AAReST Spacecraft Update:

Spacecraft Bus, Propulsion, ADCS, SSTL-50 CoreSat, RDV/Docking, OBDH and Comms.

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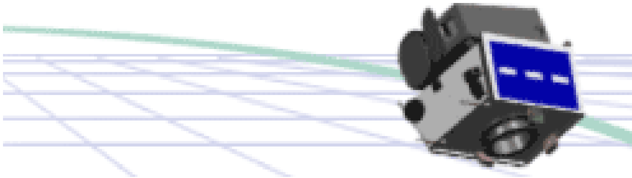
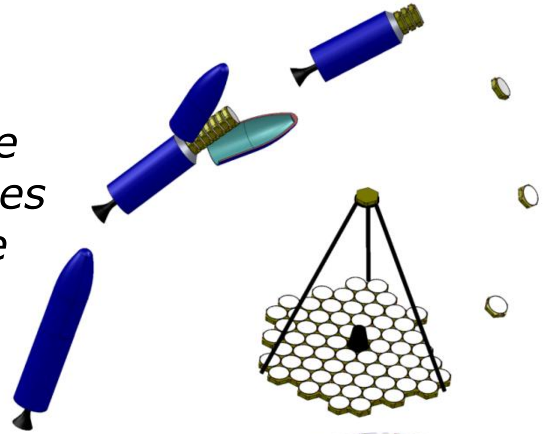
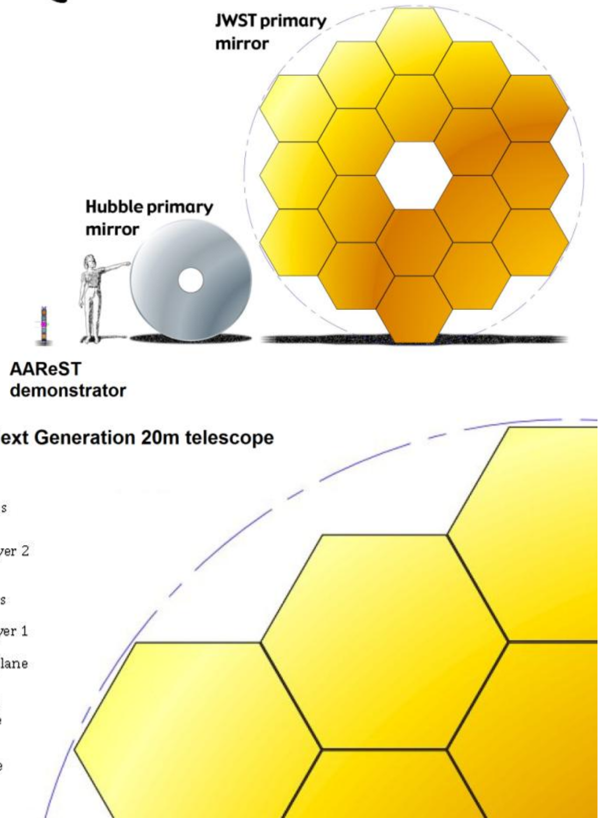
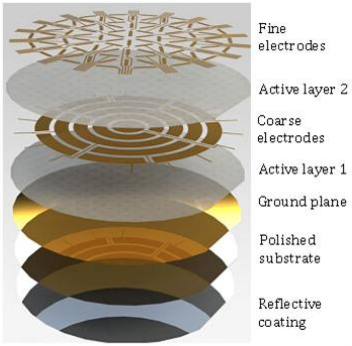


The Vision

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







Mission Concept

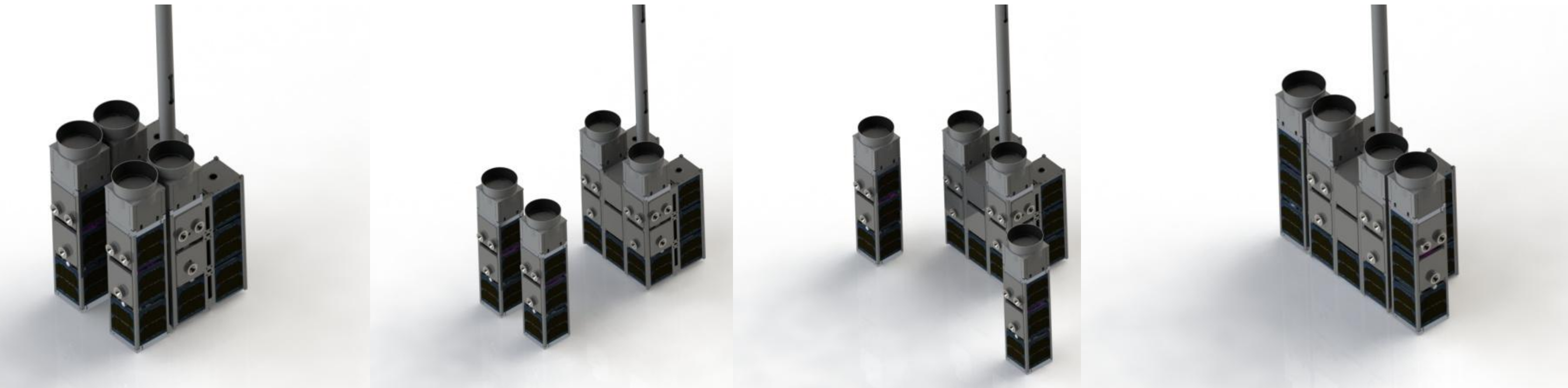
- **AAReST Mission Technology Objectives:**
  - Demonstrate <u>all</u> key aspects of *autonomous assembly* and *reconfiguration* of a space telescope based on *multiple* mirror elements.
  - Demonstrate the capability of providing *high-quality* images using a multi-mirror telescope.

AAReST: Launch Configuration

A 70lb, 18″ Cubeoid Composite Microsat to Demonstrate a New Generation of Reconfigurable Space Telescope Technology....

Mission Concept

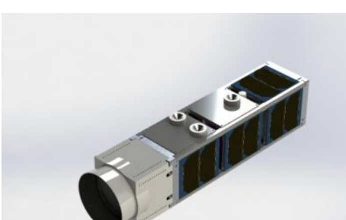
- **Flow-Down to Spacecraft Technology Objectives (Mission Related):**
  - Must involve *multiple* spacecraft elements (*CoreSat* + 2 *MirrorSats*).
  - All spacecraft elements must be *self-supporting* and "*intelligent*" and must cooperate to provide *systems autonomy* – this implies they must be each 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

Mission Concept

- **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.



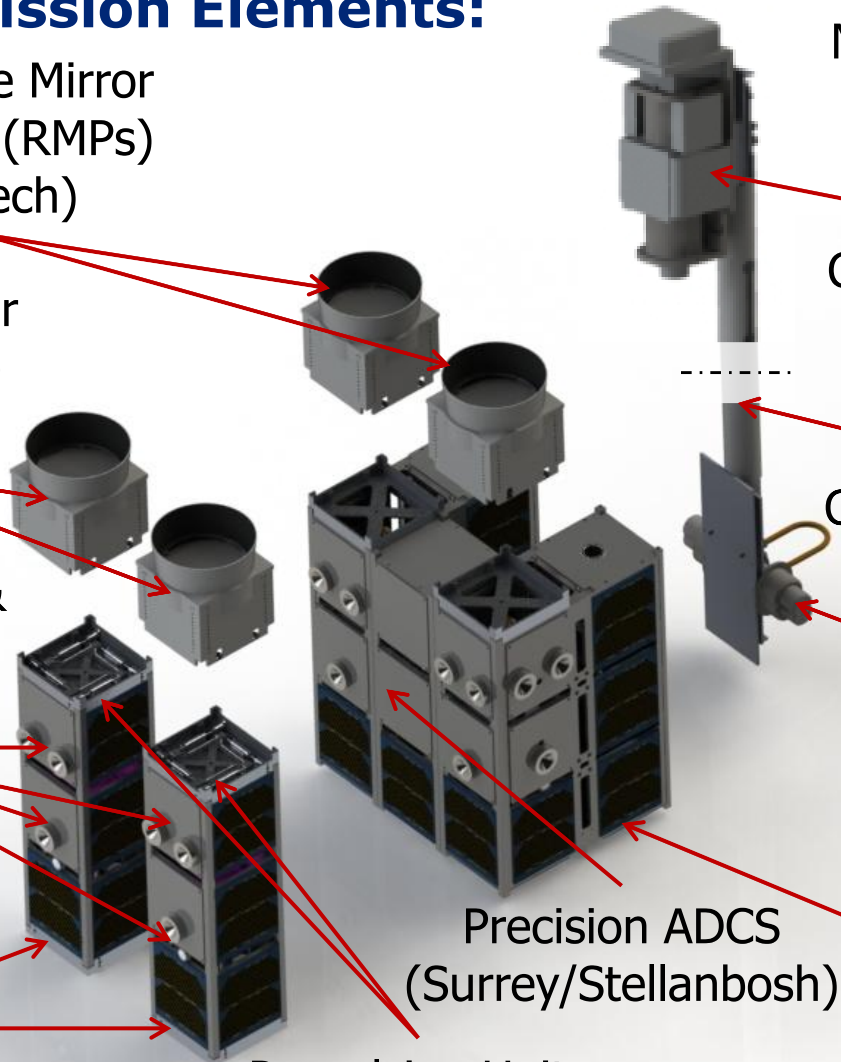
MirrorSat

AAReST: Boom and Camera Package Deployed

CoreSat (Internal View)

Mission Concept

- **AAReST Mission Elements:**

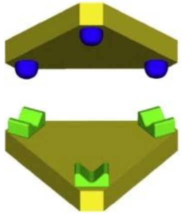


Mission Concept

- **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**
  - During launch, the MirrorSats, Camera Package and Boom are held rigidly onto the CoreSat via Frangibolts.
  - Once in orbit the Camera Package and Boom are deployed.
  - Next the Frangibolts holding the MirrorSats are fired, and the MirrorSats are then held magnetically (via permanent magnets) onto the CoreSat.
  - The EM Docking System can overcome the magnetic latching to allow the MirrorSats to separate and re-attach in the two different configurations (Compact/Wide).
  - The 3-point extended Docking Ports use a *Kelvin Clamp* arrangement to ensure rigid alignment of the spacecraft.



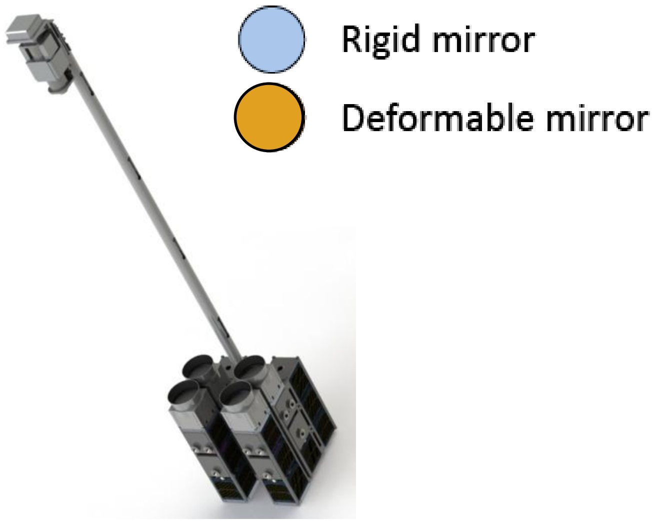
Compact Configuration

Transition

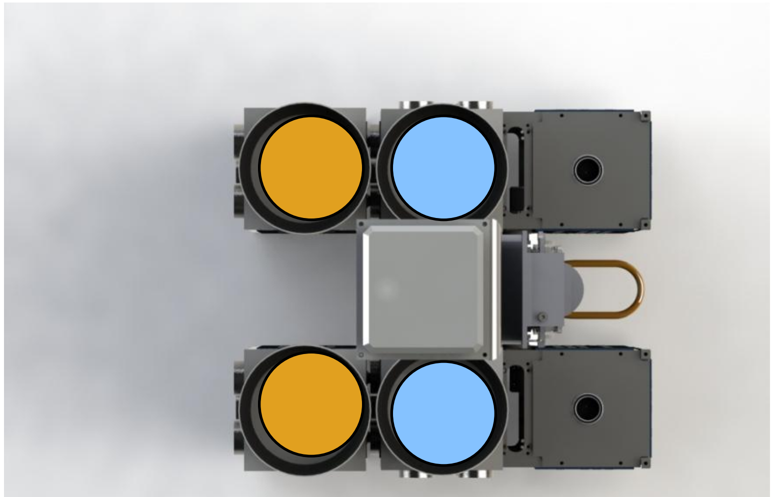
Wide Configuration

Mission Concept

- **Spacecraft and Mission Concept**
  - **Mission Phase 1**: (Minimum Mission Objective)
    - Deploys boom/Camera Package to form space telescope
    - Images stars, Moon and Earth with Reference Mirrors (c. 0.3º FoV)
    - Demonstrates precision (0.1º, 3σ) 3-axis control
  - **Mission Phase 2**: (Minimum Science Objective)
    - Images with combined Deformable and Reference Mirrors in "compact mode"
    - Demonstrates deformable mirror (DMP) technology and phase control.



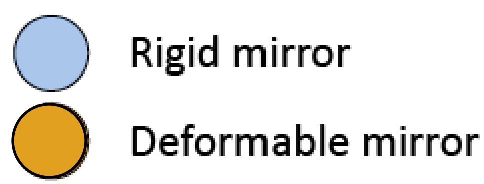
Compact Configuration Imaging Mode



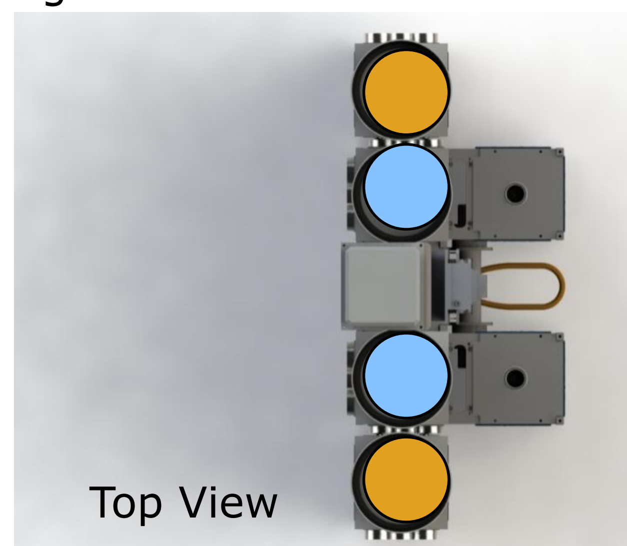
Top View

Mission Concept

- **Spacecraft and Mission Concept**
  - **Mission Phase 3**:
    - 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
  - **Mission Phase 4**:
    - 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



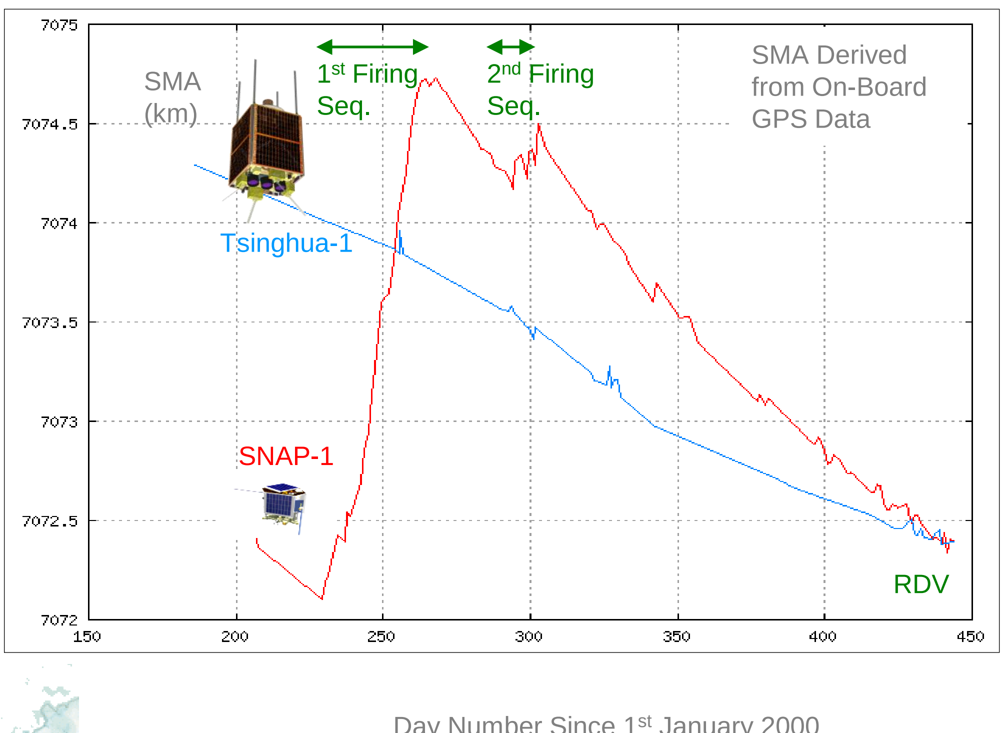
Wide Configuration Imaging Mode



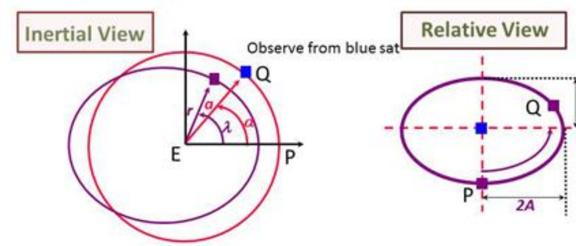
Top View

Mission Concept

- **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

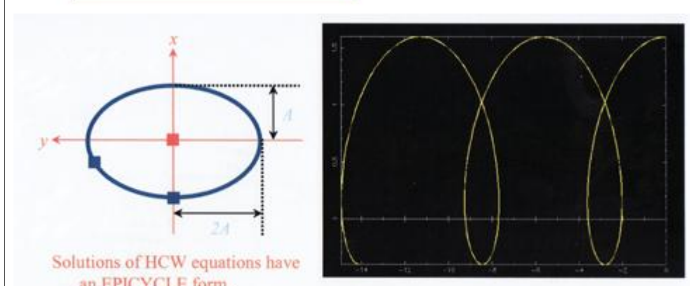


How we see slightly eccentric orbit from a neighbouring circular orbit.



$\alpha = n(t - t_p)$ Epicycle phase

A: Epicycle amplitude



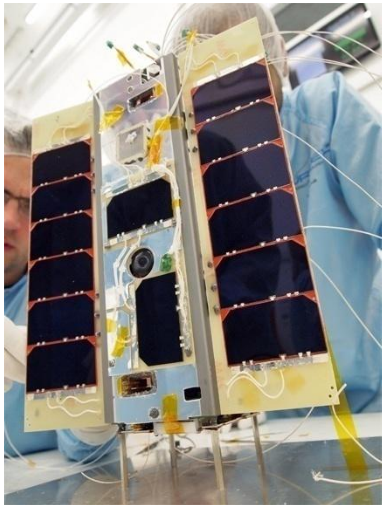
$$x(t) = (4 - 3\cos nt)x_0(\dot{x}_0 / n)\sin nt + 2\dot{y}_0(1 - \cos nt)/n$$

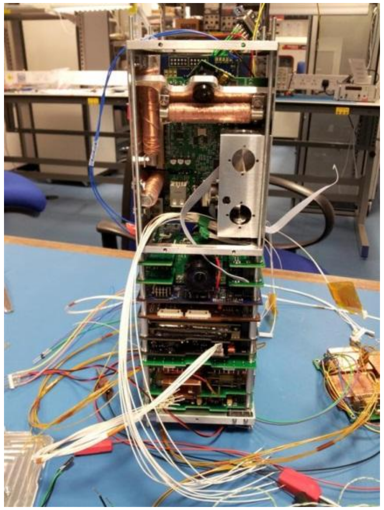
$$y(t) = 6x_0(\sin nt - nt) + y_0 + (2\dot{x}_0 / n)(-1 + \cos nt) + \dot{y}_0(4\sin nt / n - 3t)$$

Spacecraft Design

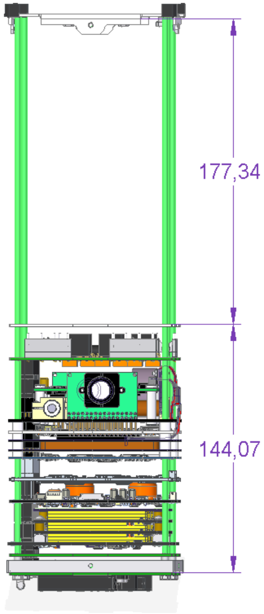
- ## Spacecraft Bus – Design Approach
  - **Low-cost** approach based on CubeSat technology
  - **Heritage** from Surrey's SNAP-1 NanoSat Programme (2000) (particularly butane propulsion and pitch MW/magnetic ADCS)
  - **Incremental** hardware, software and rendezvous/docking concepts developed through Surrey's STRaND-1, STRaND-2, and QB50/InflateSail and AlSAT1-Nano missions currently under development for launch in 2016.

SNAP-1 (2000)





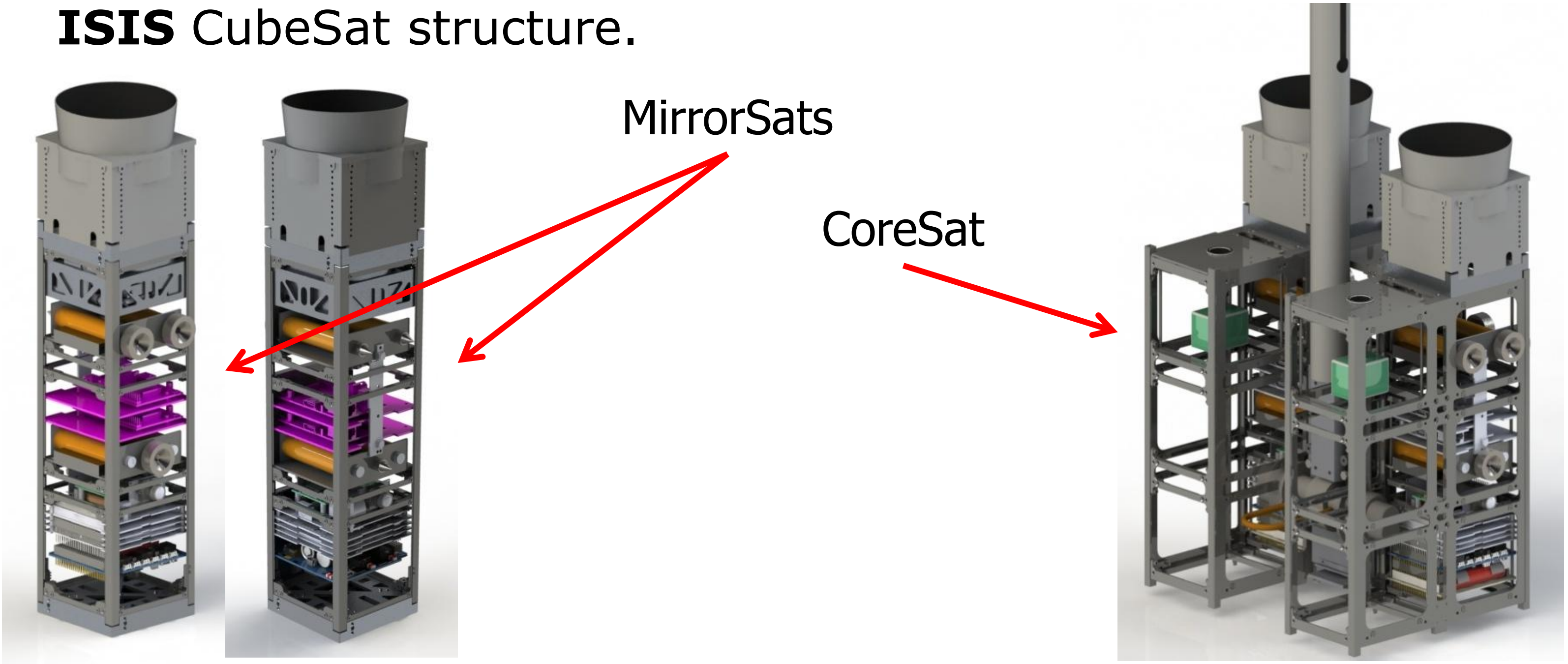
STRaND-1 (2013)



AlSAT1-Nano CAD

Spacecraft Design

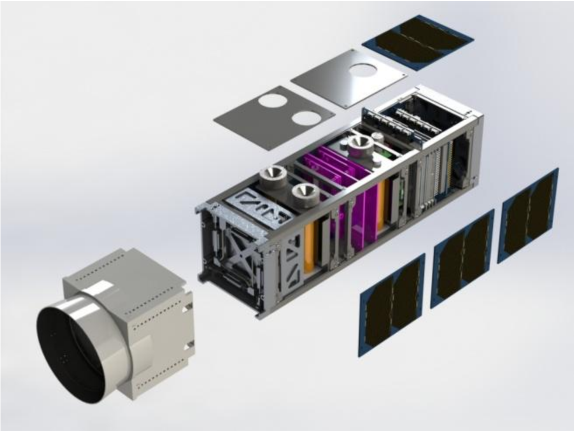
- **Spacecraft Bus – Design Approach**
  - Maximise use of COTS technology (e.g. Leverage CubeSats).
  - **Modular** approach
  - Maximise commonality with other SSC CubeSat programmes.
  - Spacecraft bus is treated as a "**CoreSat**" based on **two 6U + one 3U ISIS** CubesSat structures mechanically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



DDR Configuration Sept. 2014

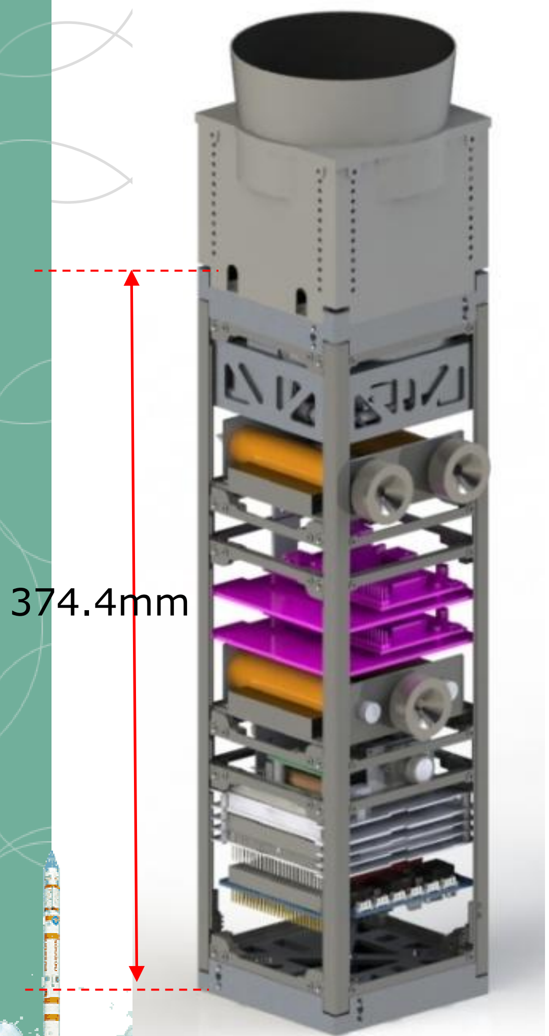
AAReST MirrorSat

- **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);
    - $\pm 45^{o}$ full cone angle; < 5 cm offset
    - $< \pm 10^{o}$ relative RPY error;
    - < 1 cm/s closing velocity at 30cm;
    - $< \pm 2^{o}$ relative RPY error at first contact.



Spacecraft Design

- ## 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)

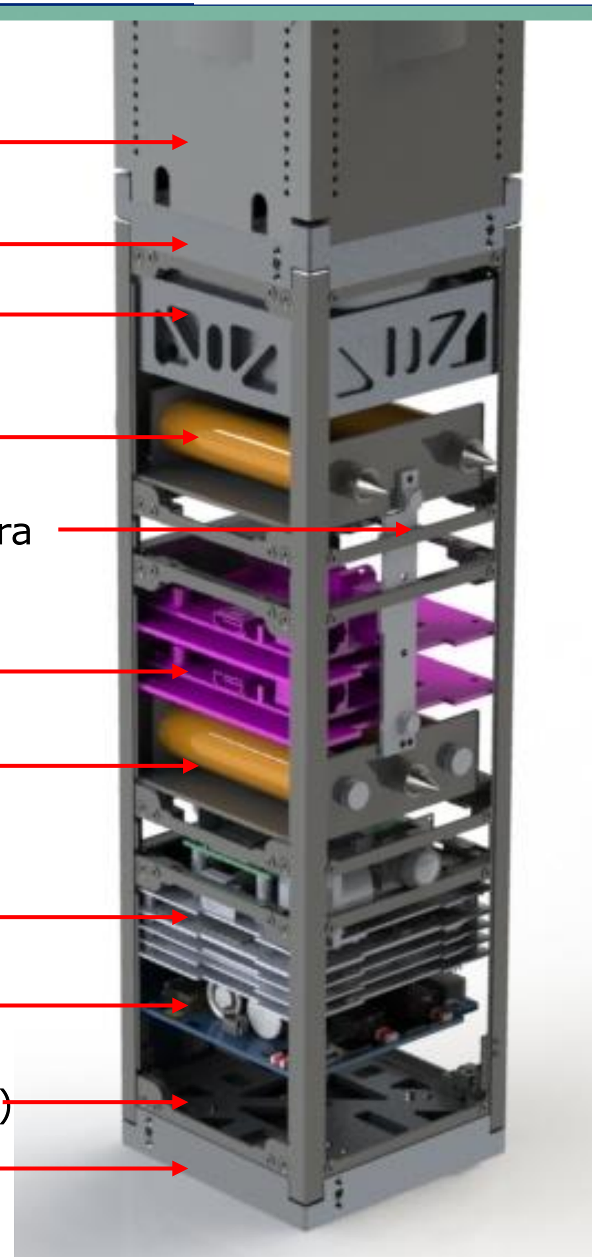
Bottom Docking System

ADCS – QB50

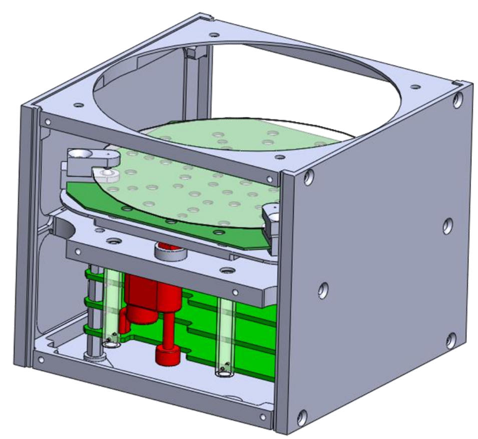
EPS - Gomspace

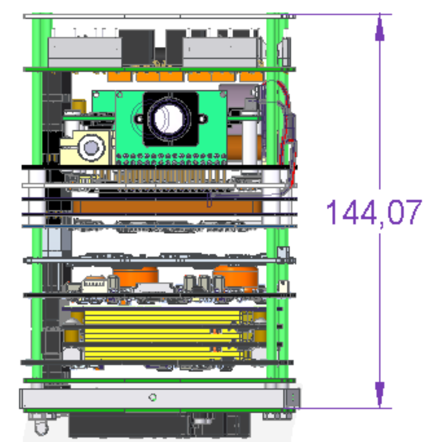
Prop. Sys. Driver (not shown)

Bottom Propulsion Unit

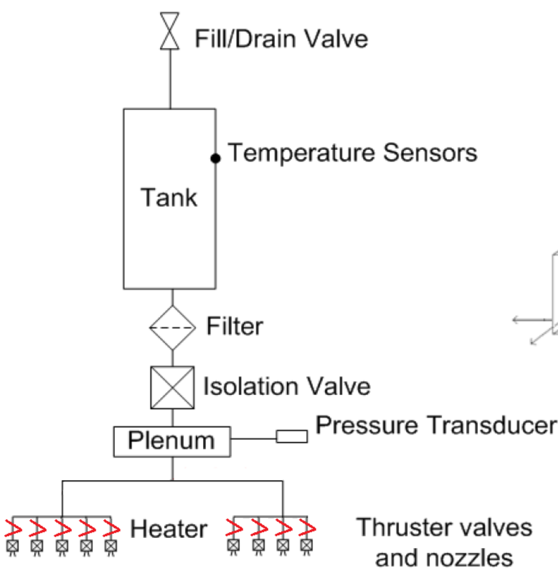


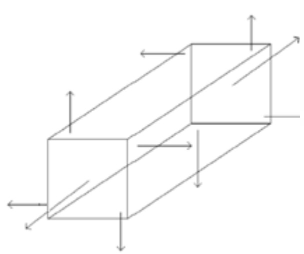
- **MirrorSat System Layout Update 2015**
  - The Softkinetic DS325 LIDAR/Camera is no longer available. However, a similar substitute has been found.
  - The 2015 Docking Sensor tests were done with an *ASUS Xtion* Sensor with the output retrieved on a COTS Raspberry Pi.
  - The dual "Industrial" R-Pi board has successfully been implemented.
  - The MirrorBox has been enlarged to accommodate the mirror (now 106mm x 106mm x 90mm), and the mechanical interface to the propulsion system suitably modified to fit.
  - The Power System may be changed to a ClydeSpace version (as per AlSAT-1N).

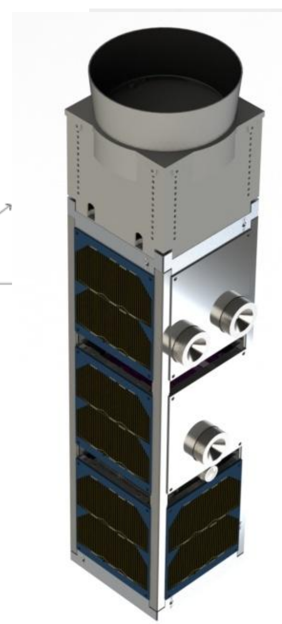


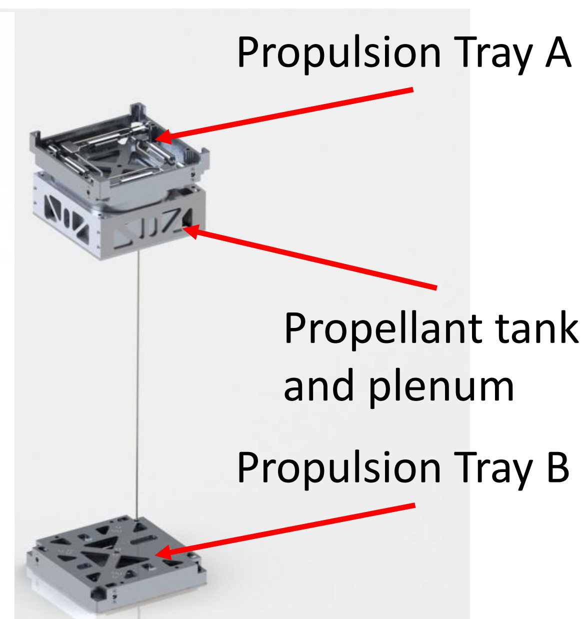


- **MirrorSat Propulsion System**
  - Propulsion unit consists of nine 1W micro-resistojet thrusters to provide ~6DOF (+Z thruster not flown on AAReST due to mirror payload).
  - A new, smaller resistojet design has been made to fit nine thrusters into 3U CubeSat (traditional resistojets are too large)
  - 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

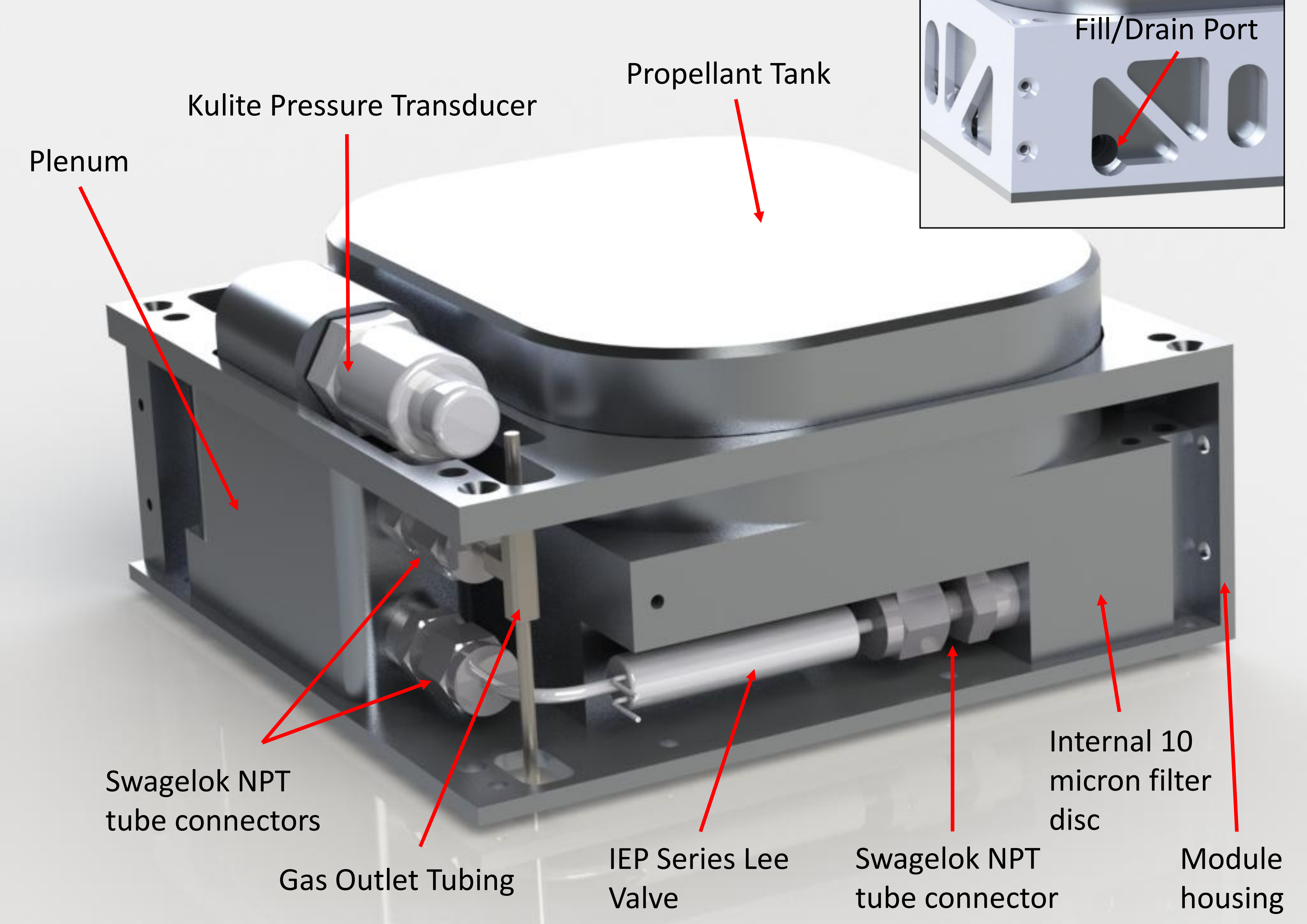






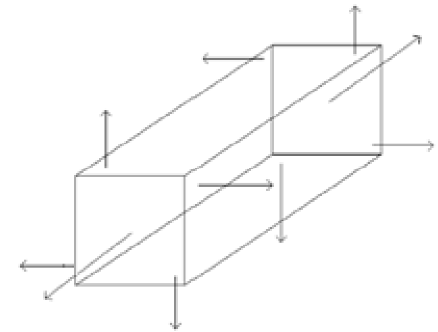


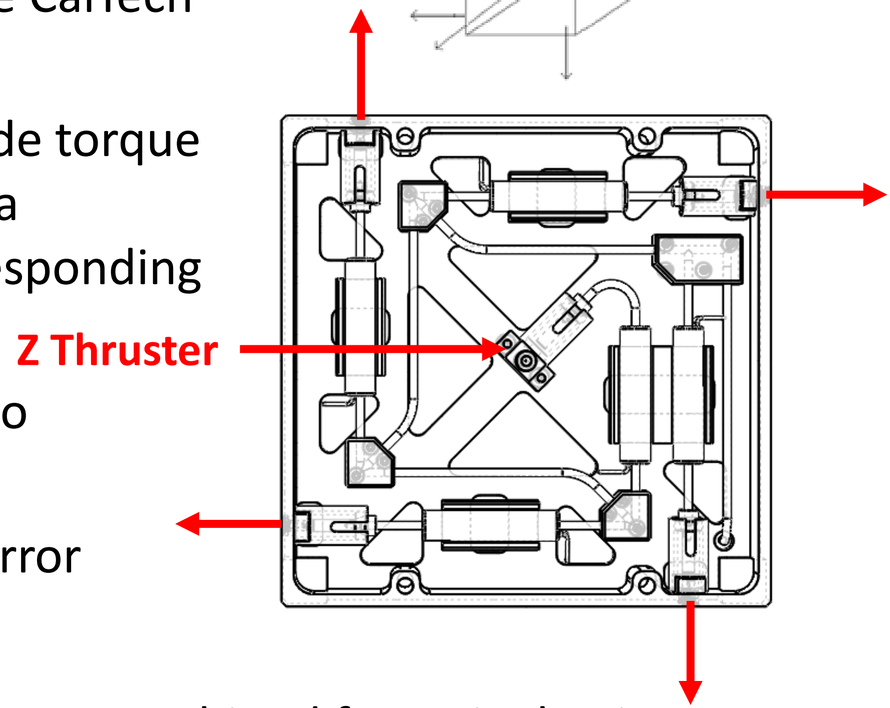
Propellant System with Front Housings Removed

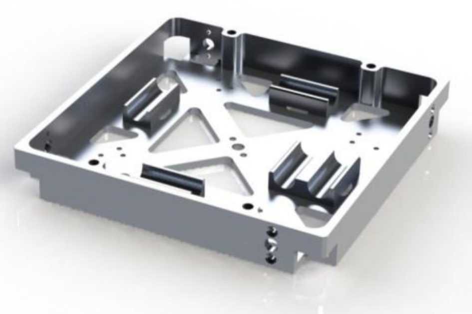


Thruster Mounting Configuration

- Thrusters mounted in propulsion trays on upper and lower end of ISIS structure
- Provides mechanical interface to the CalTech MirrorBox.
- 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





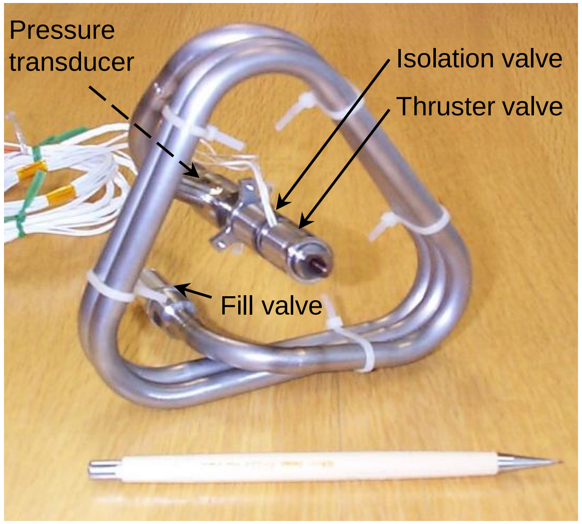


- Thrust trays machined from single piece of stock aluminium for extra rigidity
- Valve mounts built-in to structure

- **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.

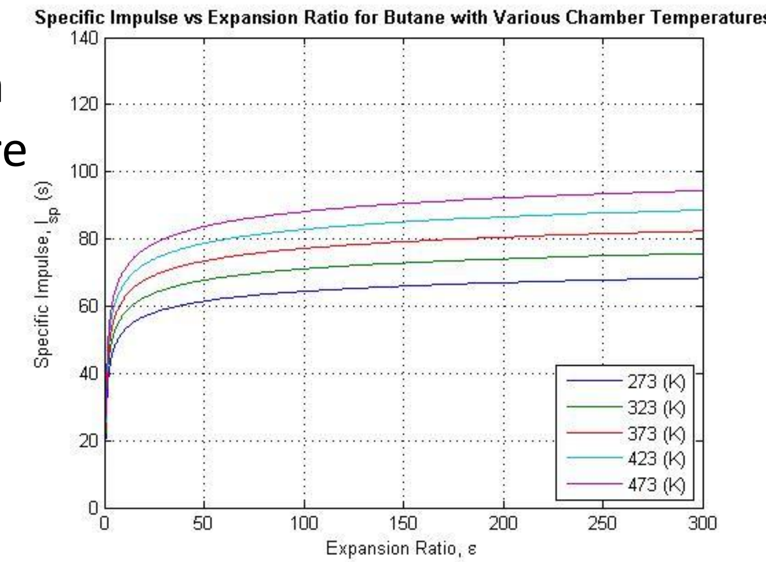
SNAP-1 System for Comparison

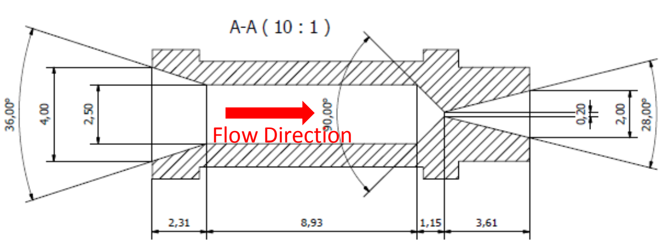
Propellant	**32.6 g butane**
Total impulse	**22.3 Ns**
Thrust range	**25 to 100 mN**
Module mass	**455 grams**
ΔV imparted	**2.1m/s (actual)**



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 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 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.
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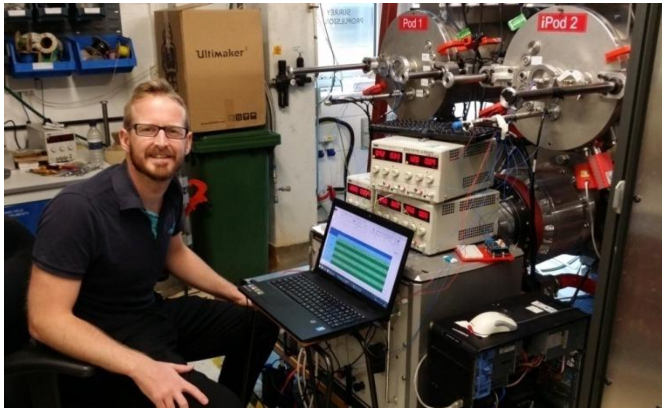
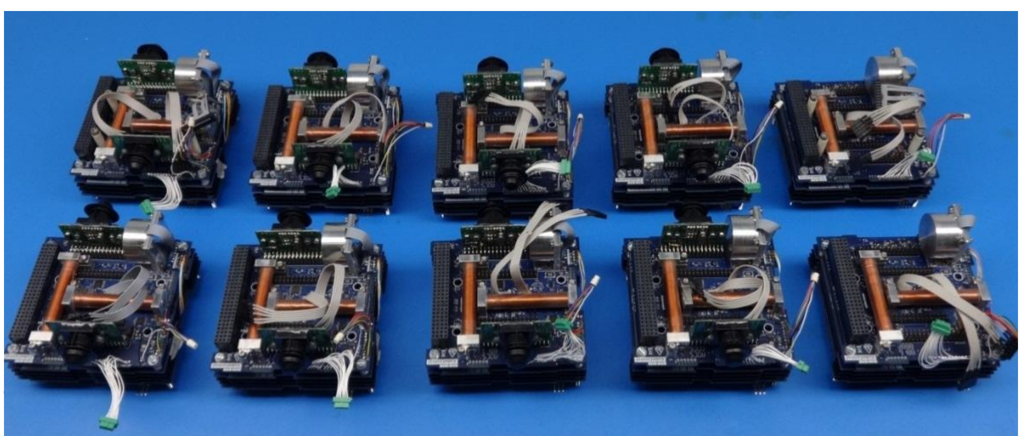
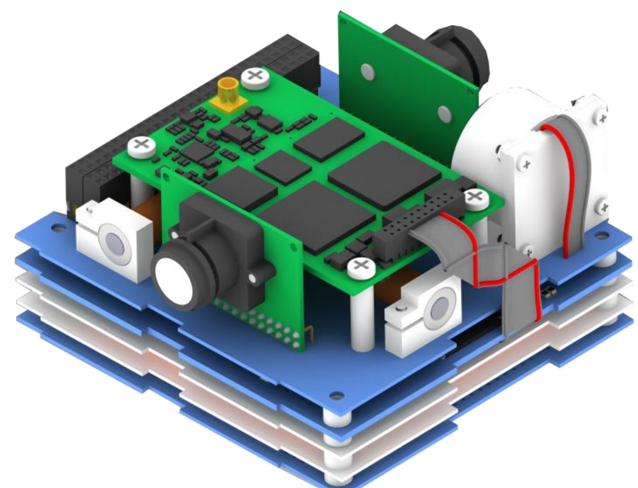


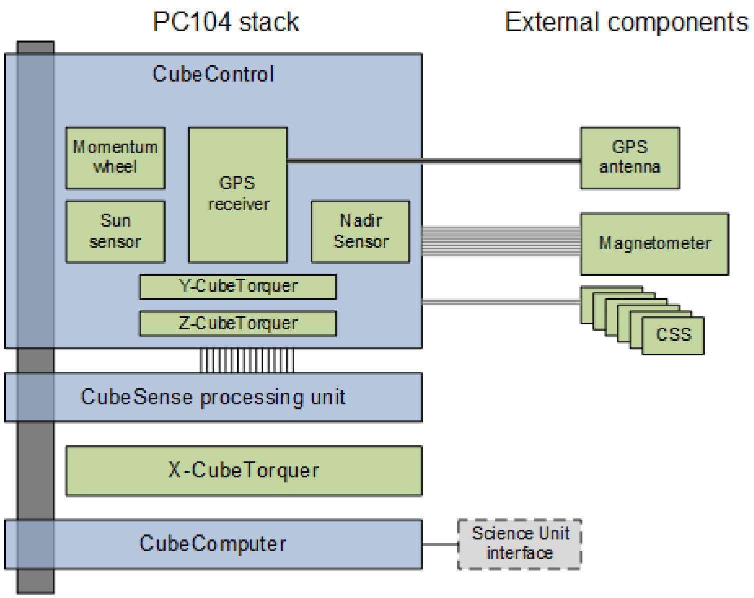
Spacecraft Design

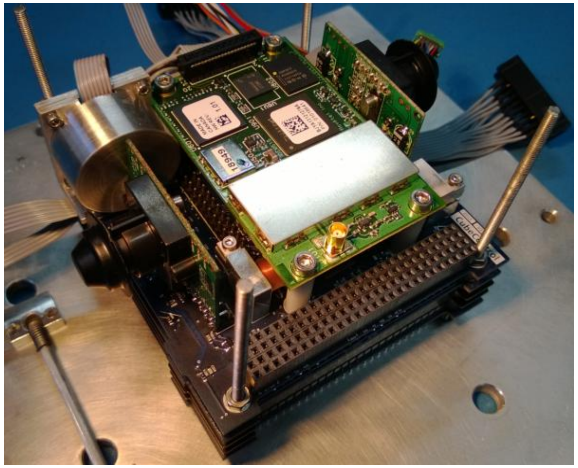
- **MirrorSat ADCS**
  - New compact (450g) Integrated ADCS System developed for QB50 by Prof. Steyn (Stellenbosch) and Lourens Visagie (Surrey).
  - Comprises:
    - CMOS Camera Digital Sun Sensor
    - CMOS Camera Digital Earth Sensor
    - 3-Axis Magnetoresistive Magnetometer
    - 3-Axis Magnetorquer (2 Rods + 1 Coil)
    - Pitch-Axis Small Momentum Wheel
    - GPS Receiver
    - EKF and B-dot control software built-in
    - $\sim 2^{o}$ 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 6 coarse sun sensor photodiodes
- 15 QB50 ADCS Units delivered.
- Flight heritage on STRaND-1, two QB50 pre-cursor missions and DeploySail.

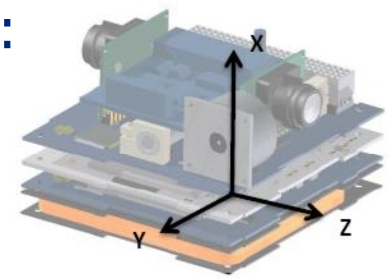


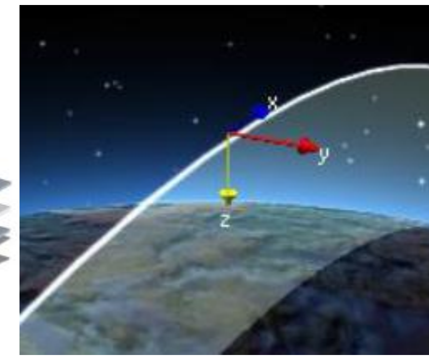


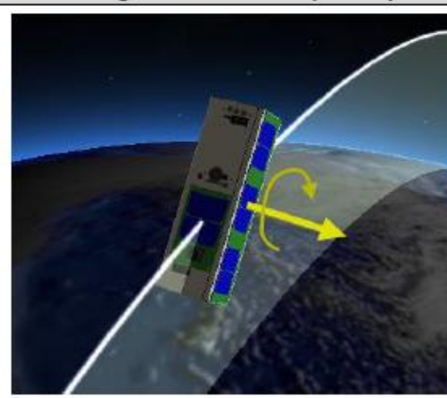
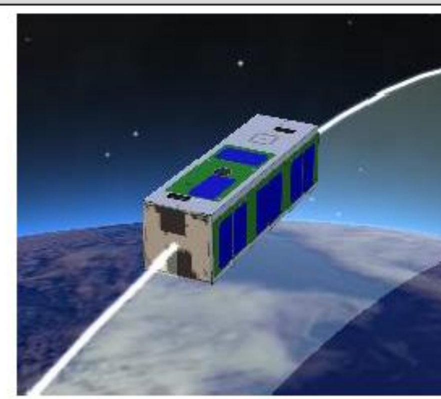
Spacecraft Design

- **MirrorSat ADCS Update 2015**
  - A PhD student: Abdelmadjid Lassakeur, started in July 2015 with the topic of Precision ADCS for CubeSats.

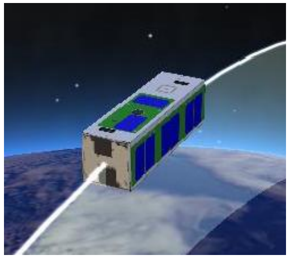
- Results from QB50 Precursors:
  - Note X and Z axes swapped with respect to AAReST MirrorSat





Control mode	Detumbling control mode (steady-state)	Y-momentum mode
		
Attitude angles	Roll = yaw = 0 Pitch: 	Roll = yaw = 0 Pitch = θ_{ref}
Angular rates	$\boldsymbol{\omega} = [0 \quad \omega_{y,ref} \quad 0]$	$\boldsymbol{\omega} = [0 \quad 0 \quad 0]$

- **MirrorSat ADCS Update 2015**
- QB50 Precursor ADCS Status
  - In-flight calibration of QB50p1 and p2 magnetometers
  - Unexpectedly high rotation rates due to disturbance torques when ADCS is off – however, with ADCS on, Y-momentum stabilized attitude demonstrated on both satellites
  - Y-momentum mode on P2 activated for a full orbit
  - P1 for 15 minutes (power budget issues)
  - Pitch angle controlled to zero
  - Angular rates controlled to zero
  - Roll and Yaw angles drift due to external disturbances



- Proposed Solutions:
  - Increased magnetic control gains.
  - Include quaternion error terms in cross-product magnetic controller (requires code upload – cannot be done for precursor satellites).
  - Both fixes now implemented in Version 2.0 of the ADCS code.
  - AAReST would use updated flight code.

- **MirrorSat ADCS Update 2015**
- Need for all 6 Coarse Sun Sensors (CSSs)
  - Most QB50 satellites will have a science payload on one end, which precludes the use of 6 CSSs (one per facet) – only 5 are used.
  - From the precursors we found the strategy of using only 5 photodiodes (and estimating missing facet value) is not accurate – there is an ambiguity when the Sun is almost at 90 degrees to the facet with the missing sensor.
  - The ADCS does not *need* the CSSs, but they do provide valuable feedback (Magnetometer deployment, angular rates, attitude angles without requiring CubeSense)
- Proposed Solution:
  - Apply 6th photodiode to the AAReST MirrorSat, attached to the MirrorBox (they are very small).

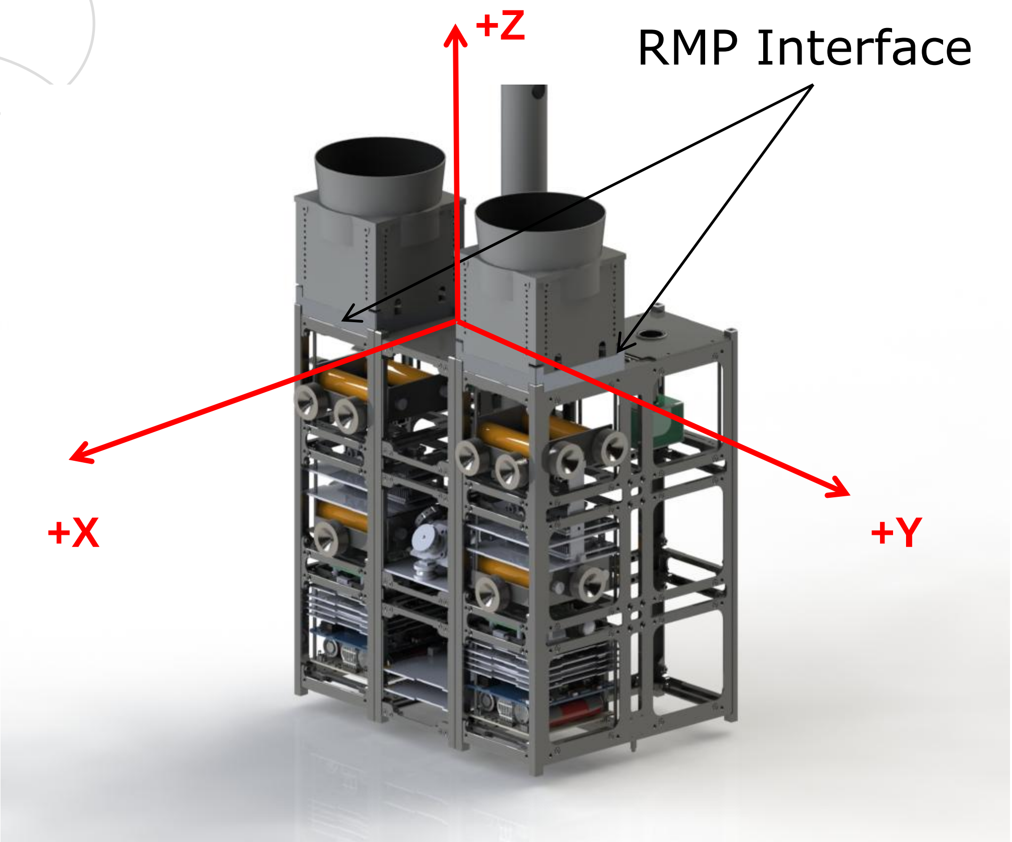
AAReST CoreSat

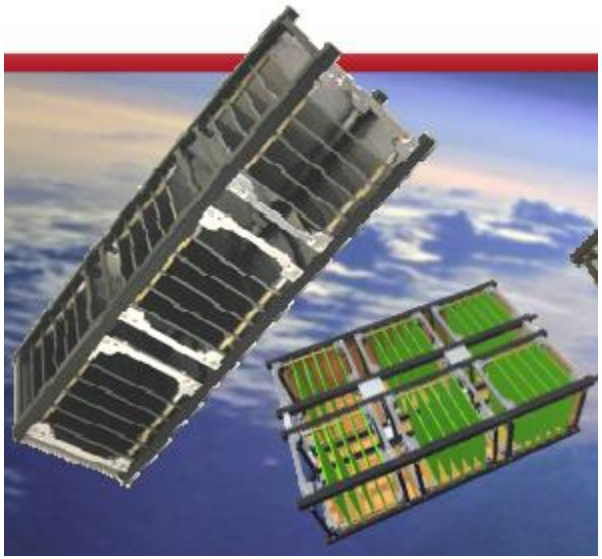
Spacecraft Design

- **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

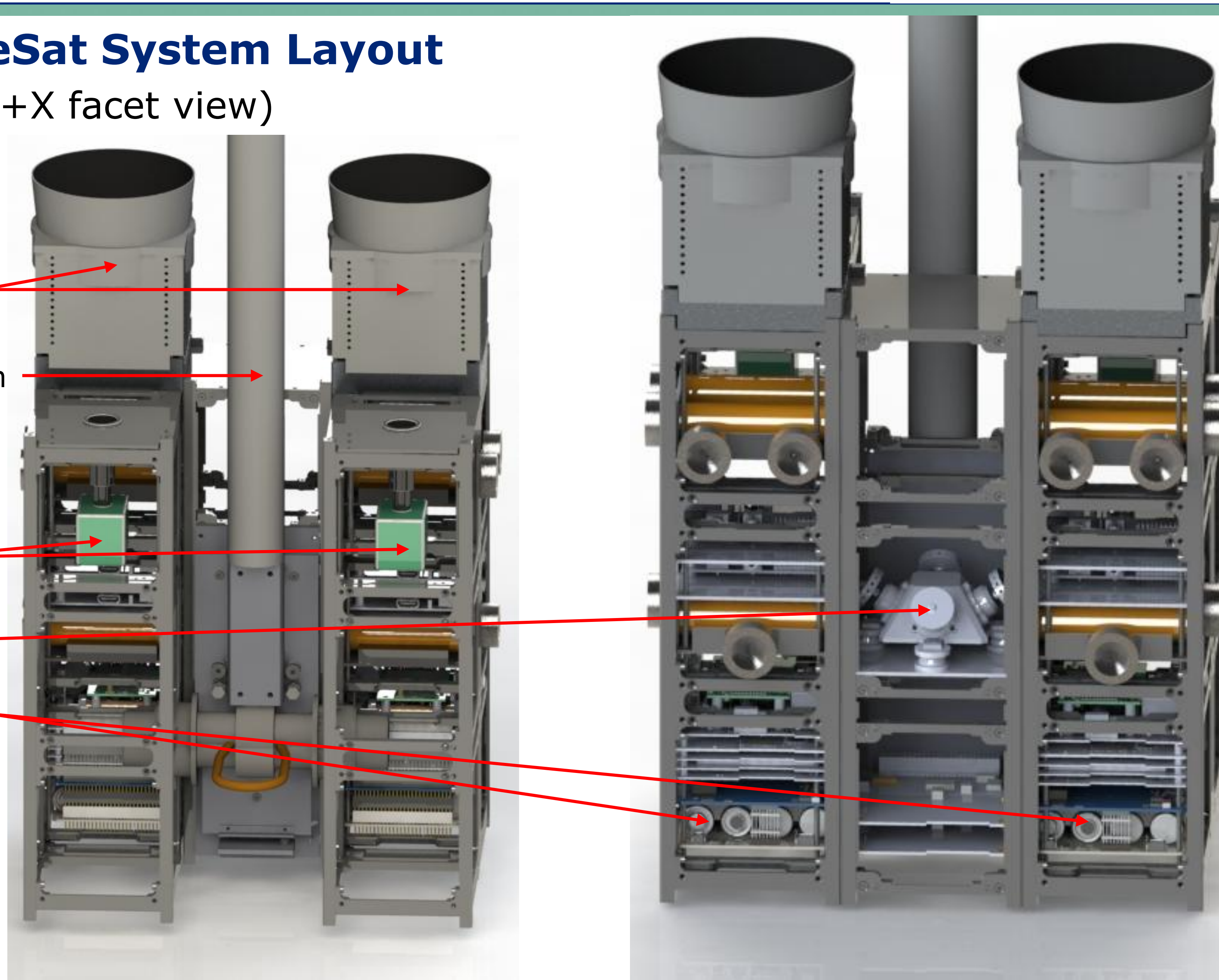
- **CoreSat Structure**
  - Structure rendering showing two 6U structures (+Y and -Y) separated by a single 3U structure (MirrorSats not shown)





Spacecraft Design

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



- **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

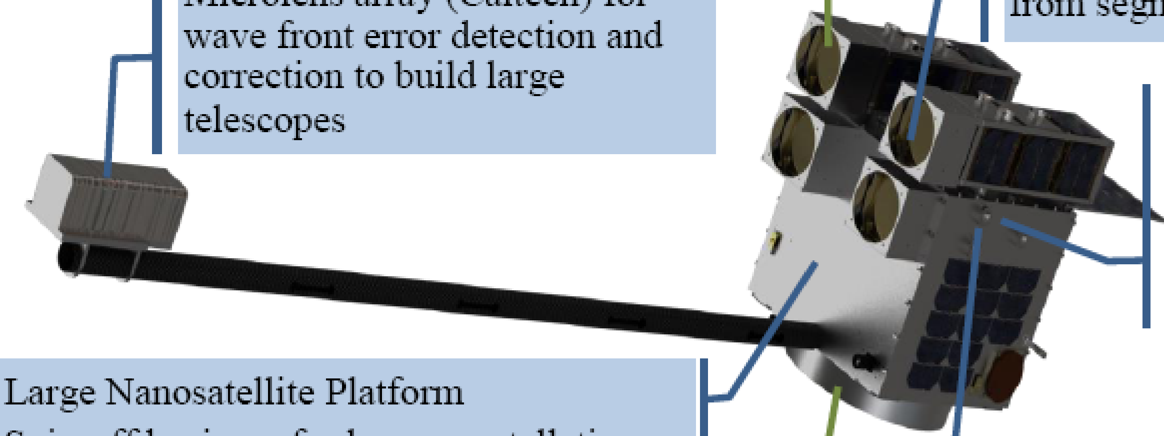
Spacecraft Design

CoreSat System Layout Update 2015

MirrorSat, with deformable mirror assemblies

Microlens array (Caltech) for wave front error detection and correction to build large telescopes

Piezo-electric deformable mirrors to build large, precise mirrors in orbit from segments



Docking Mechanism (University of Surrey)
Enabling technology for Active Debris removal and in-orbit services

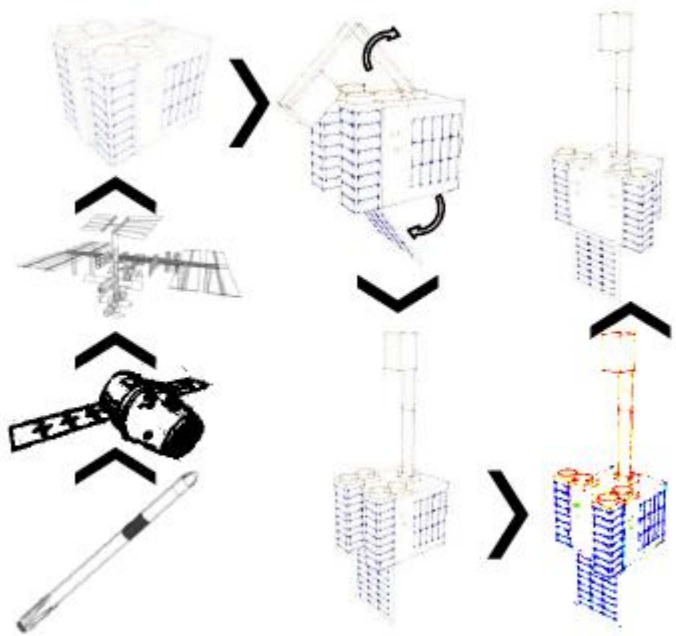
Large Nanosatellite Platform
Spin-off business for large constellation applications

CoreSat, hosting the Camera payload on a deployable boom, the main avionics and two rigid mirrors

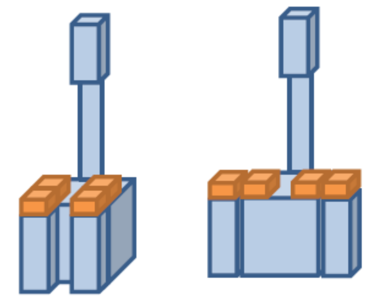
Advanced GNC Suite
Enabling technology for Active Debris removal, in-orbit services

Spacecraft Design

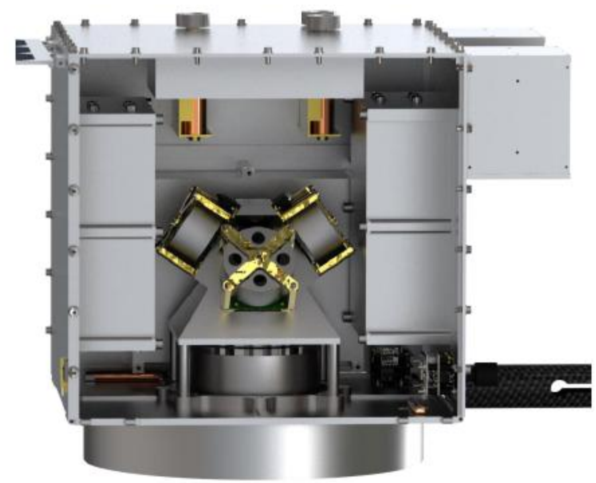
- **CoreSat System Layout Update 2015**
  - The High-Level Mission CONOPS are unchanged, however, here we are explicitly targeting a launch from the ISS:



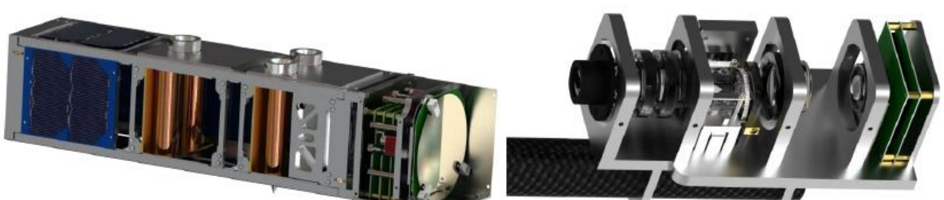
SSTL-50-Based AAReST Mission Launch and Deployment (from ISS)



SSTL-50 Based AAReST Compact and Wide Imaging Modes



CoreSat Internal Layout
SSTL-50 (27U – 34cm x 34cm x 34cm)

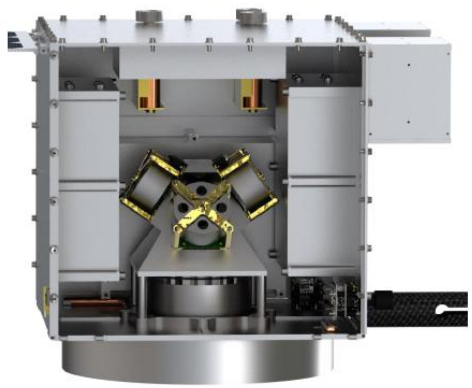


MirrorSat and Camera Internal Layout

Spacecraft Design

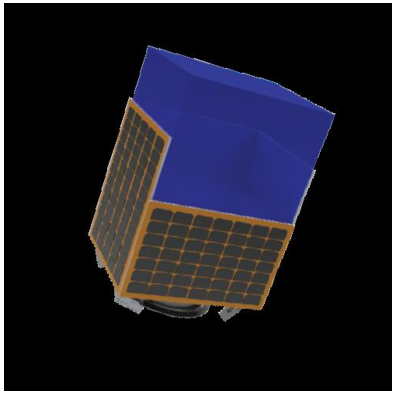
- **CoreSat ADCS**
  - Uses Compact Integrated ADCS system (as per MirrorSats), but replaces the single small pitch MW with four Surrey RWs (**4-RWA**) with dampers for increased control authority/low jitter control
  - Pointing (< 0.1^{o} error all axes), stability (< 0.02^{o}/s for 600s)
  - Slew-Rate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

- **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 the preferred option.



SURREY SATELLITE TECHNOLOGY LTD

Generic SSTL-50 Platform and Specifications

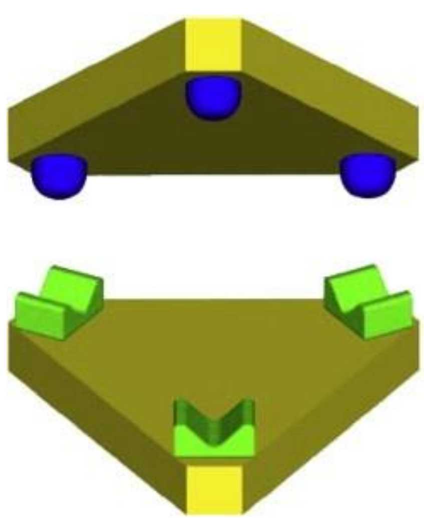


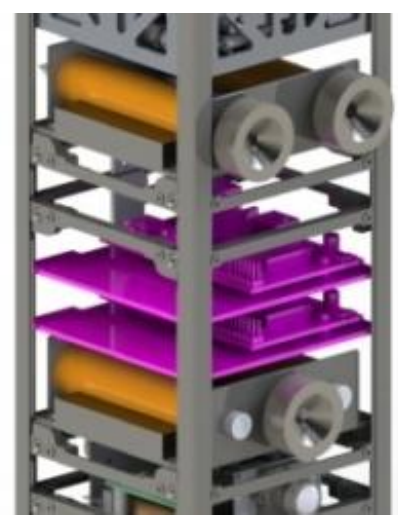
Payload Instrument Mass	Up to 45 kg
Payload Volume	Width 530 mm, Depth 430 mm, Height 400 mm
Payload Orbit Average Power	Typically 35 W
Payload Peak Power	Typically 85 W
Payload Data Bus	Gigabit per second to on-board storage or high speed downlink.
Attitude Control	Earth referenced or inertial; stability: 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

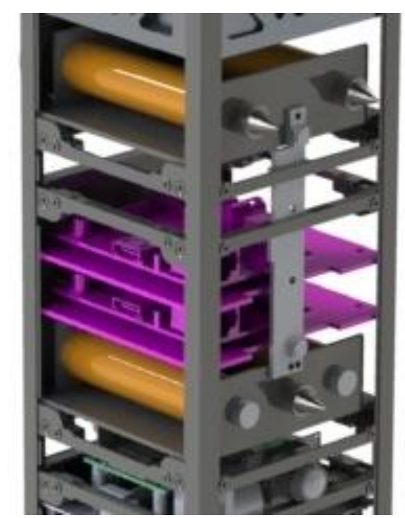
AAReST RDV & Docking

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" (60º cone and 45º cup) type mechanical docking ports
  - Kinematic constraint is established using the Kelvin Clamp principle (3 spheres into 3 V-grooves arranged at 120º)

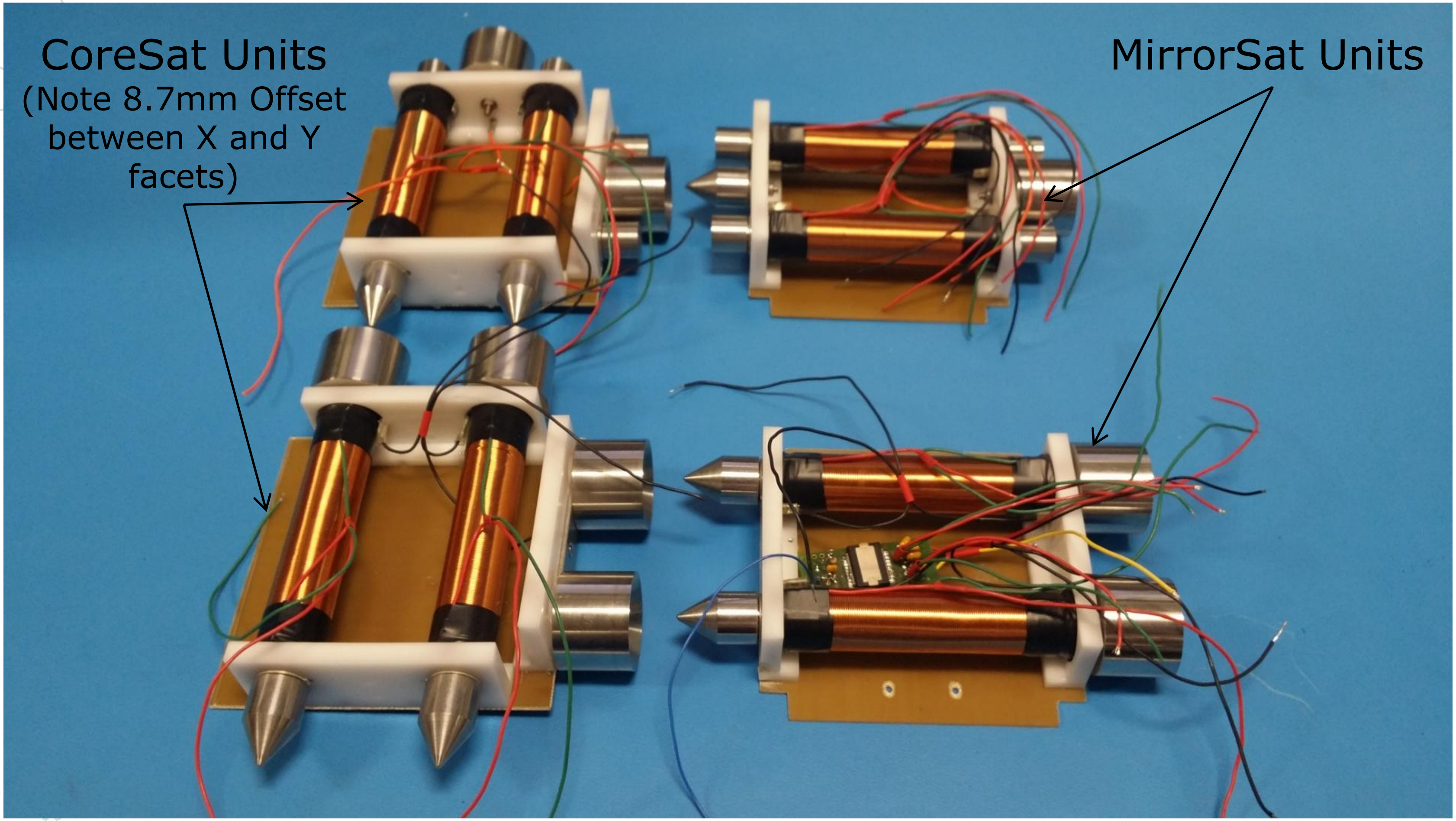






RDV/Docking

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



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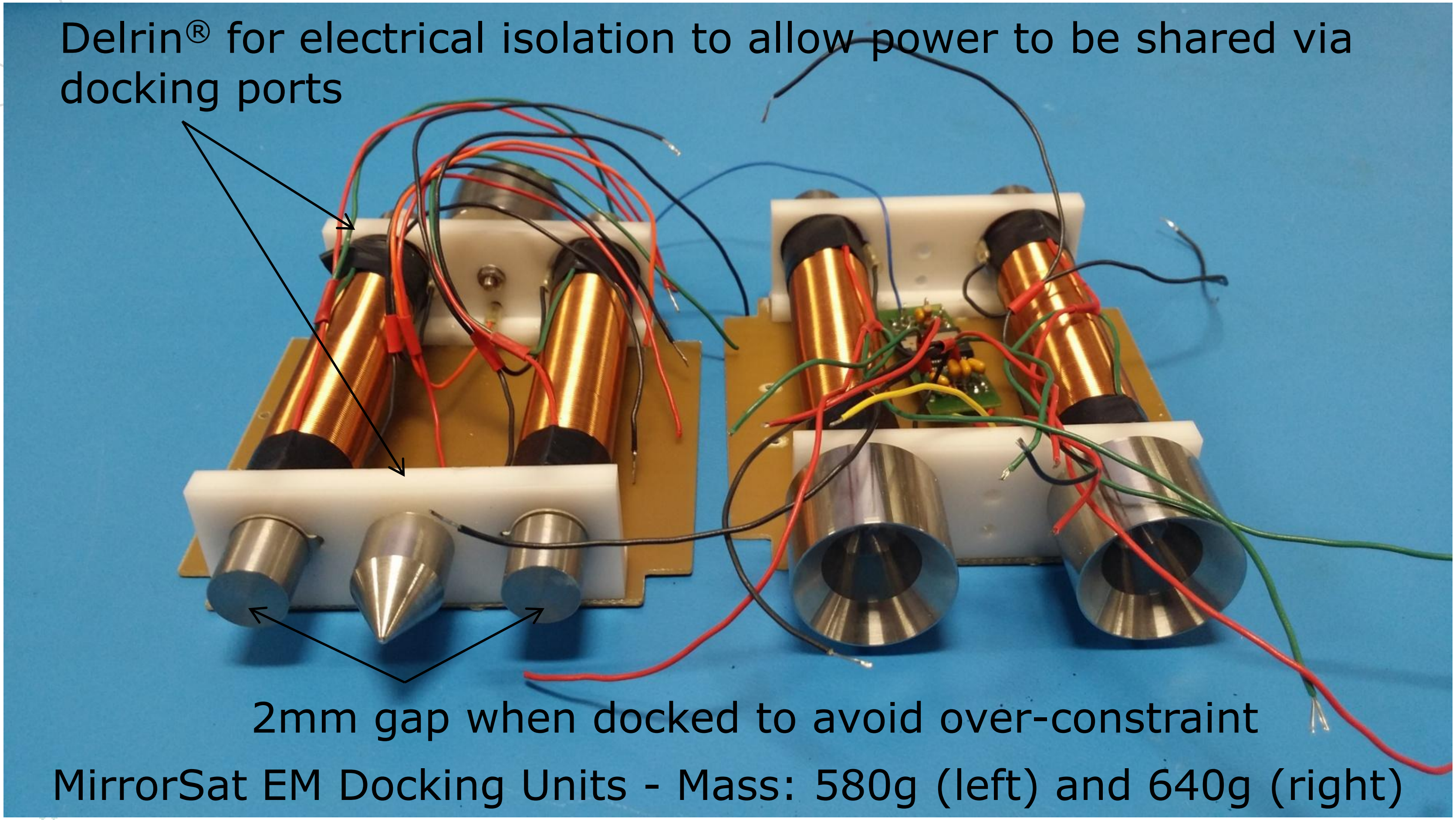

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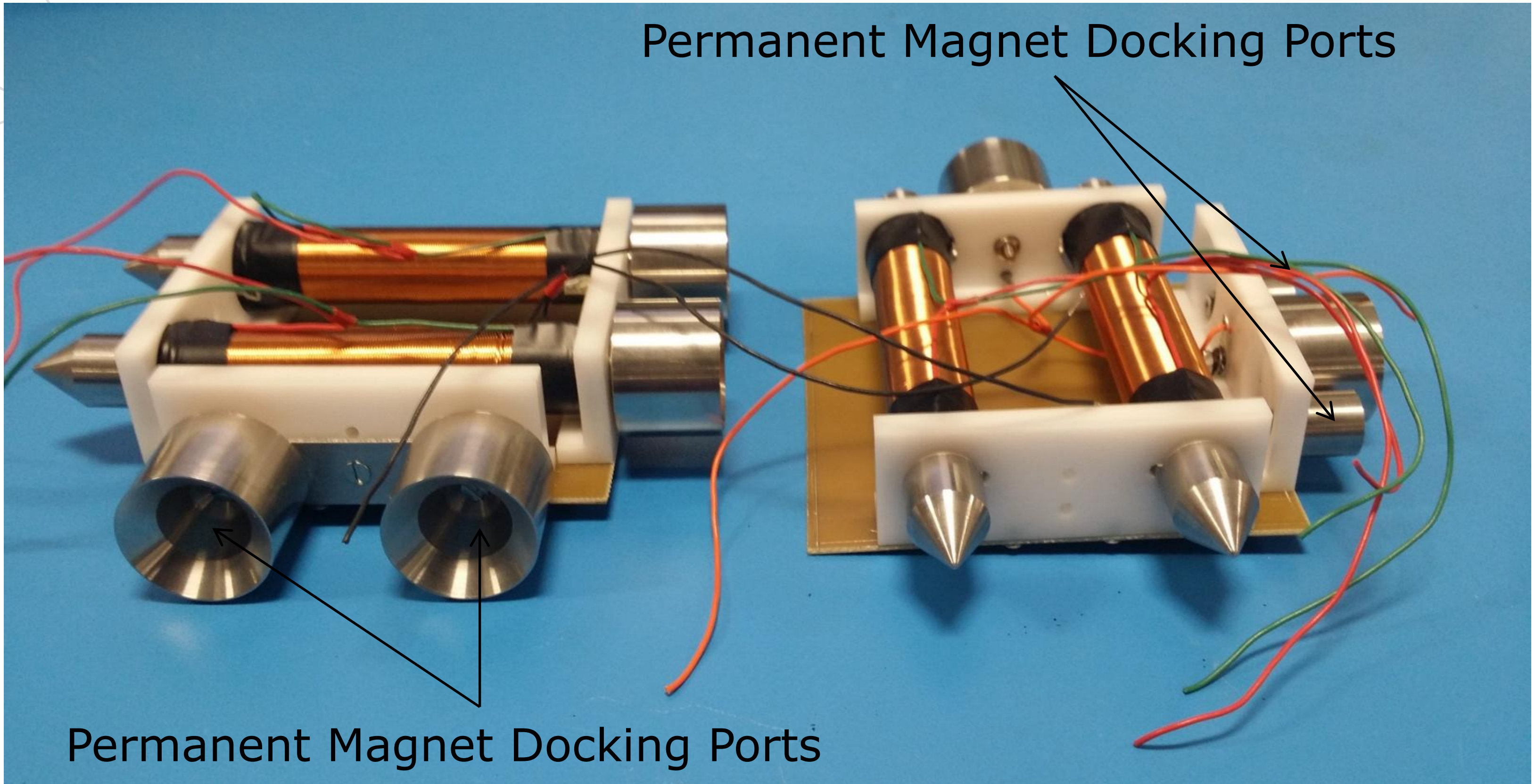
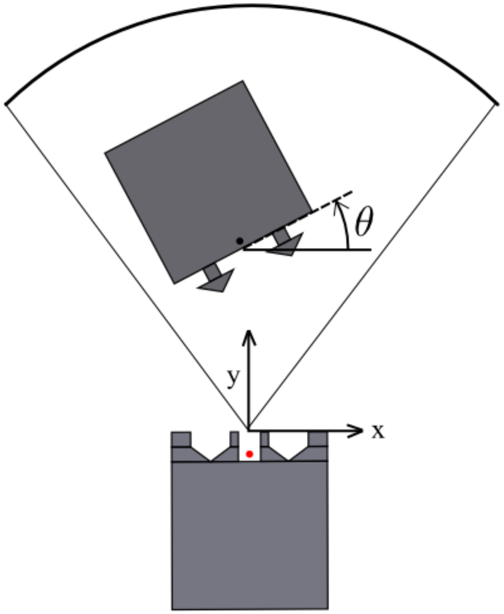


CoreSat EM Docking Units - Mass: 830g (left) and 760g (right)

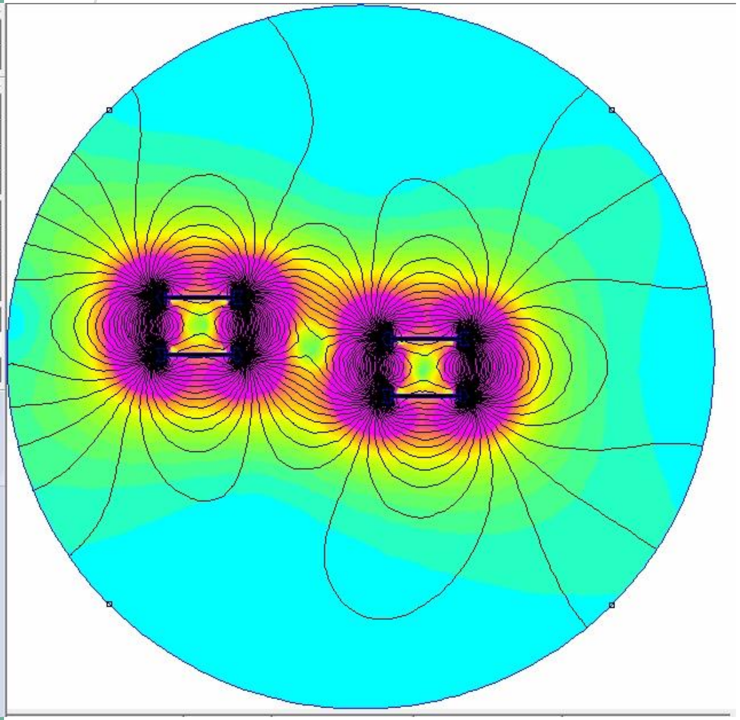
RDV/Docking

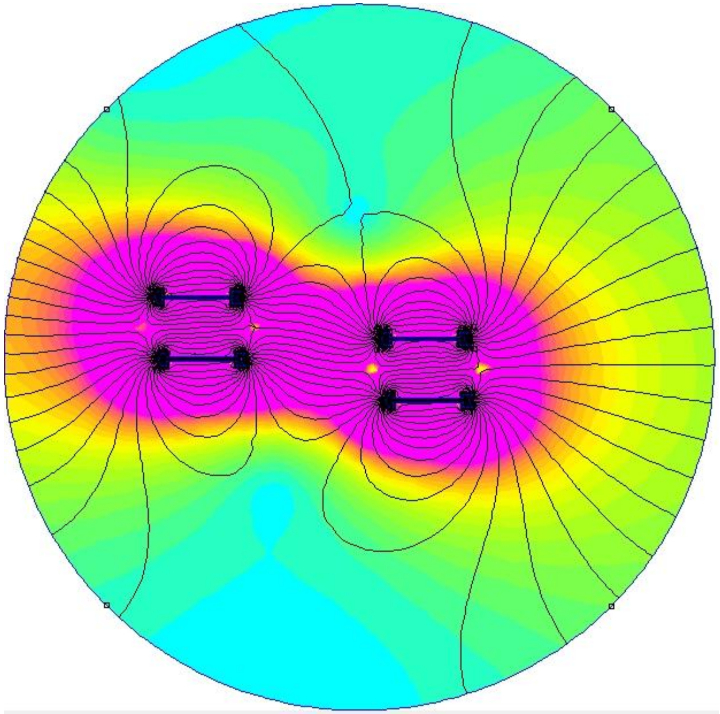
- **EM Docking System Testing**
  - CalTech and SSC initial Air-Bearing Table experiments show:
    - Capture distance is between 20-30cm for two pairs
    - Automatic self-alignment works, but choice of polarities is important to avoid miss-alignment/false-capture.
    - Attractive force is highly non-linear!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

- **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.

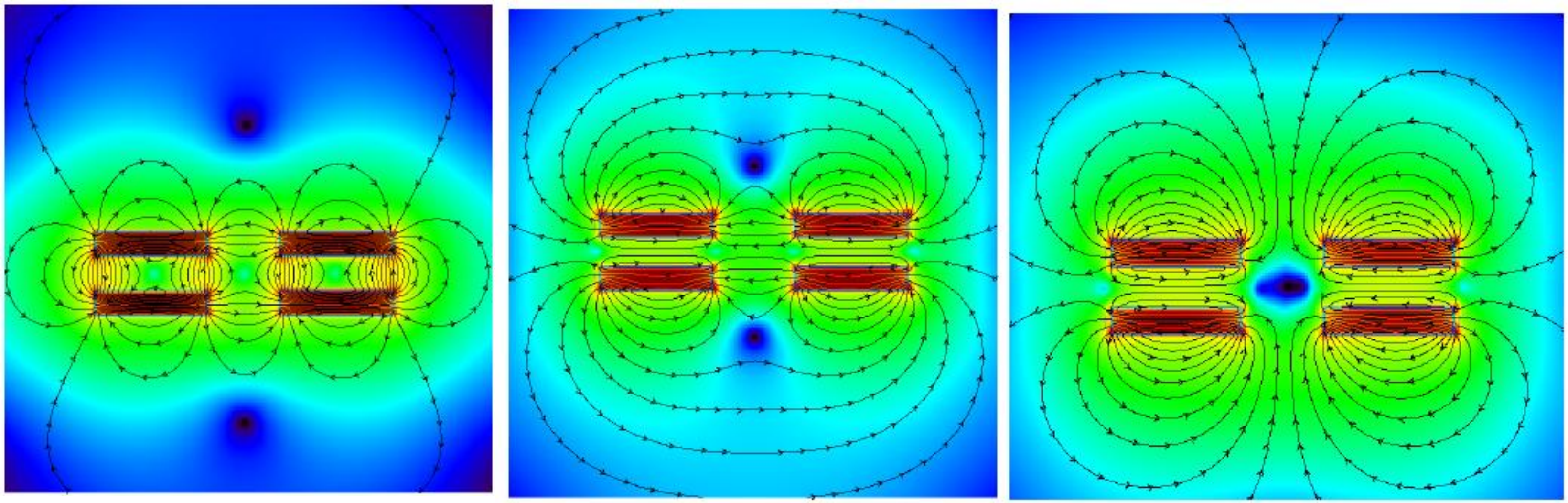
Distance/cm	Force/N	Acc./ms^{-2}	Time to Impact*/s
0.2 (min)	6.07	1.21	< 0.06
0.5	1.62	0.324	< 0.17
1.0	0.564	0.113	< 0.42
2.0	0.181	0.036	< 1.05
5.0	0.036	0.0072	< 3.73
10	0.009	0.0018	< 10.5
15	2.68 mN	0.000536	< 23.7
20	1.140 mN	0.000228	< 41.9
25	0.569 mN	0.000114	< 66.2
30	0.334 mN	0.000067	< 94.6

RDV/Docking

- **EM Docking System Update 2015**
  - A PhD Student: Ahmad Modibbo, started in January 2015, with the topic of examining the control and dynamics of the EM Docking System on AAReST.
  - He is currently looking at modelling the magnetic forces in 3D
  - An MSc project (Enda McKenna) "AAReST Spacecraft Electro-magnetic Docking System" was completed this year.
  - Objectives:
    - Redesign docking port receiving cup or 'Drogue' to allow acceptable kinematic constraint.
    - Investigate whether including small permanent magnets would be suitable for achieving powerless hold.
    - Re-design module base plate to CubeSat standard size and incorporate H-bridge driver circuit into PCB.
    - Assemble test models of CoreSat and MirrorSat.
    - Demonstrate docking on an air-bearing table and characterise the system.

RDV/Docking

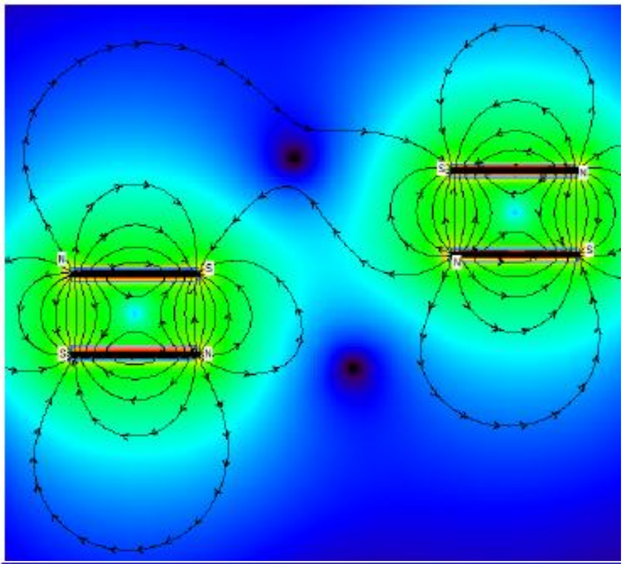
- **EM Docking System Update 2015**
- (MSc Project)
  - A simple 2D simulation was set up using the Vizimag software to help visualise the characteristics of the solenoids placed at various distances, polarity configurations and angular offsets.

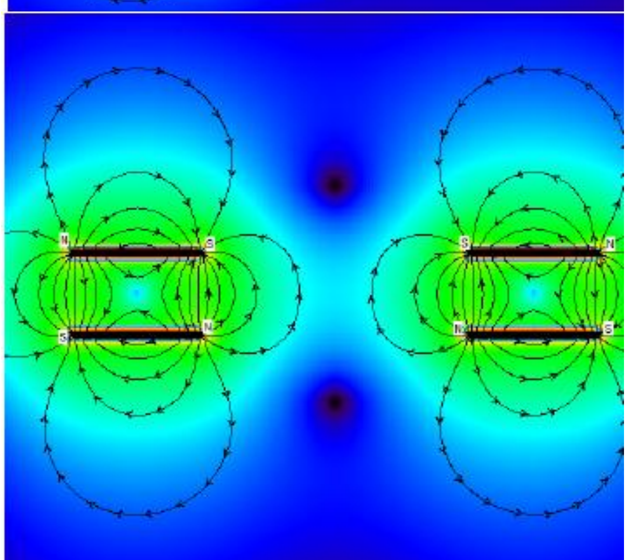


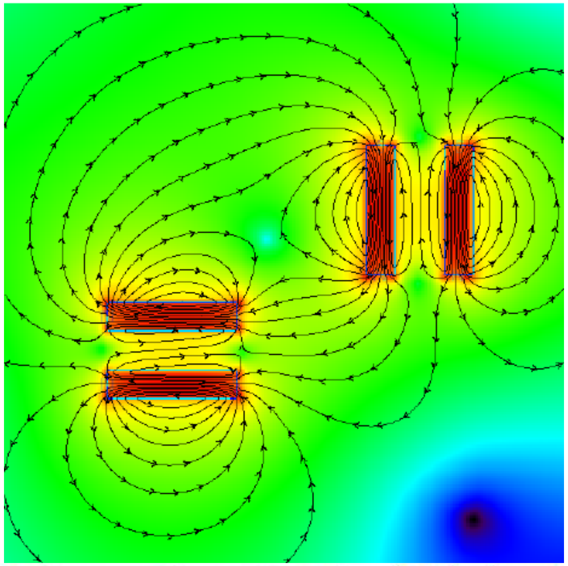
EM Docking Systems at 10cm Separation – Attract and Repel Modes
Note – when alternating polarities are used on each spacecraft (left panel) – the attractive/repulsive forces are smaller than if the same polarities are used (middle and right panels)

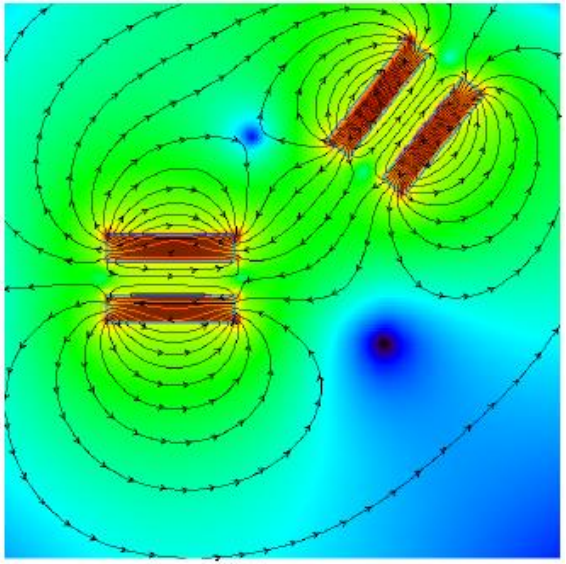
RDV/Docking

- **EM Docking System Update 2015**







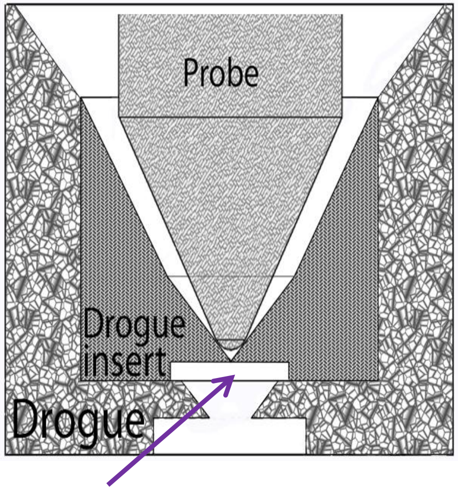


RDV/Docking

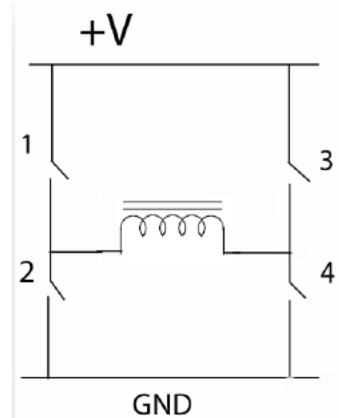
- **EM Docking System Update 2015**
  - Simulation and practical experiment show that if the magnets on each spacecraft have alternating polarities, then disturbance torques from the geomagnetic field are minimised, however, the forces between the spacecraft are small.
  - If the magnets on each spacecraft are polarised the same way, then the attraction/repulsion forces are large – but the geomagnetic torque is also large.
  - The best compromise appears to be to use the ADCS system to counter the geomagnetic torque when operating the Docking System. This is a subject for further study.
  - Care has to be taken to avoid miss-alignment/false-capture.
  - We see "near field" and "far field" effects determined by separation distance in comparison to solenoid spacing.
  - **Conclusions**: the spacecraft need to be in each others "capture cone" with the appropriate relative pointing in order for the docking system's self-alignment action to occur – thus there needs to by a well constructed *dynamic control loop* between the RDV sensor and the EM Docking System.

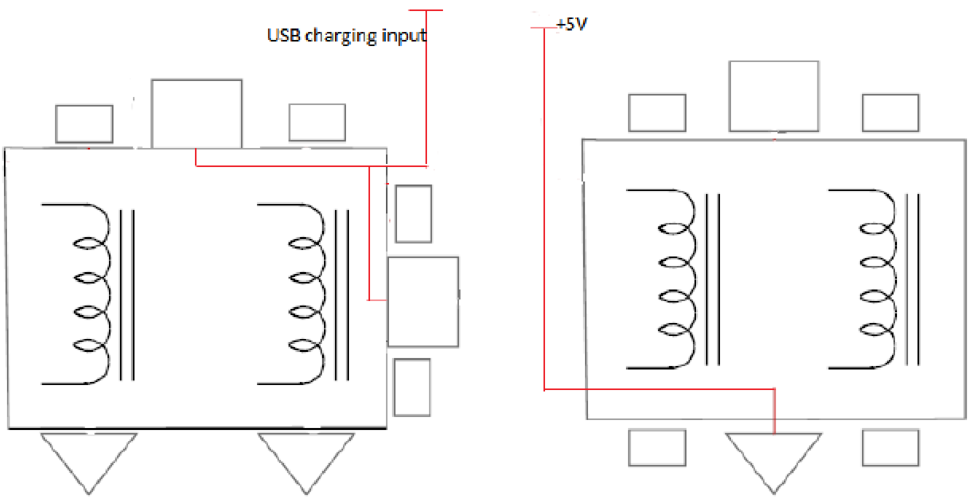
RDV/Docking

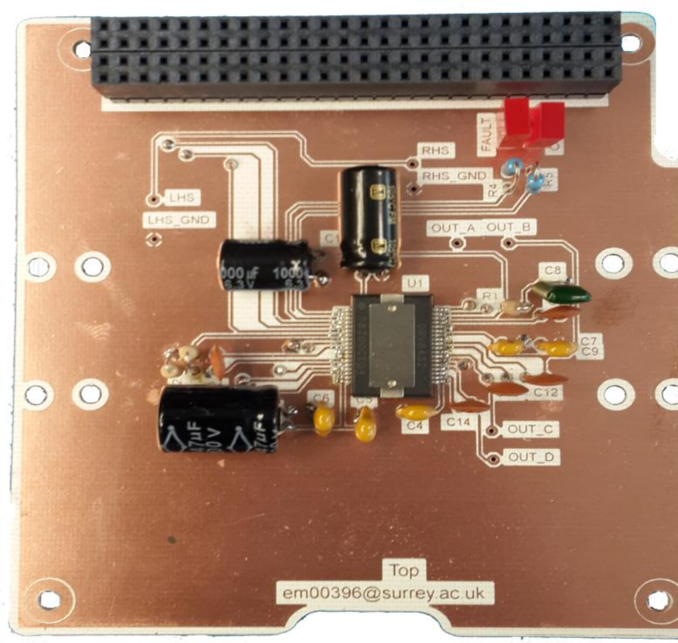
- **EM Docking System Update 2015**
  - A new two-part drogue has been developed, which aids manufacture and assembly.
  - A built in neodymium permanent magnet (6mm dia., 1mm thick) provides the latching action to hold the spacecraft together when the electro-magnets are turned off.
  - We found the 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).



- **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:

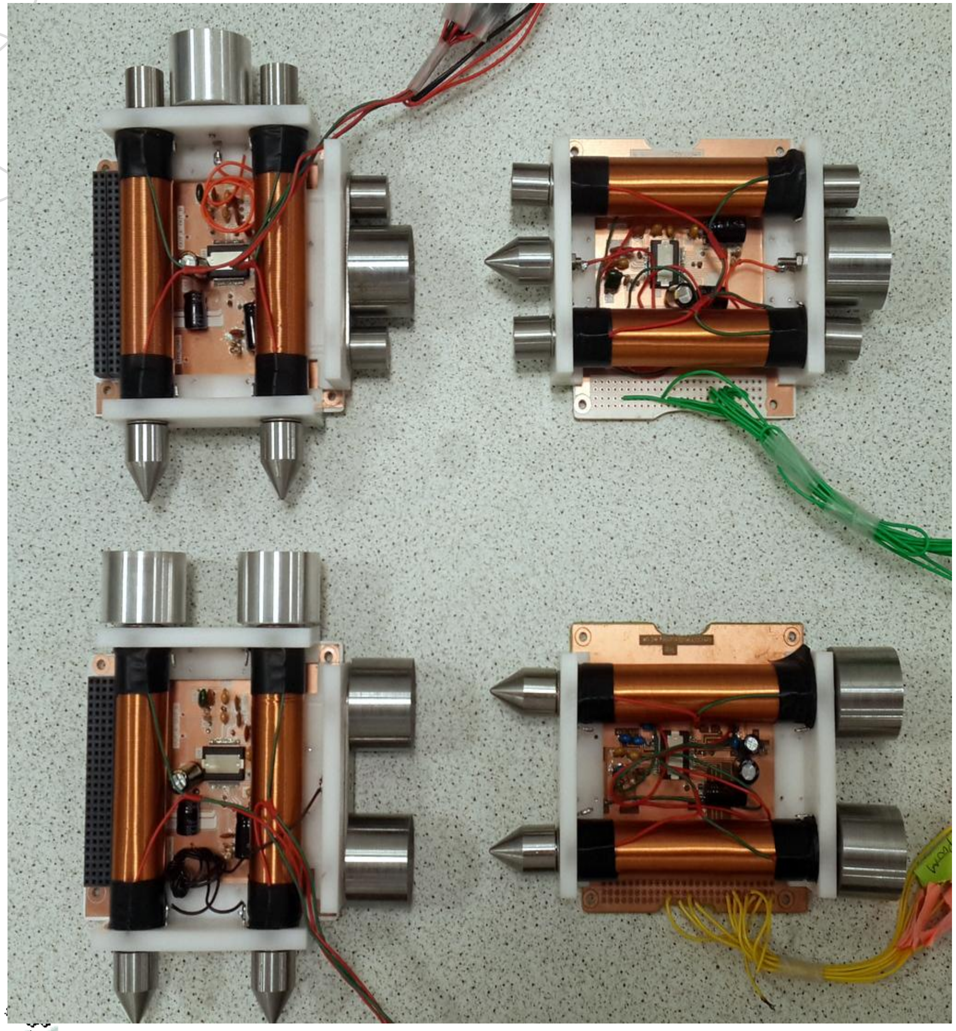


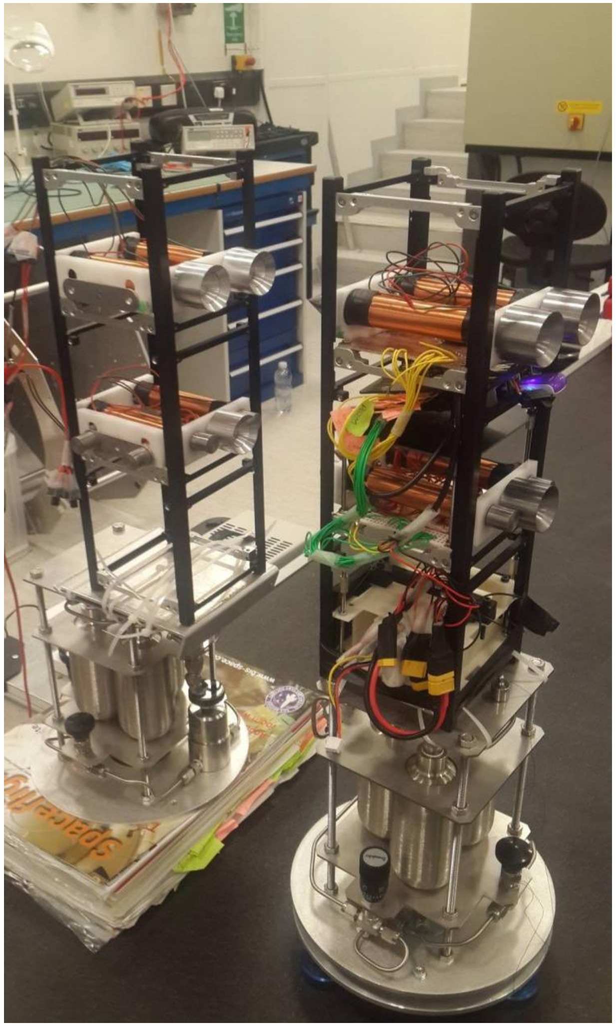




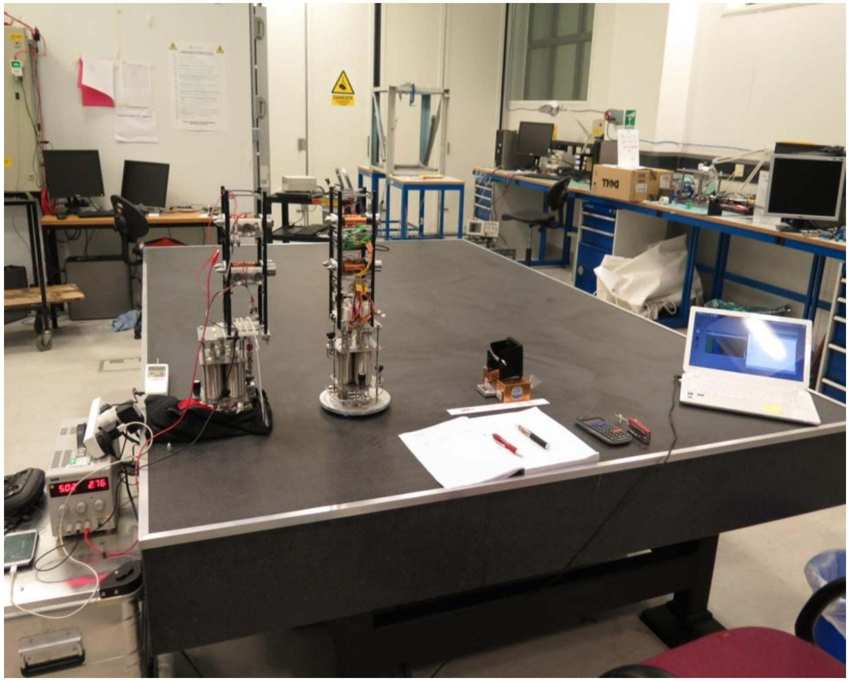
RDV/Docking

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

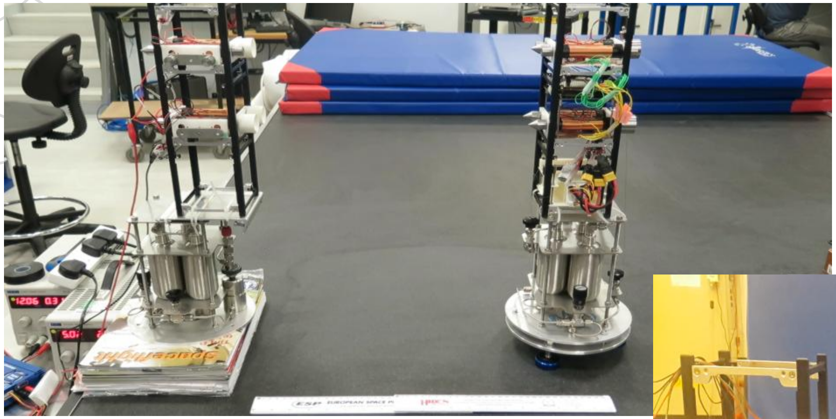




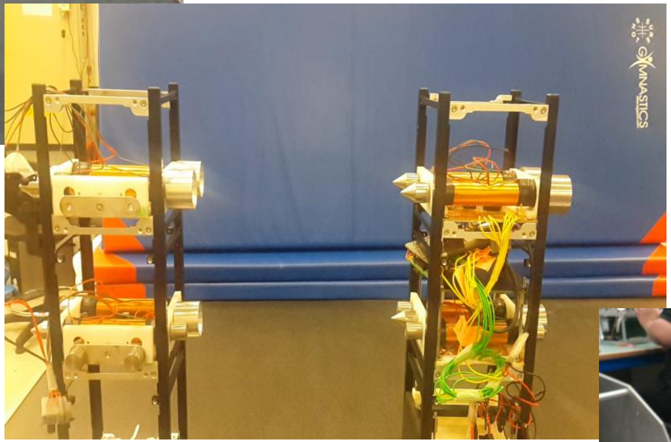
- **EM Docking System Update 2015**
  - 2D air bearing table tests were conducted for:
    - Forces (measured by force meter and weight offset)
    - Acceptance angles (confirmed previous results)
    - Viability of the permanent magnets (~350 mN latching force corresponding to 40% PWM duty cycle to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



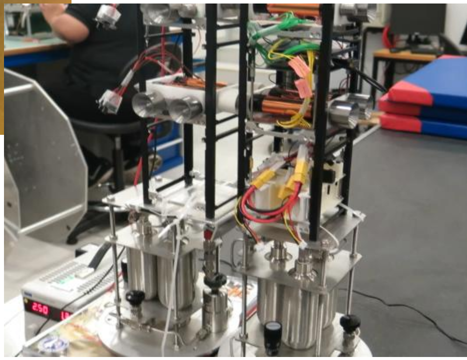
- **EM Docking System Update 2015**
  - Videos: 50cm Docking; 20cm Docking; Repel and Hold at Distance



Docking from 50cm



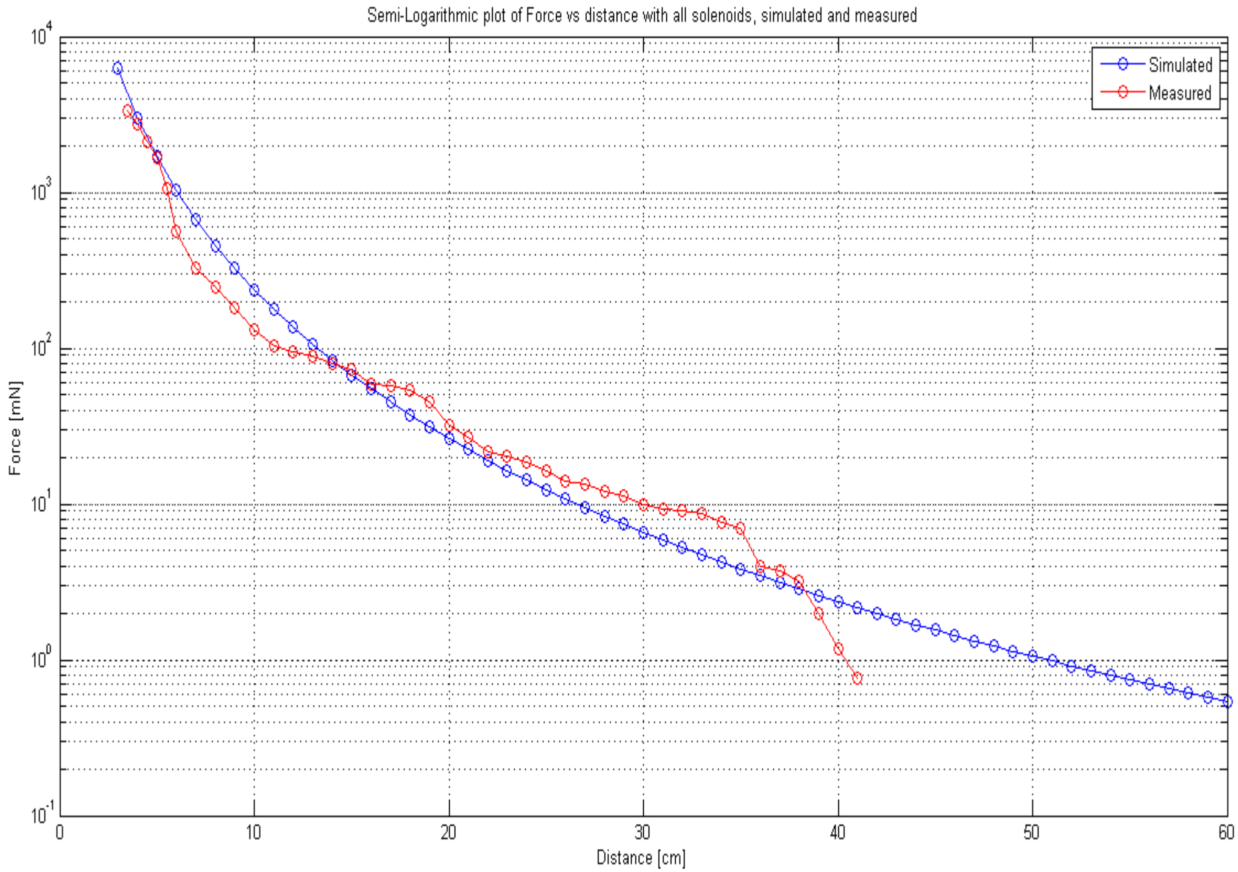
Docking from 20cm



Repel and Hold

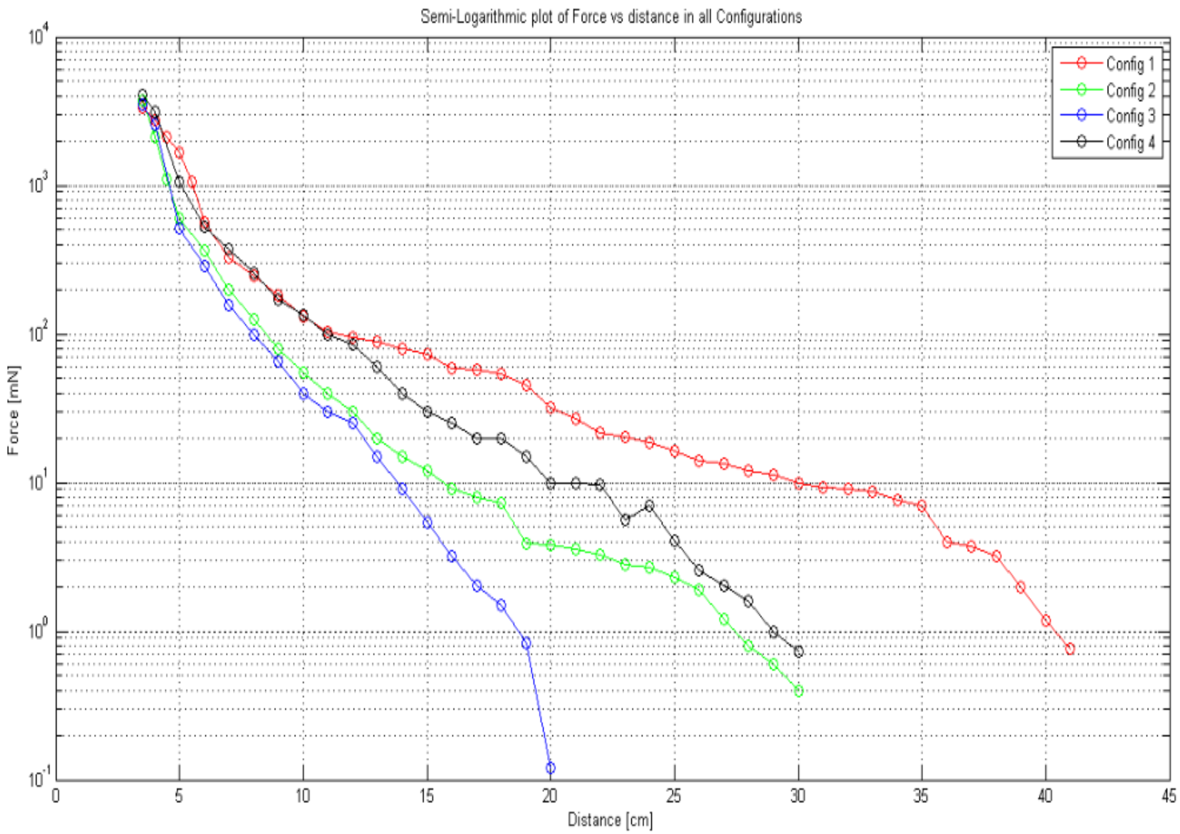
RDV/Docking

- **EM Docking System Update 2015**
  - Attraction forces simulated using the 'Gilbert model'
  - Assumes all 8 solenoids are at max power
  - Treats solenoids as point sources of magnetism



RDV/Docking

- **EM Docking System Update 2015**
  - Attraction forces simulated using the 'Gilbert model'
  - Measured attraction forces in different solenoid polarity configurations.
  - Measured at a 0 degree offset and within a 5 degree half cone to the target.

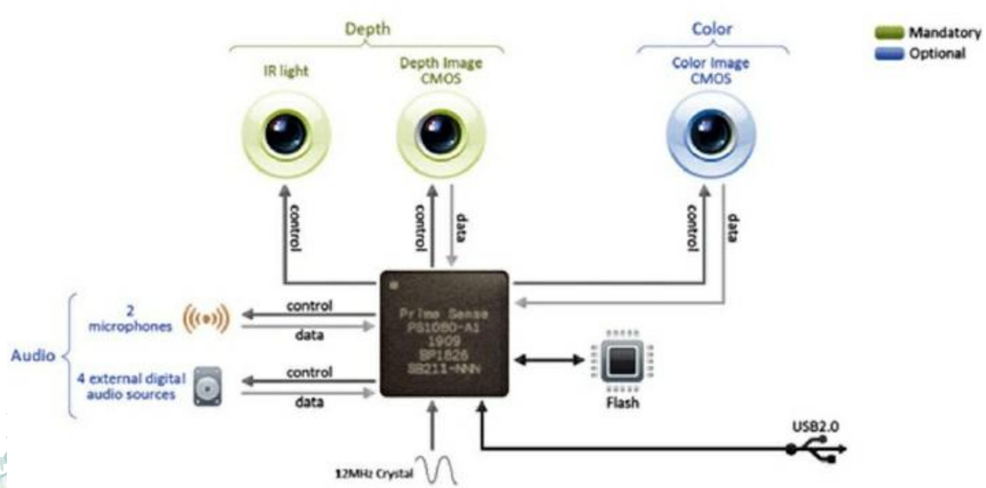


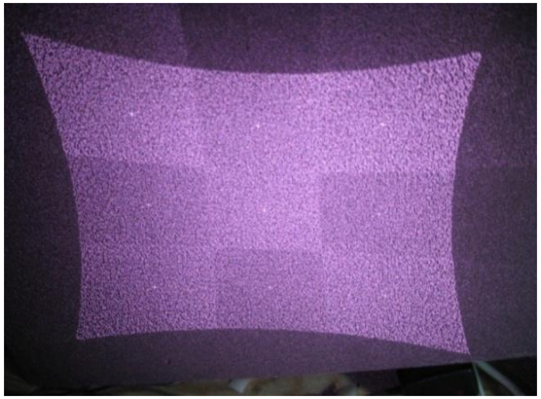
RDV/Docking

- **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):
  - 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

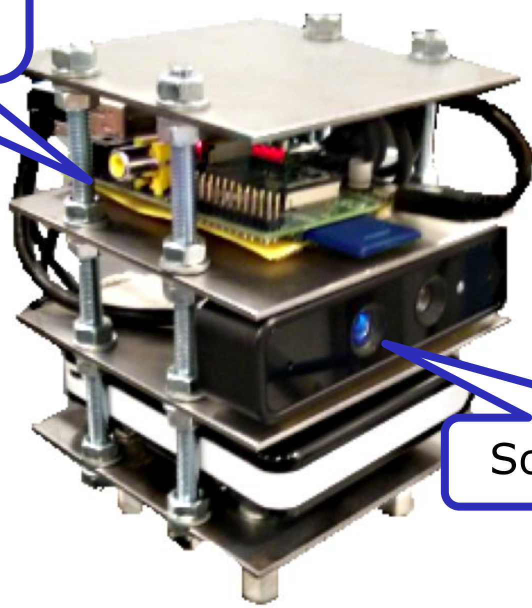
RDV/Docking

Softkinetic DS325
FoV: 87° x 58°
Range: 0.15 – 1m
QVGA: 320 x 240
USB 2.0 powered

RDV/Docking

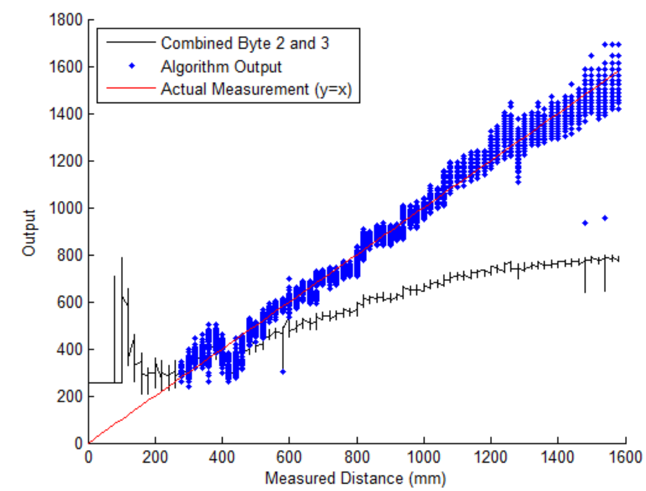
- **RDV & Docking Sensor Air Bearing Tests**

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.

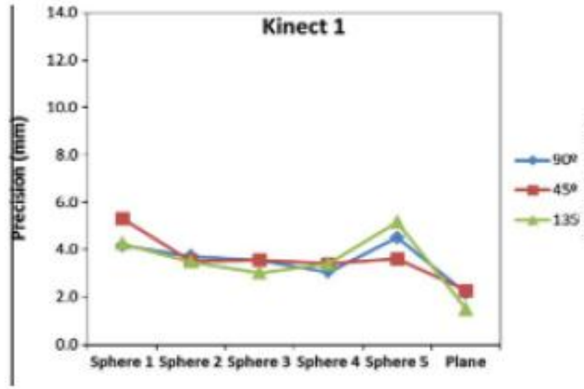


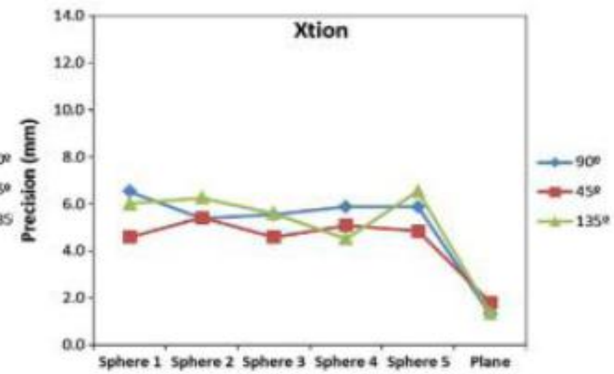
RDV/Docking

- **RDV & Docking Sensor Update 2015**
  - An MSc project (Patrick Maletz) "AAReST MISSION: Rendezvous Sensor" was completed this year.
  - Objectives:
    - Design and build the (short range) rendezvous sensor.
    - Test the accuracy and performance of the sensor and verify its performance using physical tests and computer simulations.
  - The SoftKinectic DS325 is no longer available on the open market, so for this work the larger ASUS Xtion sensor was used – however, at appears a suitable replacement for the SoftKinetic DS325 is now available.
  - Having confirmed the basic operation of the ASUS LIDAR, attention switched to a new camera/LED based sensor.

RDV/Docking

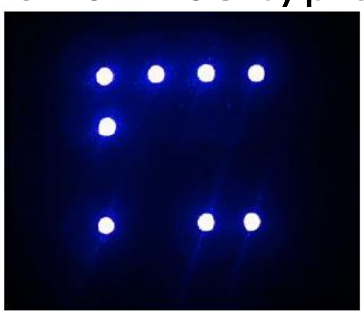
- **RDV & Docking Sensor Update 2015**
  - As the ASUS Xtion sensor performance and the detection algorithms needed are essentially identical to those of our previous work, no further testing was done on the LIDAR.

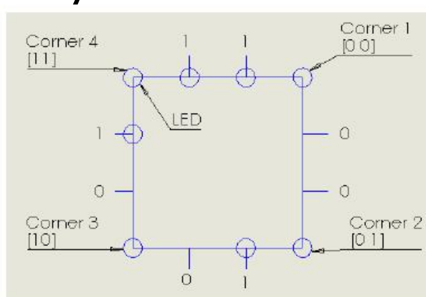




Power Consumption	Distance of Use	Field of View	Sensor	Depth Image Size
<2.5W	0.8-3.5m	58/45/70 Degrees H/V/D	RGB & Depth	VGA (640x480): 30fps QVGA(320x240): 60fps
Resolution	**OS Support**	**Programming Language**	**Dimensions**	**Software**
SXGA (1280*1024)	Win 32/64:XP, Vista, 7, 8 Linux Ubuntu 10.10:X86, 32/64	C++/C#/JAVA	18 x 3.5 x 5cm	Software Development Kits (OpenNI SDK)

- **RDV & Docking Sensor Update 2015**
  - Instead, 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 ~5º – with a maximum error of ~10º.

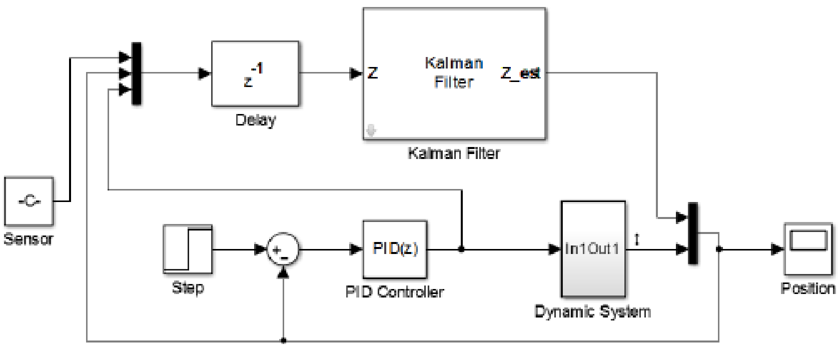


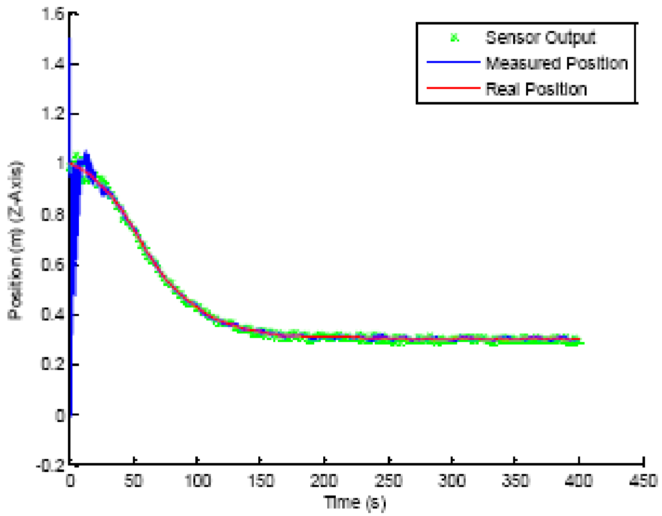


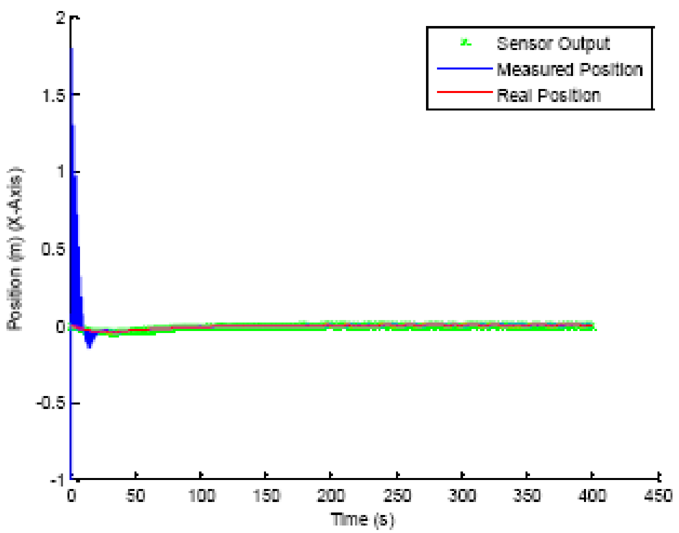
Axis	Range Interval (m)	Root Mean Square Error(mm)	Maximum Error (mm)	Standard Deviation (mm)	Confidence (%)
Z Axis	0-0.30	3.106	1.949	4.166	100
	0.30-0.80	5.787	11.265	3.687	100
	0.80-1.15	20.958	39.843	13.250	100
X Axis	0-0.30	1.9	0.2794	0.684	83
	0.30-0.80	1.7	2.851	0.585	91
	0.80-1.15	0.95	1.466	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):
  - Address solar blinding issue (via narrow pass-band filter high-intensity LEDs).
  - Combine with Docking System.

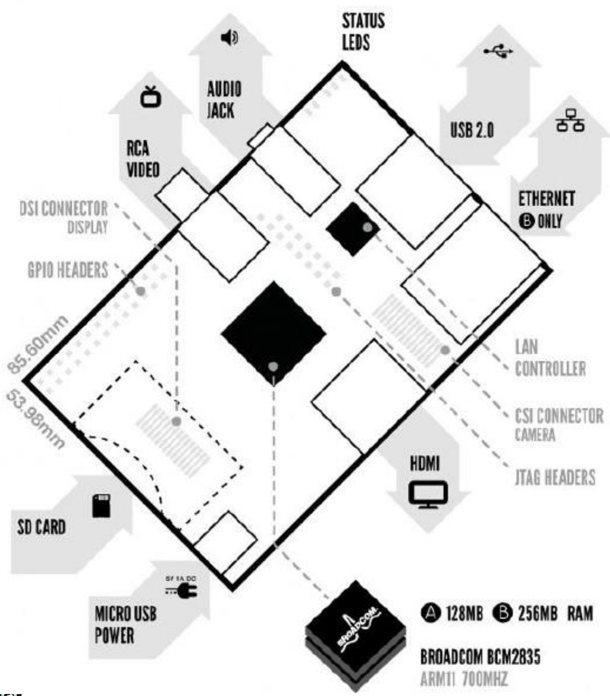






AAReST OBDH & Comms.

- **OBCs; Control/Communications/Data Link**
  - The primary controller and communications link to the is via the Raspberry-Pi (B) based **OBC1** and the COTS WiFi link
  - RPi has two USB master ports – one will be used for the WiFi "dongle" and the other will be dedicated to the mirror payloads
  - ISL data rate is programmable – effective range ~ 1km / < 1W



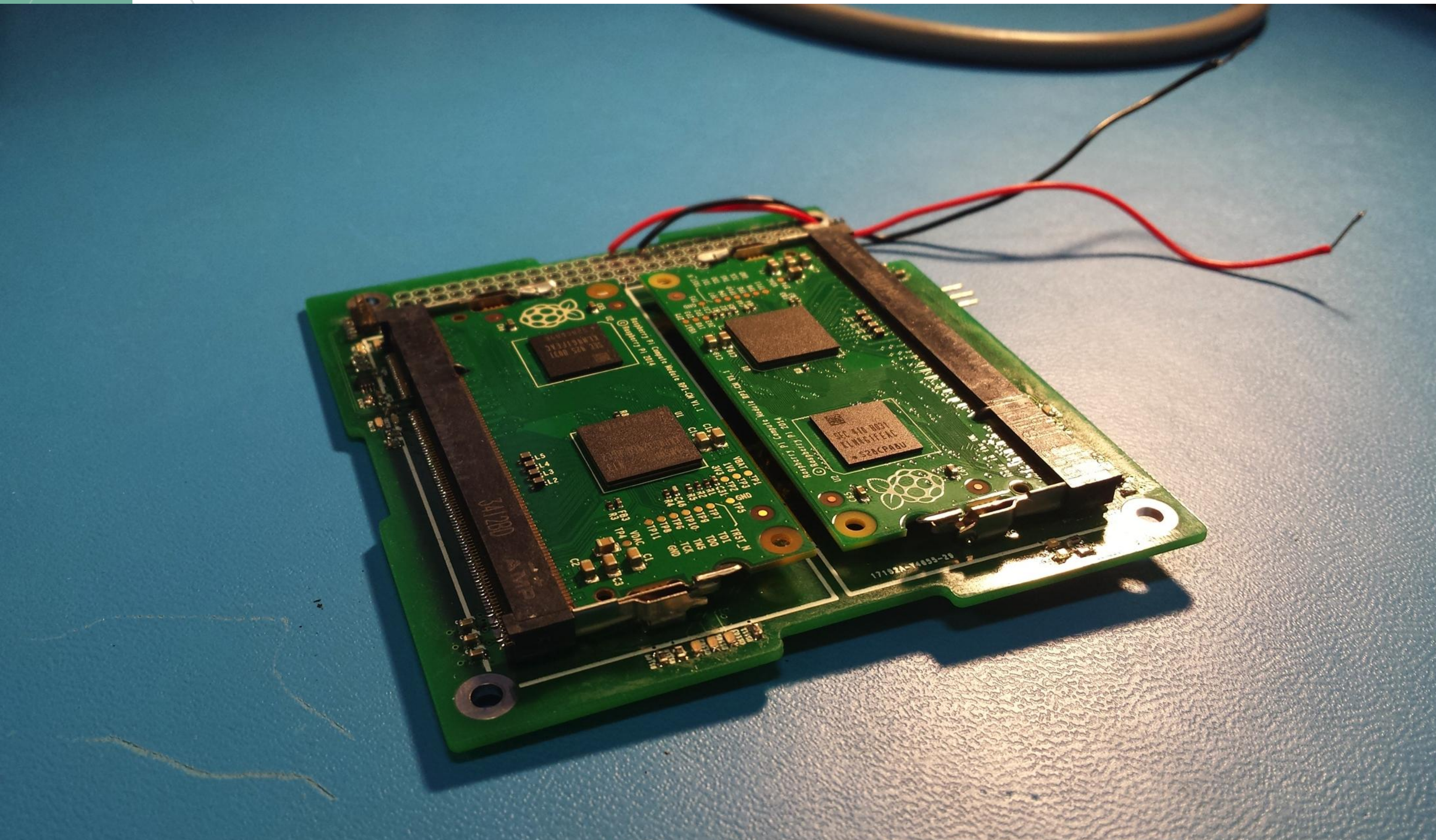
2014 Spacecraft OBC

- **OBC1**
  - OBC1 is based on a modified COTS Raspberry Pi (B) with 512 MB SDRAM
  - 400-800 MHz ARM11
  - Operates with a Linux kernel
  - The primary uses are to provide I2C OBDH interfaces and Wi-Fi ISL communications
  - Services include:
    - Telemetry & telecommand handling;
    - ISL communications support 2.4 GHz WiFi (USB 2.0);
    - PDM Payload control (USB 2.0; 5V sw. 1A max (2W cont));
    - Converting data to I2C formats;
    - Monitoring spacecraft health;
    - Implementing safe (minimum power consumption) mode
  - Note: SEE effects in processor not mitigated, but code, telemetry and WoD data is stored in SD cards (software TMR)
  - OBC1 is reloadable/re-bootable in orbit via UART bootloader

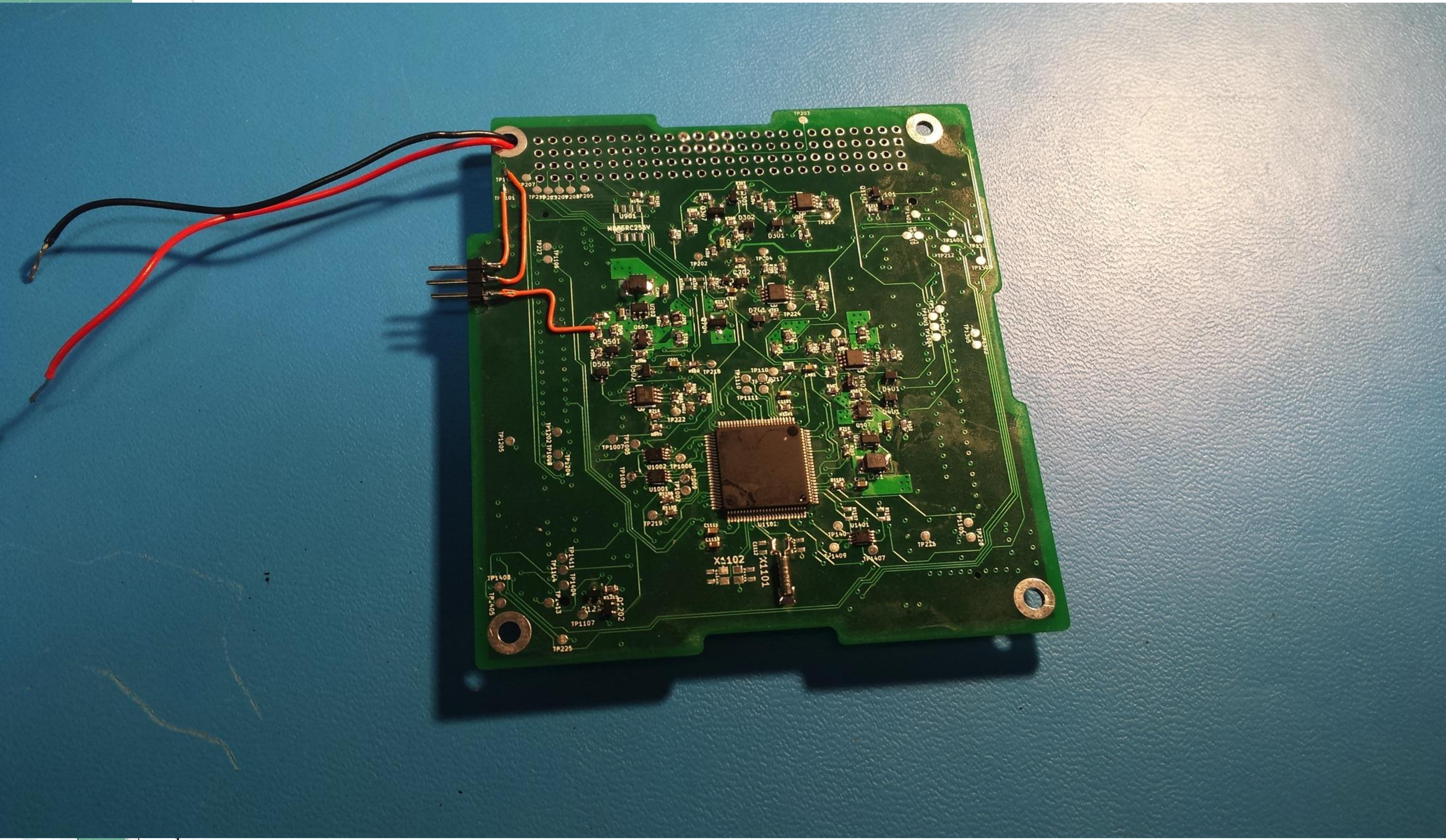
2014 RPi-B > RPi Compute

- Released RPi Compute (industrial grade) with SO-DIMM connector.
  - BCM2835 Processor (400-800 MHz)
  - 512 MB NAND RAM 46 GPIO (than 21)
  - Capacitor changes required
- 2 RPi Computes on PC/104 Board

2014 > 2015 RPi Board Built



2014 > 2015 RPi Board Built



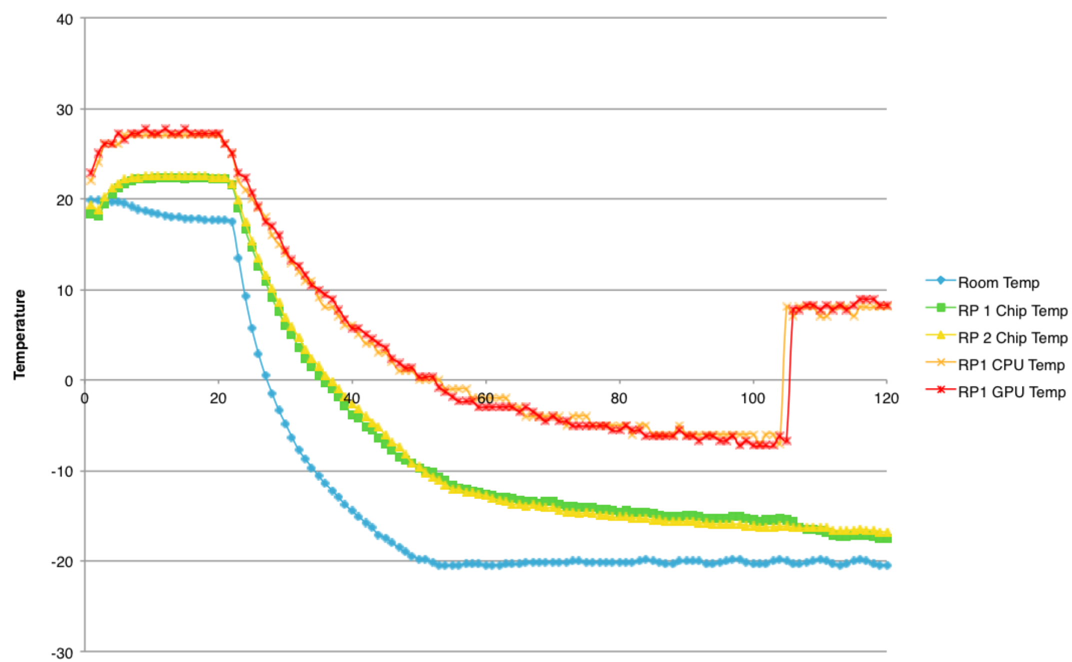
2015 RPi Board Spec

- Key Specs:
  - BCM2835 Processor (400-800 MHz)
    - NASA Goddard TID & SEE Radiation Tests, 4 RPi B+ DUTs
    - TID to 40 krad OK, 50-60 2 USB failures, 2 fine to 150 krad.
  - 512 MB NAND RAM 46 GPIO (than 21) > + 4 GB NAND Flash.
  - Capacitor changes required > None required.
  - External MSP430 as:
    - Watchdog on RPi-Computes & Switch Power via UART / ADC.

2015 RPi Software System

- Key changes:
  - USB Host Service added to allow WiFi software upgrades.
  - Custom Device Tree Service (.dts) added to configure GPIO.
  - Linux daemon service used to configure startup binaries:
    - Basic applications written to test UART & GPIO.
  - Bootloader added (developed in OTB Mission) allowing direct memory access, partition management, basic controls.

  - E.g. direct on-chip hardware control:
  - CPU & GPU Temp stable at 62°C
  - Turn ON/OFF at hot & cold (see right).
  - Core voltage & CPU freq. stable too.



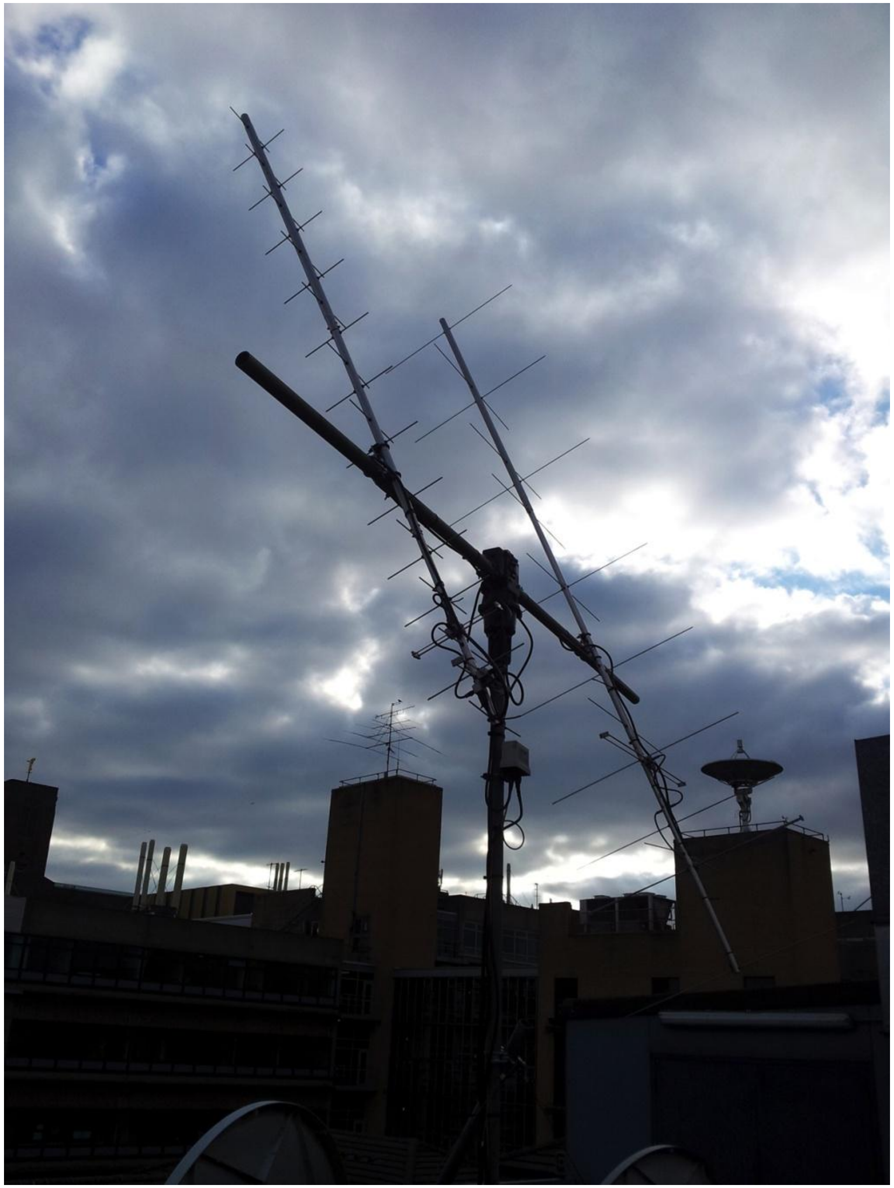
2015 Tests & Future Work

- Hardware:
  - PCB power tracks need investigation / increasing as voltage drop on RPi inrush was higher than previously noted.
  - Add electrical USB interface points.
  - Decide on header manufacturer & pin allocations.
  - Add non-volatile memory accessible to both MSP430 + RPi's > 128 Mb I2C Flash
  - Consider direct communication lines between RPi's.

- Software:
  - Continue MSP430 development to monitor power modes and scope safety measures / limits.
  - Add RTOS to RPi, add EDAC / TMR control thread.
  - Continue 2014 work which takes the 16 Hz LIDAR data to estimate range and pose to close loop control with attitude perturbations / stabilisation.

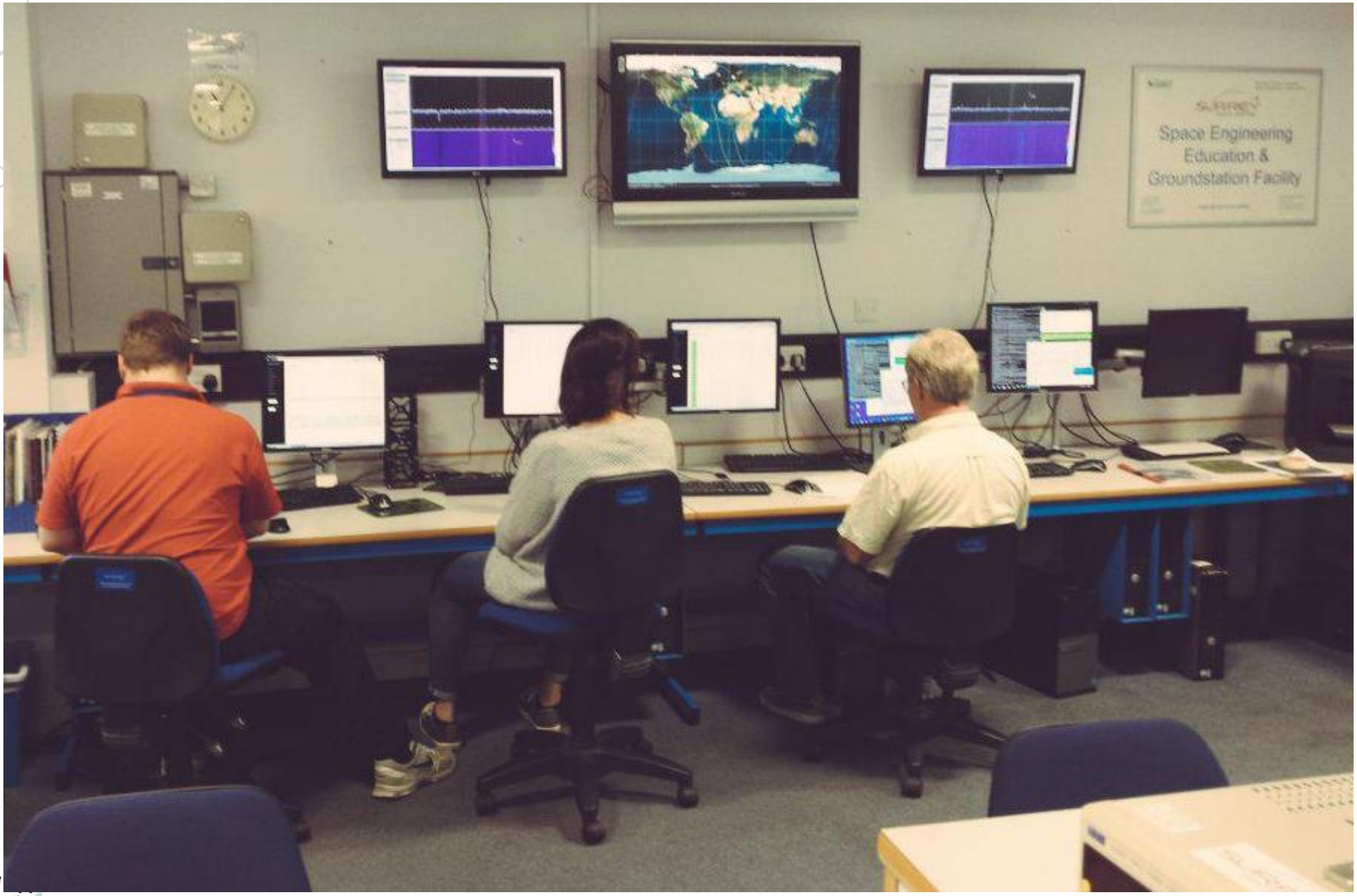
2014 Ground Comms.

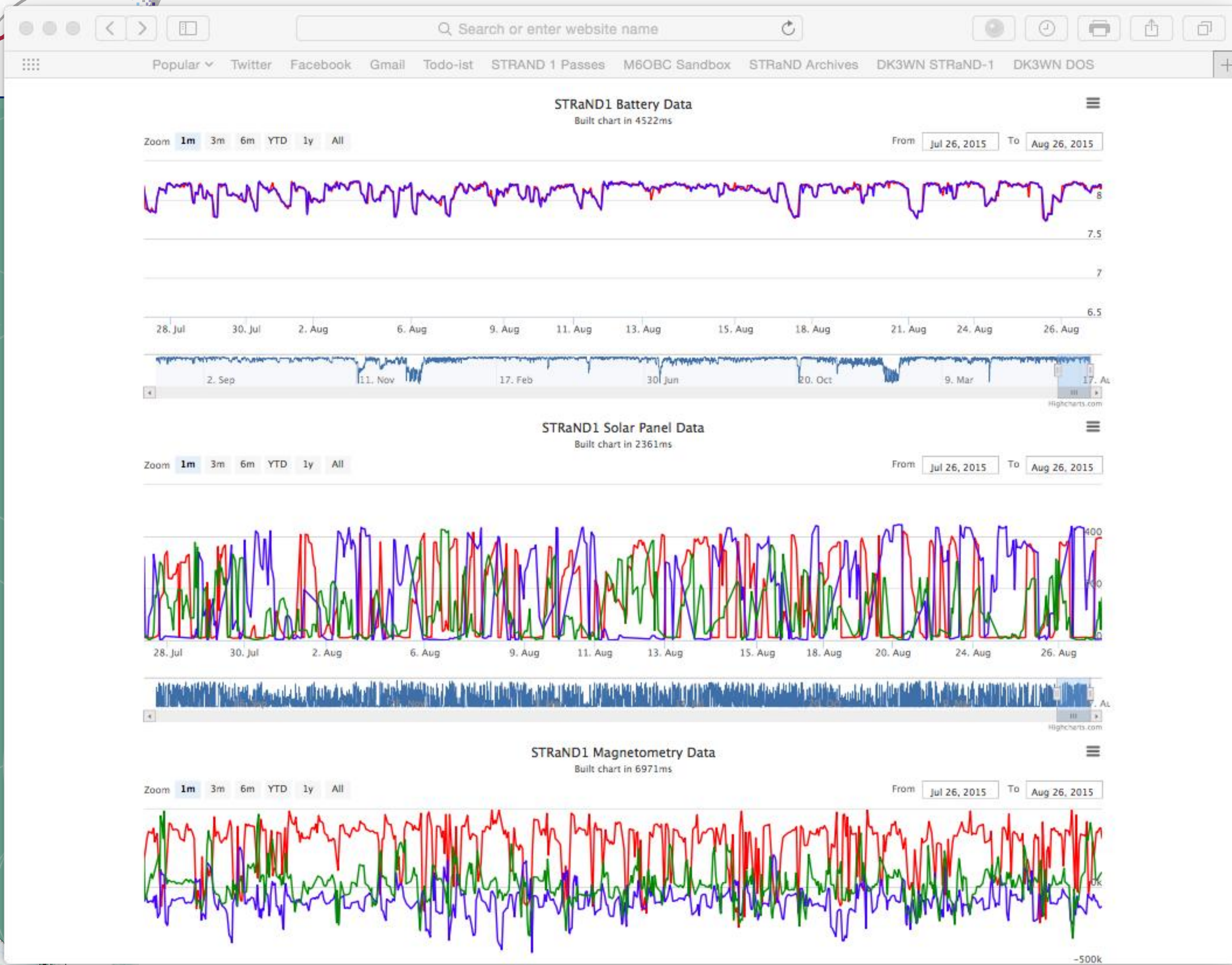
- Demonstrated 1k2 on VHF
  - From cleanroom to ground-station (same building)
  - No LNA, HPA required.
- Front-end
  - Dr Bridges' Team
  - Handles RF, Packetisation, error coding/checking
  - Acts as UDP Server
- Back-end
  - Dr. Bridges' Team
  - Sends/receives raw data over UDP as client
  - Multiple clients possible per satellite



2015 Ground Comms.

- Now full SDR facility, includes automated data plotting.





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STRAND 1 Passes
M6OBC Sandbox
STRaND Archives
DK3WN STRaND-1
DK3WN DOS
STRaND1 Battery Data
Built chart in 4522ms
Zoom 1m 3m 6m YTD 1y All
From Jul 26, 2015 To Aug 26, 2015
8
7.5
7
6.5
28. Jul
30. Jul
2. Aug
6. Aug
9. Aug
11. Aug
13. Aug
15. Aug
18. Aug
21. Aug
24. Aug
26. Aug
2. Sep
11. Nov
17. Feb
30. Jun
20. Oct
9. Mar
Highcharts.com
STRaND1 Solar Panel Data
Built chart in 2361ms
Zoom 1m 3m 6m YTD 1y All
From Jul 26, 2015 To Aug 26, 2015
400
28. Jul
30. Jul
2. Aug
6. Aug
9. Aug
11. Aug
13. Aug
15. Aug
18. Aug
20. Aug
24. Aug
26. Aug
Highcharts.com
STRaND1 Magnetometry Data
Built chart in 6971ms
Zoom 1m 3m 6m YTD 1y All
From Jul 26, 2015 To Aug 26, 2015
-500k

FSW Packet Formats

- 2014 > 2015: Built DeorbitSail, and need to deliver more CubeSats requiring various flight software.
- Build up a unified Excel file; STRaND1's is online.

STRAND-1 GROUND TO SKY PACKET FORMAT / DR C. P. BRIDGES

NOTATION: B = BYTE, b = BIT, TM = TELEMETRY POINT

TNC FLAG (0xC0 00)	HDLC FLAG (0xC0 80)	LENGTH (2B)	OBC LAYER (DATA)	CRC-ITT	TNC FLAG (0xC0)

FOR GROUNDSEGMENTS USE KISS PROTOCOL
JAMES MILLER ENCODING, NRZI, CRC-ITT
CHANGE 0xC0 to 0xDB DC
WIKIPEDIA KISS TNC LINK

HDLC PACKET
WIKIPEDIA HDLC LINK

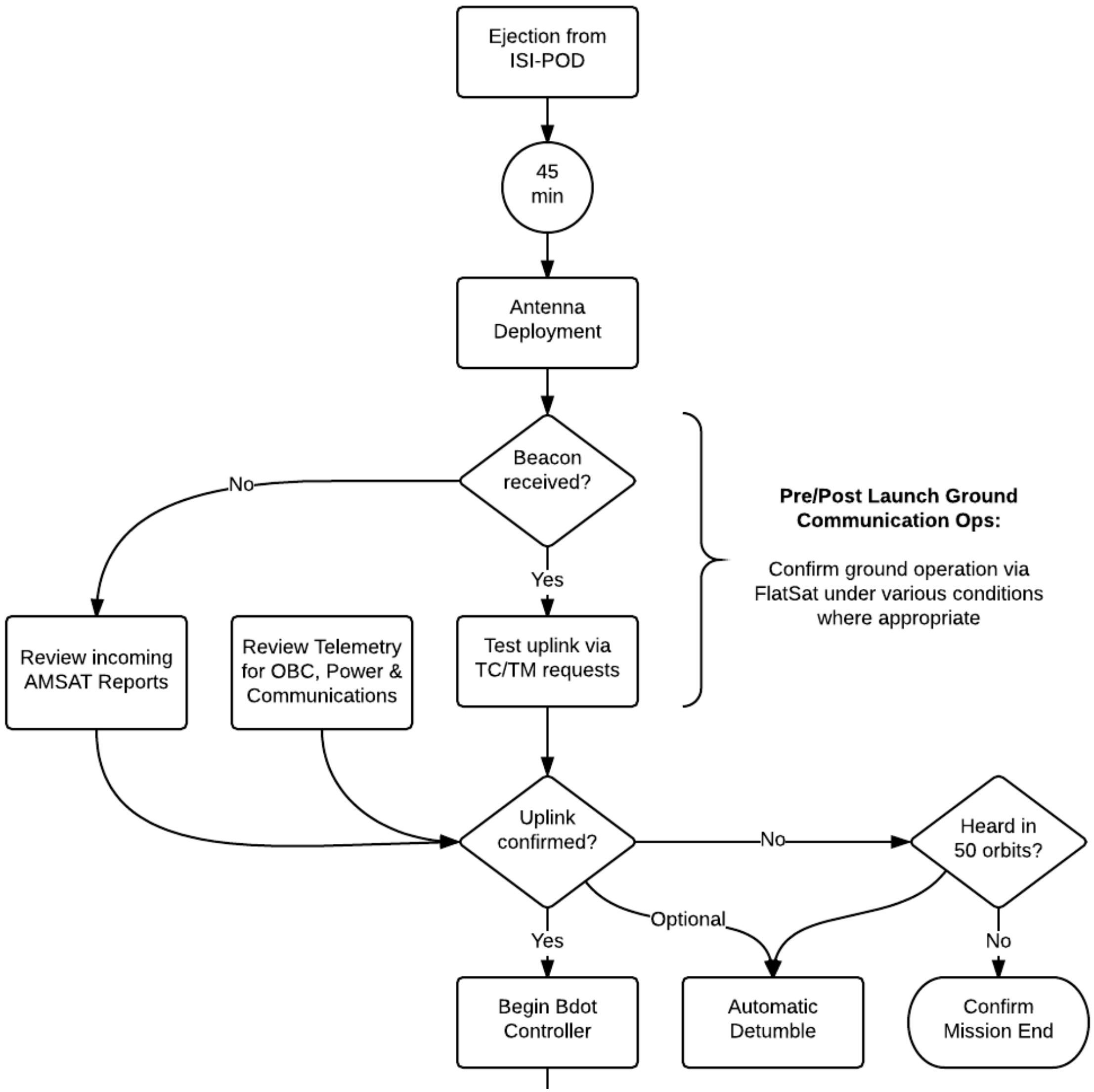
ID (1B)	I2C NODE ADDRESS (7b)	NODE CHANNEL (1B)	DATA_SIZE (1B)
0x00 NOT USED 0x01 MODEM BEACON TM 0x02 OBC BEACON TM			BYTES TO READ/WRITE

IF 0x01, MODEM BEACON TM	CHANNEL	4B TM
	0xE0 TIME SINCE LAST OBC I2C MESSAGE 0xE1 PACKETS UP COUNT 0xE2 PACKETS DOWN COUNT 0xE3 PACKETS UP DROPPED COUNT 0xE4 PACKETS DOWN DROPPED COUNT	

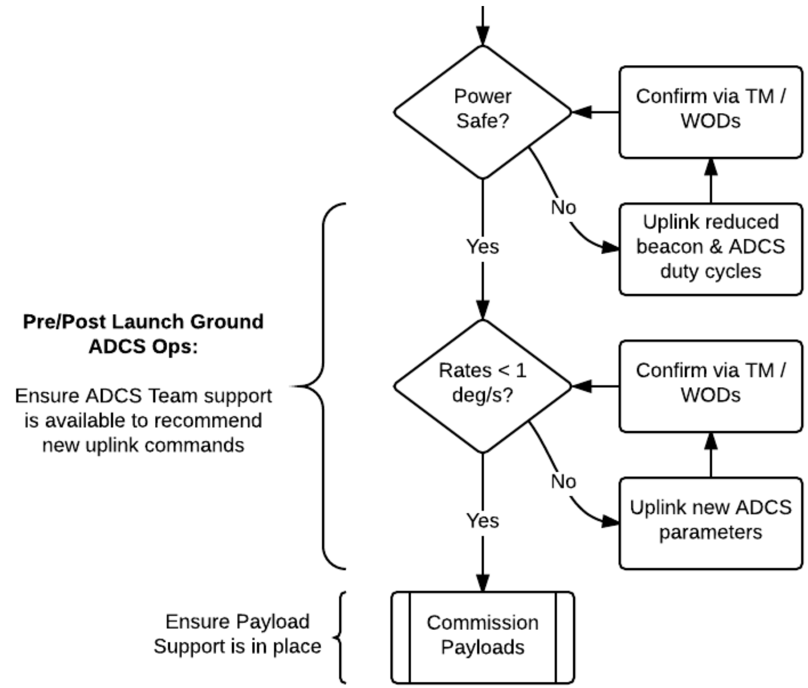
IF 0x02, OBC BEACON TM	I2C NODE ADDRESS (7b)	NODE CHANNEL (1B)	DATA_SIZE (1B)
CLICK TO OPEN	0x2C C/S EPS		CALIBRATION EQUATION, LITTLE ENDIAN
CLICK TO OPEN	0x2D C/S BATTERY		CALIBRATION EQUATION, LITTLE ENDIAN
CLICK TO OPEN	0x66 SWITCH BOARD		CALIBRATION EQUATION, BIG ENDIAN

- Key concepts:
  - Basic TC / TM breakouts for simple debugging over assumed poor communications link > 4 to 8B commands.
  - File Transfer using Saratoga.

Platform CONOPS



Platform CONOPS

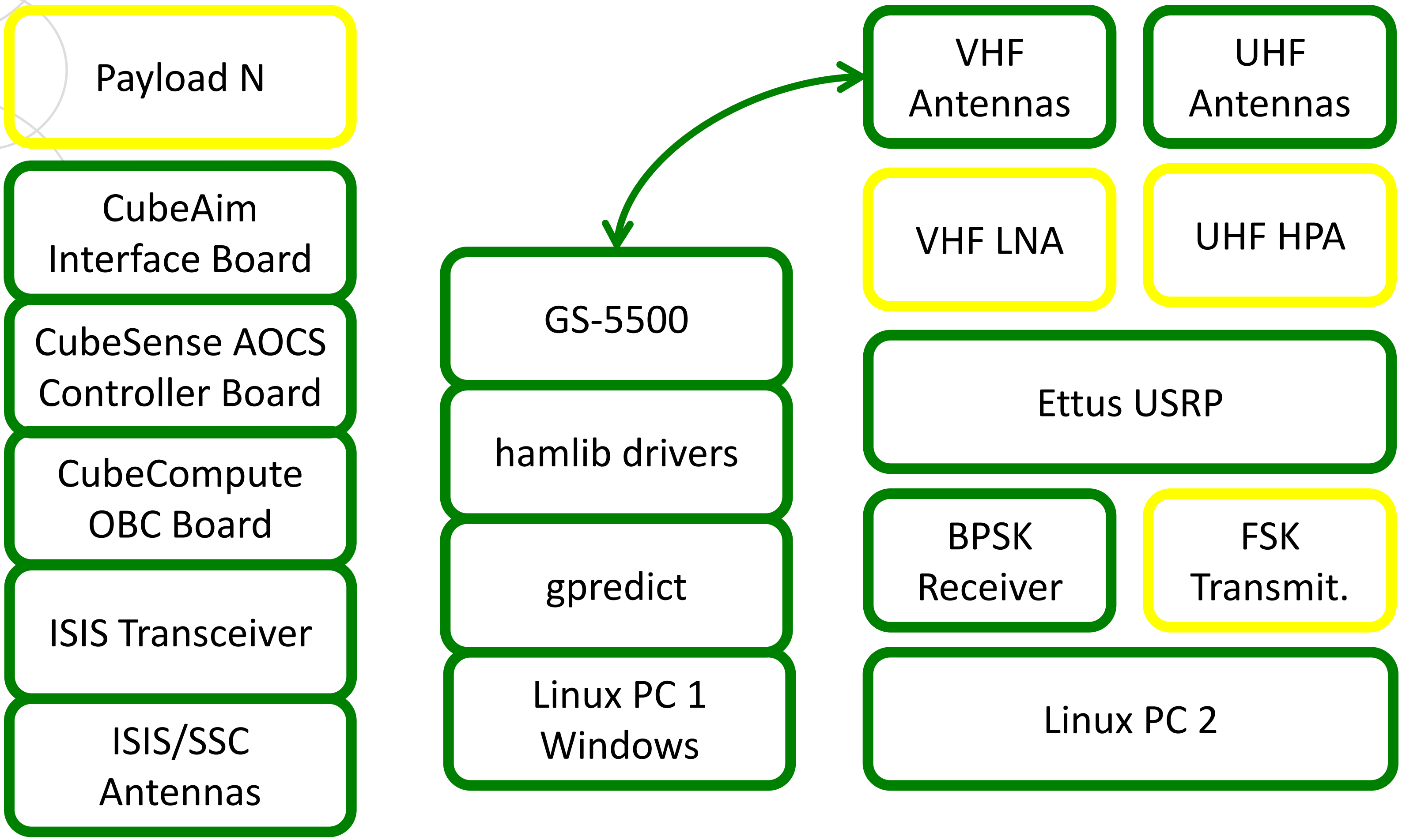


Payload Operations:

- Switch Parameters
- TC/TM Collection & Mode Changes
- Modem > OBC > RPi Payload > Mirror Payload
- Short Experiments (50-100 KB) for easy downloadable chunks (file operations)

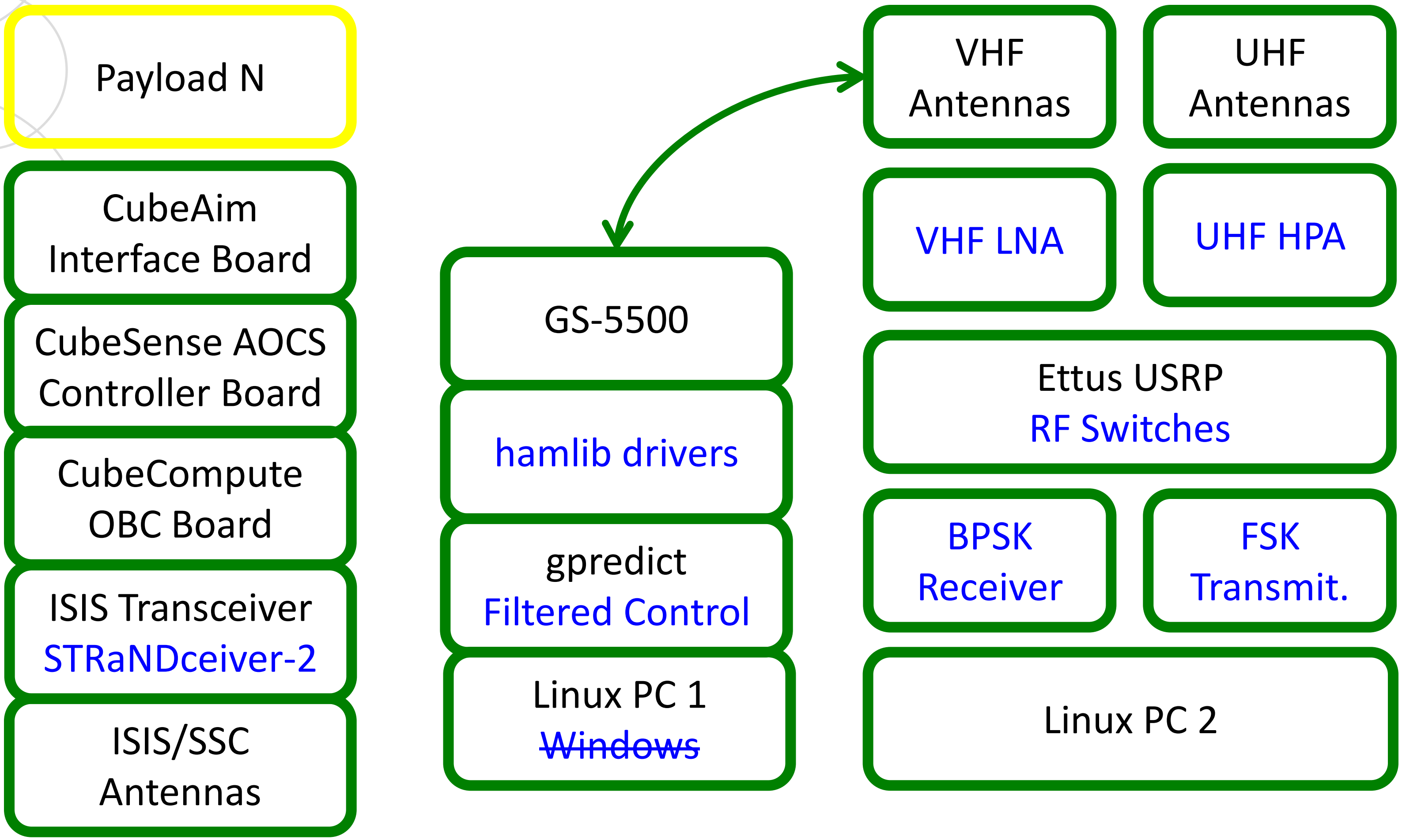
Q3-2014 System Ops.

- Includes both space & ground-segments in details with experience from STRaND1, QB50p1, QB50p2.



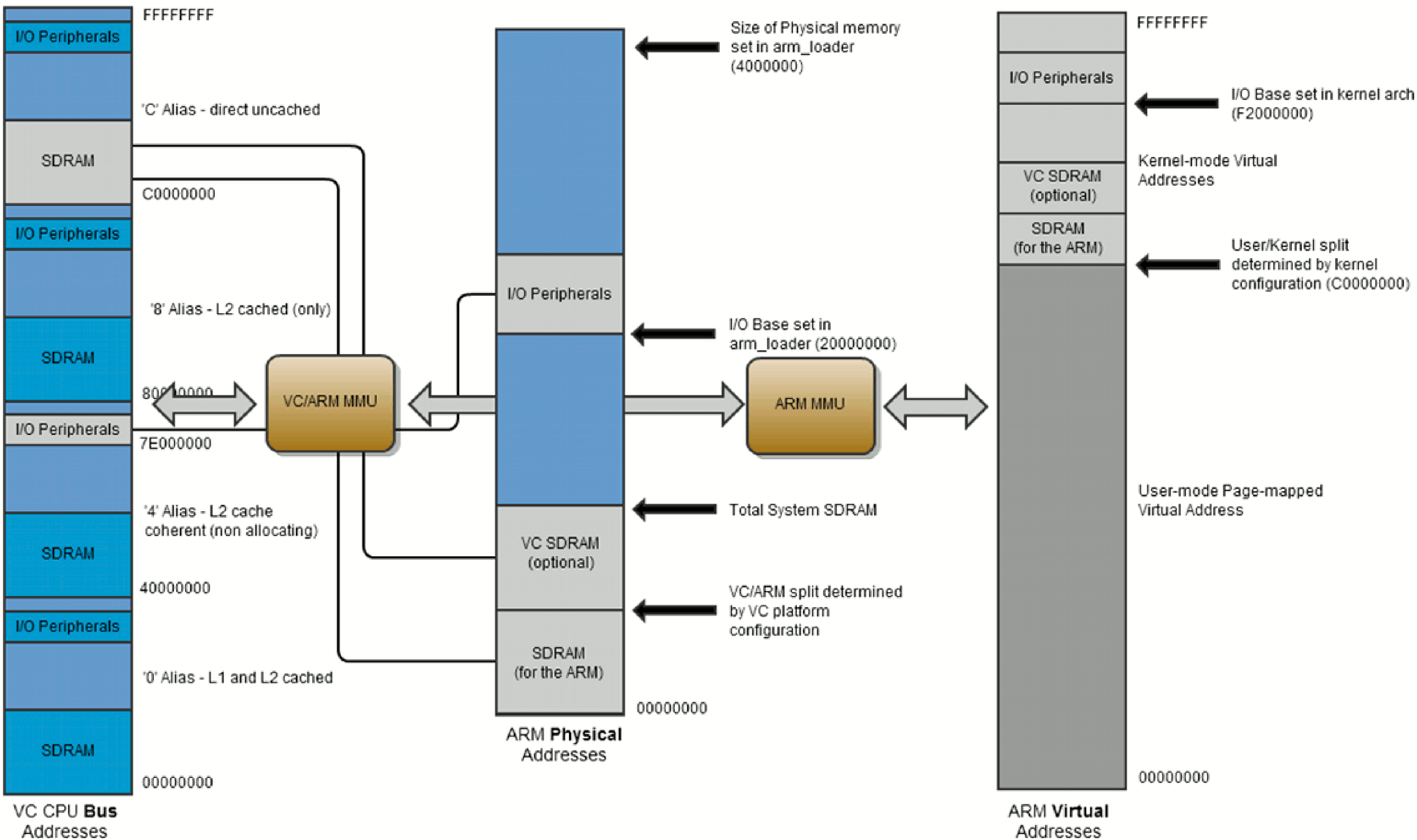
2015 System Ops.

- Includes both space & ground-segments in details with experience from STRaND1, QB50p1, QB50p2 & DeorbitSail.



Device Formats & Complexity

(Taught in EEEM059 Space Avionics)



Conclusions

- The AAReST project 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.
- 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).
- Funding remains an issue for the UK – however, a recent proposal to the UK scored highly and was just under the threshold for funding. A new bid is in preparation for submission in the Autumn 2015.

Acknowledgements

- We wish to acknowledge and thank the people at Surrey who contributed to this presentation, in particular: Richard Duke, David Lines, Ben Taylor and Lourens Visage at the Surrey Space Centre (SSC), Shaun Kenyon at SSTL and Herman Steyn at Stellenbosch University, South Africa.

- We also acknowledge the support of the STRaND, QB-50/InflateSail, CubeSail, DeorbitSail and SMESat Teams at Surrey (both at SSC and SSTL).

- The micro-porous carbon air-bearing table simulator, used in the earlier rendezvous and docking experiments, was developed through funding from the UK Engineering and Physical Sciences Research Council (EPSRC) under grant EP/J016837/1.

Acknowledgements

- We should also like to acknowledge the contributions made by current and past members of the AAReST team at Caltech (http://pellegrino.caltech.edu/aarest4.html).
- The development of the optical systems for AAReST has been supported by the California Institute of Technology and by the Keck Institute of Space Studies.
- For the 2015 Surrey updates, we should like to give particular thanks to the graduating students: David Lines, Enda McKenna, Patrick Maletz and Oliver Launchbury-Clark.

Thank-You

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