USING SMALL SATELLITE TECHNOLOGY TO DEMONSTRATE THE AUTONOMOUS ASSEMBLY OF A RECONFIGURABLE SPACE TELESCOPE (AAReST)

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The Vision

Autonomous Assembly of Large Aperture Space Telescopes Using Multiple Deformable Mirror Elements...

Demonstrator - 2017

Operation - 2020's
AAReST Mission Technology Objectives:

- Demonstrate all key aspects of autonomous assembly and reconfiguration of a space telescope based on multiple mirror elements.
- Demonstrate the capability of providing high-quality images using a multi-mirror telescope.

Mission Concept

A 70lb, 18” Cubeoid Composite Microsat to Demonstrate a New Generation of Reconfigurable Space Telescope Technology....
Flow-Down to Spacecraft Technology Objectives (Mission Related):

- Must involve *multiple* spacecraft elements (*CoreSat* + 2 *MirrorSats*).

- 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 ISL capability.

- Spacecraft elements must be *agile* and *manoeuvrable* and be able to *separate* and *re-connect* in different configurations – this implies an effective AOCS, and RDV&D capability.
Flow-Down to Spacecraft Technology Objectives (Payload Related):

- **All Spacecraft** elements must lock together *rigidly* and *precisely* and provide a *stable* platform for imaging – this implies a *precision docking adapter* and *precision ADCS*.

- **MirrorSat** must support *Deformable Mirror Payload* (DMP) in terms of mechanical, power (+5V, 1A max.) and telemetry/telecommand data (USB 2.0) interfaces.

- **CoreSat** must support *Reference Mirror Payload* (RMP) in terms of mechanical, power (+5V, 1A max.) and telemetry/telecommand data (USB 2.0) interfaces.

- **CoreSat** must support *Boom/Camera Package* in terms of mechanical, power (+5V, 1A max.), and telemetry/telecommand and image data (I2C) interfaces.
**Mission Concept**

- **AAReST Mission Elements:**
  - MirrorSats (Surrey)
  - Deformable Mirror Payloads (DMPs) (CalTech)
  - Reference Mirror Payloads (RMPs) (CalTech)
  - EM Rendezvous & Docking Systems (Surrey)
  - Propulsion Units (Surrey)
  - Precision ADCS (Surrey/Stellenbosh)
  - Composite Boom (AFRL)
  - Boom Mounting & Deployment Mechanism (CalTech)
  - Camera Package (CalTech)
  - Mission Support (JPL)

**CoreSat** (Surrey)
• **Spacecraft and Mission Concept**
  - Launched as a single “microsat” into LEO
  - Comprises a “Fixed Core NanoSat” + 2 separable “MirrorSats”
  - Total Mass (incl. attach fitting) < 40kg (est. at ~32kg)
  - Envelope at launch (inc. att. fit.) within 40cm x 40cm x 60cm
  - Autonomously reconfigures to achieve mission science goals.
• **Spacecraft and Mission Concept**

  - **Science Mission Phase 1**: (Minimum Mission Objective)
    - Deploys boom/Camera Package to form space telescope
    - Images stars, Moon and Earth with Reference Mirrors (c. 0.3° FoV)
    - Demonstrates precision (0.1°, 3σ) 3-axis control

  - **Science Mission Phase 2**: (Key Science Objective 1)
    - Images with combined Deformable and Reference Mirrors in “compact mode”
    - Demonstrates deformable mirror (DMP) technology and phase control.

![Compact Configuration Imaging Mode](Top View)
• **Spacecraft and Mission Concept**

  – **Science Mission Phase 3**: (Key Science Objective 2)
    - Autonomously deploys and re-acquires “MirrorSat” (manoeuvres within c. **10cm-20cm** distance)
    - Demonstrates electromagnetic docking technology
    - Demonstrates ability to re-focus and image in compact mode

  – **Science Mission Phase 4**: (Key Science Objective 3)
    - Autonomously deploys MirrorSat(s) and re-configures to “wide mode” (manoeuvres within c. **30cm-100cm** distance)
    - Demonstrates Lidar/camera RDV sensors and butane propulsion
    - Demonstrates ability to re-focus and image in wide mode
Spacecraft Design

- **Spacecraft Bus – Design Approach**
  - **Low-cost** approach based on CubeSat technology
  - **Heritage** from Surrey’s SNAP-1 NanoSat Programme (2000) (particularly butane propulsion and pitch MW/magnetic ADCS)
  - **Incremental** hardware, software and rendezvous/docking concepts developed through Surrey’s STRaND-1, STRaND-2, and QB50/InflateSail missions currently under development.

**Spacecraft Bus – Design Approach**

- Maximise use of COTS technology (e.g. Leverage CubeSats).
- **Modular** approach
- Maximise commonality with other SSC CubeSat programmes.
- Spacecraft bus is treated as a “CoreSat” based on **two 6U + one 3U ISIS** CubesSat structures mechanically joined, plus two detachable free-flying “**MirrorSats**”, each based on a **3U ISIS** CubeSat structure.

**DDR Configuration Sept. 2014**
**MirrorSat Requirements**

- Must support the Deformable Mirror Payload (DMP) mechanically and electrically via a 5V 1A supply (2W continuous operational power) and 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. (via Wi-Fi ISL)
- Must be able to undock, rendezvous and re-dock multiple times
- Must have 3-axis control and 6 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 Port’s acceptance cone:
  - 20-30cm distance (mag. capture);
  - ±45° full cone angle; < 5 cm offset
  - <±10° relative RPY error;
  - < 1 cm/s closing velocity at 30cm;
  - < ±2° relative RPY error at first contact.
**MirrorSat System Layout**

- Payload (DMP)
- Top Propulsion Unit
- Propellant Tank
- Top Docking System
- Softkinetic DS325 LIDAR/Camera (will be mounted horizontally)
- 2 x Raspberry Pi (new units fit on single board)
- Bottom Docking System
- ADCS – QB50
- EPS - Gomspace
- Prop. Sys. Driver (not shown)
- Bottom Propulsion Unit

374.4mm
• **MirrorSat Propulsion System**
  
  – Propulsion unit consists of nine 1W micro-resistojet thrusters to provide ~6DOF (+Z thruster not flown on AARest due to mirror payload).
  
  – New, smaller resistojet design to fit nine thrusters into 3U CubeSat (traditional resistojets are too large)
  
  – Liquefied Butane propellant stored at 2 bar and expelled in gaseous phase at 0.5 to 1 bar via pressure controlled plenum.
  
  – Butane has good density, specific impulse and no toxic or carcinogenic qualities
Propellant System with Front Housings Removed

- Kulite Pressure Transducer
- Plenum
- Propellant Tank
- Fill/Drain Port
- Swagelok NPT tube connectors
- Gas Outlet Tubing
- IEP Series Lee Valve
- Internal 10 micron filter disc
- Swagelok NPT tube connector
- Module housing
**Thruster Mounting Configuration**

- Thrusters mounted in propulsion trays on upper and lower end of ISIS structure
- Thrusters placed off centre to provide torque around the Flyer’s central axis with a reciprocal configuration in the corresponding tray
- Reciprocal thrusters fired together to provide lateral translation
- +Z axis thruster not flown due to mirror mounting

- Thrust trays machined from single piece of stock aluminium for extra rigidity
- Valve mounts built-in to structure
MirrorSat Propulsion Capability
- 5 – 10 mN thrust range at ~ 80s Isp.
- Propulsion system provides 10m/s ΔV - 6 m/s for ΔV manoeuvres, 4 m/s for attitude control and contingency
- Minimum valve opening time = 2ms (500 Hz); Minimum Impulse bit = 10-20 μNs.
- System mass estimated at 880 grams (800 grams dry mass) 80g butane.
- 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.

SNAP-1 System for Comparison

<table>
<thead>
<tr>
<th>Propellant</th>
<th>32.6 g butane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total impulse</td>
<td>22.3 Ns</td>
</tr>
<tr>
<td>Thrust range</td>
<td>25 to 100 mN</td>
</tr>
<tr>
<td>Module mass</td>
<td>455 grams</td>
</tr>
<tr>
<td>ΔV imparted</td>
<td>2.1m/s (actual)</td>
</tr>
</tbody>
</table>
MirrorSat Propulsion Tests

- Heating tests performed in vacuum on a test piece yielded a thruster temperature of 140°C with 1 watt input power.
- Expelled gas temperature initially assumed to be in the region of 100°C leading a chosen nozzle expansion ratio ($A_e/A_t$) of 100 to provide a specific impulse of 80 seconds while still maintaining a small nozzle size.
- Fully representative system now under construction for testing.

- Isentropic flow relations used to predict optimum throat geometry for nominal plenum pressure of 0.5 bar.
- Nozzle throat diameter of 0.2mm and exit diameter of 2mm.
• MirrorSat ADCS
  – New compact (450g) Integrated ADCS System being developed for QB50 by Prof. Steyn (Stellenbosch) and Lourens Visagie (Surrey).
  – Comprises:
    • 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
    • EKF and B-dot control software built-in
    • ~1° pointing stability (in sunlight)
• **QB50 ADCS**
  - 3x PC104 boards
    - CubeComputer
    - CubeSense processing board
    - CubeControl
  - Peripheral components
    - Fully integrated ADCS has momentum wheel, sun- and nadir cameras, GPS receiver and magnetorquers contained in stack
    - External GPS antenna, magnetometer and coarse sun sensor photodiodes
• In qualification (testing)
• 15 ADCS Units to be delivered in Nov 2014 (QB50)
• Flight heritage on STRaND-1
• **CoreSat Requirements**
  - Must be able to **point accurately** (< 0.1° 3σ error all axes)
  - Must be **stable in attitude** (< 0.02°/s for 600s) during payload operations.
  - Must be able to slew at >3°/s for RDV manoeuvres.
  - Must be able to mechanically support 2 Reference Mirror Payloads (RMPs) and to supply 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° 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 (TBD)
• **CoreSat Structure**
  – Structure rendering showing two 6U structures (+Y and -Y) separated by a single 3U structure (MirrorSats not shown)
Spacecraft Design

- **CoreSat System Layout**
  (-X/+X facet view)

- Payload (RMP)
- Composite Boom
- CubeStar Cameras
- ADCS – 4 RWA
- Battery – BP4
**CoreSat ADCS**

- Uses Compact Integrated ADCS system (as per MirrorSats), but replaces the single small pitch MW with four Surrey RWs (4-RWA) with dampers for increased control authority/low jitter control
- Pointing (< 0.1° error all axes), stability (< 0.02°/s for 600s)
- Slew-Rate (>3°/s about Z (telescope) axis for RDV manoeuvres)
- 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
- For high precision pointing/stability we use the **CubeStar** camera + STIM210 multi-axis IMU
**EM Docking System**

- SSC Electro-Magnetic Kelvin Clamp Docking System (EMKCDS)
- Comprises four PWM controlled, H-bridge-driven, dual polarity electro-magnets, each of over 900 A-turns
- These are coupled to three “probe and drogue” (60° cone and 45° cup) type mechanical docking ports
- Kinematic constraint is established using the Kelvin Clamp principle (3 spheres into 3 V-grooves arranged at 120°)
EM Docking System

- Prototype Docking Port hardware designed and built:

CoreSat Units
(Note 8.7mm Offset between X and Y facets)

MirrorSat Units
• **EM Docking System**
  – Prototype Docking Port hardware designed and built:

Delrin® for electrical isolation to allow power to be shared via docking ports

2mm gap when docked to avoid over-constraint

MirrorSat EM Docking Units - Mass: 580g (left) and 640g (right)
**EM Docking System**

- Prototype Docking Port hardware designed and built:

Permanent Magnet Docking Ports

CoreSat EM Docking Units - Mass: 830g (left) and 760g (right)
**EM Docking System**

- CalTech and SSC Air-Bearing Table experiments show:
  - Capture distance is between 20-30cm for two pairs
  - Automatic self-alignment works, but choice of polarities is important to avoid miss-alignment/false-capture.
  - Attractive force is highly non-linear!

- Capture and alignment experiments show:
  - Within 30 cm offset*, 45 degree cone**
    - Tolerate +/- 30 degree roll/pitch/yaw
    - Reasonable Relative Velocity
  - Within 15 cm offset, 45 degree cone
    - Tolerate +/- 20 degree roll/pitch/yaw
    - Reasonable Relative Velocity
  - Within 5cm offset, 45 degree cone
    - Tolerate +/- 10 degree roll/pitch/yaw
    - Reasonable Relative Velocity

- **Status:** Prototyped. New form/controller ready by Q3 2015.

*Radius from centre of one face to centre of ‘docking plane’;  **Half angle
EM Docking System

- FEM of magnetic flux linking confirmed experimental findings:

- Force is highly non-linear if the electro-magnets are simply energised.

- PWM control is used to vary the current to compensate for the distance effect.

- Useful force beyond 30cm separation.
LIDAR Sensor

- Much experimentation has been made at SSC using the Microsoft KINECT™ and Softkinetic DS325 LIDAR/Camera system to monitor and control the rendezvous/docking process to the point of automatic capture.
- These project a NIR speckle pattern via a laser diode which is picked up by a NIR sensitive camera for depth processing using PrimeSense SoC technology (60 fps).
- They also carry a full colour (VGA) camera for machine vision (MV).
RDV/Docking

Softkinetic DS325

- FoV: 87° x 58°
- Range: 0.15 – 1m
- QVGA: 320 x 240
- USB 2.0 powered
• **LIDAR Sensor Air Bearing Tests**

- COTS RPi-B
- 4 GB SD-Card
- WiFi Dongle

- SoftKinectic DS325

- OpenNI2DS325 driver used initially but tests showed it to be inaccurate.

- Driver was reverse engineered and new algorithms were developed to convert raw sensor data into depth measurements leading to much more accurate results.
Conclusions

- AAReST demonstrates how nano-satellite technology can be used to provide confidence building demonstrations of advanced space concepts.
- This joint effort has brought together students and researchers from CalTech and the University of Surrey to pool their expertise and is a good model for international collaboration in space.
- The spacecraft bus and docking systems will be based on flight proven systems through Surrey’s SNAP-1 and STRaND programs, whilst the optical payload is undergoing extensive design and ground testing.
- The mission will demonstrate autonomous rendezvous and docking, reconfiguration and the ability to operate a multi-mirror telescope in space.
- CDR is planned for September 2015, with launch potentially in 2017.
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Thank-You

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