanical baseline for the adjustable mirrors.

Using wavefront sensors in the Camera Package, the mirrors can be adjusted and calibrated in order to minimize the size of the mirrors' individual point spread functions (PSFs). The RMPs are rigid in shape, but can be adjusted using tip, tilt and piston motions. The DMPs have these motions, but in addition have the capability of changing shape.

The optics have been designed so that the mirrors can be co-phased to synthesise a common aperture (as would be required for an actual science mission). As well as being challenging optically, this gives significant requirements for the pointing stability of the spacecraft.

III. TECHNOLOGY DEVELOPMENTS

III.1 Spacecraft Buses

The design approach taken to spacecraft is that common to all Surrey's spacecraft, that is:

- **Low-cost:** Where possible use tried and tested Commercial-Off-The-Shelf (COTS) technology (e.g. leverage CubeSats).
- **Heritage:** Leverage of Surrey's 35 year SmallSat experience, with particular reference to the SNAP-1 (2000) NanoSat Programme (butane propulsion and pitch-axis momentum wheel/ magnetic control ADCS) and STRaND-1 (2013) (UK's first CubeSat) missions (Fig. 5) [2], [3].
- **Incremental:** Hardware, software, propulsion and rendezvous/ docking concepts developed through Surrey's STRaND-1, STRaND-2, and QB50/CubeSail and SMESat missions, recently flown or currently under development at SSC.
- **Modular approach:** Maximise commonality between MirrorSat and CoreSat systems and also with other SSC CubeSat programmes.

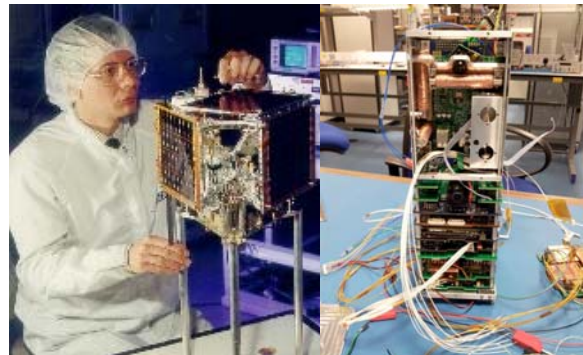


Fig. 5: Surrey's SNAP-1 and STRaND-1 CubeSat

MirrorSat

The MirrorSat requirements can be summarized as:

- Must support the Deformable Mirror Payload (DMP) mechanically and electrically via a 5V 1A supply (2W continuous operational power) and telemetry/telecommand (TTC) via a USB 2.0 interface.
- Must be able to operate independently of other units.
- Must be able to communicate with the CoreSat out to 1km max distance. (via COTS Wi-Fi based ISL)
- Must be able to undock, rendezvous and re-dock multiple times.
- Must have 3-axis control to $\pm 2^\circ$ precision and 6 degree-of-freedom (DOF) propulsion capability.
- Must provide low/zero power magnetic latch to hold in position on CoreSat in orbit.
- Must be able to safely enter the CoreSat Docking System's acceptance cone:

- 20-30cm distance (mag. capture);
- $\pm 45^\circ$ full cone angle; < 5 cm offset;
- $< \pm 10^\circ$ relative RPY error;
- < 1 cm/s closing velocity at 30cm;
- $< \pm 2^\circ$ relative RPY error at first contact.

Given these requirements, a spacecraft design based on a COTS ISIS 3U CubeSat structure was made (Fig. 6).

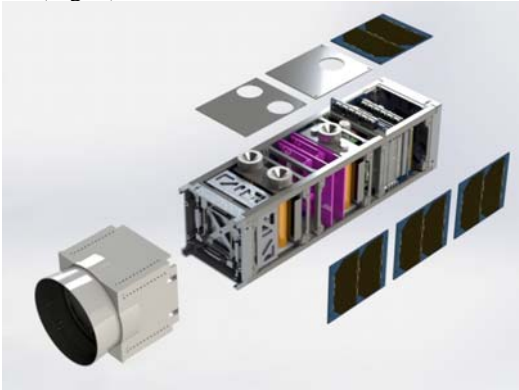


Fig. 6. MirrorSat Design

This comprises the following subsystems:

- **DMP Payload:** CalTech supplied
- **Structure:** modified COTS 3U CubeSat – ISIS
- **Thermal:** passive thermo-optical controlled
- **Power:** COTS GOMSPACE NanoPower P31u EPS (30W) power system boosted when docked through the EMDS power sharing system; COTS GOMSPACE NanoPower P110 Series solar panels.
- **ADCS:** COTS CubeSense, CubeControl, CubeComputer, with 1 pitch axis MW as per the QB-50 spacecraft giving 3-axis control to at least $\pm 2^\circ$ precision.
- **GPS Rx.:** for long range ops. > 10 m separation
- **OBC1:** Raspberry-Pi, Wi-Fi, and DMP Support
- **ISL Comms/Data:** 2-off 2.4 GHz Wi-Fi; USB
- **OBC2:** Raspberry Pi – RDV/ Docking/ LIDAR control and redundant Wi-Fi support
- **Docking Sensor:** Softkinetic DS325 LIDAR/ Camera for RDV.
- **Docking Illumination/Optical RDV:** (IR LEDs; ADCS Nadir Sensor)
- **EM Docking System:** SSC designed EMDS
- **Launch Retaining Structure:** Frangibolts + EMDS
- **On-Orbit Retaining Structure:** permanent magnets + EMDS
- **Propulsion:** Surrey designed 9 thruster 6DOF butane ~ 10 m/s ΔV

The structure, power, ADCS and GPS systems all have flight heritage.

Fig. 7 shows the MirrorSat System Block Diagram, and Fig. 8 the internal layout of the spacecraft.

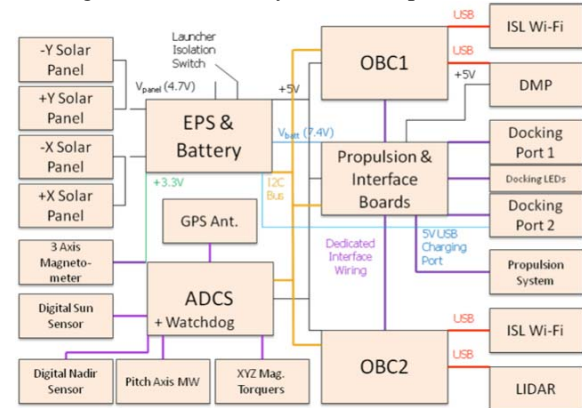


Fig. 7. MirrorSat System Block Diagram

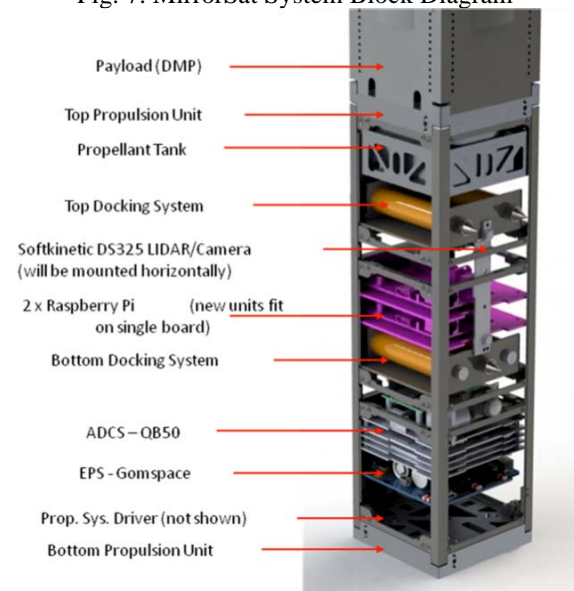


Fig. 8. MirrorSat Internal System Layout

CoreSat

The CoreSat requirements can be summarized as:

- Must be able to point accurately ($< 0.1^\circ$ 3σ error all axes)
- Must be stable in attitude ($< 0.02^\circ/\text{s}$ for 600s) during payload operations.
- Must be able to slew at $> 3^\circ/\text{s}$ for RDV manoeuvres.
- Must be able to mechanically support 2 Reference Mirror Payloads (RMPs) and to supply each of them with 2W power at 5V.
- Must provide up to 5W at 5V power and I2C comms. to the “camera” (image data transfer only) and support boom.
- Must provide up to 5W at 5V power to both docked MirrorSats

- Must be able to communicate with the MirrorSats via Wi-Fi and to the ground via a VHF U/L (1.2 kbps) & UHF D/L (9.6 kbps)
- Must be able to operate with Sun $>20^\circ$ off optical (Z) axis.
- Must be able to independently sense MirrorSats during RDV/docking
- Must provide hold-downs for MirrorSats, camera and boom during launch.
- Must provide launcher interface.

Given these requirements, a spacecraft design based on two COTS ISIS 6U structures placed either side of a COTS ISIS 3U CubeSat structure was made (Fig. 9).

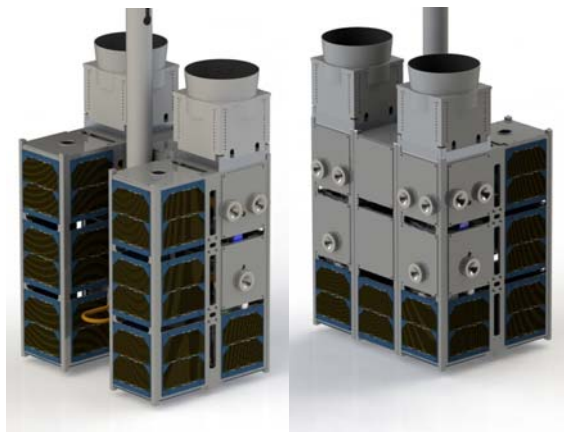


Fig. 9. CoreSat Design (front and back view)

This comprises the following subsystems:

- **RMP Payload:** 2-off, CalTech supplied
- **Structure:** modified COTS 3U and two 6U CubeSat – ISIS
- **Thermal:** passive thermo-optical controlled
- **Power:** 2-off COTS GOMSPACE NanoPower P31u-S EPS (30W) power systems cross-strapped and boosted when docked through the EMDS power sharing system; 2-off COTS GOMSPACE NanoPower BP-4 battery packs; COTS GOMSPACE NanoPower P110 Series solar panels.
- **ADCS:** 2-off COTS CubeSense, CubeControl, and CubeComputer – High Precision 3-axis control $<0.1^\circ$ error systems; 2-off: CubeStar Star Cameras; 2-off STIM210 a high-performance multi-axis gyro Inertial Measurement Unit (IMU) modules + 1 off Viscoelastic vibration damped 4-Reaction Wheel Assembly (RWA)
- **GPS Rx.:** 2-off for long range ops. $>10\text{m}$ separation
- **OBC1:** 2-off Raspberry-Pi, Wi-Fi, and DMP Support
- **ISL Comms/Data:** 4-off 2.4 GHz Wi-Fi; USB

- **RF Comms.:** COTS ISIS VHF uplink receiver at 1200 bps; VHF quarter-wave monopole antenna; COTS ISIS UHF downlink transmitter at 9600 bps; UHF quarter-wave monopole antenna.
- **OBC2:** 2-off Raspberry Pi – RDV/ Docking/ LIDAR control and redundant Wi-Fi support
- **Docking Sensor:** 2-off Softkinetic DS325 LIDAR/ Camera for RDV.
- **Docking Illumination/Optical RDV:** 2-off (IR LEDs; ADCS Nadir Sensor)
- **EM Docking System:** 2-off SSC designed EMDS + 2-off passive magnetic docking ports
- **Launch Retaining Structure:** Frangibolts + EMDS
- **On-Orbit Retaining Structure:** permanent magnets + EMDS
- **Attach Fitting:** RUAGSpace PAS 175 Launcher Interface (low shock - $< 200\text{g}$) or Dassault MicroSat Launcher Interface

The structure, power, GPS, RF and launch adapter systems all have flight heritage. Most of the ADCS system (i.e. that common with the QB-50 precursor missions) has also flown.

Fig. 10 shows the CoreSat System Block Diagram and Fig. 12 the internal layout of the spacecraft.

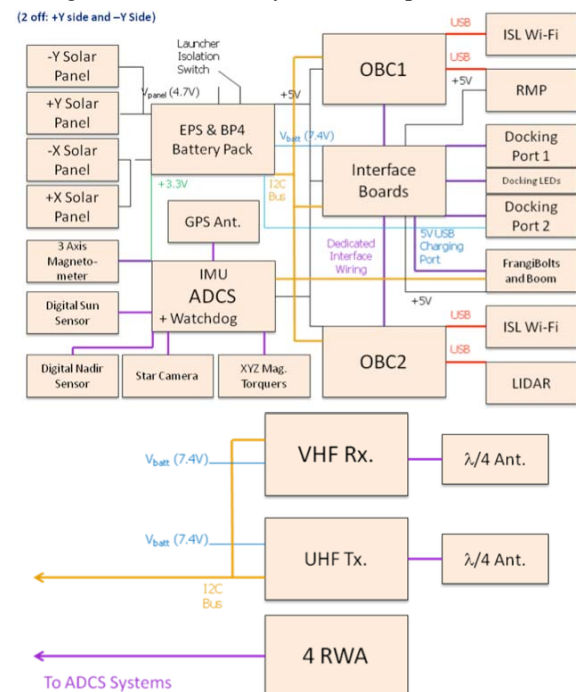


Fig. 10. CoreSat System Block Diagram

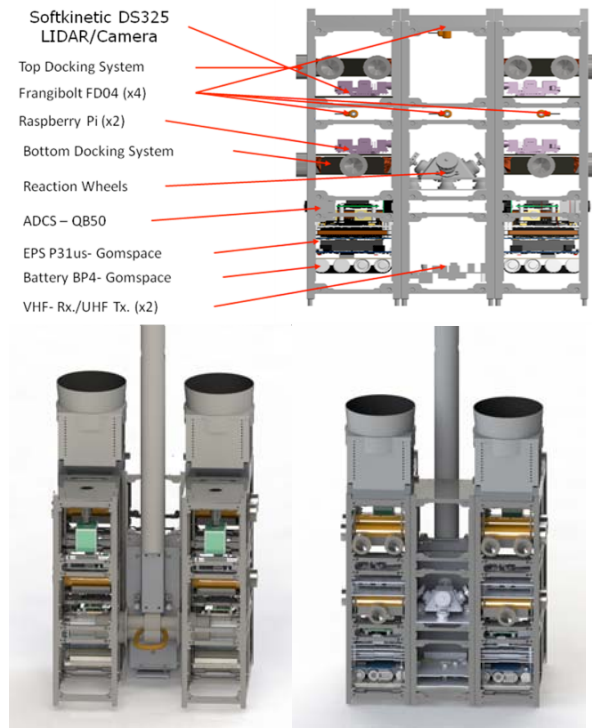


Fig. 11. CoreSat Internal System Layout (front and back view)

III.II Propulsion System

The MirrorSats each have an AOCS propulsion system which comprises nine 1W micro-resistojet thrusters to provide 6DOF motion. Resistojets have a high degree of reliability, low system complexity and can be operated as a cold gas system in the event of heater failure. This is a new development by Surrey, making use of miniaturized technology to fit so many thrusters into a CubeSat form-factor.

Fig. 12 and Fig. 13 show the system layout. Note, a +Z thruster is not flown, due to presence of the DMP on that facet.

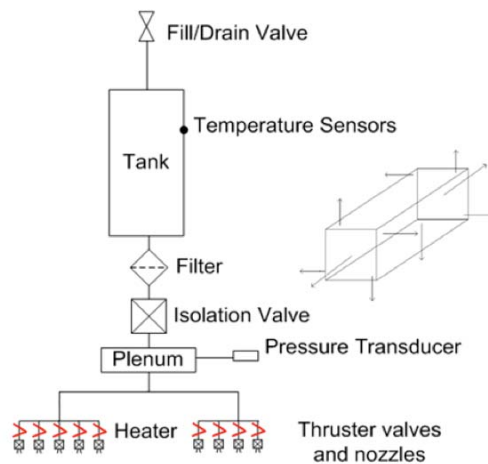


Fig. 12. Propulsion system

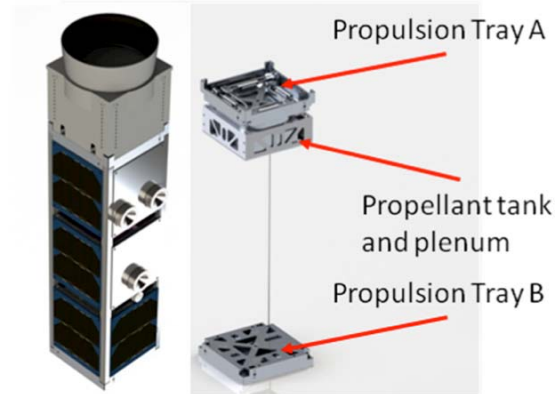


Fig. 13. MirrorSat propulsion system

The thrusters use liquefied Butane propellant stored at 2 bar and expelled in gaseous phase at 0.5 to 1 bar via a pressure controlled 7 ml plenum. The 150ml propellant tank holds 80g liquefied butane, chosen because it has good density, reasonable specific impulse and has no toxic or carcinogenic qualities. Also, Surrey has much flight experience of using butane propellant since its use on SNAP-1 [4].

The plenum and tank are highly integrated as shown in Fig. 14.

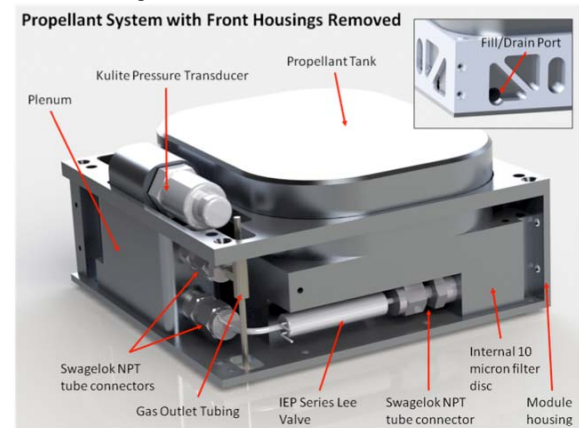


Fig. 14. Integrated plenum and propellant tank

The spacecraft design requires a 5 – 10 mN thrust range at ~80s Isp, with 10m/s ΔV - 6 m/s for ΔV manoeuvres, and 4 m/s for attitude control and contingency. The resultant Z-axis torque is ~0.5-1 mNm; and the X/Y-axis Torque ~2-4 mNm.

The minimum valve opening time is 2ms (500 Hz), giving a minimum Impulse bit of 10-20 μ Ns corresponding to a minimum angular speed step change of ~ 0.1 %/s. The mass is estimated at 880 grams (800 grams dry mass).

The current status is that the thruster has been built and its performance verified. The integrated plenum/propellant tank is in manufacture for delivery in September 2014. An all-up test firing in vacuum will be carried out Q4 2014.

III.III Rendezvous & Docking System

The Rendezvous & Docking (RDV&D) system uses the SSC Electro-Magnetic Kelvin Clamp Docking System, which comprises four pulse-width modulated (PWM), H-bridge-driven, dual polarity electro-magnets, each of over 900 A-turns passing through the body of the both the MirrorSat and CoreSat spacecraft. These are coupled to three “probe and drogue” (60° cone and 45° cup) type mechanical docking ports, arranged to form and extended area docking surface (Fig. 15). Kinematic constraint is established using the Kelvin Clamp principle (3 spheres slotting into 3 V-grooves arranged at 120°).



Fig. 15. MirrorSats showing the EM docking systems

Once the launch hold-down frangibolts are released, the MirrorSats are just held in place on the CoreSat via the docking ports and small permanent magnet latches. When activated, the electro-magnets overcome the fixed magnetic attraction, and allow the satellites to separate. By pulsing the magnets, and changing their polarities, the satellite's relative motion can be controlled within the “capture cone” of the docking port. This has been simulated and experimentally verified on air bearing table tests to extend out to some 30cm from the port's surface, with a half-cone angle of approximately 45° (Fig. 16).

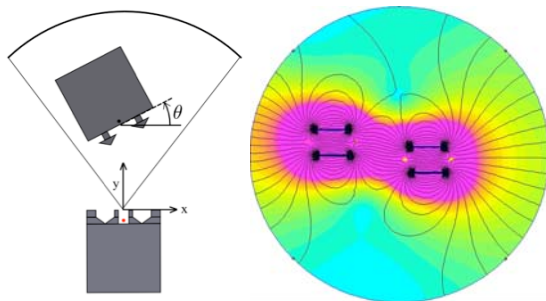


Fig. 16. Finite element modeling of the magnetic interaction between the docking ports elements

The idea is to use the butane propulsion system to maneuver the MirrorSat into the capture cone at an appropriate relative velocity ($< 1\text{cm.s}^{-1}$), and then for the final docking maneuver to be controlled electromagnetically by the ports. The relative pose, distance and velocity of the satellites will be determined by the SoftKinetic LIDAR/camera systems present on both the MirrorSats and the CoreSat. During the maneuver, the satellites communicate with each other via the Wi-Fi ISL, and the maneuver is controlled by the RPi OBCs.

Over the last two years, much practical simulation work has been carried out on air-bearing tables, using rapid-prototyped (3D printed) versions of the docking ports incorporated into EM spacecraft structures floating on air cushions and maneuvered by ducted fans or compressed air gas jets [5,6]. In these tests, we initially used the Microsoft KINECT® hardware to form the RDV sensor, however, its size meant that we could not mount it in the free-floating spacecraft.

We have now switched to using the Softkinetic DS325 LIDAR/ Camera, which fits in the CubeSat form-factor. Further air-bearing table tests are in progress (Fig. 17), and we are evaluating the performance of the hardware in a simulated space environment.

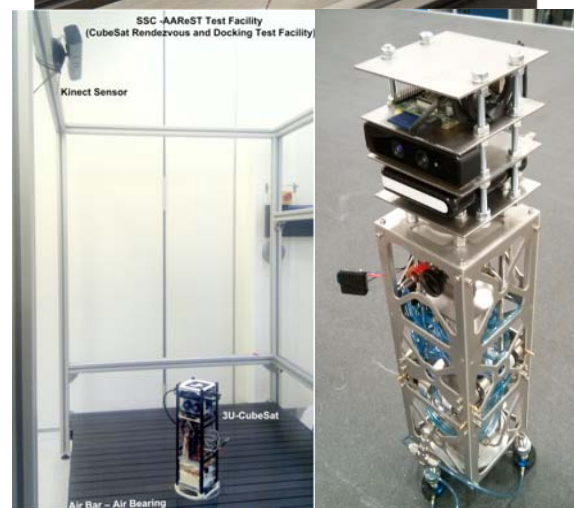
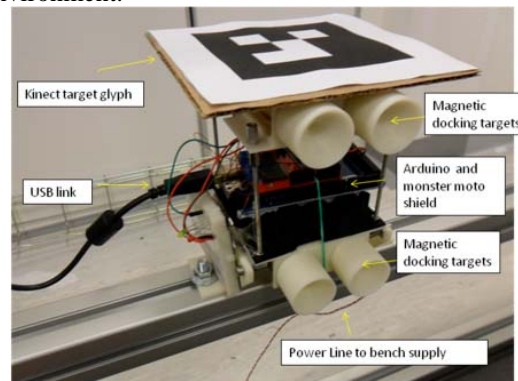


Fig. 17. Air bearing tests of the docking systems

Through extensive software development, we have enhanced the range detection performance of the LIDAR driver, on the Raspberry Pi and proved its utility as a docking sensor (Fig. 18).

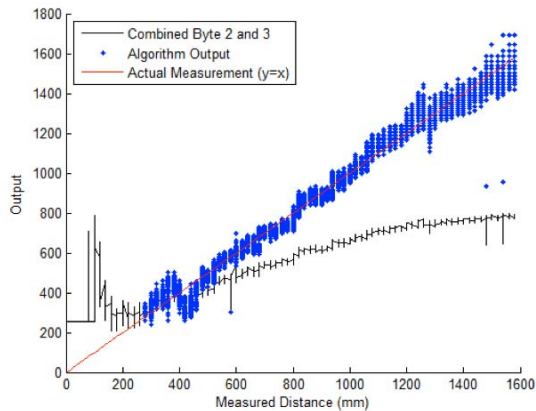


Fig. 18. Measured response of the Softkinetic DS325 LIDAR/ Camera using an advanced algorithm

The docking port design has now been refined and full metal prototypes have been produced ready for further testing (Fig. 19).

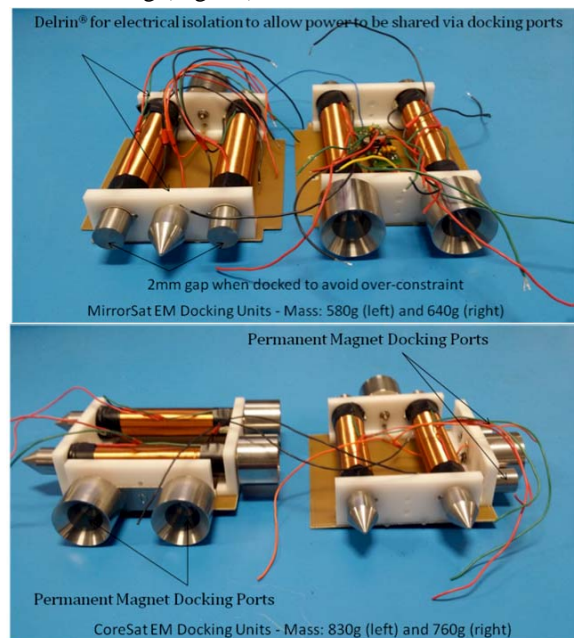


Fig. 19. Electro-magnetic docking systems

Once the complete system has been tested on the 2D air-bearing table, we plan to test under more degrees of freedom by placing the satellite on a freely moving carrier system.

III.IV Precision ADCS

The ADCS system for the MirrorSats is identical to that produced for the two QB-50 precursor missions launched in 2014. It is made up from three PC104

(standard CubeSat) boards, housing CubeComputer, the CubeSense processing board, and Cube Control. The ADCS implements an extended Kalman filter (EKF) and also contains “B-dot” control software for magnetic control of the attitude.

The boards interface to the following sensors and actuators:

- CMOS Camera Digital Sun Sensor
- CMOS Camera Digital Earth Sensor
- 3-Axis Magnetoresistive Magnetometer
- 3-Axis Magnetorquer (2 Rods + 1 Coil)
- Pitch-Axis Small Momentum Wheel
- GPS Receiver

Fig. 20 shows a CAD rendition of the MirrorSat ADCS and Fig. 21 shows the QB-50 flight hardware.

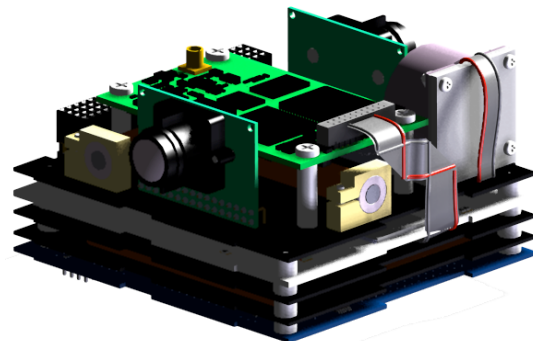


Fig. 20. MirrorSat ADCS

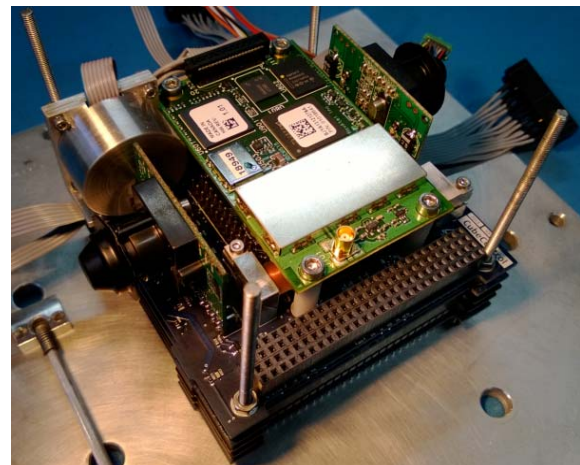


Fig. 21. QB-50 ADCS

The system is adequate for the relatively relaxed ADCS requirements of the MirrorSat (pointing accuracy $\sim \pm 2^\circ$ in all axes), however, the ADCS requirements for the CoreSat/MirrorSat combination, when imaging, are much more challenging:

- pointing ($< 0.1^\circ$ error (3σ) in all axes)
- stability ($< 0.02^\circ/s$ for 600s during imaging)
- slew-rate ($> 3^\circ/s$ about Z (telescope) axis for RDV manoeuvres)

- ultra-low vibration at the resonant frequencies of the telescope.

This requires the development of a new, high performance precision ADCS system suitable for the CubeSat form-factor.

The core of this advanced system is based on the MirrorSat ADCS, but without the pitch-axis momentum wheel. Instead, a new four wheel, reaction-wheel assembly (RWA), utilising precision balanced wheels with viscoelastic damped mountings, is being developed. Each wheel has the following specification:

- 30 mNms @ 5600 rpm
- 2 mNm nominal torque
- 50mm x 50mm x 40mm volume, 185g
- 3.4V - 6.0V operation (maximum 8V)
- 1.5 W power consumption at maximum torque
- 0.4W – 0.1W in normal operation

The wheels are mounted in a pyramid configuration, give full 3-axis control, with redundancy (Fig. 22).



Fig. 22. View of the 4-wheel RWA in the CoreSat

To achieve the pointing/stability requirements, precision sensors are needed. To this end two star cameras (CubeStar) and two precision inertial measurement units (IMUs) are fitted. A third star camera may be necessary to achieve the desired precision.

The CubeStar (Fig. 23) is a low cost, ultra miniature (<100g, 46x33x70mm) star camera developed by Stellenbosch University (South Africa). It has an accuracy (1σ) of 0.01° cross bore and 0.03° in roll. It can track 20 stars over a $52^\circ \times 27^\circ$ field of view, and has a maximum tracking rate of $0.3^\circ/\text{s}$, and an update rate of 1 Hz.

The IMU is an SSC development under the SMESat project, based on Sensoror MEMS Gyros. The STIM210 (Fig. 23) is a high-performance multi-axis gyro module including up to 3 gyroscopes (1, 2 or 3 axes). It has:

- Low bias instability ($0.5^\circ/\text{h}$)
- Low bias drift over temperature gradients ($10^\circ/\text{h}$)
- Low noise ($0.15^\circ/\sqrt{\text{h}}$)

- Short start-up time (1s)
- Integrated electronics



Fig. 23. CubeStar camera and STIM210 multi-axis MEMS gyro

Initial simulations show that this combination of sensors and actuators should meet the demanding ADCS requirements of the mission. The next steps are to:

- assess the RW jitter (Kistler table tests)
- test the new damping system on the RW (Kistler table tests)
- develop a jitter disturbance model and to determine the type of resonance modes we have at spacecraft level, camera level and RW level (Finite Element Analysis)
- To determine the predominant micro-vibration sources from the reaction wheel (Kistler test)

IV. CONCLUSIONS

AAReST is an ambitious yet low-cost mission, designed to demonstrate, through the medium of CubeSat and micro-satellite technology, all the key technological steps needed for the autonomous, in-orbit assembly of a space telescope using multiple mirror elements

On the payload side, this requires significant progress in terms of the production of shape-adaptive mirrors [7], optical metrology and control through wave-front sensing to synthesise a common aperture, and the production of rigid and stable deployable composite booms. This work, undertaken by the project's US partners is progressing well.

However, there are also significant challenges on the spacecraft side (which is the responsibility of the UK team), especially in terms of developing autonomous rendezvous and docking capabilities, precision attitude determination and control, and ultra-compact micro-propulsion systems – all within the constraints of the CubeSat form-factor.

Much work has been done, and the project has driven significant advances in these areas, and whilst none of these capabilities is new in the mainstream “large satellite” community, they are new in the domain of CubeSats.

The project is progressing well, having passed its Detailed Design Review in September 2014. In the next phase, many of the remaining hardware and

software elements will be prototyped and tested, ready for Critical Design Review in September 2015.

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VI. REFERENCES

1. Maggie Masetti and Jonathan P. Gardner “*The James Webb Space Telescope*”, <http://www.jwst.nasa.gov/> , NASA (Accessed 15th January 2011).
2. Underwood, C.I., Richardson, G. and Savignol, J. (2001) “*SNAP-1: A Low Cost Modular COTS-Based Nano-Satellite – Design, Construction, Launch and Early Operations Phase*”. Paper presented at the 15th AIAA/USU Conference on Small Satellites, Logan, Utah, 2001. Published in Proceedings, SSC01-V-1a, AIAA/ Utah State University, 2001.
3. Kenyon, S., Bridges, C., et al, “STRaND-1: Use of a \$500 Smartphone as the Central Avionics of a Nanosatellite”, 15th Symposium on Small Satellite Missions, IAC-11,B4,6B,8,x10937, IAC 2011, Cape Town, 2011;
4. Gibbon, D., Underwood, C., Sweeting, M. and Amri. R. (2001) “Cost Effective Propulsion Systems for Small Satellites Using Butane Propellant”. Paper presented at the 52nd International Astronautical Congress, 1st – 5th October 2001, Toulouse. France. Published in the Proceedings (IAF-01-S.1.11).
5. Bridges, C. P., Kenyon, S., Taylor, B., Horri, N., Underwood, C. I., Barrera-Ars, J., Pryce, L., Bird, R., “*STRaND-2: Visual Inspection, Proximity Operations & Nanosatellite Docking*”, Paper presented at the 2013 IEEE Aerospace conference, Big Sky, Montana, March 2013;
6. Underwood, C.I., Pellegrino, S., Taylor, B., Chhaniyara, S., Horri, N., “Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) - Rendezvous and docking on a 2D test-bed”, IAA-B9-0508, presented at 9th IAA Symposium on Small Satellites for Earth Observation, Belin, April 2013;
7. Patterson, K., Yamamoto, N., Pellegrino, S., “Thin Deformable Mirrors for a Reconfigurable Space Aperture“, paper presented at 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Hawaii, USA, April 2012;