SURREY SPACE CENTRE

Self-Assembly in Orbit – The AAReST (Autonomous Assembly of a Reconfigurable Space Telescope) Mission

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Caltech

JPL

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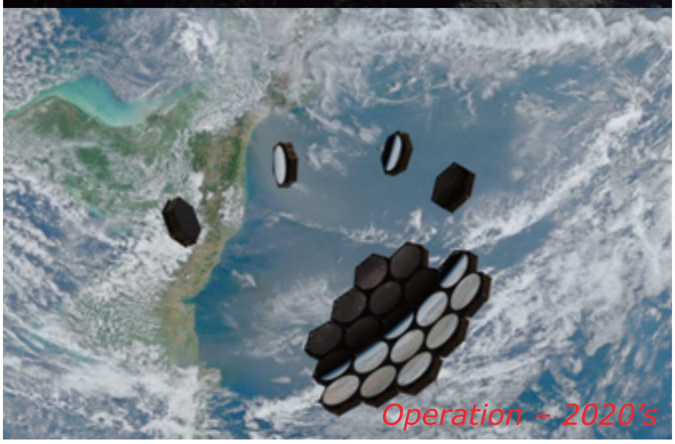
The Vision

- Motivation: Building Large Space Telescopes
  - Mirror dia. of current and planned space telescopes limited by constraints of a single launch
    - Hubble (1990): Ø 2.4 m
    - JWST (2018): Ø 6.5 m
    - HDST (2030+): Ø 11.7 m
  - New paradigms needed for Ø 30 m+ segmented primary:
    - Autonomous assembly in orbit
    - Active ultralight mirror segments
  - Active mirrors relax tolerances for assembly and manufacturing, correct thermal distortions
  - Modular, robust, low-cost architecture

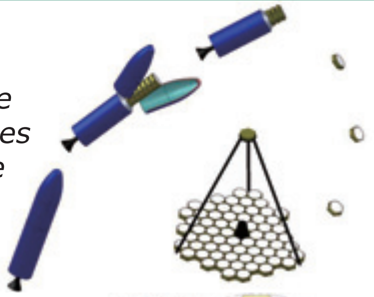
JWST

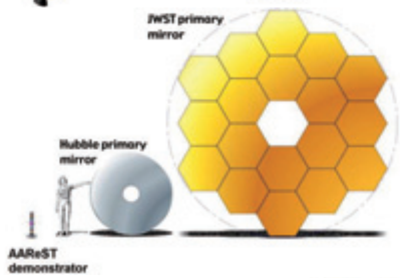
HDST

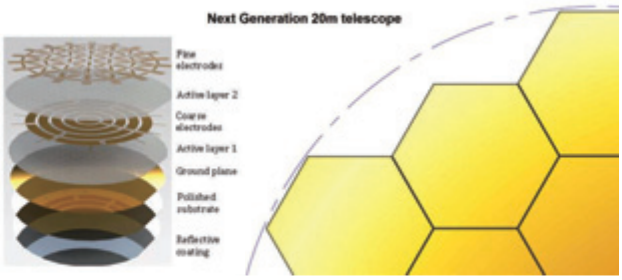
The Vision



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







AAReST History

- Mission proposed by Prof. Sergio Pellegrino (CalTech) & Prof. Craig Underwood (Surrey)

2008 November: Large Space Apertures KISS workshop
2010 June: Ae105
- Initial mission design; mission requirement definition

2011 June: Ae105
- Spacecraft configuration revision: prime focus design
- Docking testbed commissioning

2012 June: Ae105
- Composite boom design and experiments
- Reconfiguration and docking experiments

2012 September: Mission Concept Review
2012 October: Division of responsibilities
- Surrey: Reconfiguration and docking
- Caltech: Deformable mirror and telescope payload

2013 June: Ae105
- Detailed camera design
- Thermal modeling

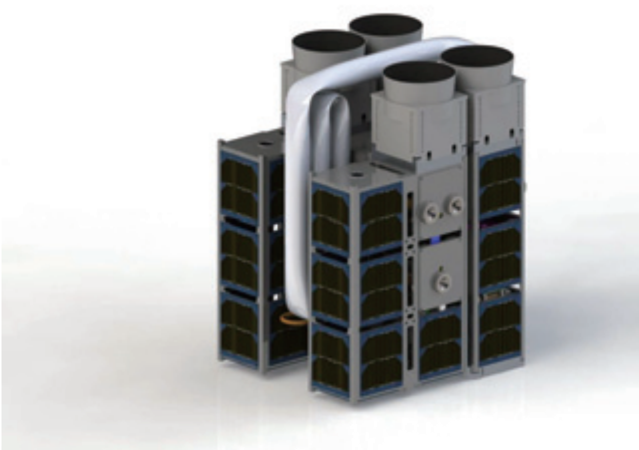
2013 September: Preliminary Design Review
2014 June: Ae105
- Camera opto-mechanical prototype
- Boom gravity offload deployment testing
- Mirror vibro-acoustic experiments
- TVAC chamber commissioning
- Telescope testbed commissioning

2014 September: Detailed Design Review
2015 June: Ae105
- Engineering models/prototypes of boom, camera
- Mirror thermal characterization
- Software and algorithms prototyping and testing

2015 September: Critical Design Review of Payload

Mission Concept

- **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.


AAReST: Launch Configuration

A 40kg Composite Microsat to Demonstrate a New Generation of Reconfigurable Space Telescope Technology....

Mission Concept

- **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.


AAReST: In-Orbit Reconfiguration - Compact to Wide Mode Imaging Configuration

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Mission Concept

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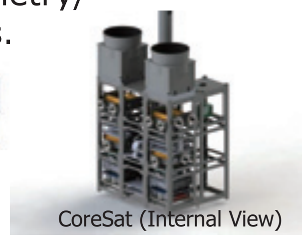
- **Flow-Down to Spacecraft Technology Objectives (Payload Related):**
  - **All Spacecraft** elements must lock together *rigidly* and *precisely* and provide a *stable* platform for imaging – this implies a *precision docking adapter* and *precision ADCS*.
  - **MirrorSat** must support *Deformable 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.

MirrorSat

AAReST: Boom and Camera Package Deployed



CoreSat (Internal View)

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Mission Concept

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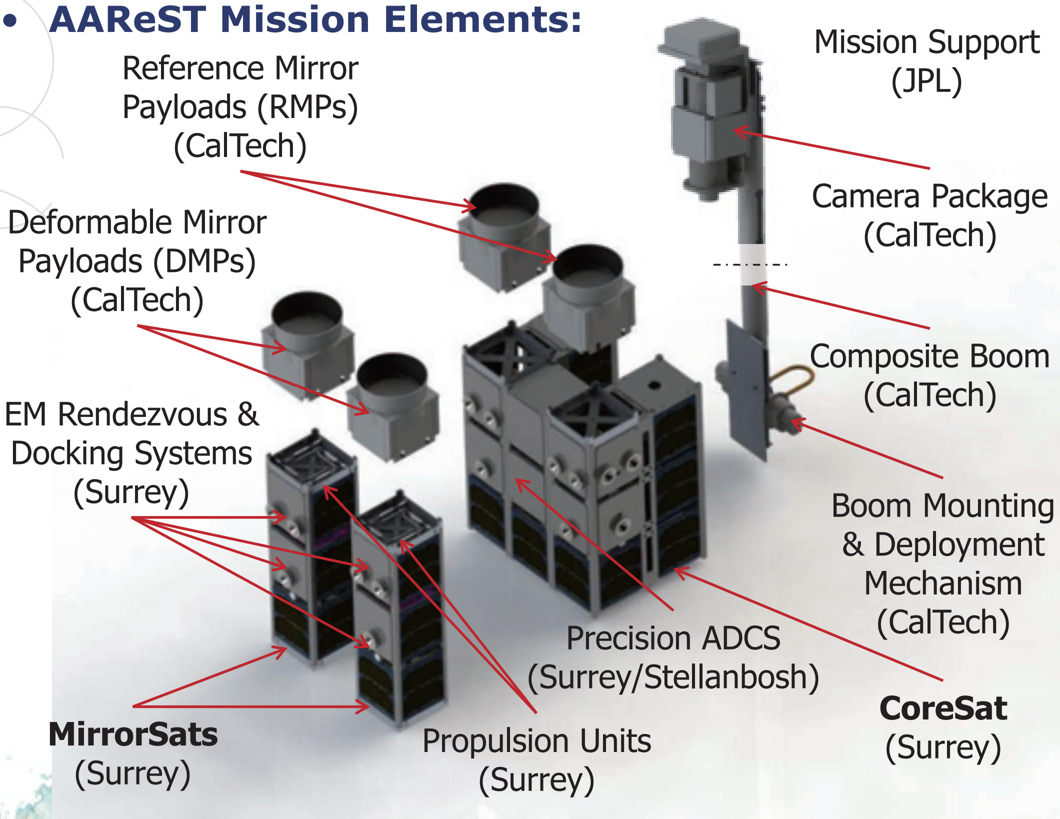
- **AAReST Mission Elements:**

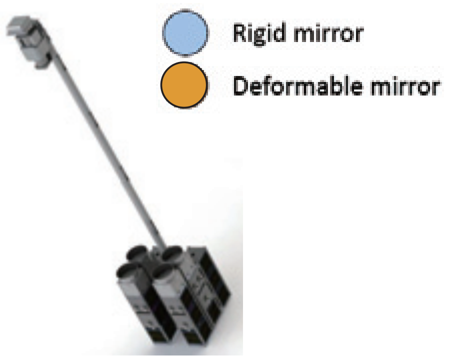


Mission Concept

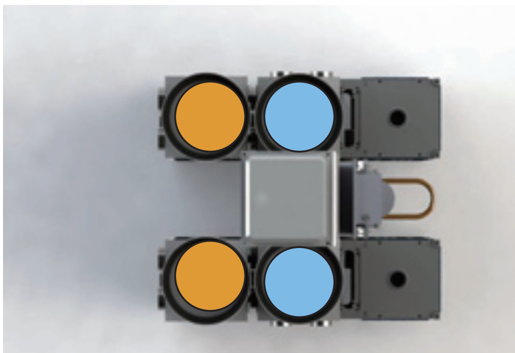
- **Spacecraft and Mission Concept**
  – Launched as a single "microsat" into LEO
  – Comprises a "Fixed Core NanoSat" + 2 separable "MirrorSats"
  – Total Mass (incl. attach fitting) < 40kg (est. at ~32kg)
  – Envelope at launch (inc. att. fit.) within 40cm x 40cm x 60cm
  – Autonomously reconfigures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

Mission Concept

- **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

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Mission Concept

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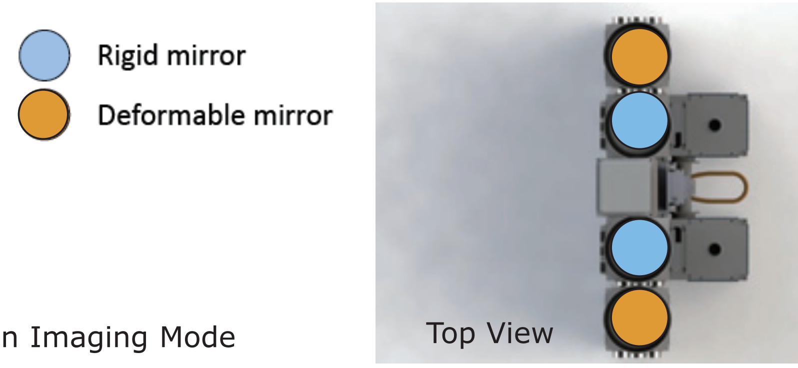
- **Spacecraft and Mission Concept**
  - **Science Mission Phase 3**: (Key Science Objective 2)
    - Autonomously deploys and re-acquires "MirrorSat" (manoeuvres within c. **10cm-20cm** distance)
    - Demonstrates electromagnetic docking technology
    - Demonstrates ability to re-focus and image in compact mode
  - **Science Mission Phase 4**: (Key Science Objective 3)
    - Autonomously deploys MirrorSat(s) and re-configures to "wide mode" (manoeuvres within **c. 30cm-50cm** distance)
    - Demonstrates Lidar/camera RDV sensors and butane propulsion
    - Demonstrates ability to re-focus and image in wide mode

Wide Configuration Imaging Mode



Top View

SURREY SPACE CENTRE

Mission Concept

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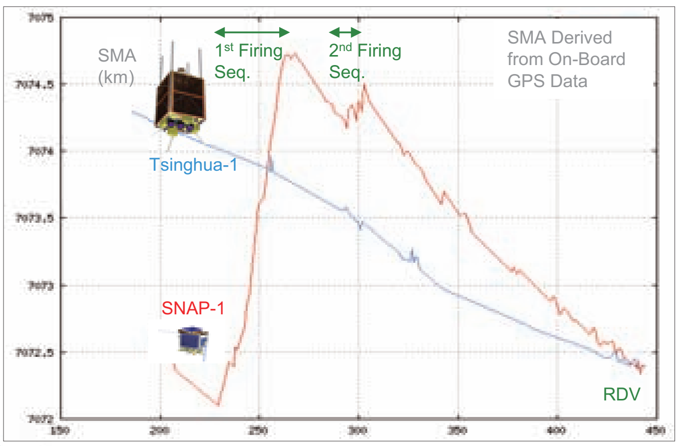
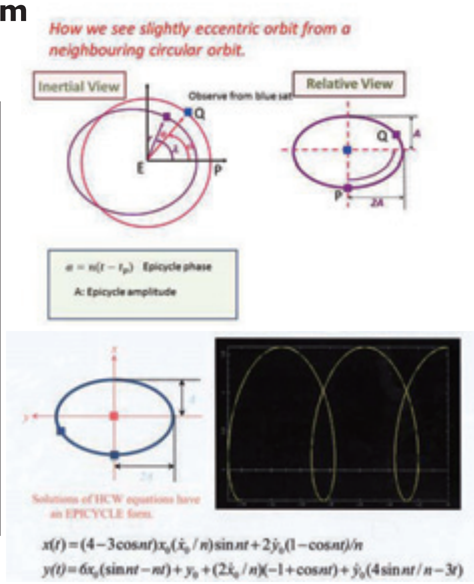
- **Spacecraft and Mission Concept**
  - **Mission Phase 5**: (Extended Mission Objective)
    - Use AAReST as an In-Orbit RDV Test-Bed – similar to SNAP-1
    - Deploys MirrorSat(s) into a relative orbit beyond **10m** distance)
    - Demonstrates ISL/differential GPS/ optical relative navigation
    - For safety, ISL must operate out to **1km**

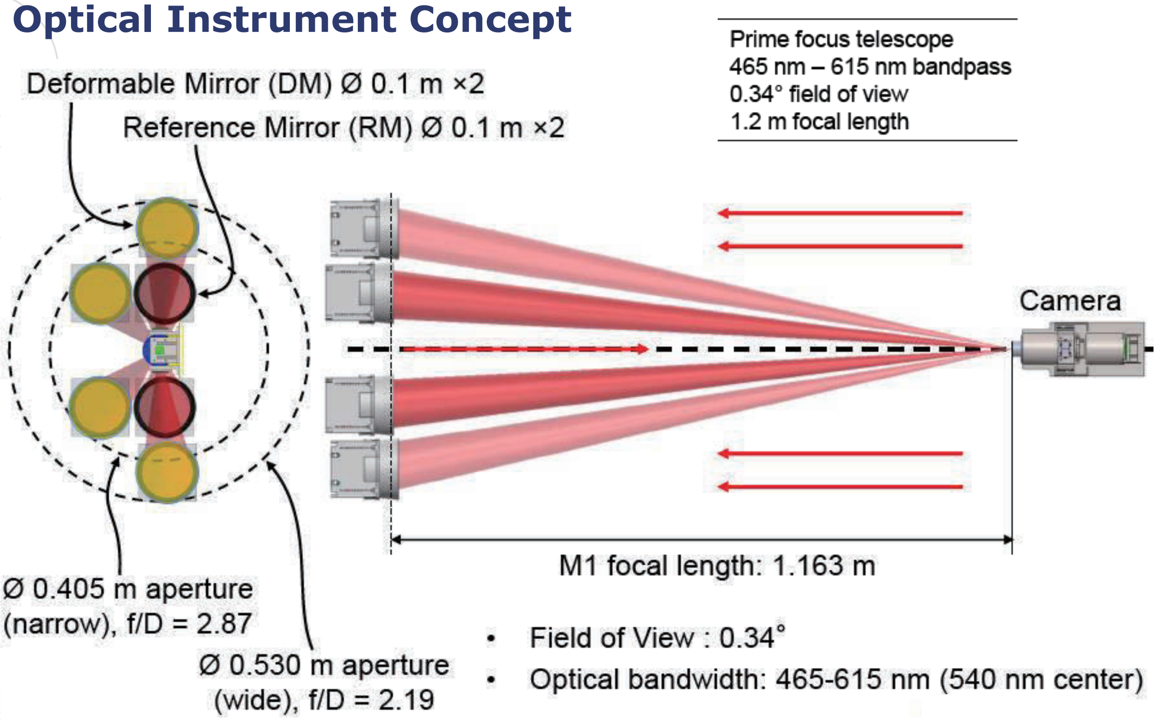


Day Number Since 1st January 2000



Payload Design

- **Optical Instrument Concept**

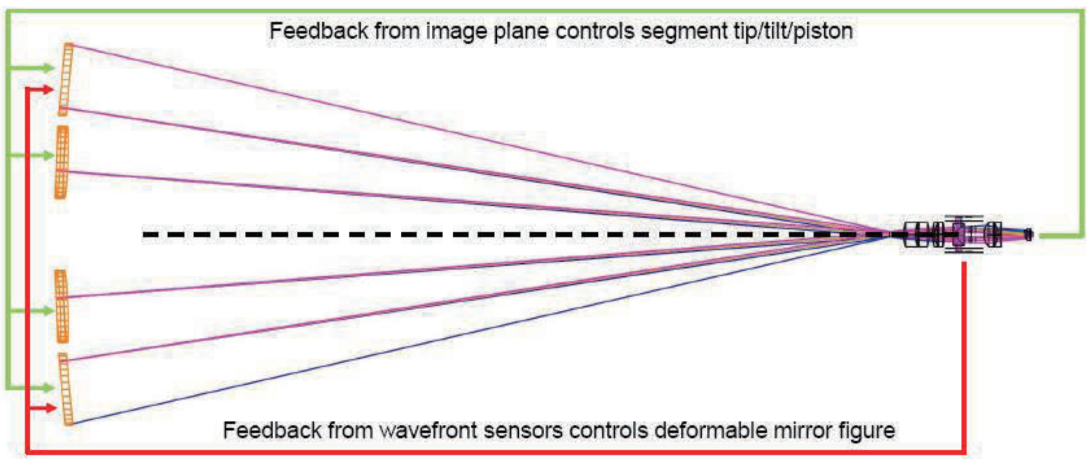


- Field of View : 0.34°
- Optical bandwidth: 465-615 nm (540 nm center)

Payload Design

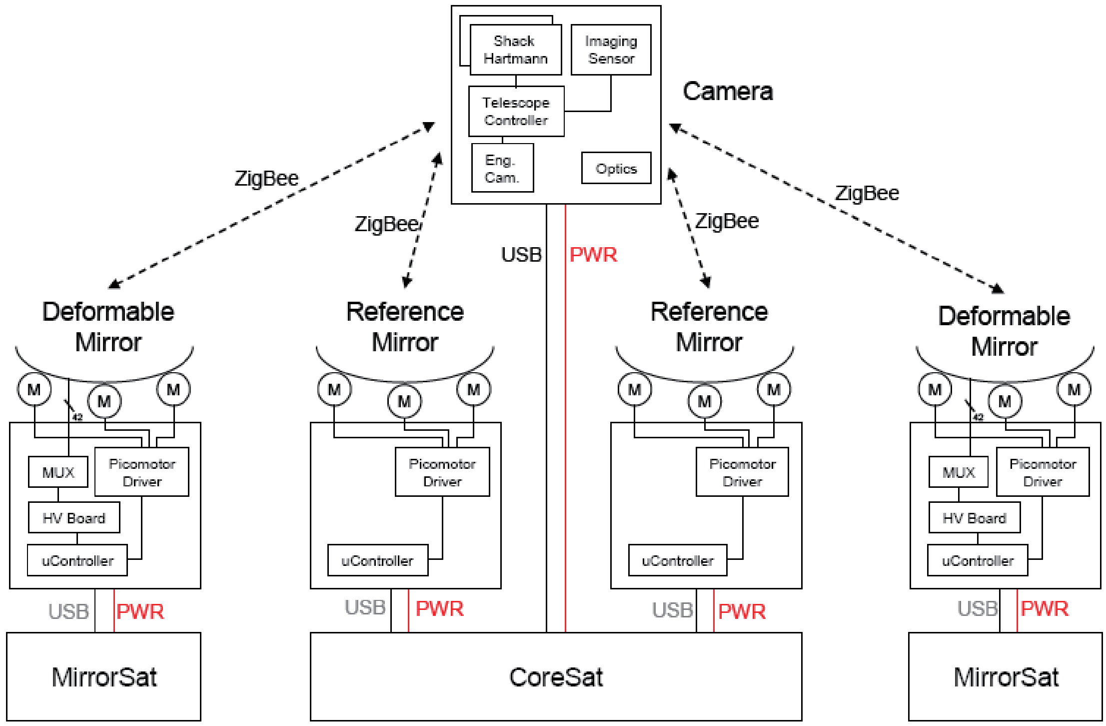
- **Telescope Alignment and Control**

- Automatically correct for deployment errors, manufacturing errors and thermal disturbances with active calibration in-flight
- Actuators:
  - 3 rigid body motion (RBM) actuators per segment
  - 41 piezoelectric actuators per deformable mirror
- Sensors:
  - Image plane camera
  - Shack-Hartmann Wavefront Sensors (SHWS)



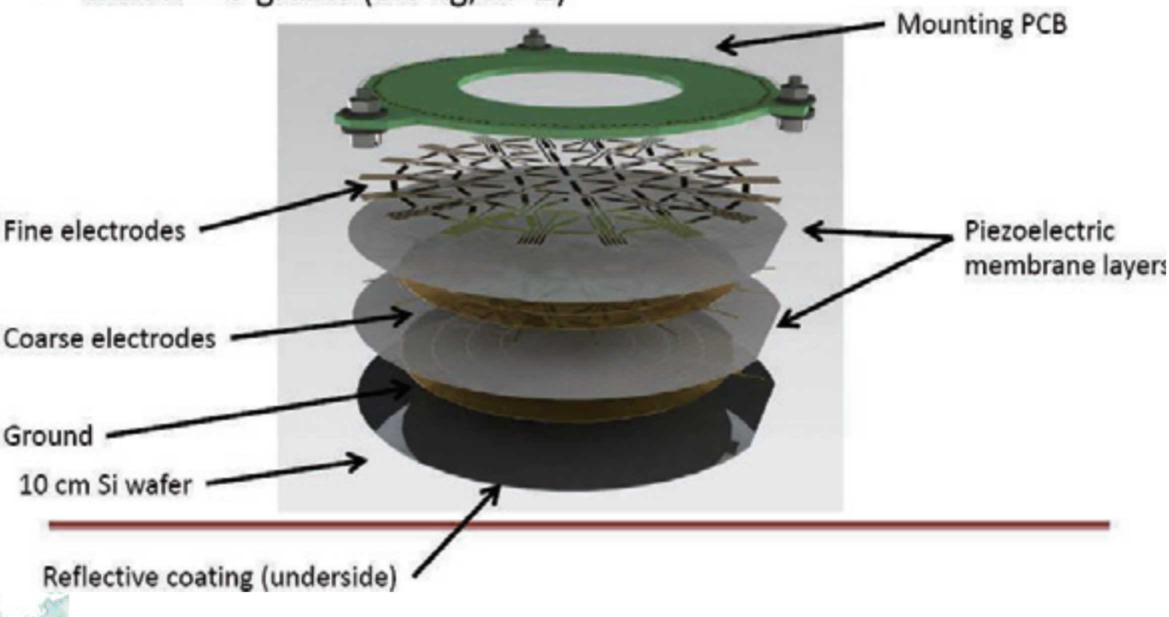
Payload Design

- **Payload Block Diagram**



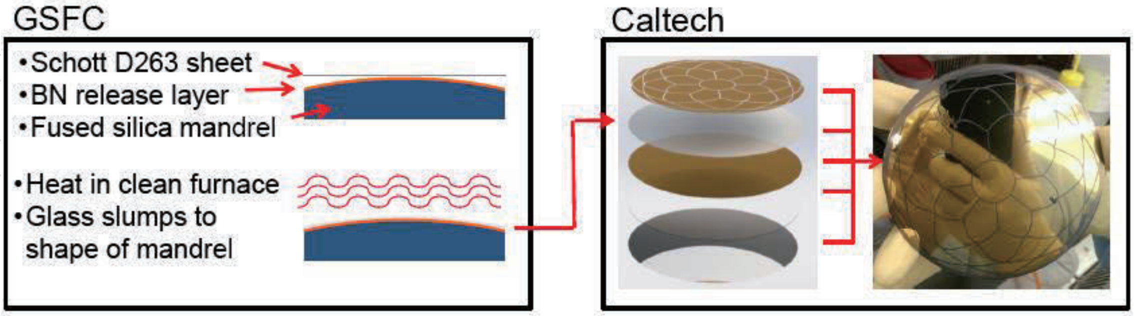
Payload Design

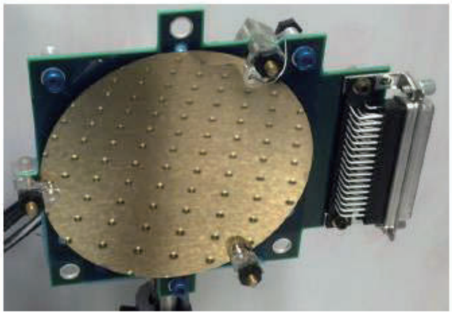
- **CalTech Developed Deformable Mirror Technology**
  - Alternating layers of electrodes and active material
  - 90 (fine pattern) + 16 (coarse pattern) channels
  - Mirror < 5 grams (0.6 kg/m^2)

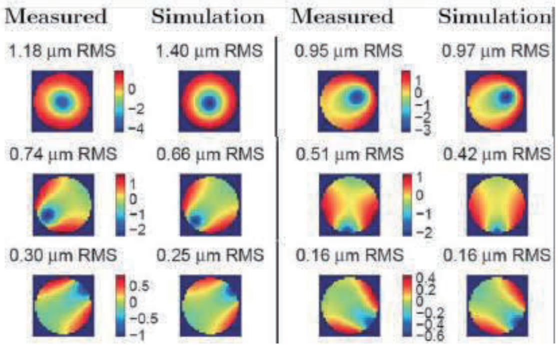


Payload Design

- **CalTech Developed Deformable Mirror Technology**

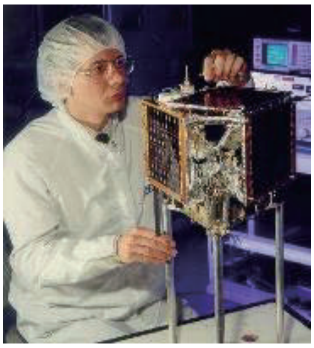


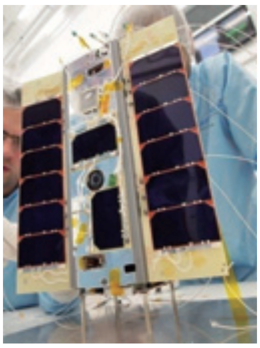


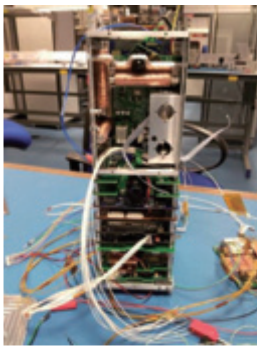


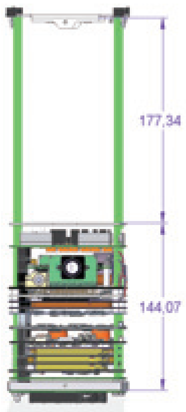
Spacecraft Design

- **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 and AlSAT1-Nano missions currently under development for launch in 2016.





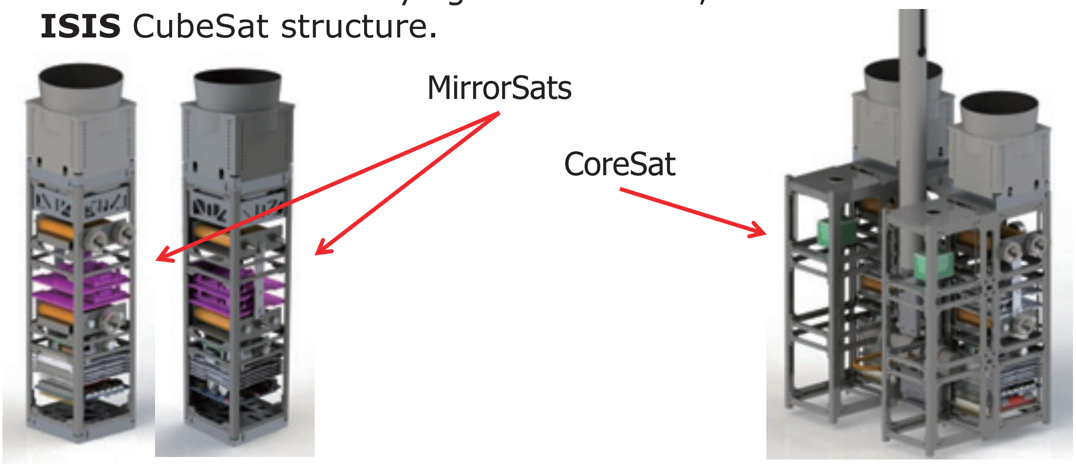




SNAP-1 (2000) STRaND-1 (2013) AlSAT1-Nano CAD

Spacecraft Design

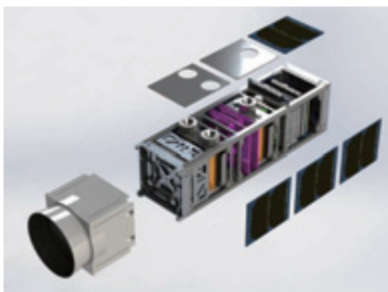
- **Spacecraft Bus – Design Approach**
  - Maximise use of COTS technology (e.g. Leverage CubeSats).
  - **Modular** approach
  - Maximise commonality with other SSC CubeSat programmes.
  - Spacecraft bus is treated as a "**CoreSat**" based on **two 6U + one 3U ISIS** CubesSat structures mechanically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



DDR Configuration Sept. 2014

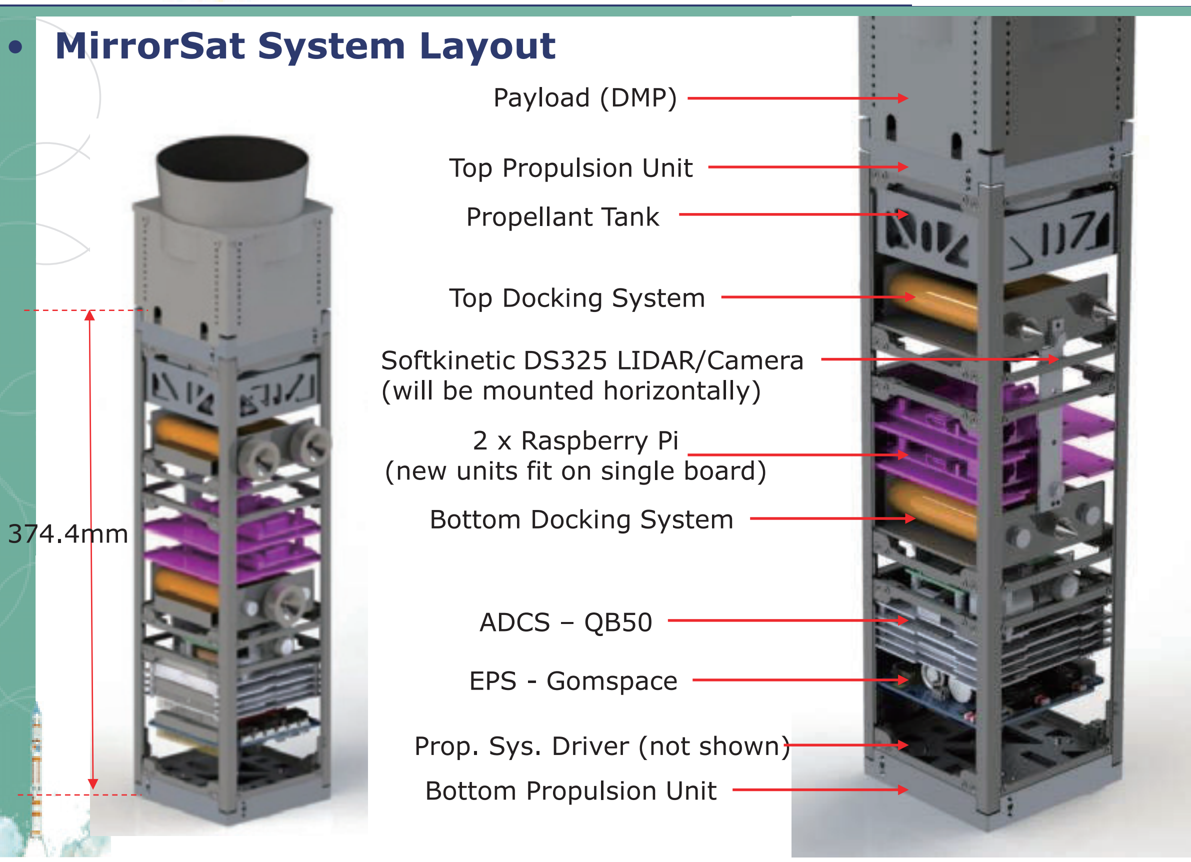
Spacecraft Design

- **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:
    - 20-50cm 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.



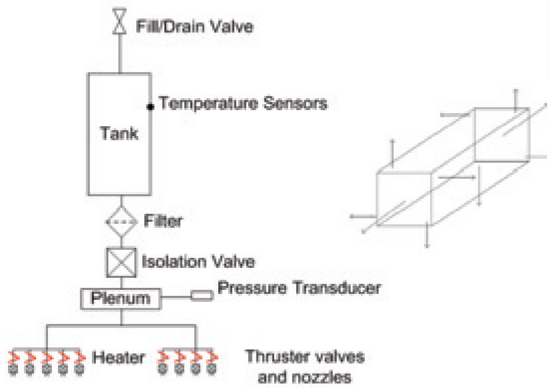
Spacecraft Design

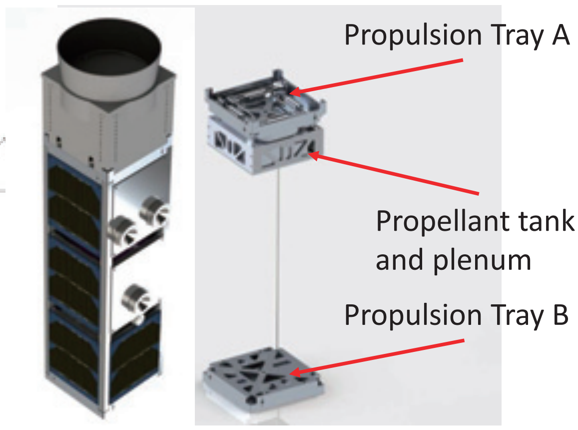
- **MirrorSat System Layout**



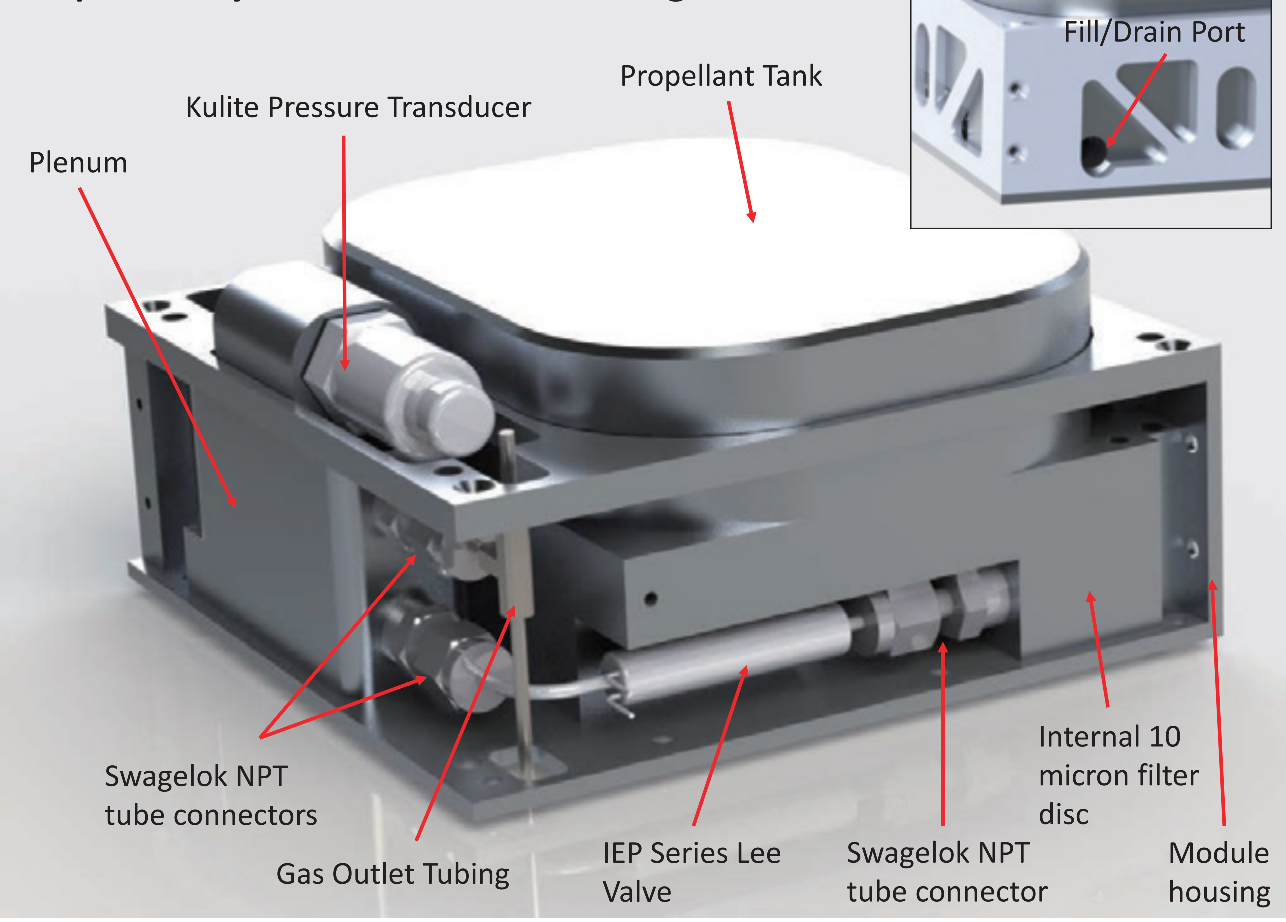
Spacecraft Design

- **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



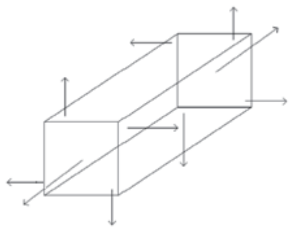


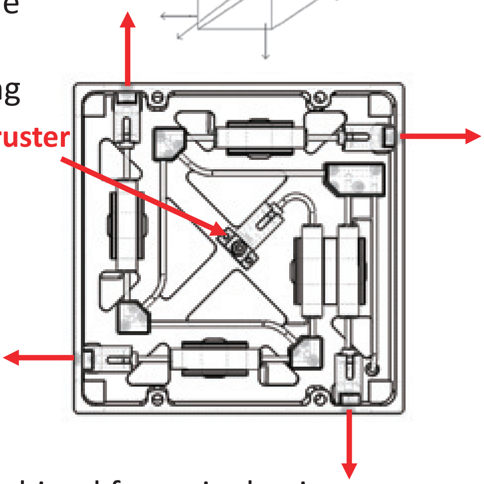
Propellant System with Front Housings Removed



Spacecraft Design

- **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





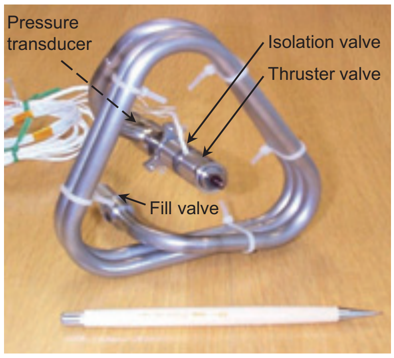
- Thrust trays machined from single piece of stock aluminium for extra rigidity
- Valve mounts built-in to structure

Spacecraft Design

- **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.

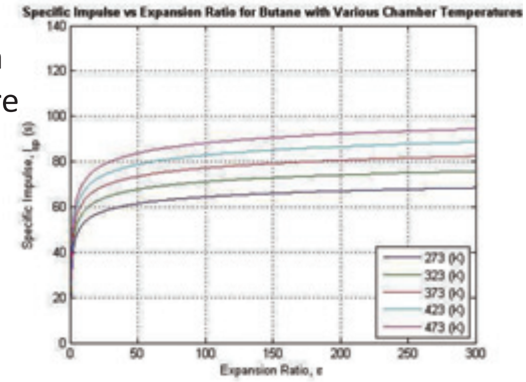
SNAP-1 System for Comparison

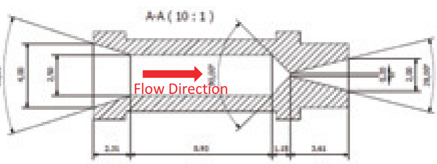
Propellant	**32.6 g butane**
Total impulse	**22.3 Ns**
Thrust range	**25 to 100 mN**
Module mass	**455 grams**
ΔV imparted	**2.1m/s (actual)**



Spacecraft Design

- **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





- 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

Spacecraft Design

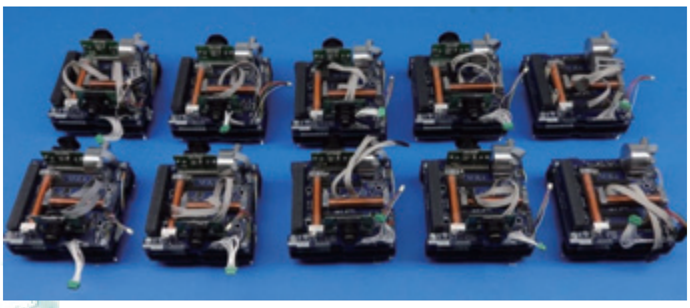
MirrorSat Propulsion Update 2015

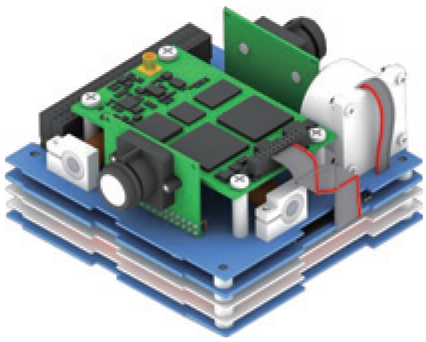
- All system components built and tested – Propulsion tank, plenum chamber, (single) thruster/heater and valves.
- Two-part aluminium propellant tank welded successfully.
- Butane filling very straight-forward from standard COTS cartridges.
- Multiple cycle operation demonstrated in the SSC Daedalus vacuum chamber. Valve operation at <5V – low power in latched mode.
- Gas temperature slightly lower than in initial tests – but thrust is good (3 and 10 mN dependent on plenum pressure)
- Testing was from 0 - 3 Watts in 0.5 W steps at 3 plenum pressures (0.5 bar, 1 bar and 1.5 bar) – 8 measurements at each point – 168 in total.
-

Spacecraft Design

MirrorSat ADCS

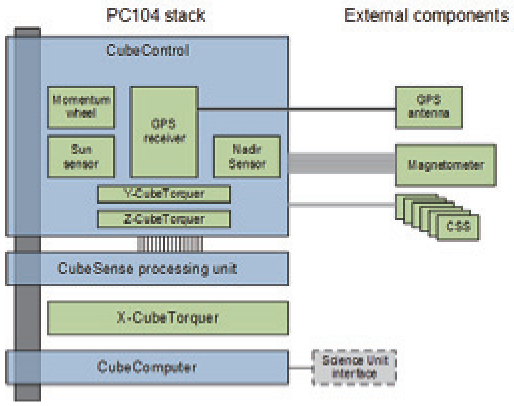
- New compact (450g) Integrated ADCS System being developed for QB50 by Prof. Steyn (Stellenbosch) and Lourens Visagie (Surrey).
- Comprises:
  - CMOS Camera Digital Sun Sensor
  - CMOS Camera Digital Earth Sensor
  - 3-Axis Magnetoresistive Magnetometer
  - 3-Axis Magnetorquer (2 Rods + 1 Coil)
  - Pitch-Axis Small Momentum Wheel
  - GPS Receiver
  - EKF and B-dot control software built-in
  - ~1° pointing stability (in sunlight)

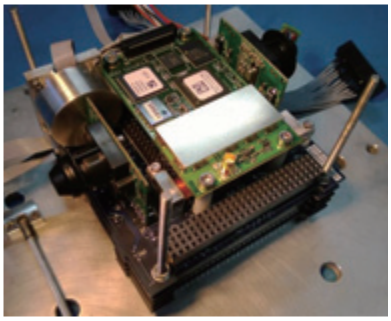




Spacecraft Design

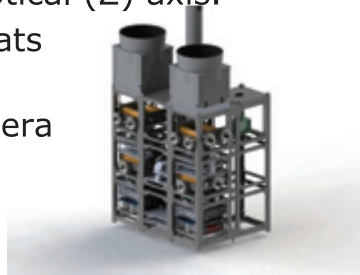
- **QB50 ADCS**
  - 3x PC104 boards
    - CubeComputer
    - CubeSense processing board
    - CubeControl
  - Peripheral components
    - Fully integrated ADCS has momentum wheel, sun- and nadir cameras, GPS receiver and magnetorquers contained in stack
    - External GPS antenna, magnetometer and coarse sun sensor photodiodes
  - In qualification (testing)
  - 15 ADCS Units delivered to te EU's QB50 Project
  - Flight heritage on STRaND-1





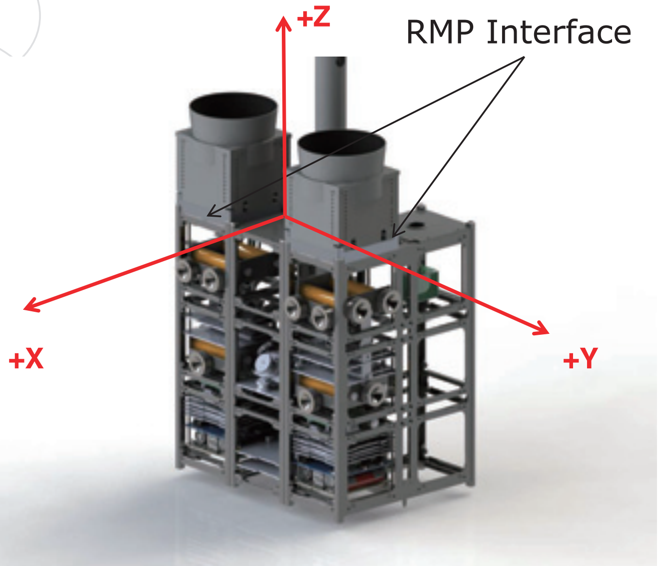
Spacecraft Design

- **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)



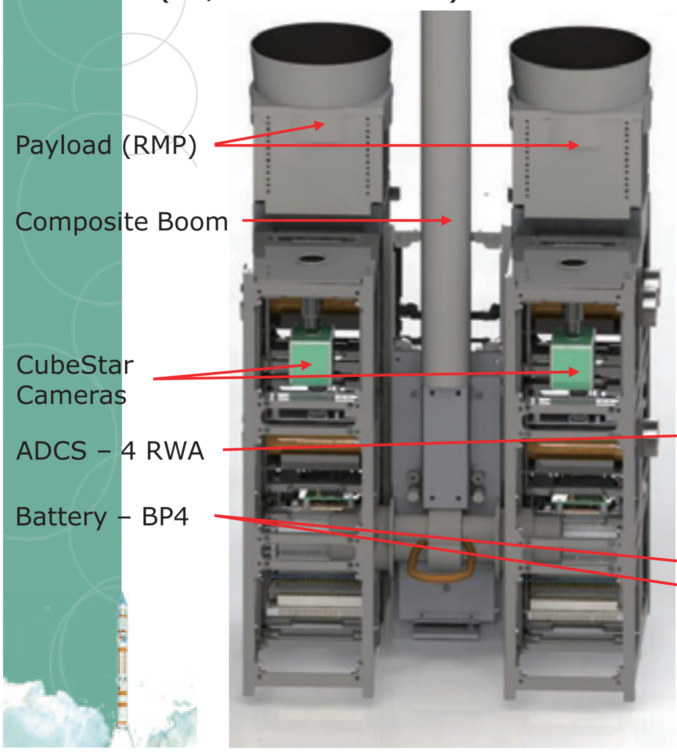
Spacecraft Design

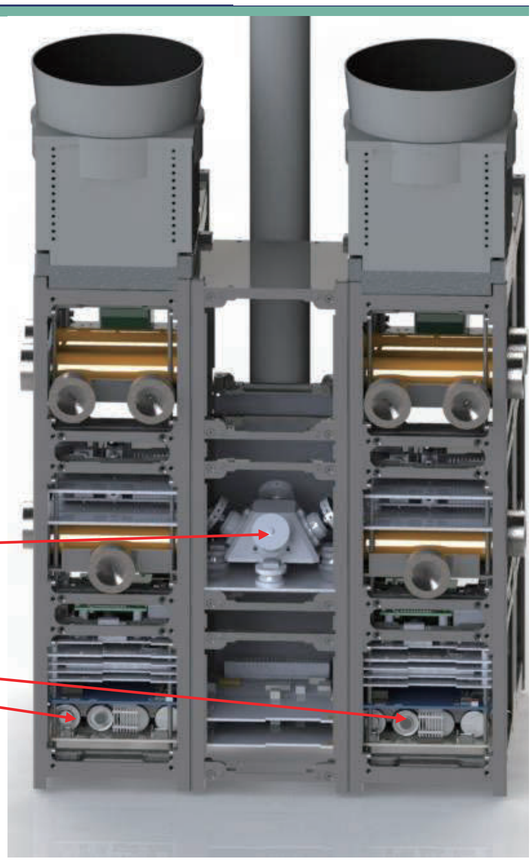
- **CoreSat Structure**
  - Structure rendering showing two 6U structures (+Y and -Y) separated by a single 3U structure (MirrorSats not shown)



Spacecraft Design

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





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Spacecraft Design

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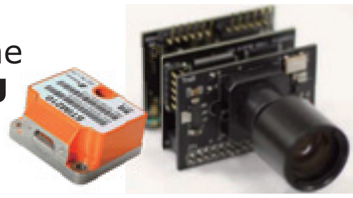
- **CoreSat ADCS**
  - Uses Compact Integrated ADCS system (as per MirrorSats), but replaces the single small pitch MW with four Surrey RWs (**4-RWA**) with dampers for increased control authority/low jitter control
  - Pointing (< 0.1° error all axes), stability (< 0.02°/s for 600s)
  - Slew-Rate (>3°/s 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**



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Spacecraft Design

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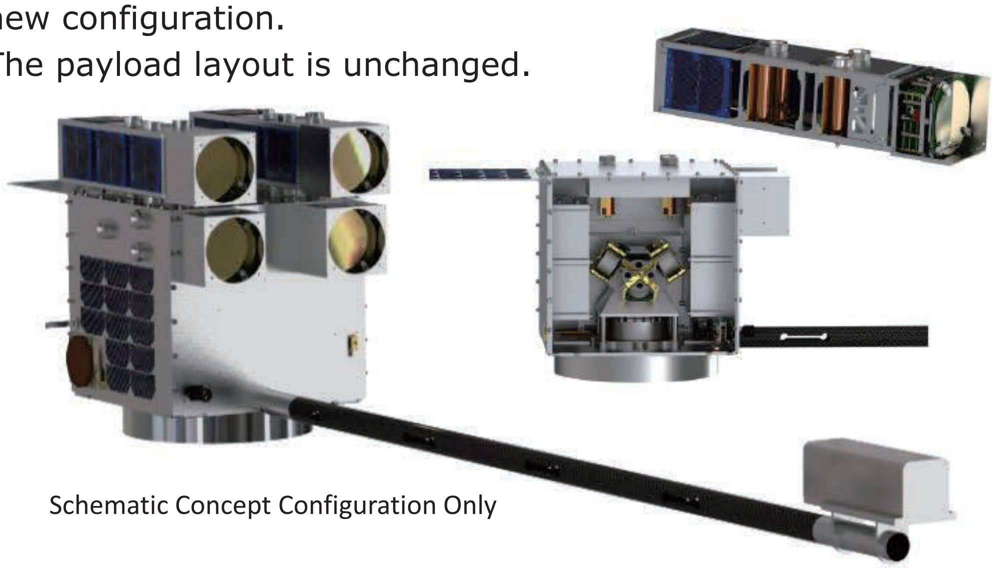
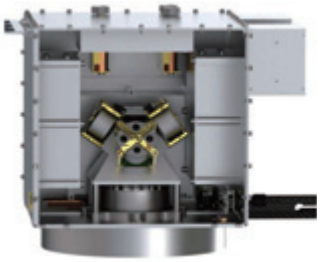
- **CoreSat System Layout Update 2015**
  - No changes have been made to the CoreSat since DDR 2014
  - However, we have studied substituting a platform derived from the SSTL-50 bus for the CubeSat Technology-Based CoreSat:
  - The MirrorSats would be retained – with minor changes to internal layout to accommodate the docking system for this new configuration.
  - The payload layout is unchanged.



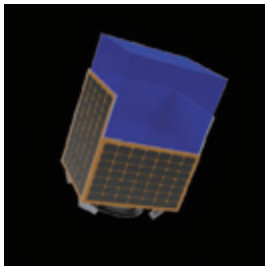
Schematic Concept Configuration Only

Spacecraft Design

- **CoreSat ADCS Update 2015**
  - No changes to DDR 2014 – however, the use of the SSTL-50 derived platform for the CoreSat would give very much improved pointing control and much greater data downlink capability (10's Mbps) – thus this is the preferred option.



SURREY SATELLITE TECHNOLOGY LTD

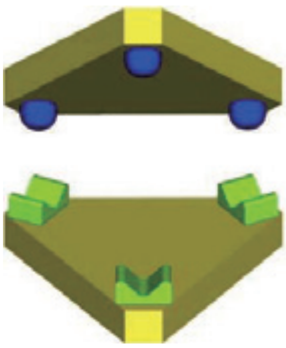


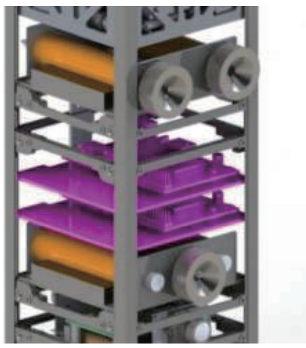
Generic SSTL-50 Platform and Specifications

Payload Instrument Mass	Up to 45 kg
Payload Volume	Width 530 mm, Depth 430 mm, Height 400 mm
Payload Orbit Average Power	Typically 35 W
Payload Peak Power	Typically 85 W
Payload Data Bus	Gigabit per second to on-board storage or high speed downlink.
Attitude Control	Earth referenced or inertial; stability: 18 arc-seconds/second; knowledge: 10 arc-seconds; control 0.07 degrees
Typical Orbit	Low-Earth Orbit – Sun-Synchronous
Platform Lifetime	5 to 7 years
Total Mass	50 kg typical – up to 75 kg

RDV/Docking

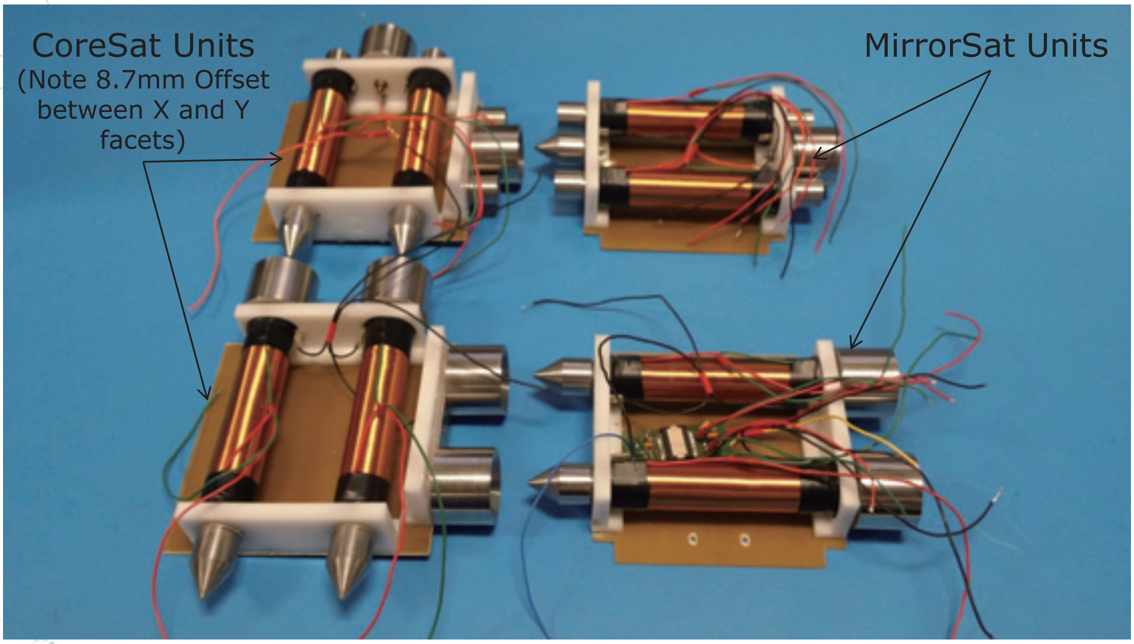
- **EM Docking System Concept**
  - SSC Electro-Magnetic Kelvin Clamp Docking System (EMKCDS)
  - Comprises four PWM controlled, H-bridge-driven, dual polarity electro-magnets, each of over 900 A-turns
  - These are coupled to three "probe and drogue" (60^{o} cone and 45^{o} cup) type mechanical docking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





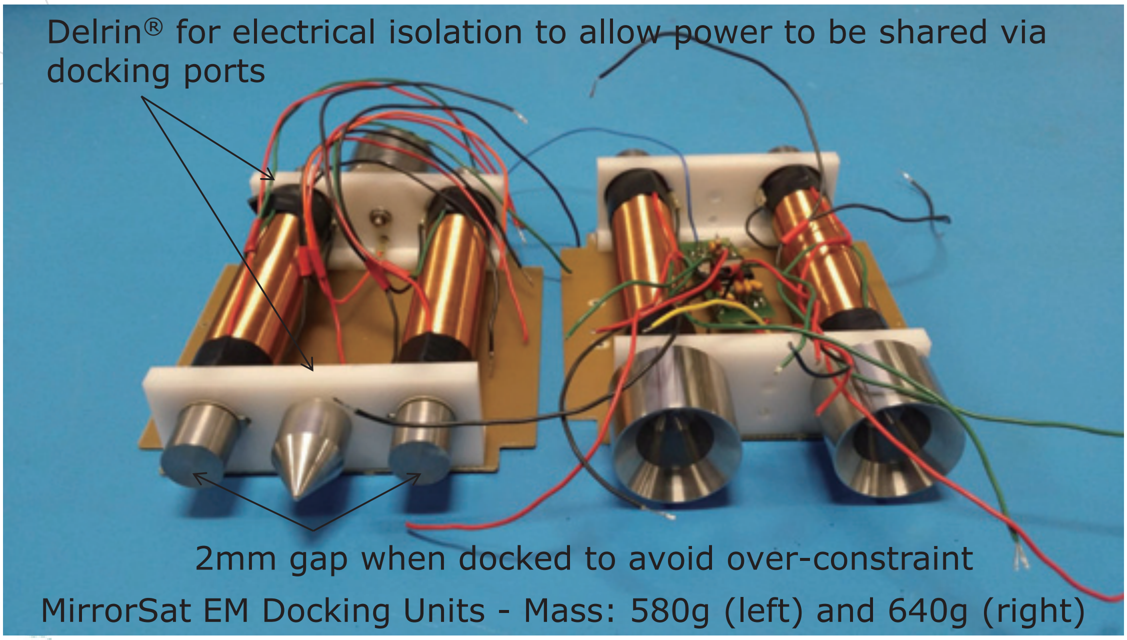
RDV/Docking

- **EM Docking System Prototype**
  - Prototype Docking Port hardware designed and built:



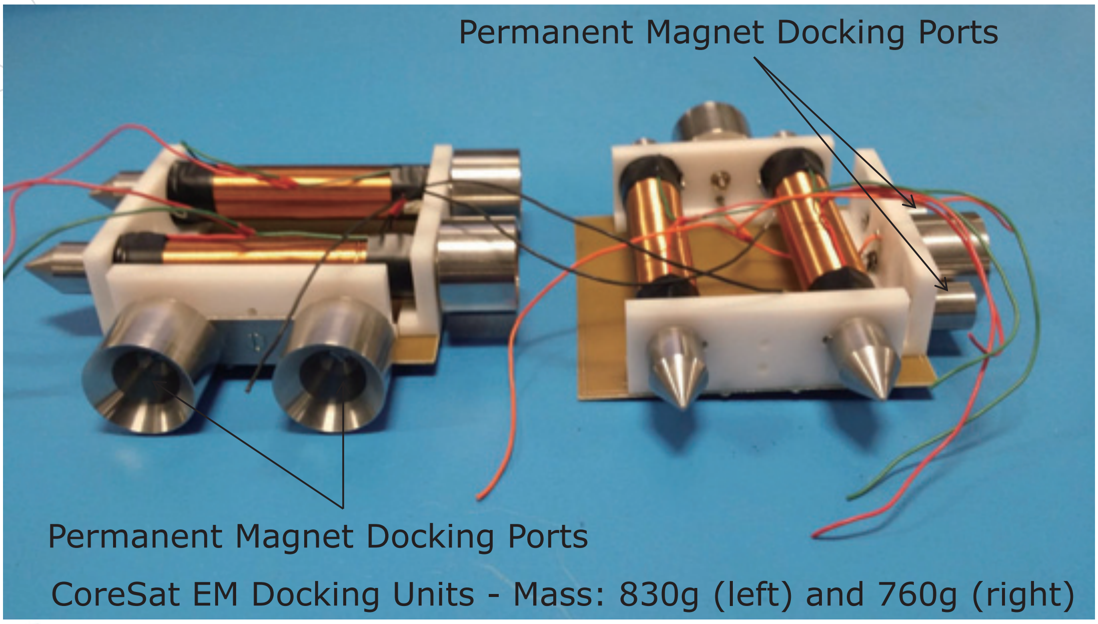
RDV/Docking

- **EM Docking System Prototype**
  - Prototype Docking Port hardware designed and built:



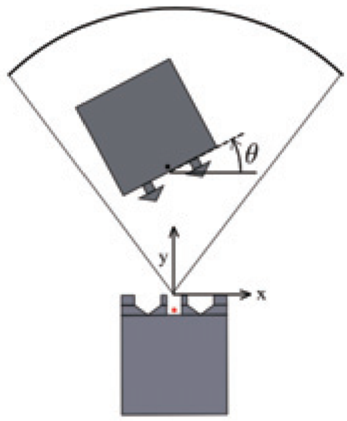
MirrorSat Spacecraft Bus

- **EM Docking System Prototype**
  - Prototype Docking Port hardware designed and built:



RDV/Docking

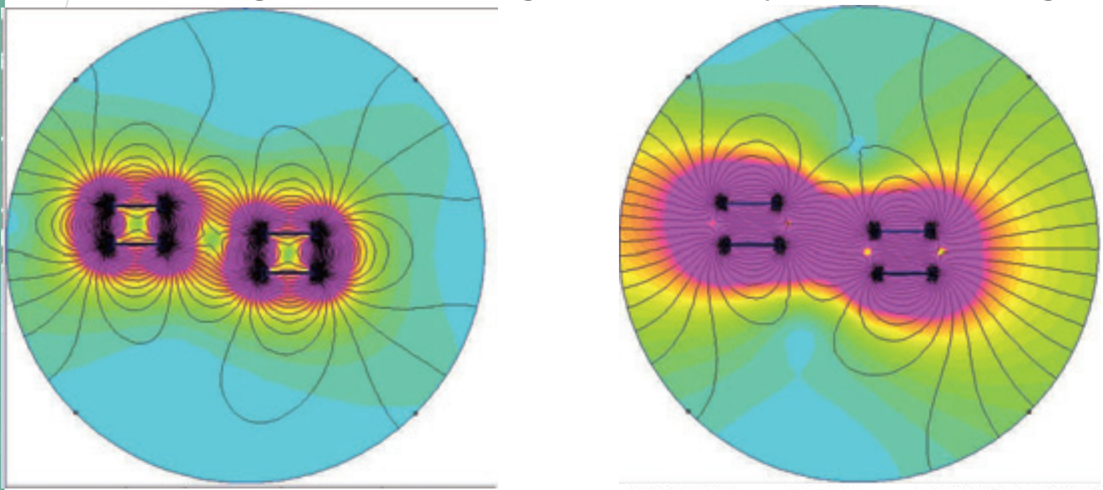
- **EM Docking System Testing**
  - CalTech and SSC initial Air-Bearing Table experiments show:
    - Capture distance is between 20-30cm for two pairs
    - Automatic self-alignment works, but choice of polarities is important to avoid miss-alignment/false-capture.
    - Attractive force is highly non-linear!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



*Radius from centre of one face to centre of 'docking plane'; **Half angle

RDV/Docking

- **EM Docking System Simulation**
  - FEM of magnetic flux linking confirmed experimental findings:

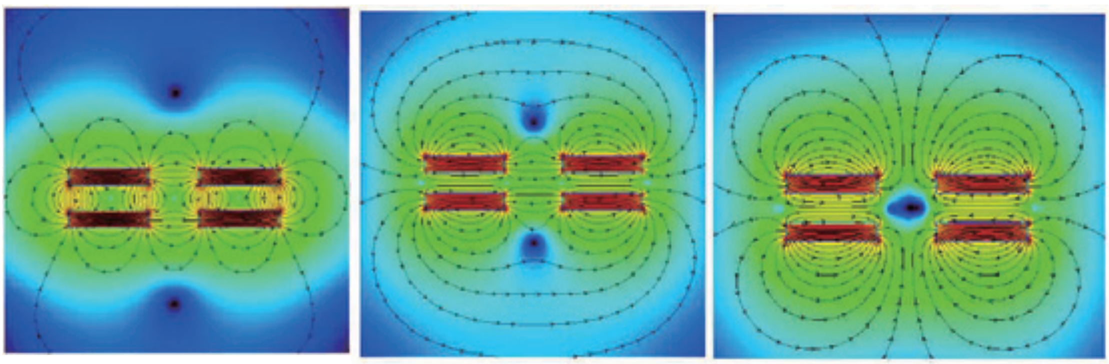


- Force is highly non-linear if the electro-magnets are simply energised.
- PWM control is used to vary the current to compensate for the distance effect.
- Useful force beyond 30cm separation.

Distance/cm	Force/N	Acc./ms^{-2}	Time to Impact*/s
0.2 (min)	6.07	1.21	< 0.06
0.5	1.62	0.324	< 0.17
1.0	0.564	0.113	< 0.42
2.0	0.181	0.036	< 1.05
5.0	0.036	0.0072	< 3.73
10	0.009	0.0018	< 10.5
15	2.68 mN	0.000536	< 23.7
20	1.140 mN	0.000228	< 41.9
25	0.569 mN	0.000114	< 66.2
30	0.334 mN	0.000067	< 94.6

RDV/Docking

- **EM Docking System Update 2015**
- (MSc Project)
  - A simple 2D simulation was set up using the Vizimag software to help visualise the characteristics of the solenoids placed at various distances, polarity configurations and angular offsets.



EM Docking Systems at 10cm Separation – Attract and Repel Modes
Note – when alternating polarities are used on each spacecraft (left panel) – the attractive/repulsive forces are smaller than if the same polarities are used (middle and right panels)

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RDV/Docking

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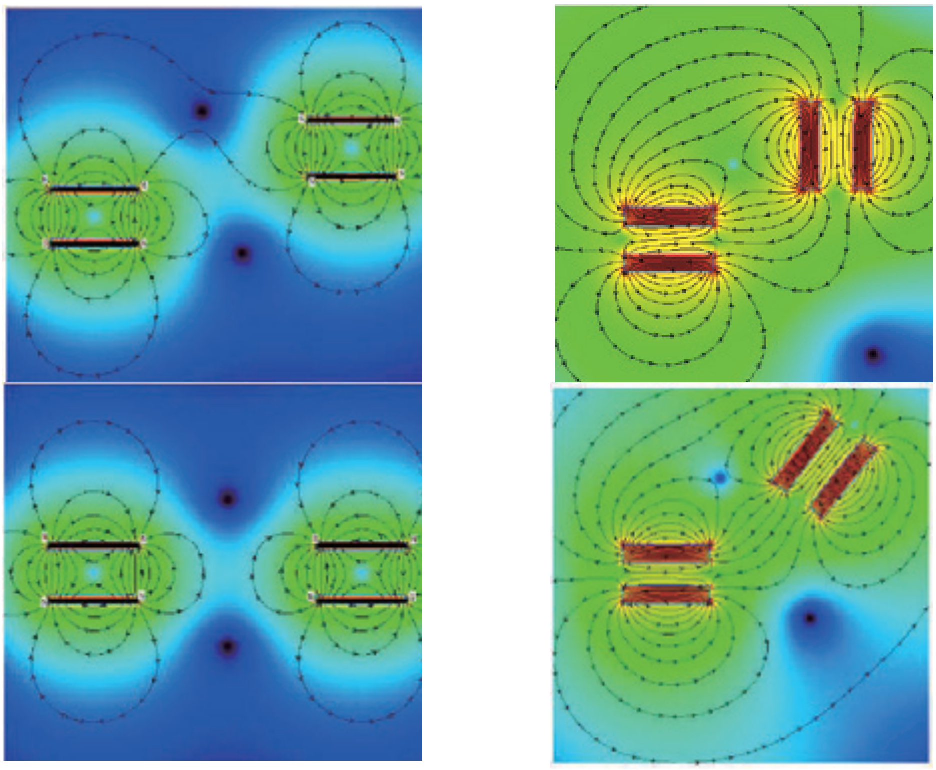
- **EM Docking System Update 2015**



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RDV/Docking

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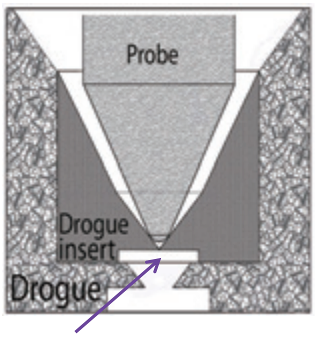
- **EM Docking System Update 2015**
  - A new two-part drogue has been developed, which aids manufacture and assembly.
  - A built in neodymium permanent magnet (6mm dia., 1mm thick) provides the latching action to hold the spacecraft together when the electro-magnets are turned off.
  - We found the drogue must be non-ferrous, otherwise the probe "feels" no pull-in force. We used aluminium.
  - The Kelvin-Clamp V-grooves would be spark etched for flight.
  - The probe, solenoid core and magnetic field extenders are all now pure iron (not Supra50 alloy).



Latching Permanent Magnet

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RDV/Docking

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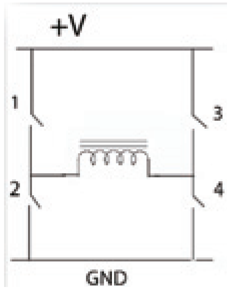
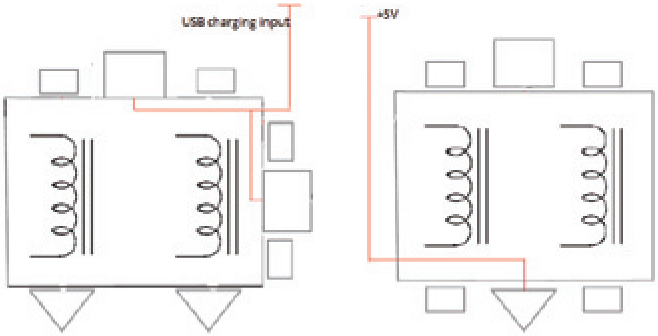
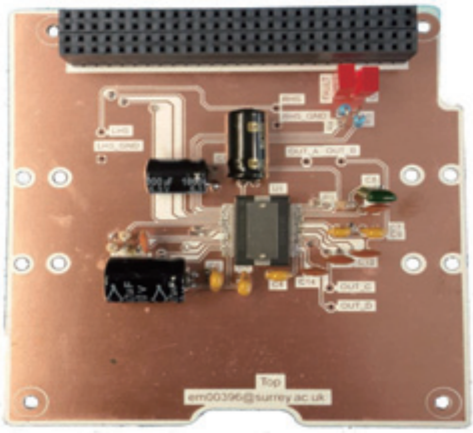
- **EM Docking System Update 2015**
  - A new solenoid controller was designed utilizing the DRV8432 stepper motor driver chip from Texas Instruments .
  - This was built to CubeSat PC104 interface standard and comprised a pulse-width modulated H-bridge driver circuit, controlled via a R-Pi over a Wi-Fi link (emulating the AAReST MirrorSat ISL).
  - The Docking Port also provides power transfer between spacecraft, as shown below:







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RDV/Docking

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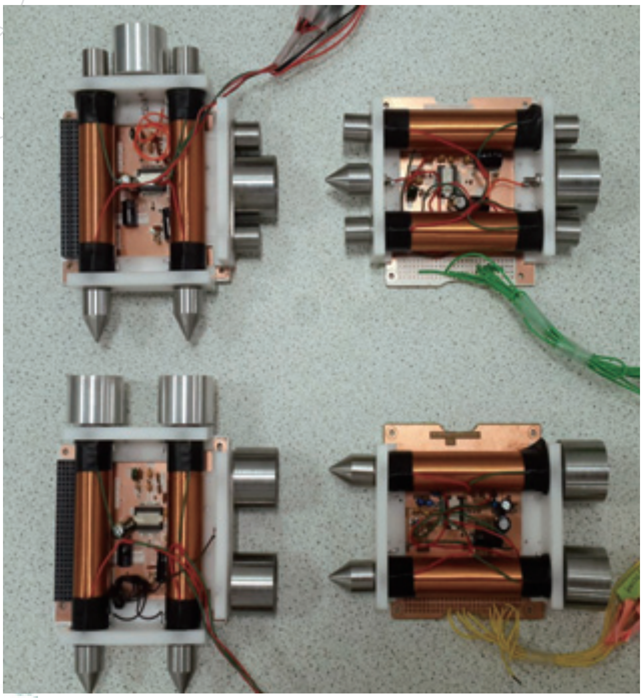
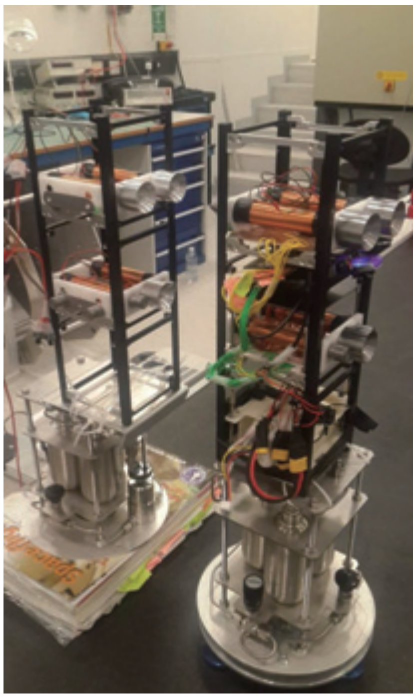
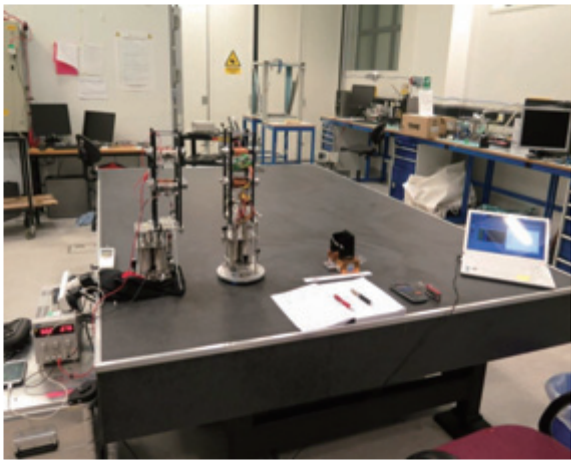
- **EM Docking System Update 2015**
  - Re-designed Docking Ports and 2D Air Bearing Test Rig





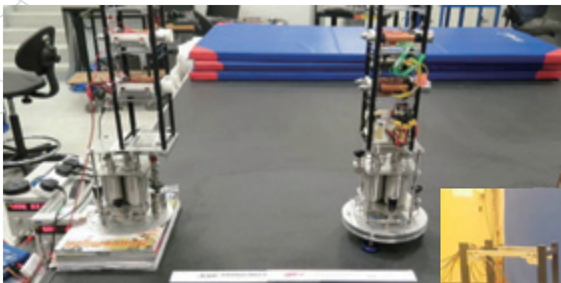
RDV/Docking

- **EM Docking System Update 2015**
  - 2D air bearing table tests were conducted for:
    - Forces (measured by force meter and weight offset)
    - Acceptance angles (confirmed previous results)
    - Viability of the permanent magnets (~350 mN latching force corresponding to 40% PWM duty cycle to un-dock).
    - Flux meter and force meter confirmed PWM linearity.



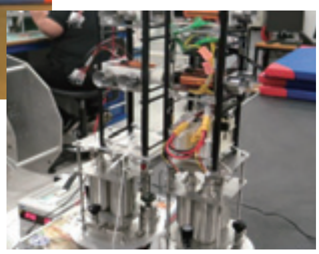
RDV/Docking

- **EM Docking System Update 2015**
  - Videos: 50cm Docking; 20cm Docking; Repel and Hold at Distance



Docking from 50cm

Docking from 20cm



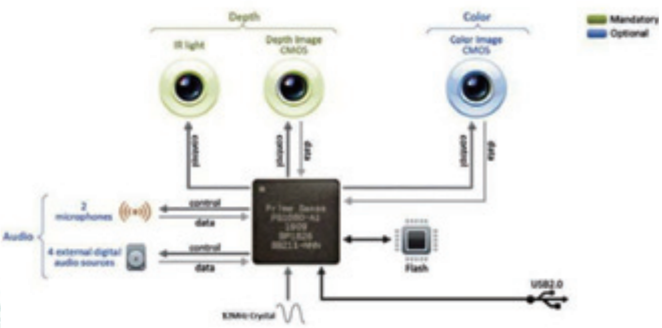
Repel and Hold

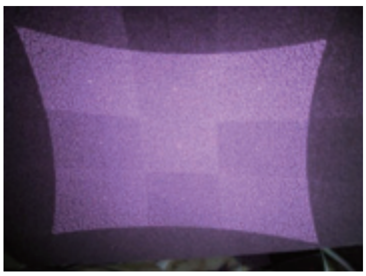
RDV/Docking

- **EM Docking System Update 2015**
- Summary (MSc):
  - Re-designed docking cone or 'drogue'
  - Designed H-bridge driver circuit on CubeSat standard PCB
  - Implemented PWM control using Raspberry Pi over Wi-Fi
  - Assembled test models on air-bearing table
  - Demonstrated docking while taking key measurements
  - Verified performance of H-bridge circuit
  - Measured attraction and separation forces
  - Measured acceptance angles, average tolerances
  - Verified performance of latch magnets
- Remaining Work (PhD) and 2016 MSc:
  - Link Docking System control to Docking Sensor system and develop dynamic control strategy.
  - Verify performance on 2D air bearing table (3DoF) and develop "2½ D" test rig (2 translations, 2 rotations).
  - Complete 6 DoF simulator and address geomagnetic field torque and magnetic field extender contact issues.

RDV/Docking

- **RDV & Docking 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).

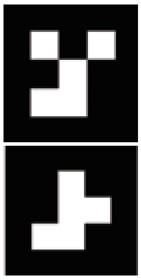
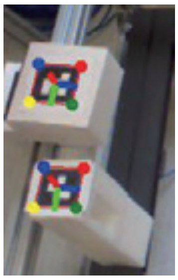


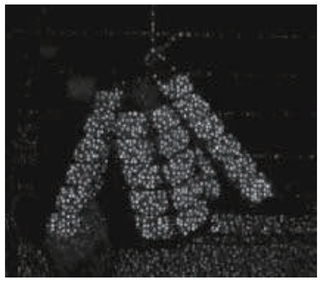


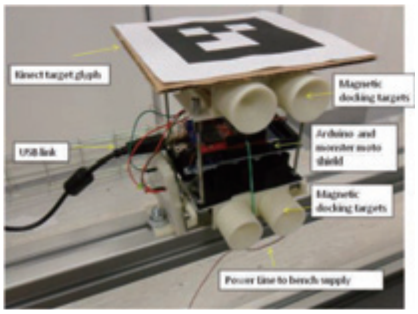
LIDAR NIR Projected Speckle Pattern

RDV/Docking

- **RDV & Docking Sensor**
  - Combined with SSC MV pose estimation software and unique visual "glyph" identifiers (or LEDs) – we can identify and find the pose of the MirrorSat to the order of a few degrees, and its range typically to better than 1% of the distance to the target.

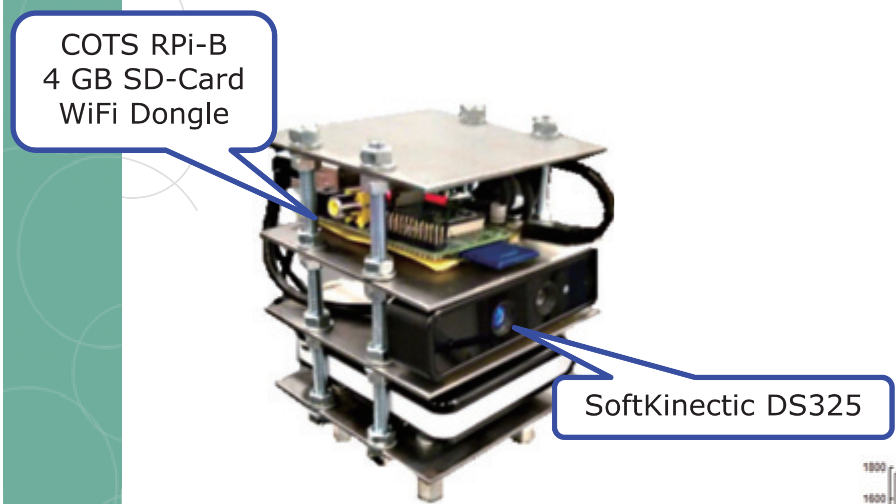



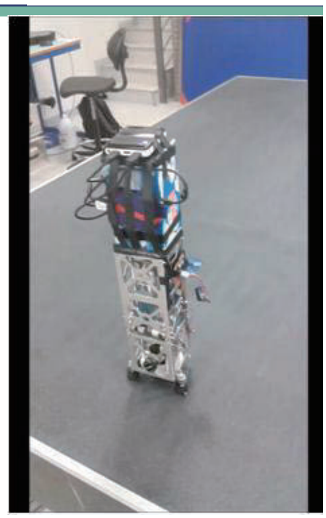




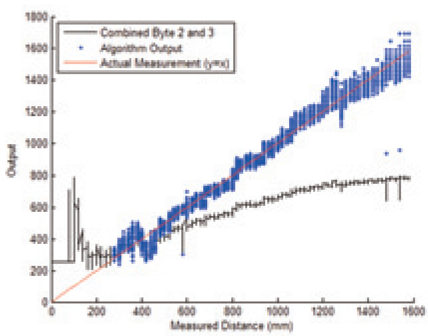
RDV/Docking

- **RDV & Docking Sensor Air Bearing Tests**



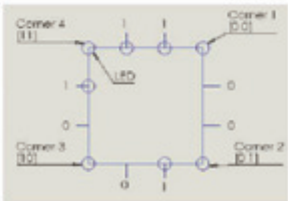


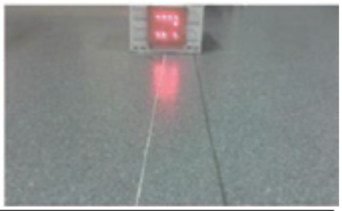
- OpenNI2DS325 driver used initially but tests showed it to be inaccurate.
- Driver was reverse engineered and new algorithms were developed to convert raw sensor data into depth measurements leading to much more accurate results.



RDV/Docking

- **RDV & Docking Sensor Update 2015**
  - A new short range sensor based on a 640 x 480 pixel (VGA) Camera and near-IR LED pattern (similar to those used for QR codes) was developed. Power consumption was <1W.
  - The detection and pose/range algorithms ran on a commercial R-Pi processor. Typical update rates were ~1Hz.
  - Translational and rotational errors were evaluated. Rotation error was typically within ~5° – with a maximum error of ~10°.

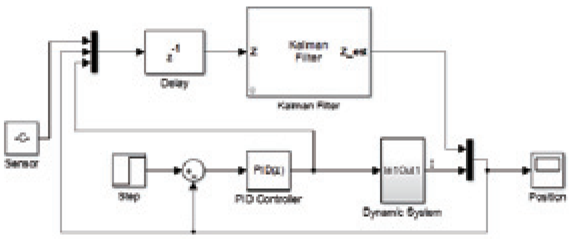



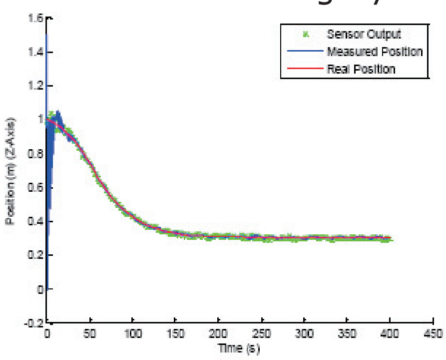


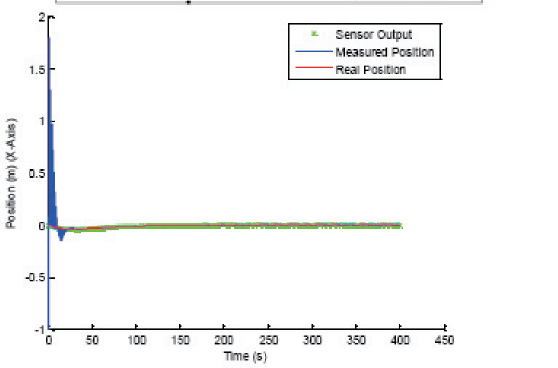
Axis	Range Interval (m)	Root Mean Square Error(mm)	Maximum Error (mm)	Standard Deviation (mm)	Confidence (%)
Z Axis	0-0.30	3.106	1.949	4.166	100
	0.30-0.80	5.787	11.265	3.687	100
	0.80-1.15	20.958	39.843	13.250	100
X Axis	0-0.30	1.9	0.2794	0.684	83
	0.30-0.80	1.7	2.851	0.585	91
	0.80-1.15	0.95	1.466	0.288	100

RDV/Docking

- **RDV & Docking Sensor Update 2015**
  - A computer simulation of the sensor performance, coupled with a dynamic model of the motion of the MirrorSat was set up.
  - After 30s of simulated run time, the Kalman Filter was seen to be effectively removing the sensor noise from both position and velocity estimates.
- Remaining Work (PhD) & 2016 MSc:
  - Address solar blinding issue (via narrow pass-band filter high-intensity LEDs).
  - Combine with Docking System.

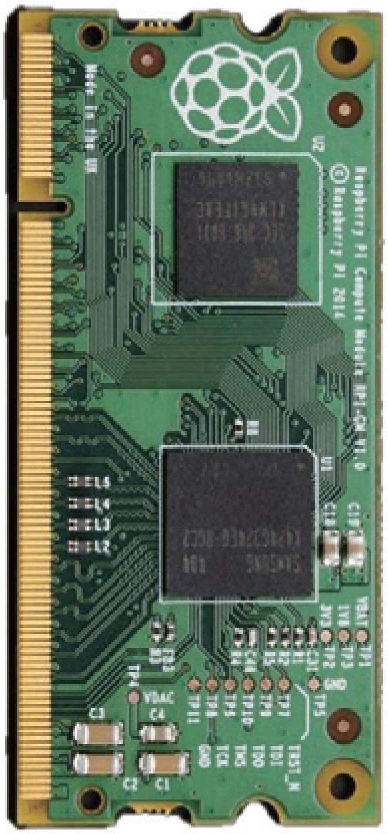






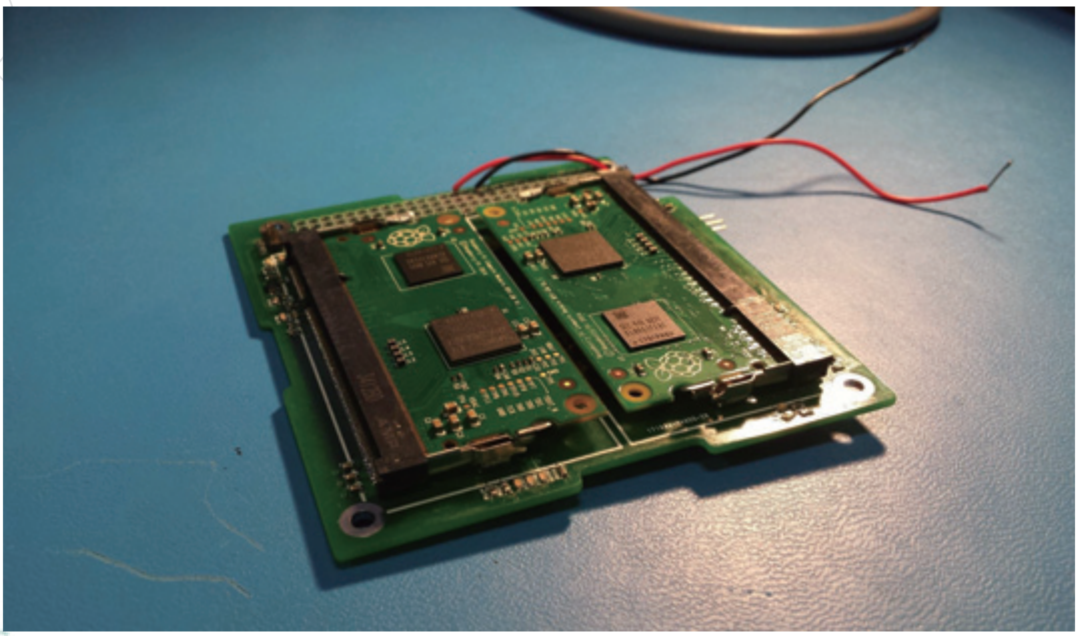
RDV/Docking

- **RDV&D Computer**
  - RPi Compute (industrial grade) released with SO-DIMM connector.
  - BCM2835 Processor (400-800 MHz)
  - 512 MB NAND RAM 46 GPIO (than 21)
- 2 RPi Computes on PC/104 Board



RDV/Docking

- **RDV&D Computer Update 2015**
  - BCM2835 Processor (400-800 MHz)
  - 512 MB NAND RAM 46 GPIO (than 21) > + 4 GB NAND Flash.



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RDV/Docking

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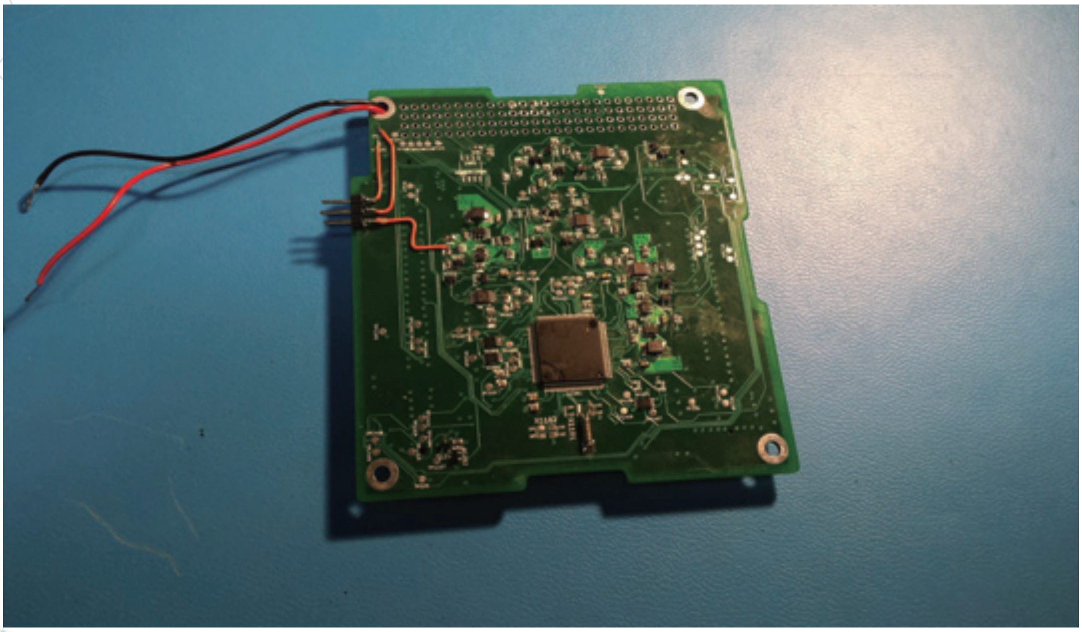
- **RDV&D Computer Update 2015**
  - External MSP430 as:
    - Watchdog on RPi-Computes & Switch Power via UART / ADC.



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Development

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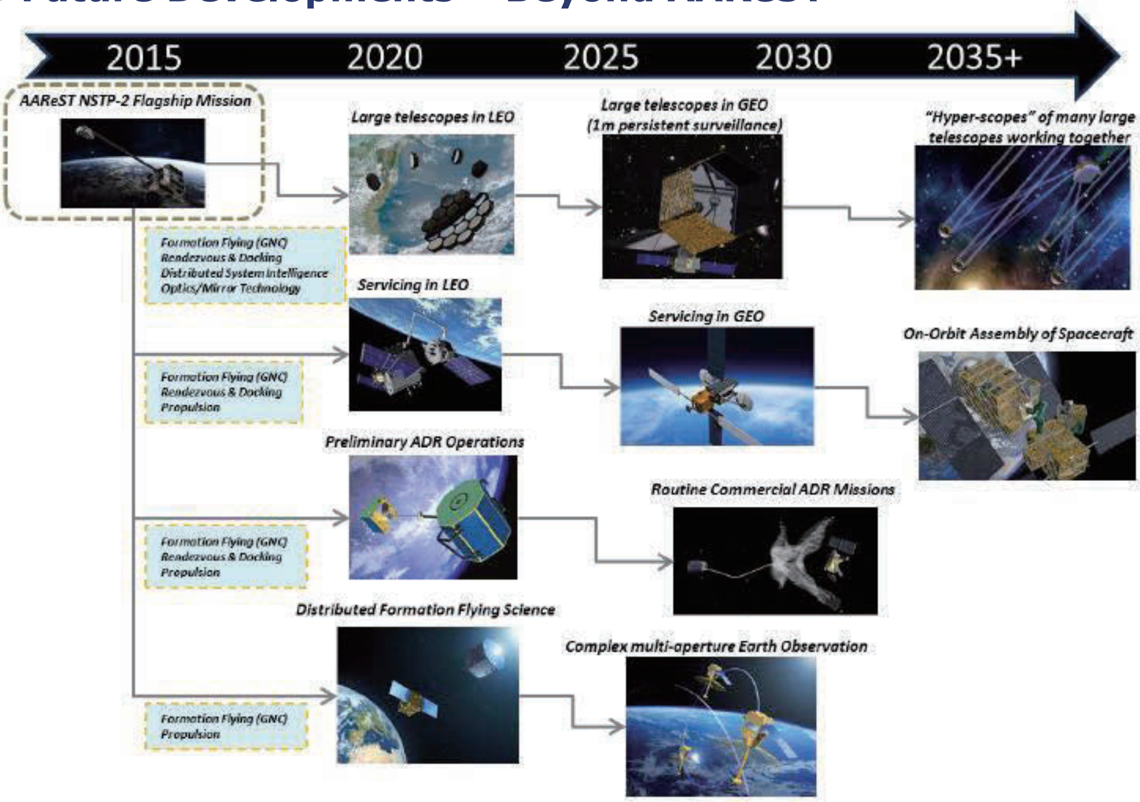
- **Future Developments – Beyond AAReST**



Conclusions

- The AAReST project demonstrates how nano-satellite technology can be used to provide confidence building demonstrations of advanced space concepts.
- The mission will demonstrate autonomous rendezvous and docking, reconfiguration and the ability to operate a multi-mirror telescope in space.
- 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.
- Since DDR in 2014, SSC has made progress on three key technologies for AAReST – the multi-thruster propulsion system, the RDV & Docking System and the dual R-Pi processor board. All systems have shown good success.
- Work is in progress via 2 Surrey PhDs (ADCS and RDV&D) and MSc projects.

Acknowledgements

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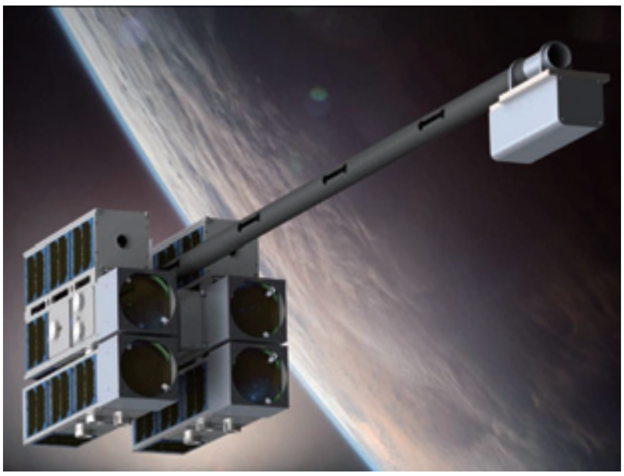
Thank-You



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