SURREY SPACE CENTRE

UNIVERSITY OF SURREY

AAReST Spacecraft Update:

Surrey MirrorSat, Propulsion, ADCS, RDV/Docking, OBDH and Comms.

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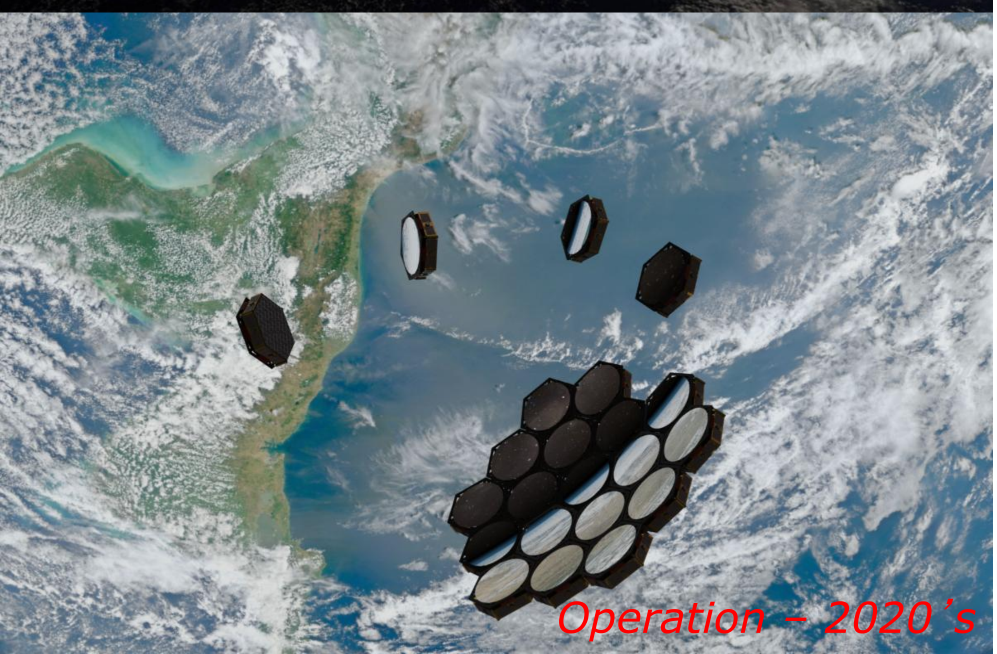
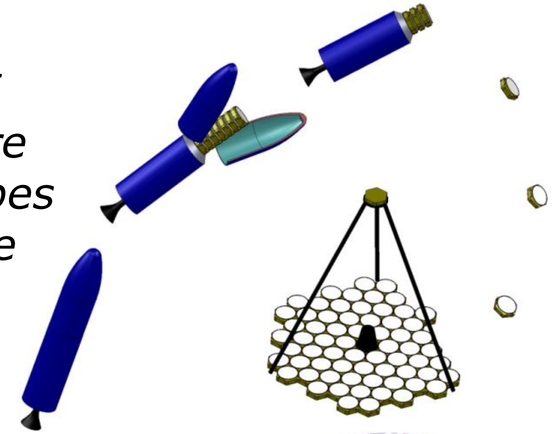
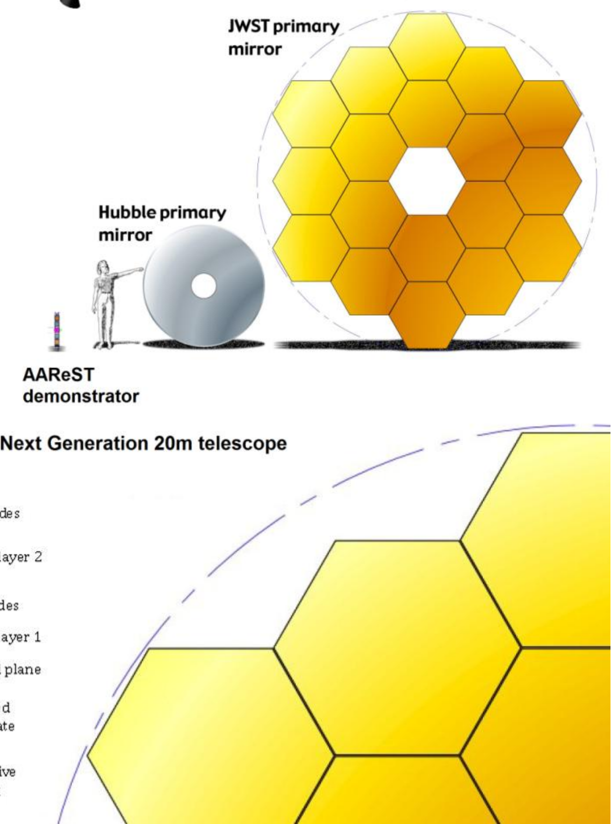
California Institute of Technology 1891 — JPL — Surrey Space Centre — IIST Indian Institute of Science and Technology — Universiteit Stellenbosch University

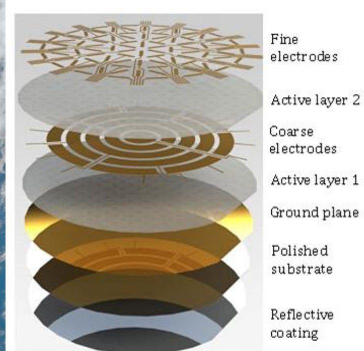
The Vision



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

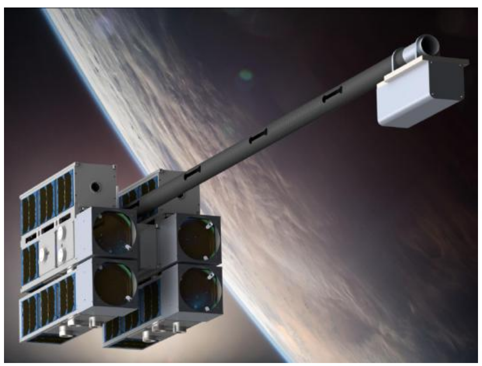
2013 September: Preliminary Design Review
2014 June: Ae105
  - Camera opto-mechanical prototype
  - Boom gravity offload deployment testing
  - Mirror vibro-acoustic experiments
  - TVAC chamber commissioning
  - Telescope testbed commissioning

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 <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

JPL
SURREY SPACE CENTRE
Caltech
UNIVERSITY OF SURREY
UNIVERSITEIT STELLENBOSCH UNIVERSITY
IIST Indian Institute of Science and Technology

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

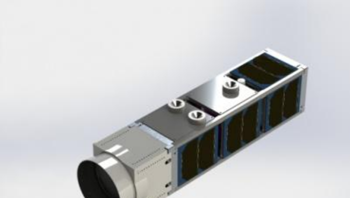
Mission Concept

- **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 ADCS, 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 (UART) interfaces
  - **CoreSat** must support *Reference Mirror Payload* (RMP) in terms of mechanical, power (+5V, 1A max.) and telemetry/ telecommand data (UART) interfaces
  - **CoreSat** must support *Boom/Camera Package* in terms of mechanical, power (+5V, 1A max.), and telemetry/ telecommand and image data interfaces.

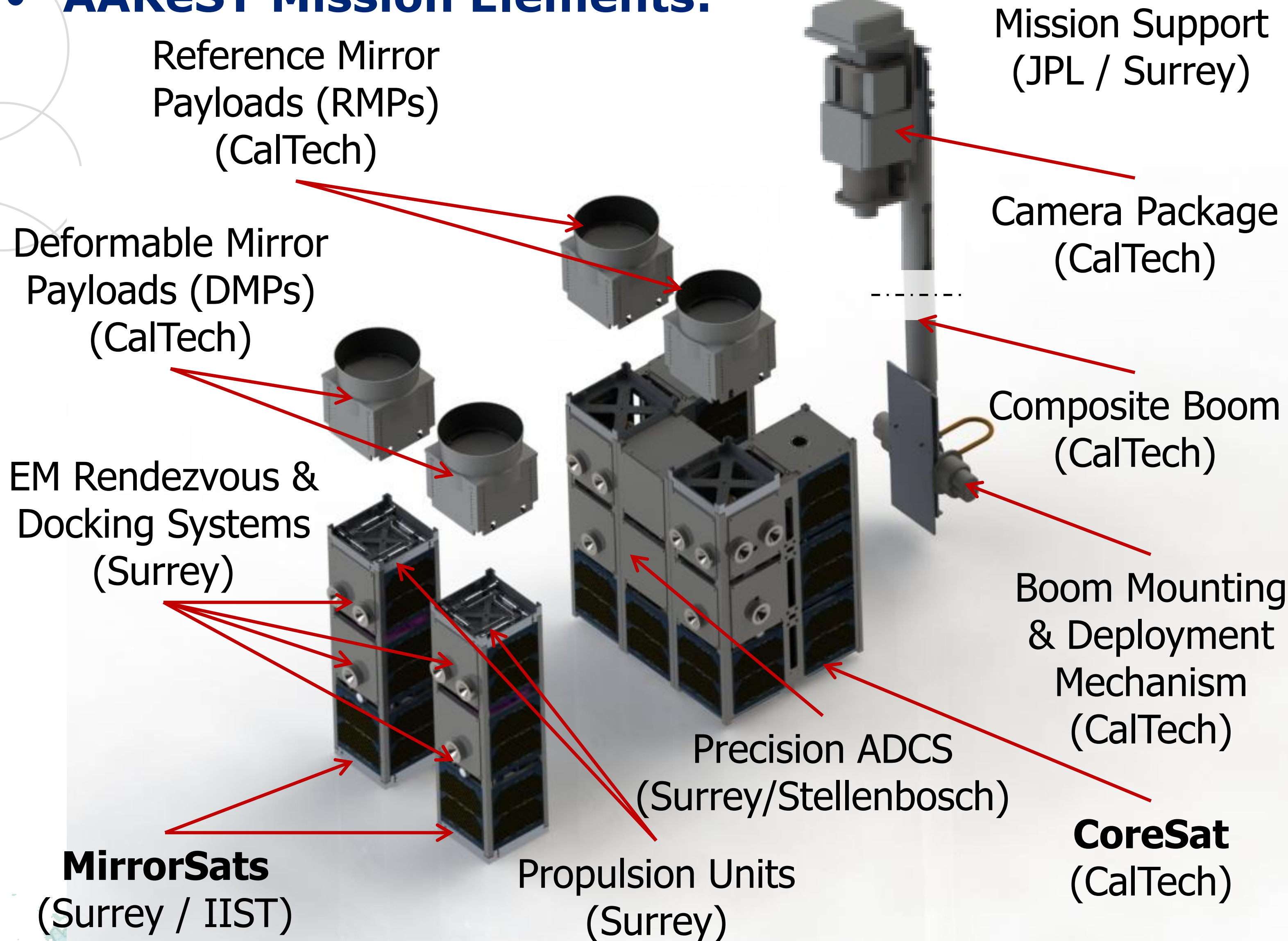

MirrorSat


AAReST: Boom and Camera Package Deployed


CoreSat (Internal View)

Mission Concept

- **AAReST Mission Elements:**

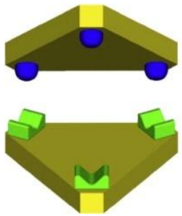


Mission Concept

- **Spacecraft and Mission Concept**
  - Launched as a single "microsat" into LEO (600 km SSO)
  - Comprises a "Fixed CoreSat" + 2 separable "MirrorSats"
  - Total Mass (incl. attach fitting) < 40 kg (est. at ~32 kg)
  - Envelope at launch (inc. att. fit.) within 40 cm x 40 cm x 60 cm
  - 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 uses a *Kelvin Clamp* arrangement to ensure rigid alignment of the spacecraft.



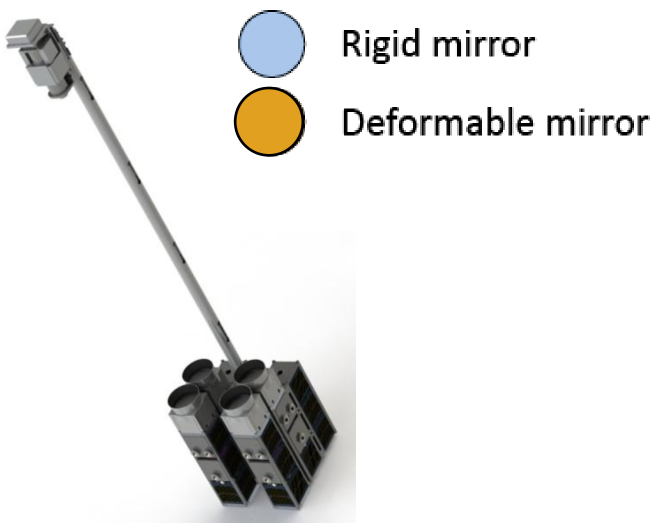
Compact Configuration

Transition

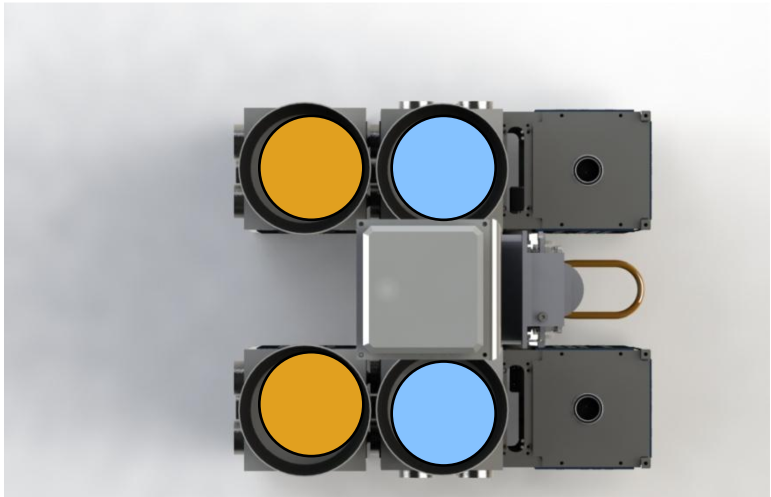
Wide Configuration

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.



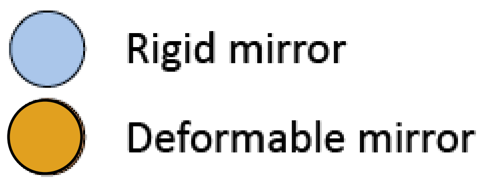
Compact Configuration Imaging Mode



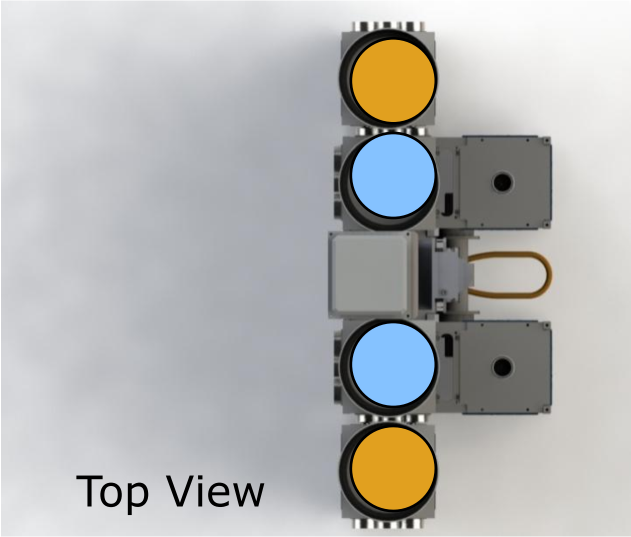
Top View

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-50cm** distance)
    - Demonstrates LIDAR/camera RDV sensors and EM docking ports
    - Demonstrates ability to re-focus and image in wide mode

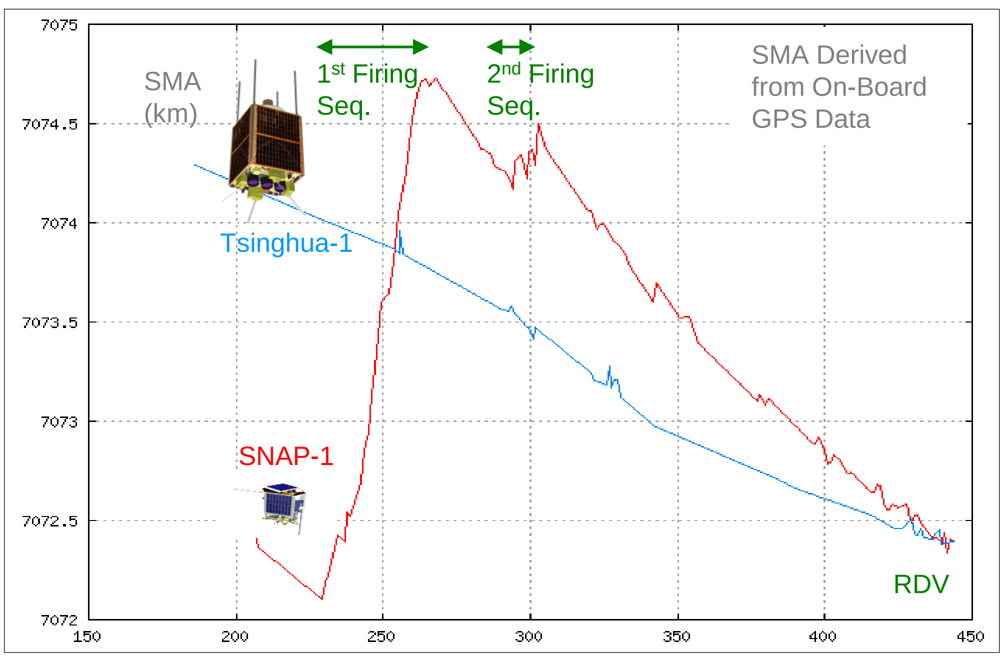


Wide Configuration Imaging Mode



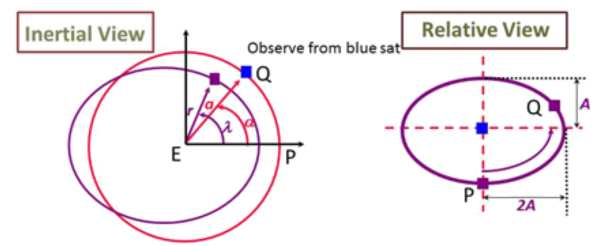
Mission Concept

- **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, butane propulsion and optical relative navigation
    - For safety, ISL must operate out to **1km**



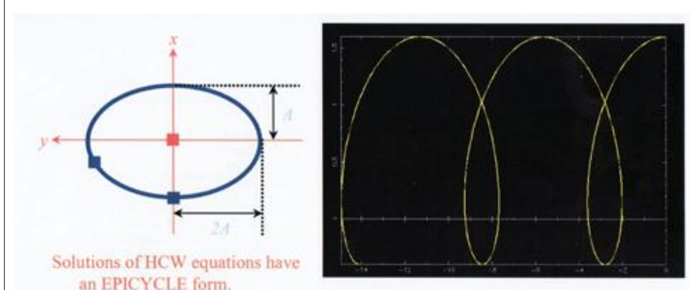
Day Number Since 1st January 2000

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



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

A: Epicycle amplitude



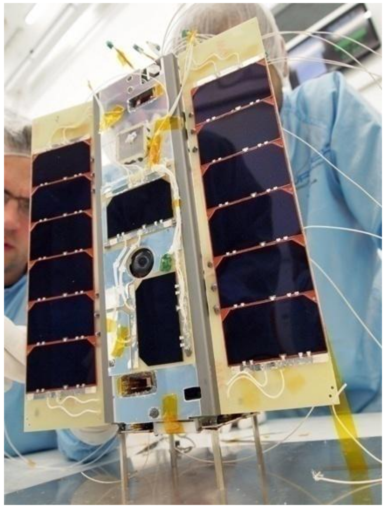
$$x(t) = (4 - 3\cos nt)x_0(\dot{x}_0 / n)\sin nt + 2\dot{y}_0(1 - \cos nt)/n$$

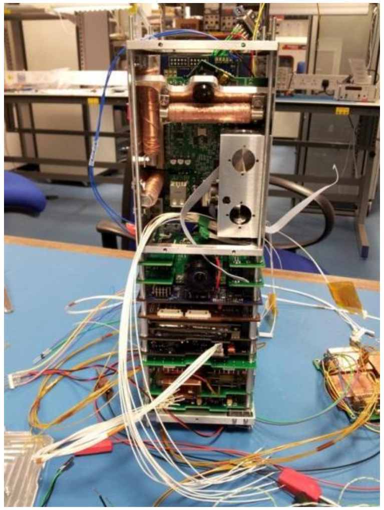
$$y(t) = 6x_0(\sin nt - nt) + y_0 + (2\dot{x}_0 / n)(-1 + \cos nt) + \dot{y}_0(4\sin nt / n - 3t)$$

Spacecraft Design

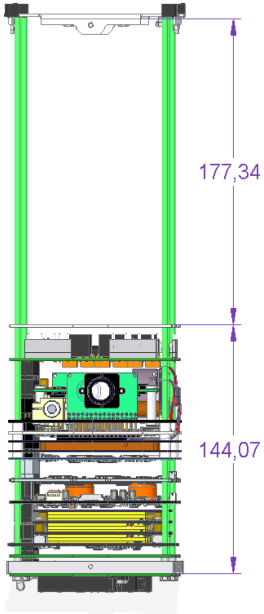
- **Spacecraft Bus – Design Approach**
  - **Low-cost** approach based on CubeSat technology
  - **Heritage** from Surrey's SNAP-1 NanoSat Programme (2000) (particularly butane propulsion and pitch MW/magnetic ADCS)
  - **Incremental** hardware, software and rendezvous/docking concepts developed through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

SNAP-1 (2000)



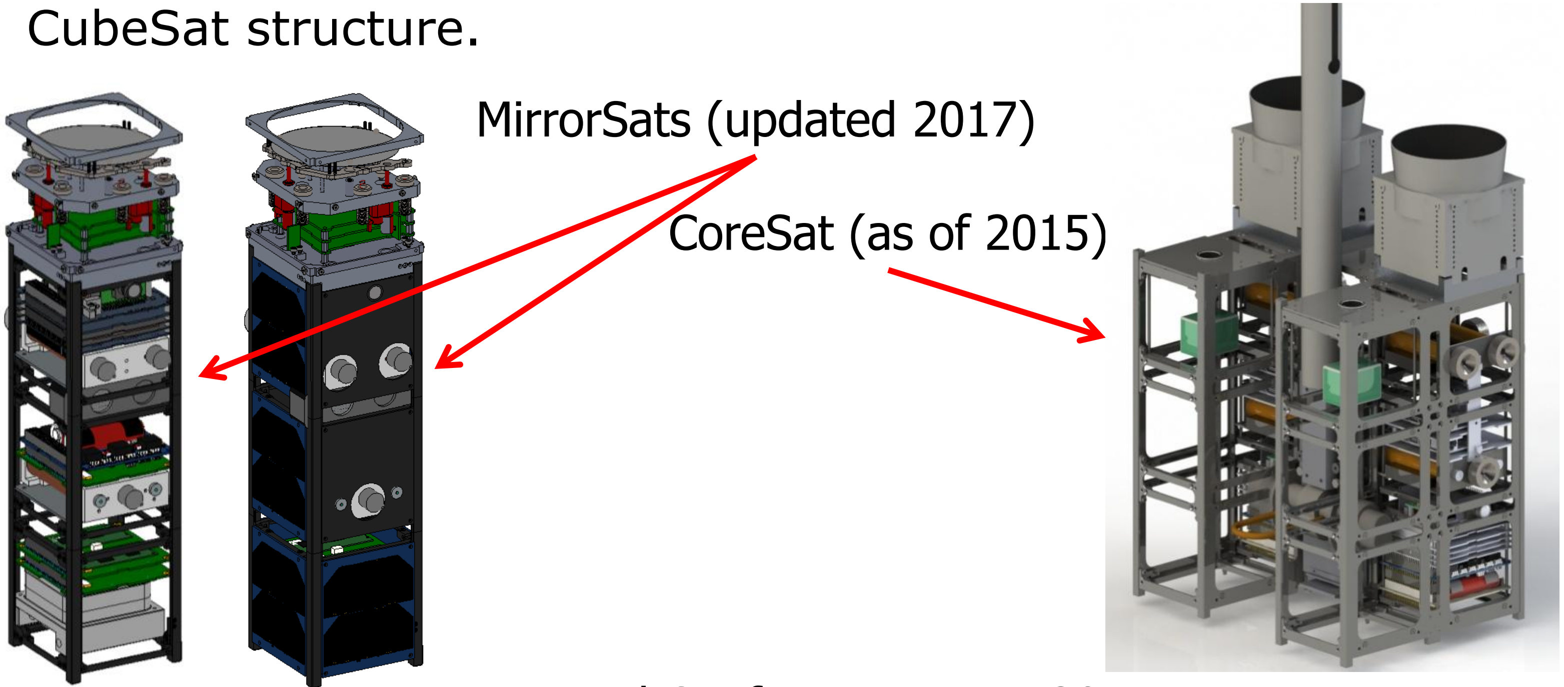


STRaND-1 (2013)



AlSat-1N CAD

- **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** CubeSat structures mechanically joined, plus two detachable free-flying "**MirrorSats**", each based on a **3U ISIS** CubeSat structure.

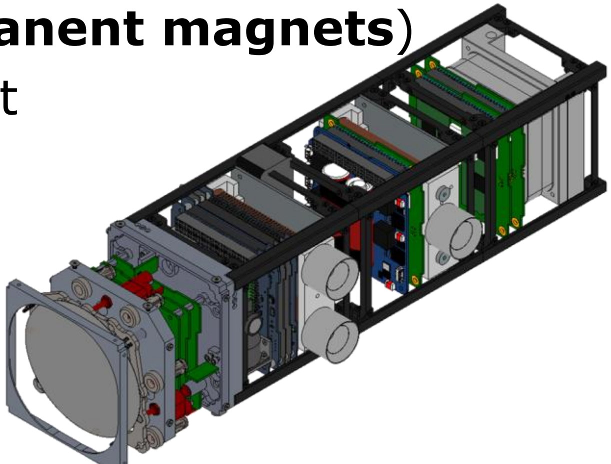


Proposed Configuration Jan 2017

Surrey AAReST MirrorSat Configuration

MirrorSat Spacecraft Bus

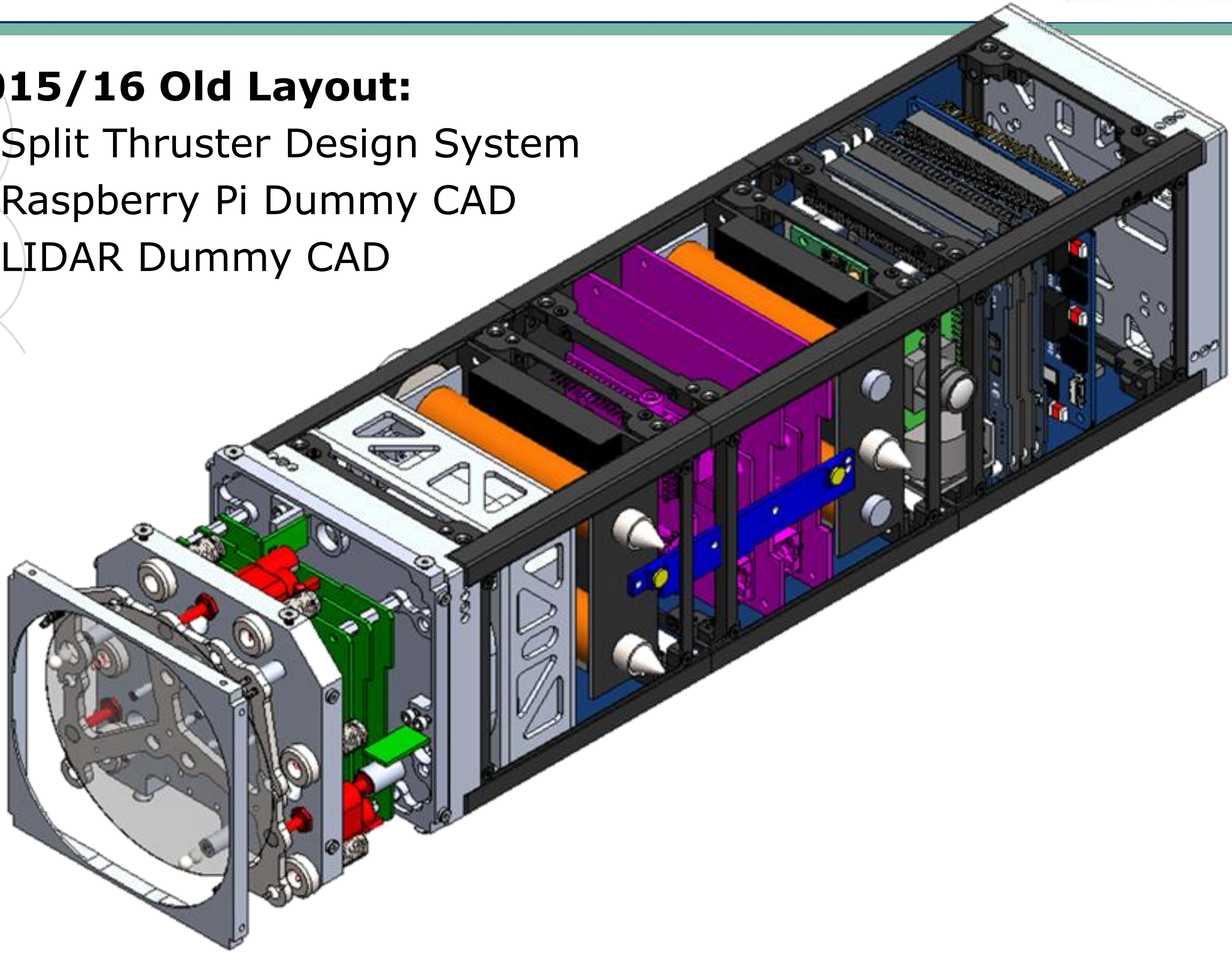
- **MirrorSat Requirements**
  - Must support the Deformable Mirror Payload (DMP) mechanically and electrically via a 5V 1A supply (2W continuous operational power) and TTC via a UART interface
  - Must be able to operate independently of other units
  - Must be able to communicate with the CoreSat out to 1km max. via Wi-Fi ISL
  - Must be able to **undock, rendezvous** and **re-dock** multiple times – **relative motion/capture/docking EM controlled**.
  - Must have **3-axis control** and **1 DOF propulsion** capability
  - Must provide low/zero power magnetic latch to hold in position on CoreSat in orbit (via **CoreSat permanent magnets**)
  - Must be able to safely enter the CoreSat Docking Port's acceptance cone:
    - ~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.



MirrorSat Spacecraft Bus

2015/16 Old Layout:

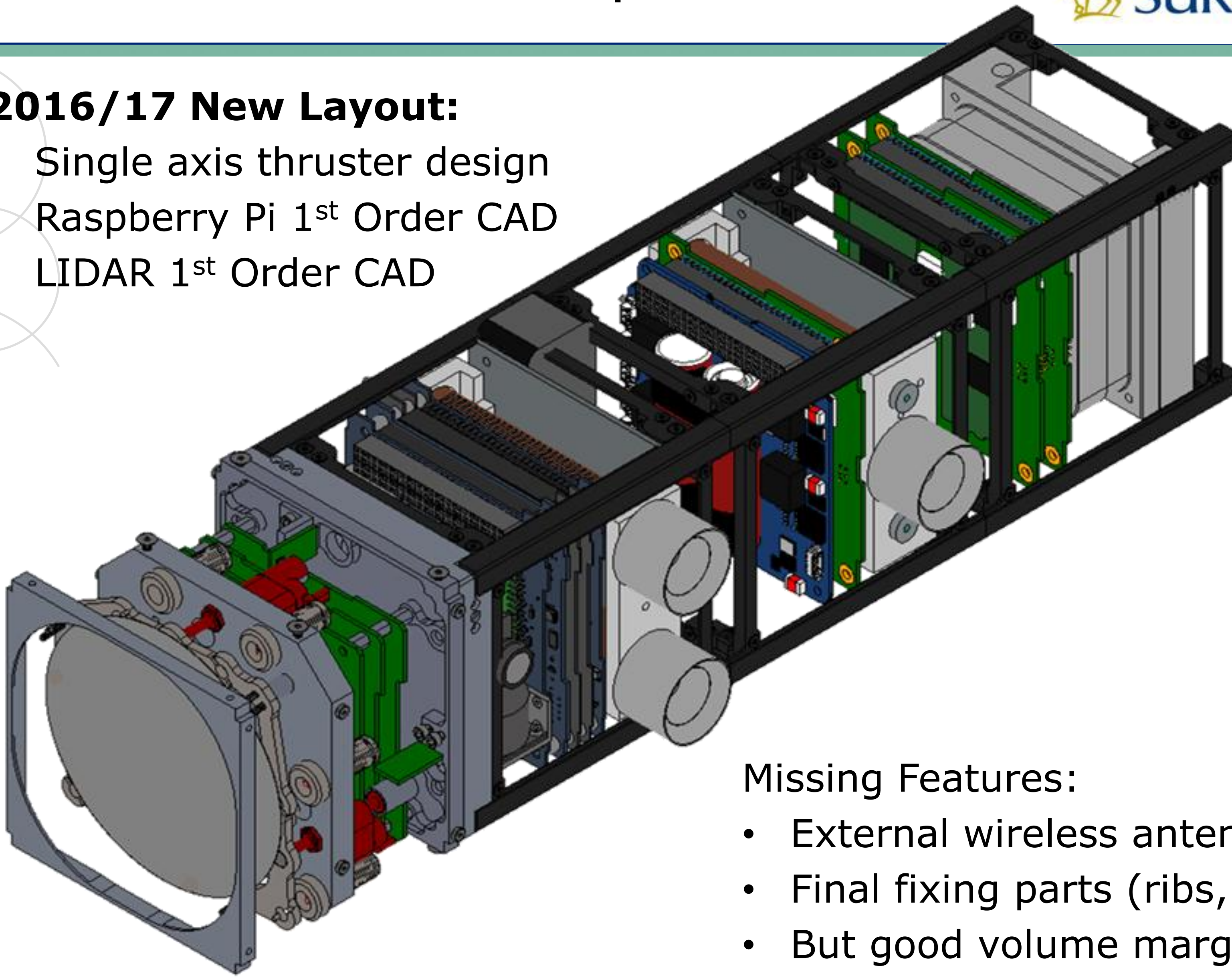
- Split Thruster Design System
- Raspberry Pi Dummy CAD
- LIDAR Dummy CAD



MirrorSat Spacecraft Bus

2016/17 New Layout:

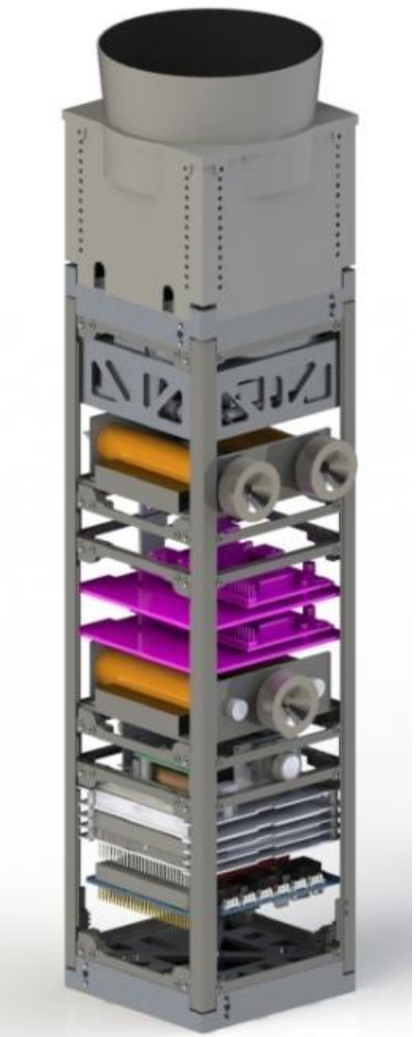
- Single axis thruster design
- Raspberry Pi 1st Order CAD
- LIDAR 1st Order CAD



Missing Features:

- External wireless antenna
- Final fixing parts (ribs, etc)
- But good volume margins allow some flexibility

- **MirrorSat System Old Layout 2015**



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

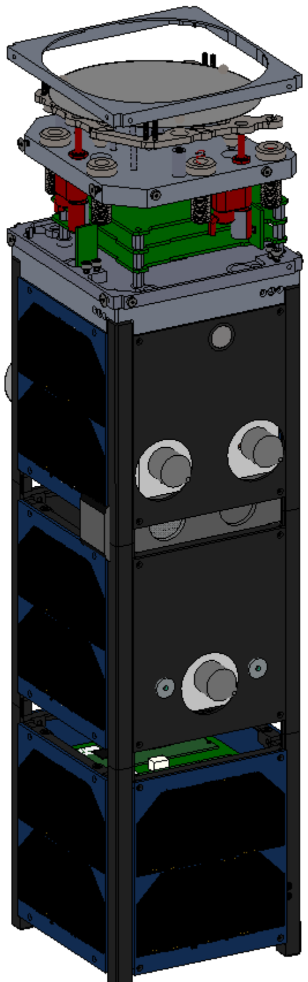
EPS - Gomspace

Prop. Sys. Driver (not shown)

Bottom Propulsion Unit

MirrorSat Spacecraft Bus

- **MirrorSat System New Layout 2017**



Note:
Preliminary CAD
– design not yet
finalised

CalTech Payload

ADCS/OBC Bundle

Top EM Docking Port

Soft Kinetic LIDAR DS325

Gomspace EPS + 20 Wh Batt.

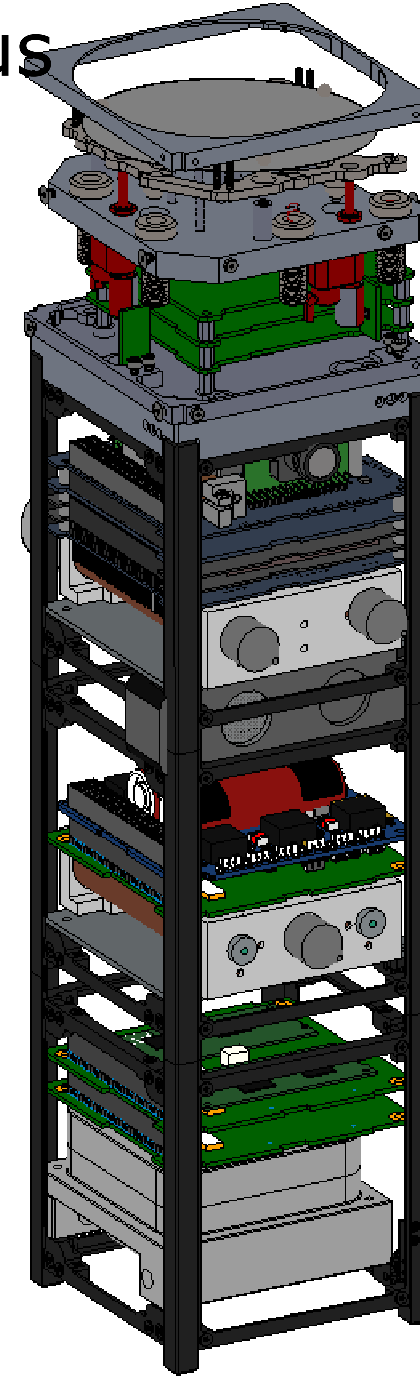
Power Switch Board (PSB)

Bottom EM Docking Port

Payload Interface Computer
(Dual redundant RPi)

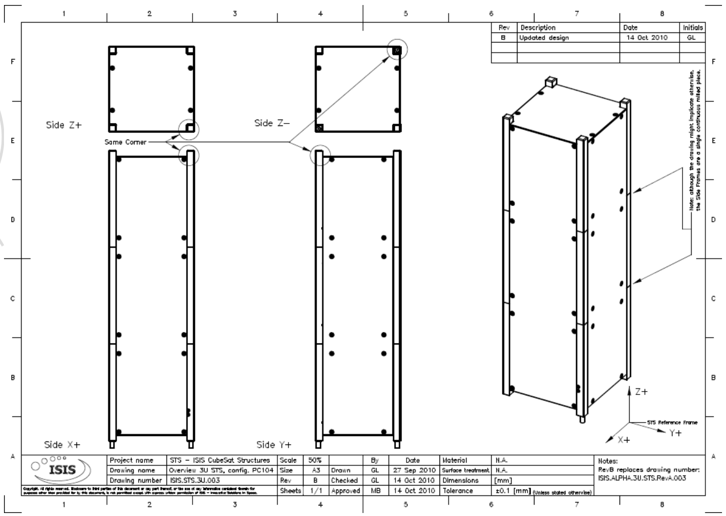
Thruster Control Board

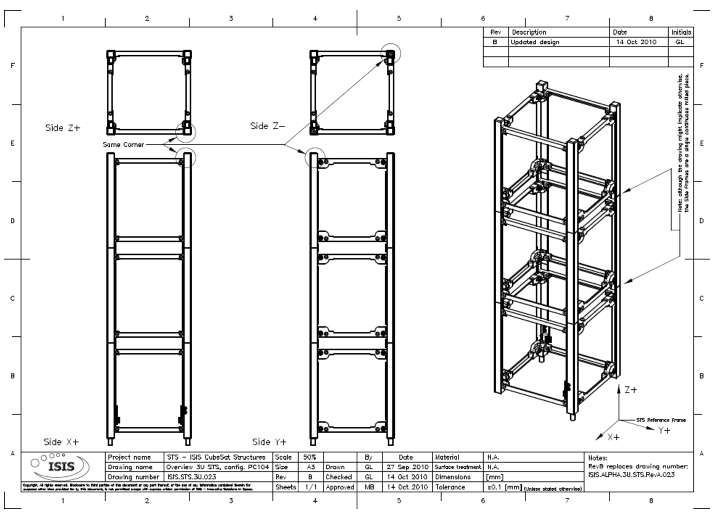
Z Axis Butane Thruster



MirrorSat Spacecraft Bus

- **MirrorSat Structure (essentially unchanged)**
  - Modified COTS **ISIS 3U CubeSat Structure** (270g for 3U)

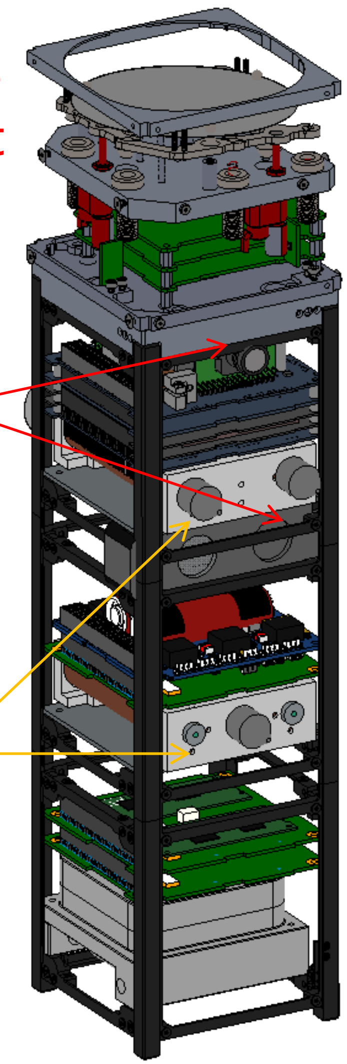




Note:
Preliminary CAD – design not yet finalised

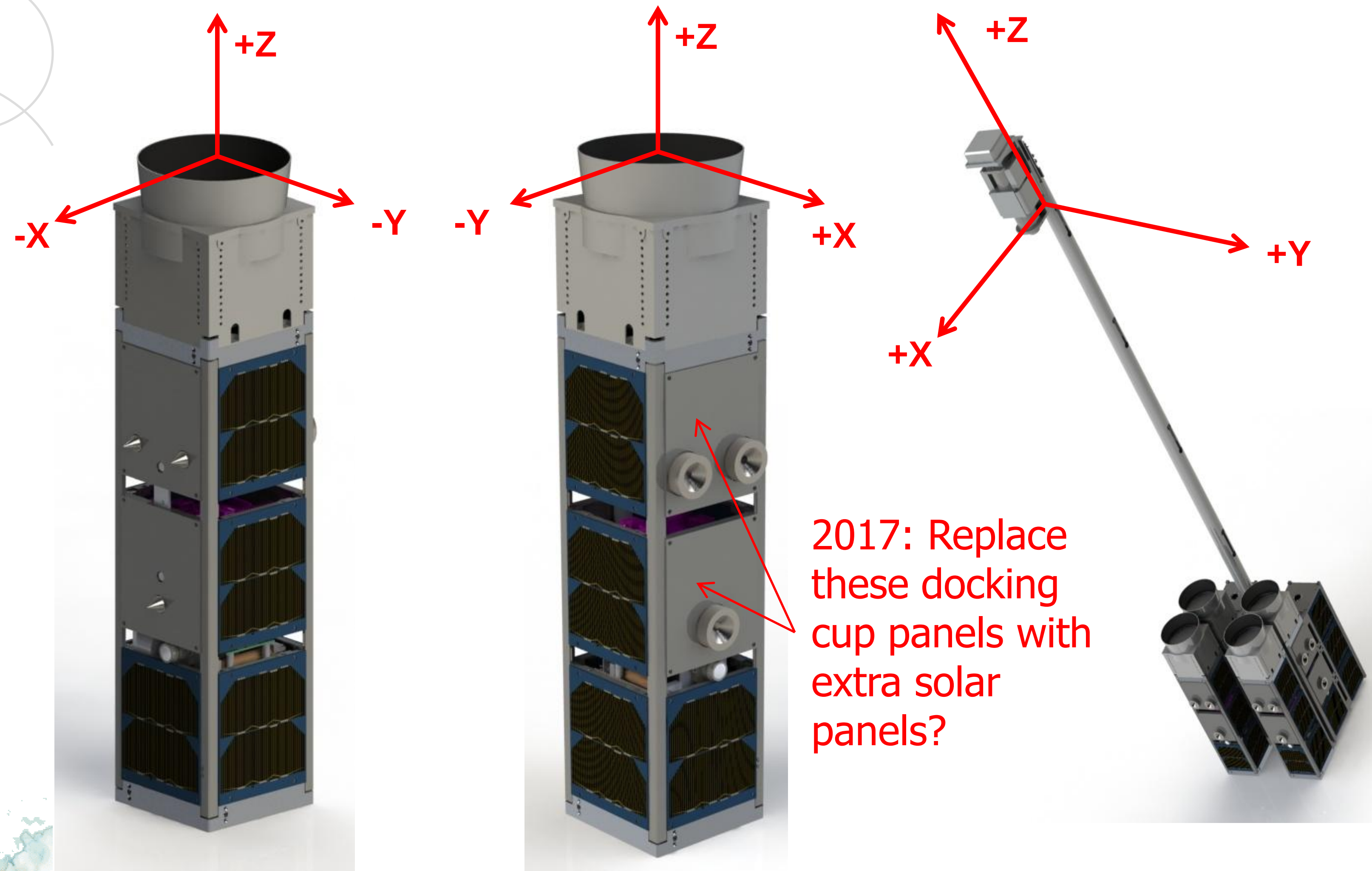
Ribs need modification so as not to block the LIDAR and cameras

Docking port location set by rib positions



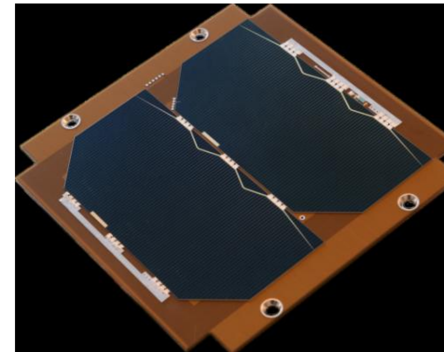
MirrorSat Spacecraft Bus

- **MirrorSat Structure (essentially unchanged)**
  - Renderings showing X (Docking) Facets, Y (Main Solar Panel) Facets and +Z (DMP) Facet (LIDAR/ADCS Sensors not shown)



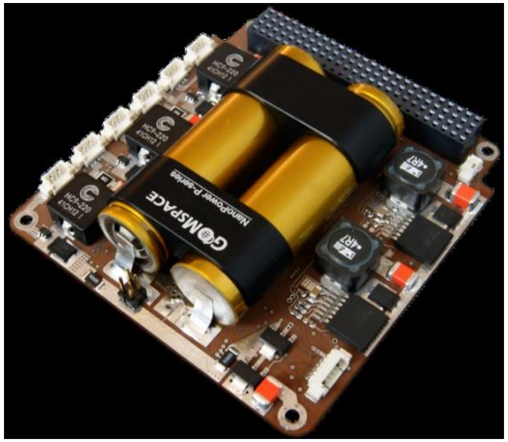
MirrorSat Spacecraft Bus

- **MirrorSat Solar Panels**



  - **COTS GOMSPACE NanoPower P110 Series**
  - Compatible with ISIS structure
  - AzurSpace 3G30A space qualified triple junction cells at ~30% efficiency with CMX 100 cover glass (100um); 26-29g per 1.1mm thick; blocking diode, Sun and Temperature Sensor included on each PCB.
  - **X facets** (Docking Port sides) each have 1 PCB – generating 500mA at 4.7V (**2.3W**) max. per facet.
  - **Y facets** have three PCBs connected in parallel – generating 1.5A at 4.7V (**6.9W**) max. per facet.
  - Orbit average power for the free-flying MirrorSat ~2.5W (depending on final orbit choice and attitude scenario).
  - When docked, all cells may be shadowed – however, an additional 5V at 0.8-1A (**4-5W**) is available to the MirrorSat via the Docking Port connected to the **USB Charger port** of the MirrorSat EPS.
  - **Note: Solar Panels may be similar bespoke Surrey design**.

- **MirrorSat EPS**
  - **COTS GOMSPACE NanoPower P31u EPS** (30W)
    - Provides compact integrated EPS , Battery and switchable, over-current protected power supplies.
    - 3 PV input MPPT converters (4.2V-8.5V, 2A max. each)
    - V_Bat (6V-8.4V, 12A); 5V, 4A Buck Reg.; 3.3V, 5A Buck Reg.; 6 switchable, configurable (3.3V or 5V), latch-up protected lines (1A typ.); External WDT; Separation Switch; Flight pin.
    - External charger port 5V at 1A (connected to Docking Port)
    - 2600mAh 2 cell (7.4V) Li-ion battery (20 Wh);
    - Battery has H/W and S/W under/over voltage protection and heater option.
    - I2C telemetry and telecommand.

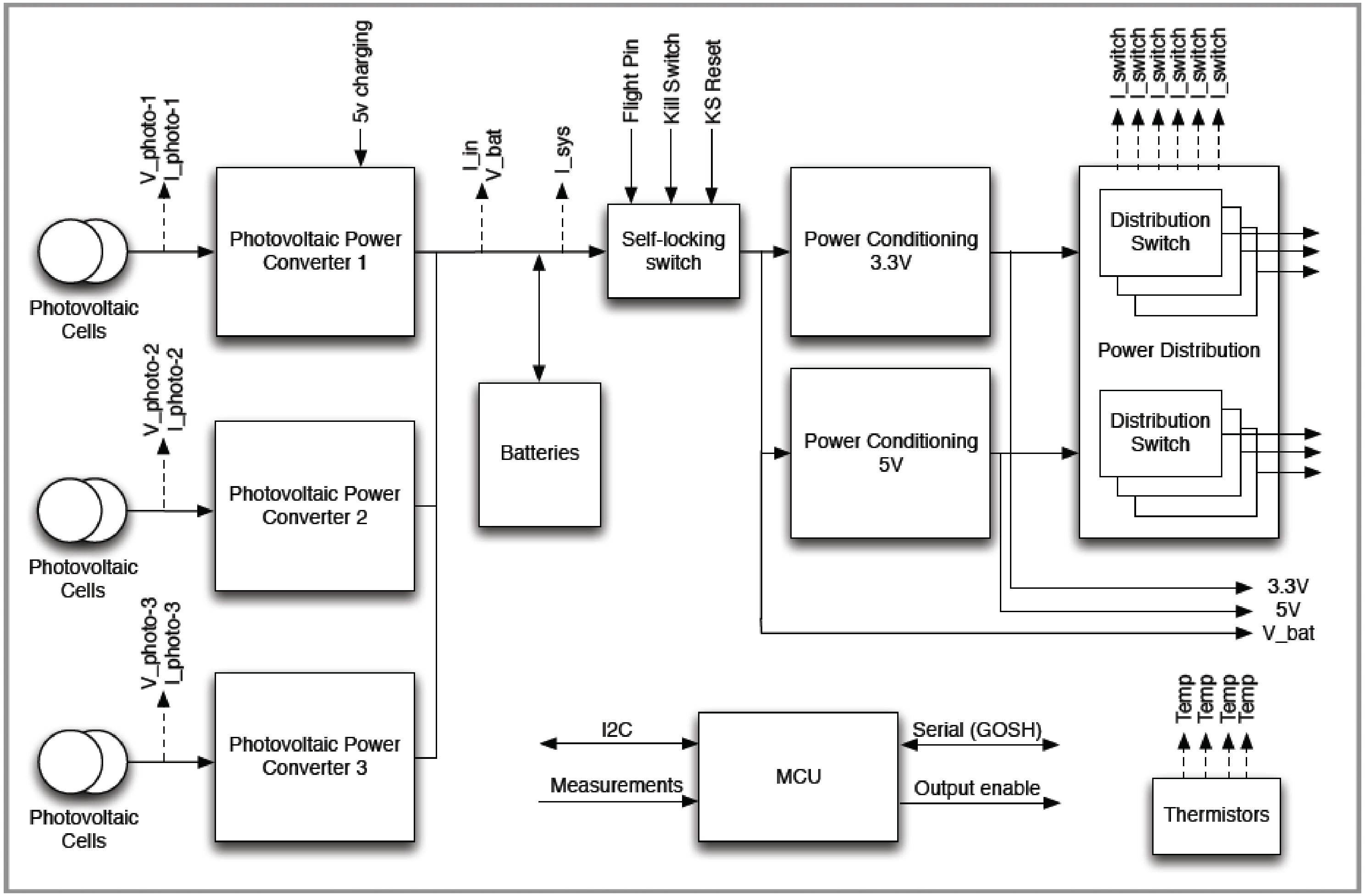


MirrorSat Spacecraft Bus

- **MirrorSat EPS**
  - **Features:**
    - Three independent MPPT inputs (input power up to 30W) optimised for 2 PV cells in series + 5V,1A charging port
    - Battery under-voltage and over-voltage protection
    - Can operate without batteries after end of battery lifetime
    - Two regulated power buses: 3.3V@5A and 5V@4A
    - Six configurable and controlled output switches with latching current limiter
    - Discrete control of output switches
    - Onboard housekeeping measurements
    - Separation-switch interface with latching mechanism
    - Remove-Before-Flight-pin interface
    - Onboard 2600 mAh lithium ion battery pack; heater option.
    - I2C interface with WDTs.
    - Operational temperature: -40 to +85 ^{o}C
    - Dimensions: 96 x 90 x 26mm; mass: 200g (inc. Bat.)

MirrorSat Spacecraft Bus

- **MirrorSat EPS**
  - PVCP1 connected to Docking Port (1A); PVPC2 connected to Y facet panels (1.5A); PVCP3 connected to X facet panels (0.5A).
  - Solar Array Voltage = 4.7V nom.; V_Bat = 6V-8.4V



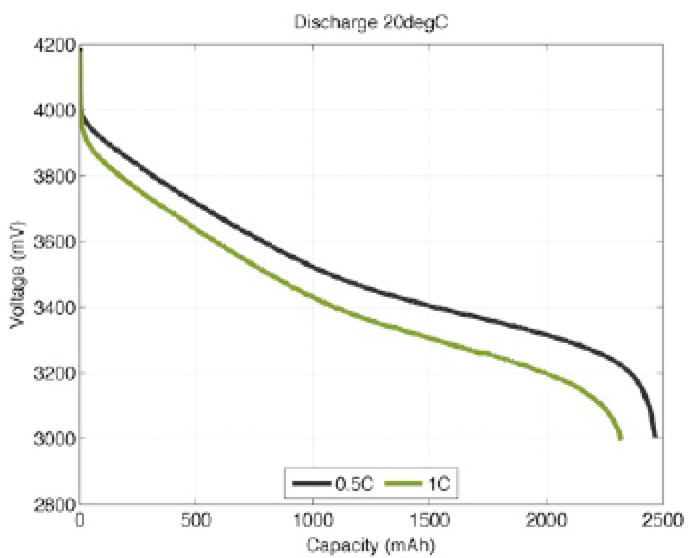
- **MirrorSat EPS**
  - **Housekeeping (I2C):**
    - Four temperatures
    - Current into and out of photovoltaic power converters
    - Photovoltaic input voltage for each input converter
    - Battery voltage
    - Total current into the output bus converters.
    - Current out of all power output channels
    - Number of latch-up events detected for each power output channel

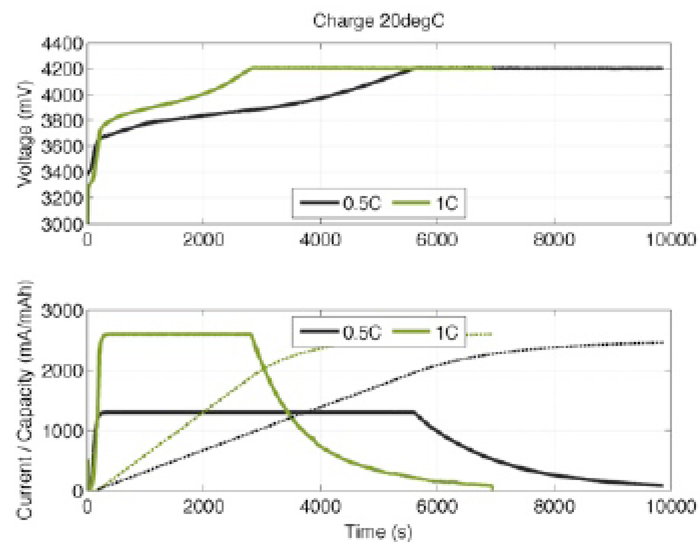
Parameter	Range (non-S)	Resolution (non-S)	Range (S)	Resolution (S)
Temperature	-40 to +125 deg C	1 deg C	-40 to +125 deg C	1 deg C
I_photo	0 to 3A	3mA	0 to 3A	3mA
I_in	0 to 6A	6mA	0 to 6A	6mA
I_sys	0 to 12A	12mA	0 to 12A	12mA
I_switch	0 to 2.4A	3mA	0 to 2.4A	3mA
V_photo	0 to 9.5V	10mV	0 to 19V	20mV
V_bat	0 to 9.5V	10mV	0 to 19V	20mV

MirrorSat Spacecraft Bus

- **MirrorSat Battery**
  - **2600mAh Li-Ion:** (note short cycle life at 100% DoD)

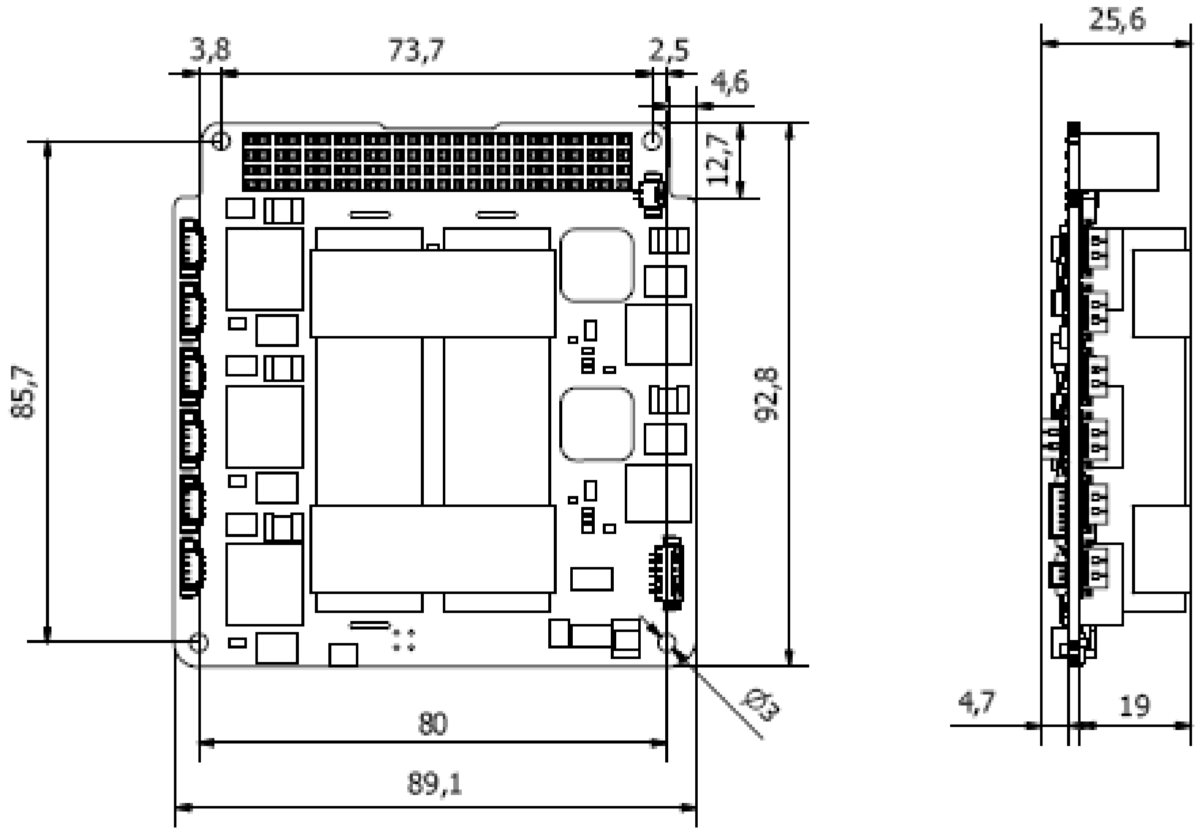
Parameter	Condition	Min	Typ	Max	Unit
Lithium-Ion Cell					
- Voltage		3.0	3.7	4.2	V
- Charge current			1000	2500	mA
- Discharge current			1000	3750	mA
- Charge temperature		-5		45	ºC
- Discharge temperature		-20		60	ºC
- Storage temperature	80% recovery after 1 year	-20		20	ºC
- Internal impedance				70	mOhm
- Cycle life (20% capacity loss)	DOD: 100%, Temp 25degC Charge/discharge: 1C/1C		350		cycles





MirrorSat Spacecraft Bus

- **MirrorSat EPS and Battery**
  - **Dimensions:** (200g mass)

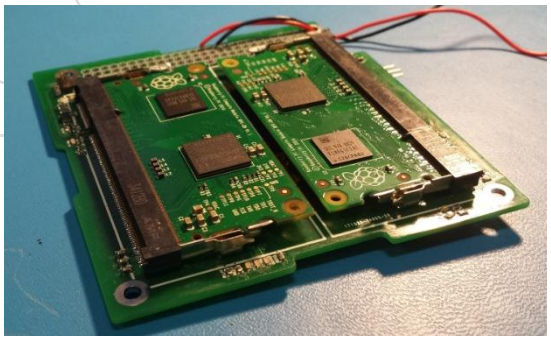


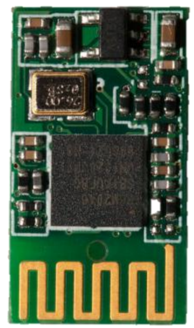
MirrorSat Spacecraft Bus

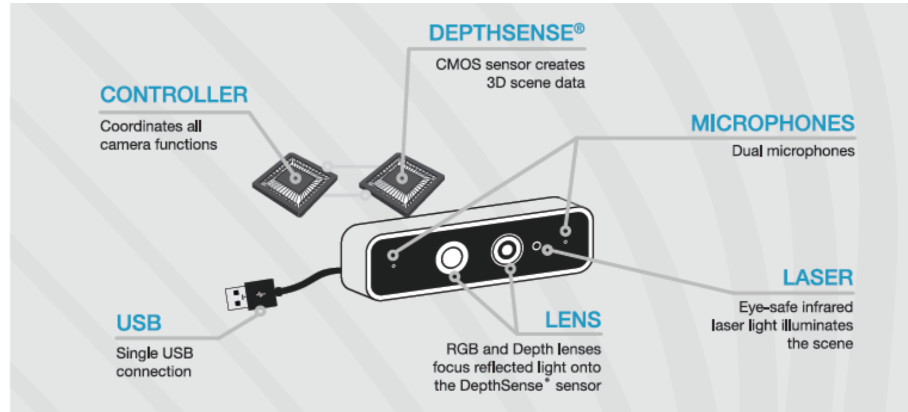
- **MirrorSat Power Budget (not updated)**
  - Systems connections/ power budget:
    - **EPS:** 125 mW on; 60 uA off (700 day min. discharge)
    - **ADCS:** (**CubeControl**; **CubeSense**; **CubeComputer**) – ADCS **3.3V sw.**; ADCS **5V sw.**; GPS **3.3V fixed**; GPS **5V fixed**; total consumption < 2W expected 0.5W (tbc).
    - **PCC:** (R-Pi; Wi-Fi) **5V sw.**; consumption 3.5W max.
    - **DPM: 5V sw.**; consumption 2W continuous.
    - **OBC2+ Softkinetic DS325 +LEDs**: **5V sw.**; 5V fixed; 6W max.
    - **EM Docking: 5V fixed**; 3.25W per coil = 13W max.
    - **Propulsion: 5V fixed;** 9W max.
  - MINIMUM Power Config. (EPS+PCC+Wi-Fi) <4W (contingent of software implementation) – aiming at 1-2W.
  - MAXIMUM Power Config. (RDV/Docking/Manoeuvre) <30W (assume few such manoeuvres to limit battery cycles)
  - MAXIMUM Power Config. (P/L Operation) <6W (aiming at 3-4W so that power can be provided by the CoreSat)

MirrorSat Spacecraft Bus

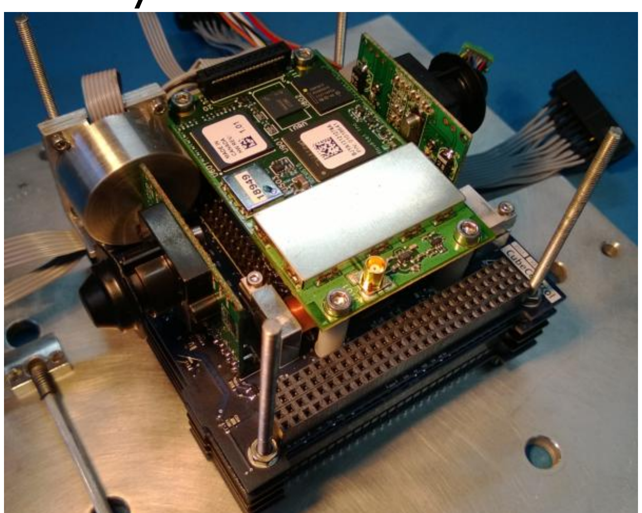
- **MirrorSat PCCs: Payload Control/ISL Communications**
  - These systems and their current status will be presented by Dr. Chris Bridges shortly.

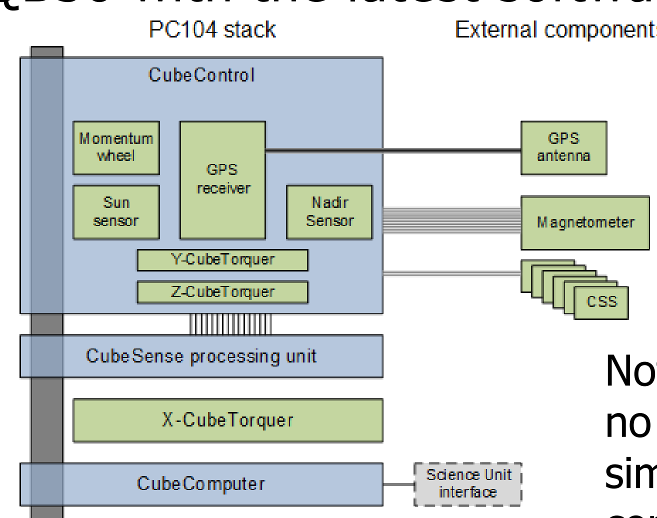






- **MirrorSat ADCS/OBC**
  - This system is as flown on QB50 with the latest software.

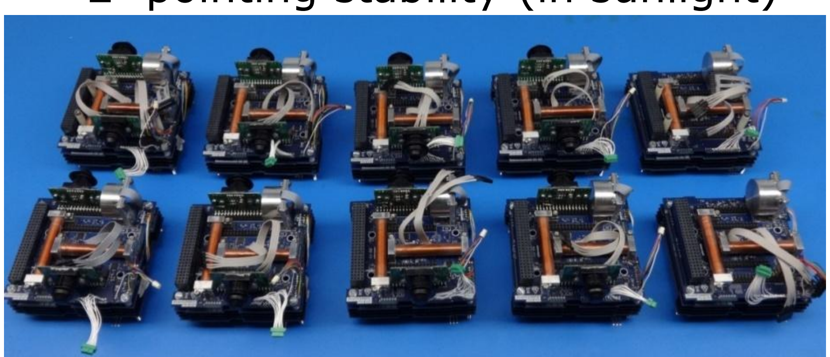


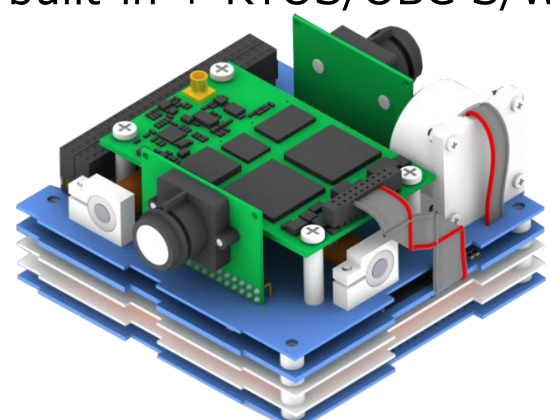


Note: Propose no GPS to simplify export control issues

MirrorSat Spacecraft Bus

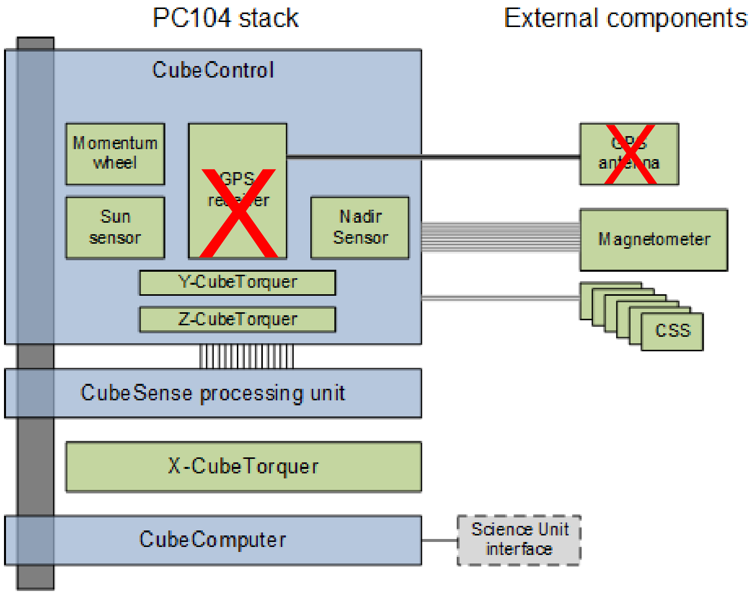
- **MirrorSat ADCS/ OBC**
  - Compact (450g) Integrated ADCS System developed for QB50 by Prof. Steyn (Stellenbosch) and Lourens Visagie (Surrey). OBC functionality/ Real-Time Operating System (RTOS) developed by SSC.
  - Comprises:
    - CMOS Camera Digital Sun Sensor
    - CMOS Camera Digital Earth Sensor
    - 6 Course Analogue Sun Sensors (must fly all 6)
    - 3-Axis Magnetoresistive Magnetometer
    - 3-Axis Magnetorquer (2 Rods + 1 Coil)
    - Pitch-Axis Small Momentum Wheel
    - GPS Receiver interface (proposed to be not populated)
    - Updated EKF and B-dot control software built-in + RTOS/OBC S/W
    - ~2º pointing stability (in sunlight)



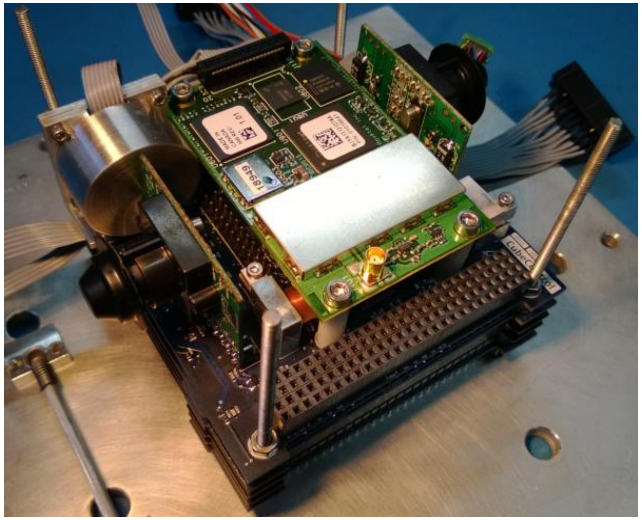


MirrorSat Spacecraft Bus

- **QB50 ADCS**
- 3 x PC/104 Boards
  - CubeComputer
  - CubeSense processing board
  - CubeControl
- Peripheral Components
  - Fully integrated ADCS has momentum wheel, Sun- and nadir cameras, and magnetorquers in stack
  - Magnetometer and 6 coarse Sun sensor photodiodes

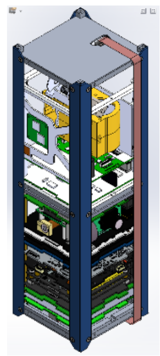
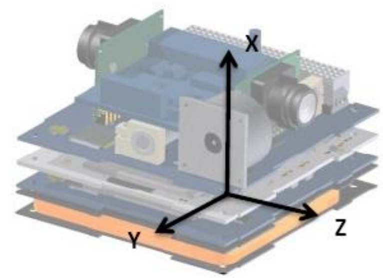


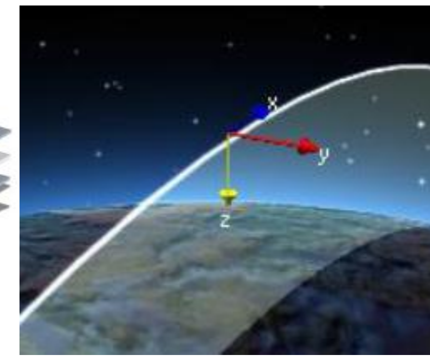
- 15 QB50 ADCS Units delivered.
- Flight heritage on STRaND-1, AlSat-1N, 2 x QB50 pre-cursor missions and DeorbitSail



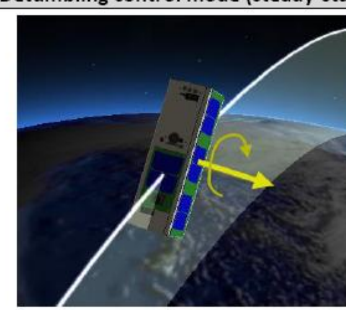
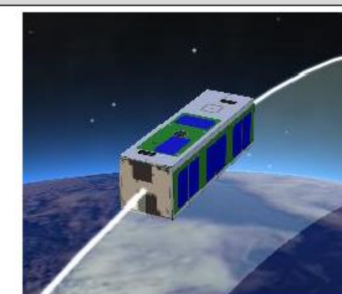
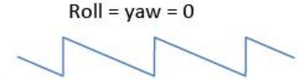
MirrorSat Spacecraft Bus

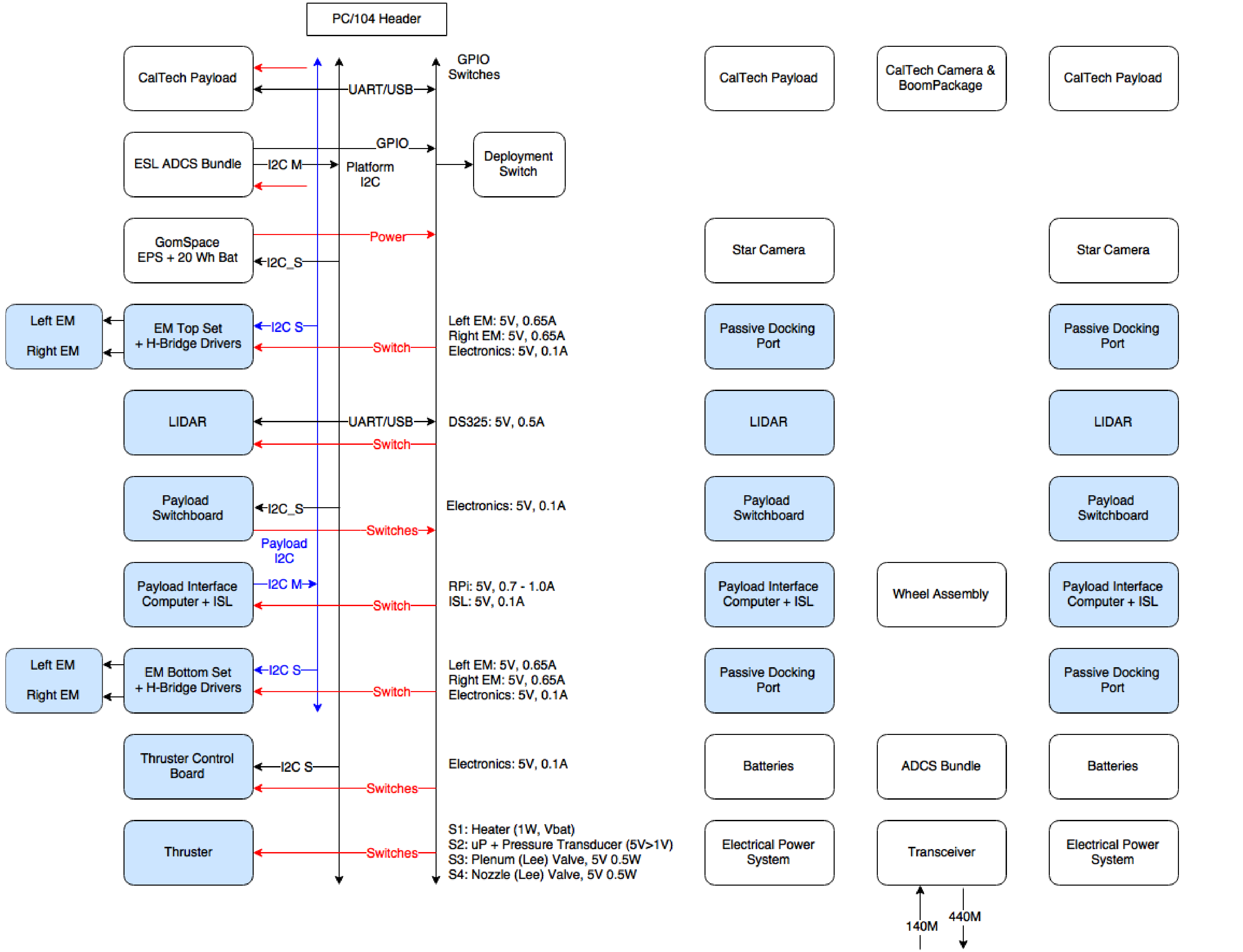
- **MirrorSat ADCS Update 2016/17**
  - A PhD student: Abdelmadjid Lassakeur, started in July 2015 with the topic of Precision ADCS for CubeSats. AlSat-1N launched in October 2016 – ADCS turn on due January 2017.



  - Helmholtz Coil Magnetic Test Facility built & used for AlSat-1N.
- Results from QB50 Precursors:
  - Performance has been analysed and the software updated.
  - QB50 satellites will launched Q1-Q3 2017.
  - Note X and Z axes are swapped w.r.t. the 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	$\omega = [0 \quad \omega_{y,ref} \quad 0]$	$\omega = [0 \quad 0 \quad 0]$


PC/104 Header
CalTech Payload
UART/USB
GPIO
Switches
ESL ADCS Bundle
GPIO
I2C M
Platform
I2C
Deployment
Switch
GomSpace
EPS + 20 Wh Bat
Power
I2C_S
Left EM
Right EM
EM Top Set
+ H-Bridge Drivers
I2C S
Switch
Left EM: 5V, 0.65A
Right EM: 5V, 0.65A
Electronics: 5V, 0.1A
LIDAR
UART/USB
DS325: 5V, 0.5A
Switch
Payload
Switchboard
I2C_S
Electronics: 5V, 0.1A
Switches
Payload
I2C
Payload Interface
Computer + ISL
I2C M
Switch
RPi: 5V, 0.7 - 1.0A
ISL: 5V, 0.1A
Left EM
Right EM
EM Bottom Set
+ H-Bridge Drivers
I2C S
Switch
Left EM: 5V, 0.65A
Right EM: 5V, 0.65A
Electronics: 5V, 0.1A
Thruster Control
Board
I2C S
Electronics: 5V, 0.1A
Switches
Thruster
Switches
S1: Heater (1W, Vbat)
S2: uP + Pressure Transducer (5V>1V)
S3: Plenum (Lee) Valve, 5V 0.5W
S4: Nozzle (Lee) Valve, 5V 0.5W
CalTech Payload
CalTech Camera &
BoomPackage
CalTech Payload
Star Camera
Star Camera
Passive Docking
Port
Passive Docking
Port
LIDAR
LIDAR
Payload
Switchboard
Payload
Switchboard
Payload Interface
Computer + ISL
Wheel Assembly
Payload Interface
Computer + ISL
Passive Docking
Port
Passive Docking
Port
Batteries
ADCS Bundle
Batteries
Electrical Power
System
Transceiver
Electrical Power
System
140M
440M

Surrey AAReST MirrorSat Propulsion Unit

Valves, Tubing, Connectors and Filters

- IEP Series Lee valves for gas isolation, thrusters and plenum pressure regulation

IEP Series Valve Part Number	Seal Material	Spike/Hold Voltage (VDC)	Power at Holding Voltage (W)	Max Operating Frequency (Hz)	Max Operating Pressure (Bar)	Max Ambient Temp (C)	Dry mass (g)
IEPA1221141H	Fluorocarbon	12 / 1.6	0.25	500	55	135	4.7

- 187 Zero Leak Chek valve used for tank fill/drain. Valve port capped off with Lee expansion plug for additional safety

Zero Leak Chek Part Number	Seal Material	Max Operating Pressure (Bar)	Max Ambient Temp (C)	Dry mass (g)
CSFA1876005A	Fluorocarbon	207	149	2.3

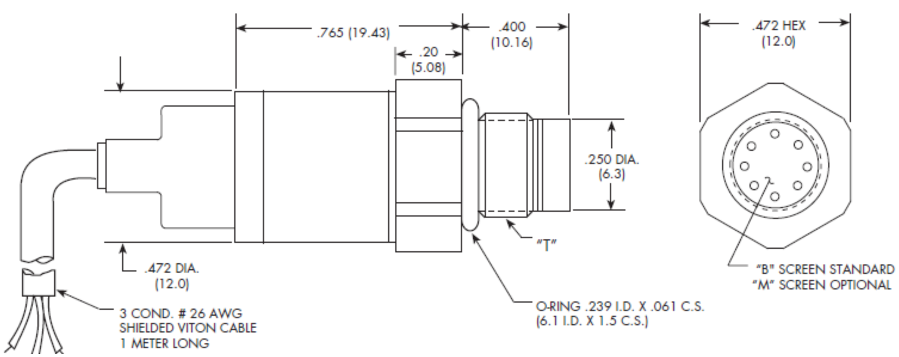
- 1/16th inch stainless steel swagelok tubing rated to 560 bar

- 1/16th inch NPT tapered pipe connectors for interface between tank, plenum, thrusters and tubing. Rated to 1034 bar

- 6mm diameter 10 micron filter discs used for system filtration

Pressure Transducer

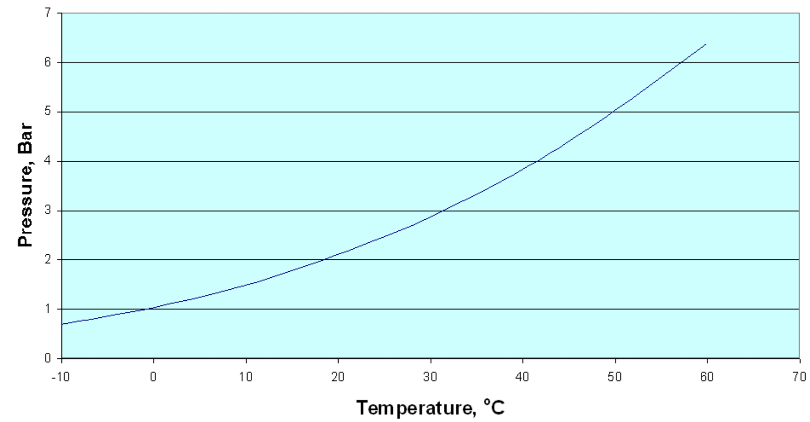
- Kulite ETM-634-312M pressure transducer used for monitoring plenum pressure and feedback input to valve
- Smallest high performance amplified transducer worldwide
- Operating temperature range of -55° C to 185° C
- Pressure range 0 – 15 Bar absolute with burst pressure of 45 bar
- Rated excitation of 12 ± 4 VDC (thus needs bespoke power supply)
- Maximum electrical current of 25mA



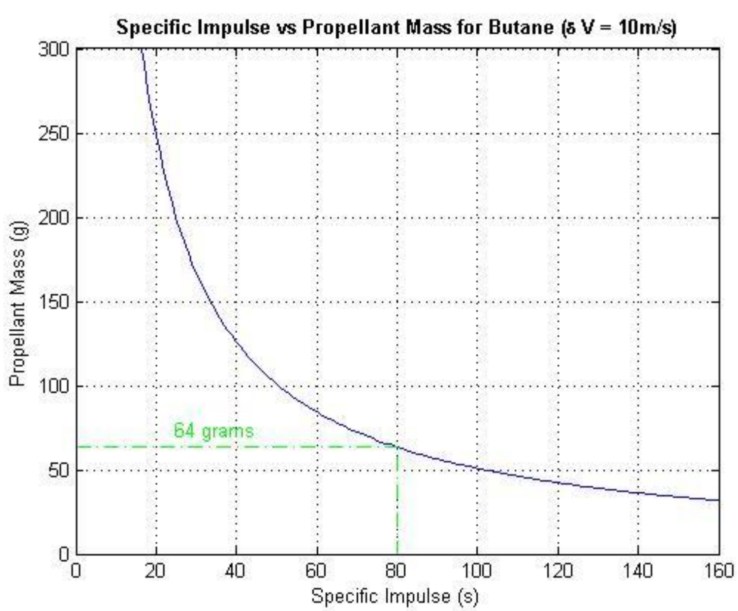
- Output impedance of 200 Ohms (Typ.)
- Analogue voltage output
- Full scale reading of 4.5V ± 1%
- Mass of 15g
- Stainless steel diaphragm

Propellant Tank

- 120 ml tank stores 64g liquefied butane propellant at 2 bar and a density of 0.53g/cm^3
- Butane chosen due to high storage density and relatively good specific impulse
- MEOP of 4 Bar corresponding to 42^{o}C
- Tank factor of safety of 12 (48 Bar predicted burst pressure)



Vapour pressure vs temperature for butane gas
Source: D.Gibbon SSTL



- Butane freezes at -138 ^{o}C so no thermal regulation is required
- Temperature sensor on tank for pressure monitoring
- 64g propellant needed for ΔV of 10m/s for 5kg flyer at 80 Isp
- Thus, we estimate 5-10 m/s ΔV

Thrusters

-0.13mm diameter Teflon insulated nichrome wire used for heater elements

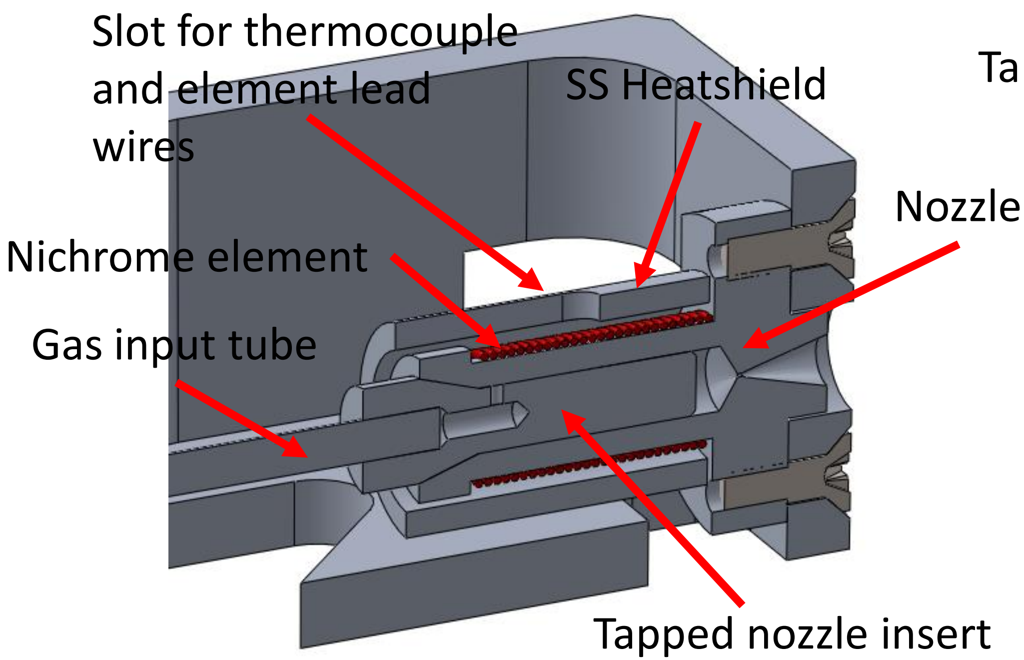
-Heating element bonded to thruster body with Duralco 133 Aluminium based epoxy resin for optimum heat transfer (Thermal conductivity of 5.8 W/m.K and maximum temperature of 316 °C)

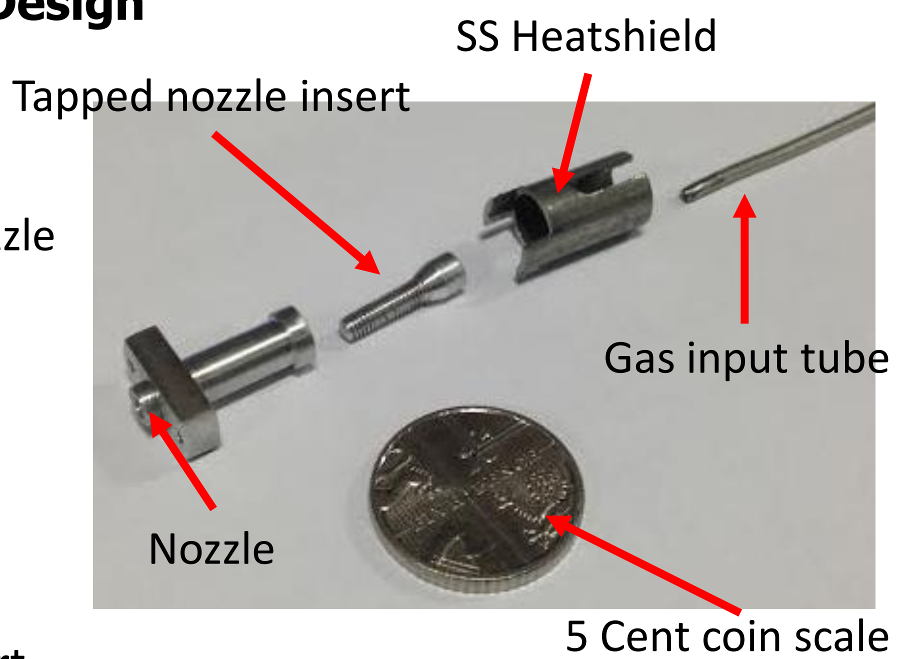
-Stainless Steel heat shield to minimise radiative heat loss

-K-Type wire thermocouple for thruster temperature monitoring (0 – 250 °C)

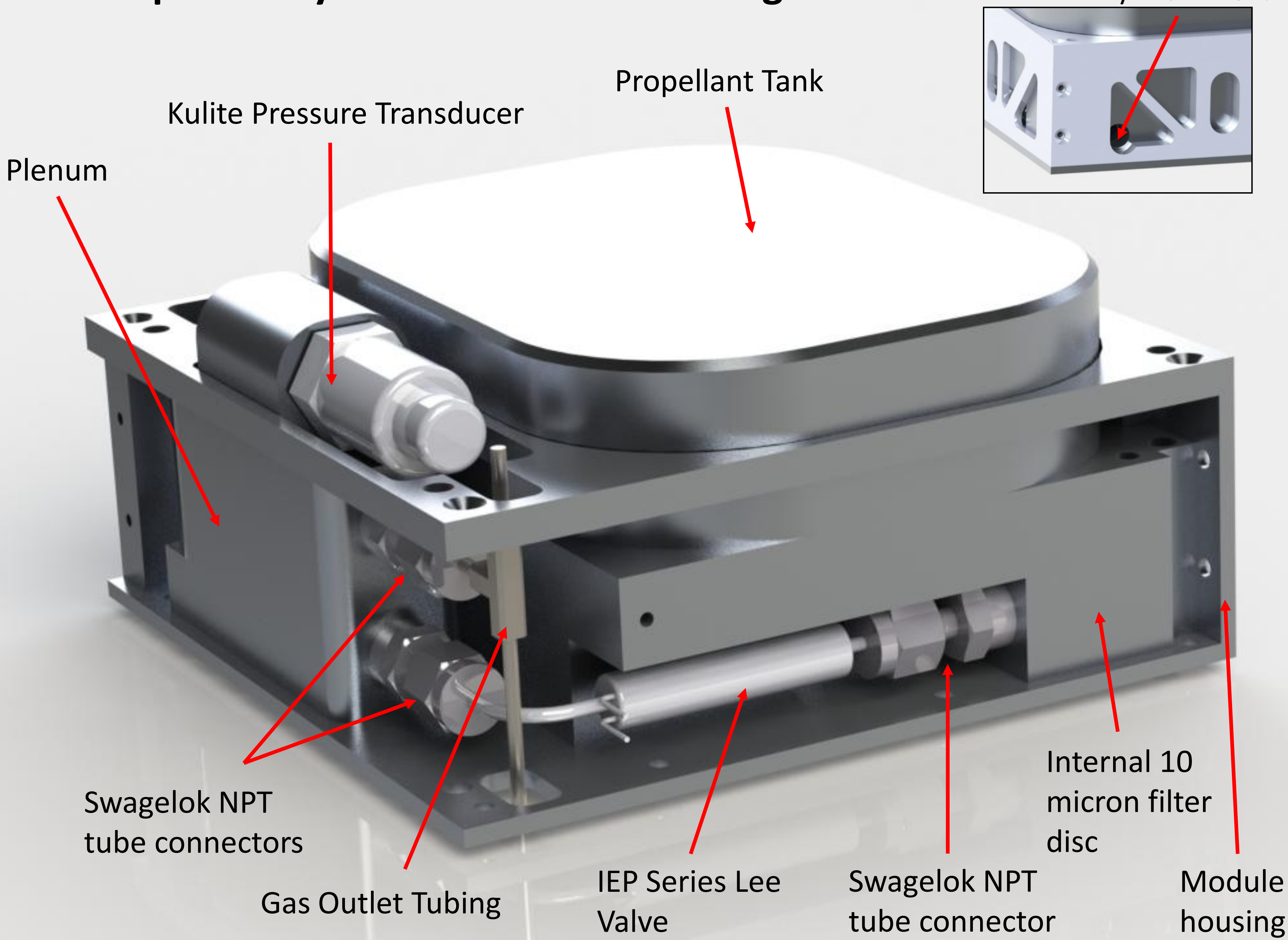
-Tapped nozzle insert to deliver gas and provide a long gas flow path around screw for optimum heating

2015 Design

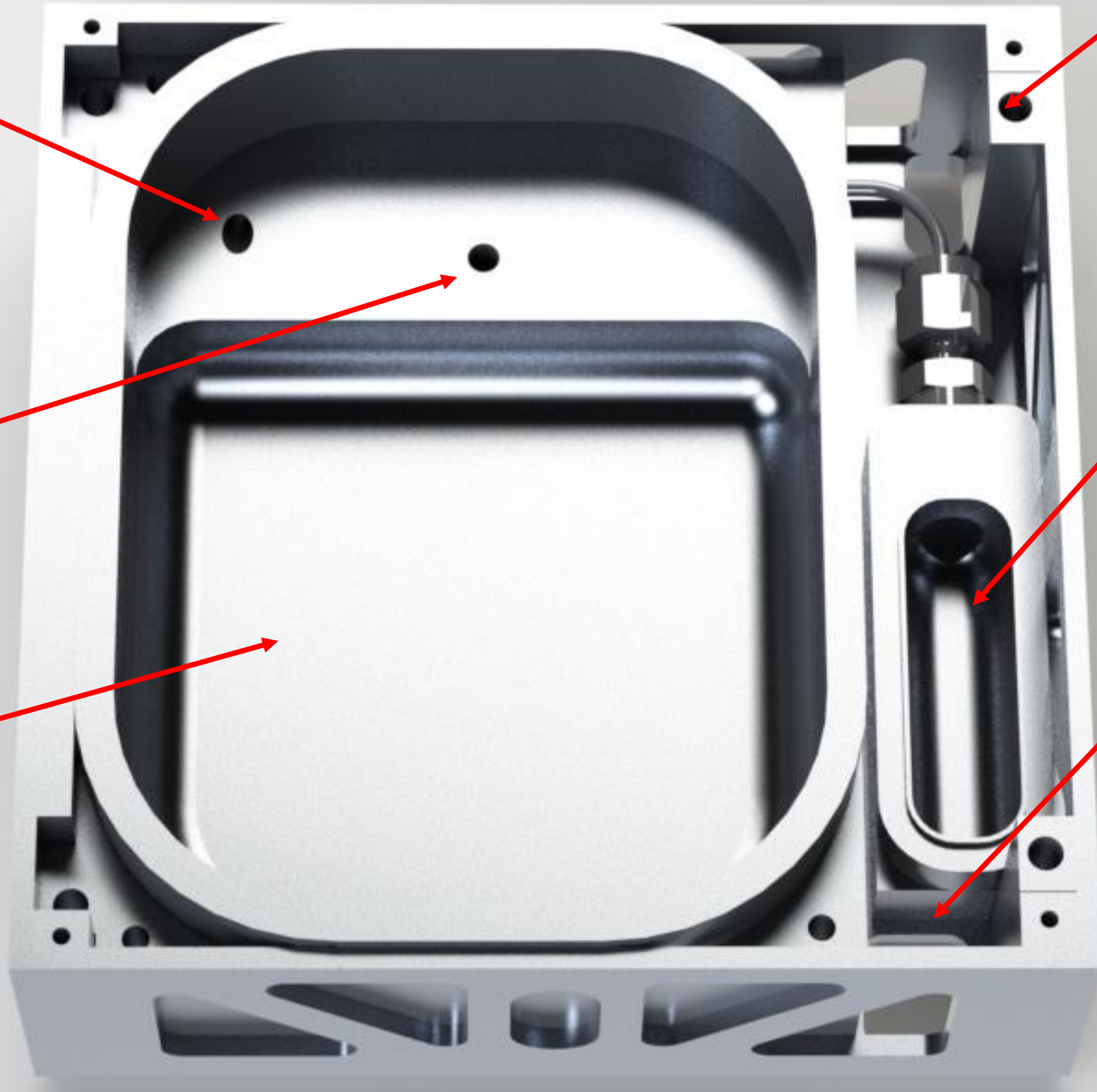




2015 Propellant System with Front Housings Removed



2015 Propellant System with Lids removed



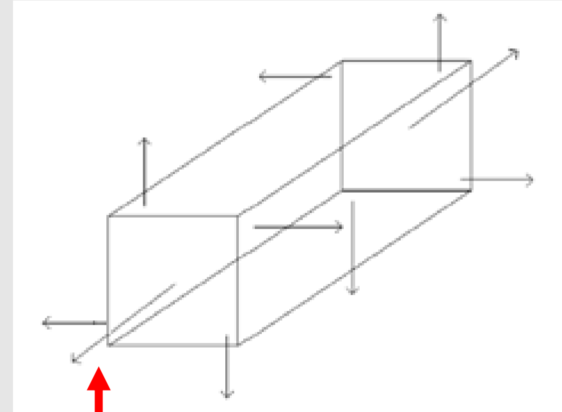
2015 Thruster Mounting Configuration

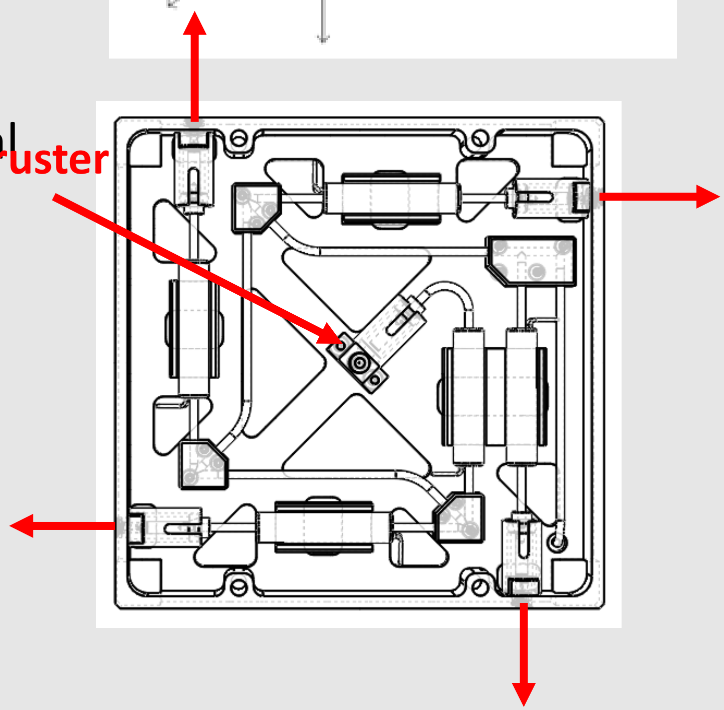
-Thrusters mounted in propulsion trays on upper and lower end of ISIS structure

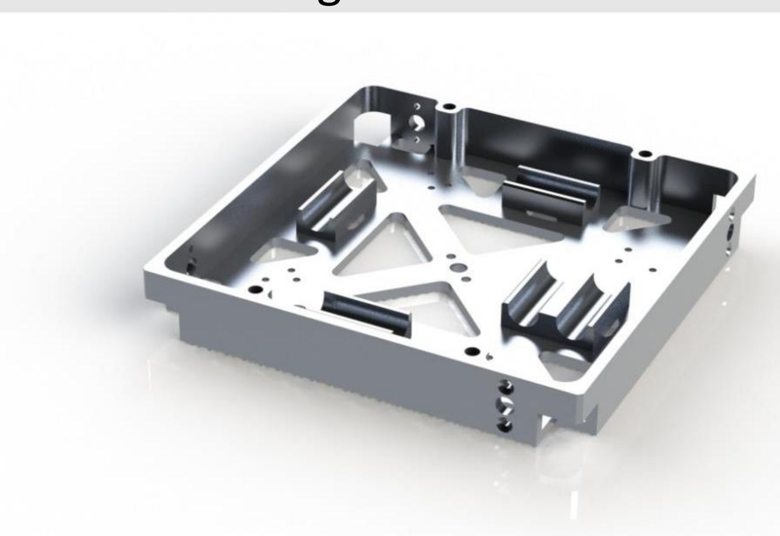
-Thrusters placed off centre to provide torque around the Flyer’s central axis with a reciprocal configuration in the corresponding tray

-Reciprocal thrusters fired together to provide lateral translation

-+Z axis thruster not flown due to mirror mounting



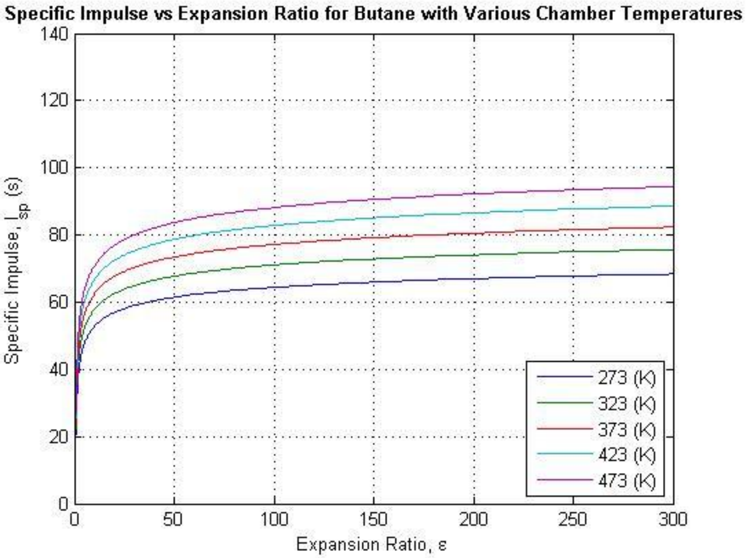


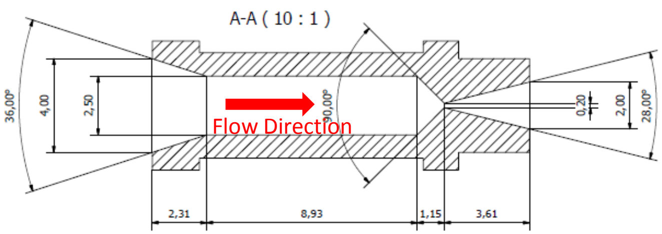


- Thrust trays machined from single piece of stock aluminium for extra rigidity
- Valve mounts built-in to structure
- **2016 tests showed tolerances were too tight**.

MirrorSat Spacecraft Bus

- **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.



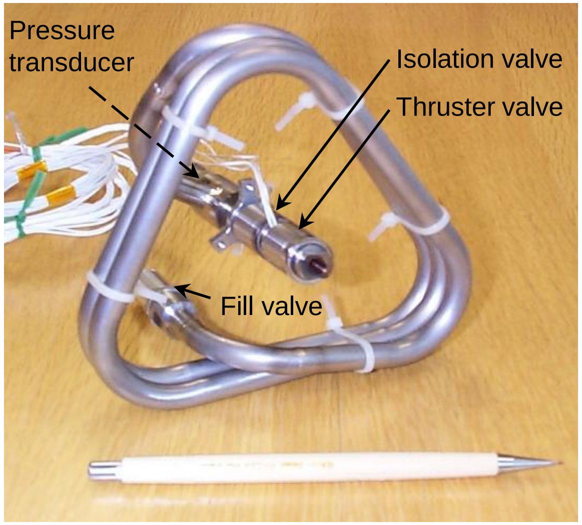


  - Isentropic flow relations used to predict optimum throat geometry for nominal plenum pressure of 0.5 bar
  - Nozzle throat diameter of 0.2mm and exit diameter of 2mm

- **MirrorSat Propulsion Capability**
  - 5 – 10 mN thrust range at ~ 80 s Isp.
  - Propulsion system provides ~5-10 m/s ΔV
  - Minimum valve opening time = 2 ms (500 Hz); Minimum Impulse bit = 10-20 μNs.
  - System mass estimated at 860 grams (wet); ~65g butane – slightly cut down from previous 2015 design.
  - 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.

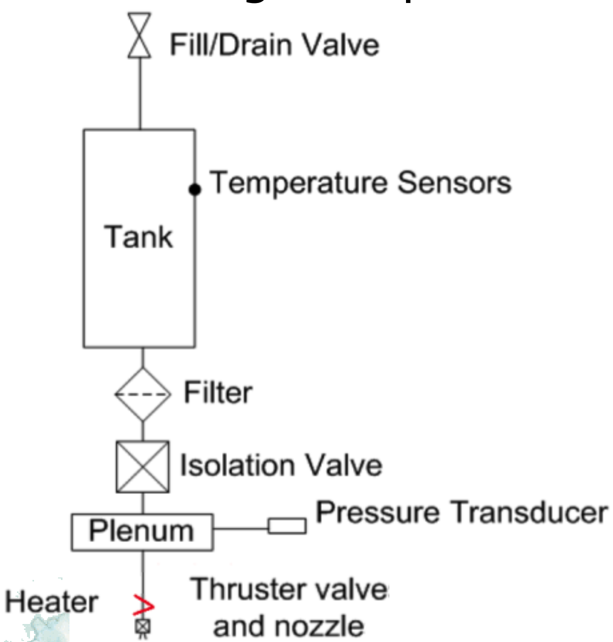
SNAP-1 System for Comparison

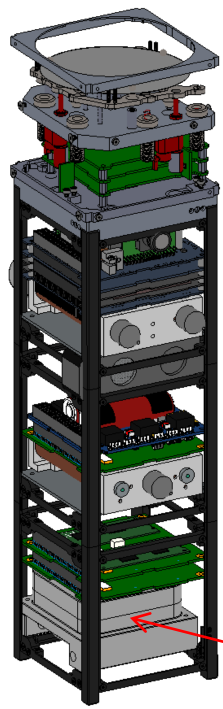
Propellant	**32.6 g butane**
Total impulse	**22.3 Ns**
Thrust range	**25 to 100 mN**
Module mass	**455 grams**
ΔV imparted	**2.1m/s (actual)**



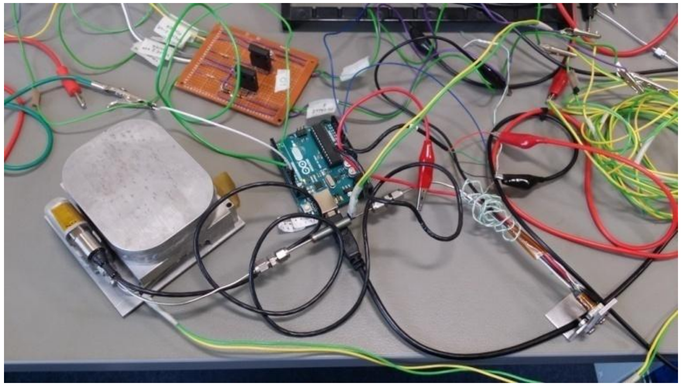
MirrorSat Spacecraft Bus

- **MirrorSat Propulsion System – Updated 2017**
  - Propulsion unit consists now of 1 x 1W micro-resistojet thruster to provide 1 DOF **single-axis thruster** (-Z axis)
  - Resistojet design simplified as a separate non-critical technology demonstration payload
  - 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



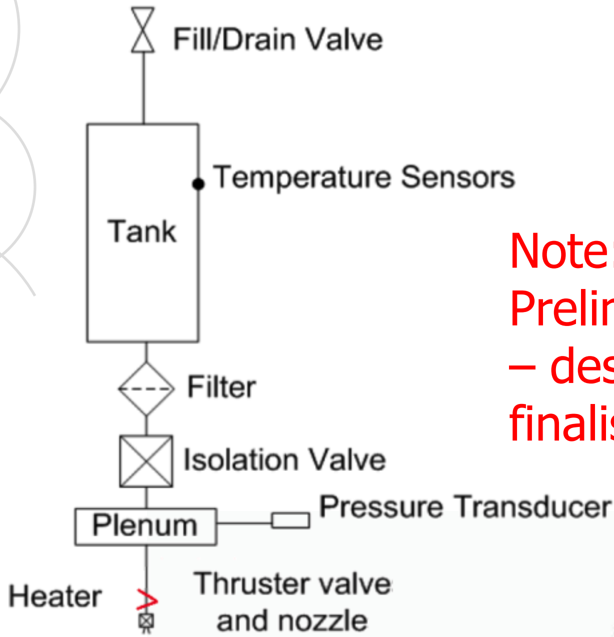


Propulsion Unit (Single Axis)

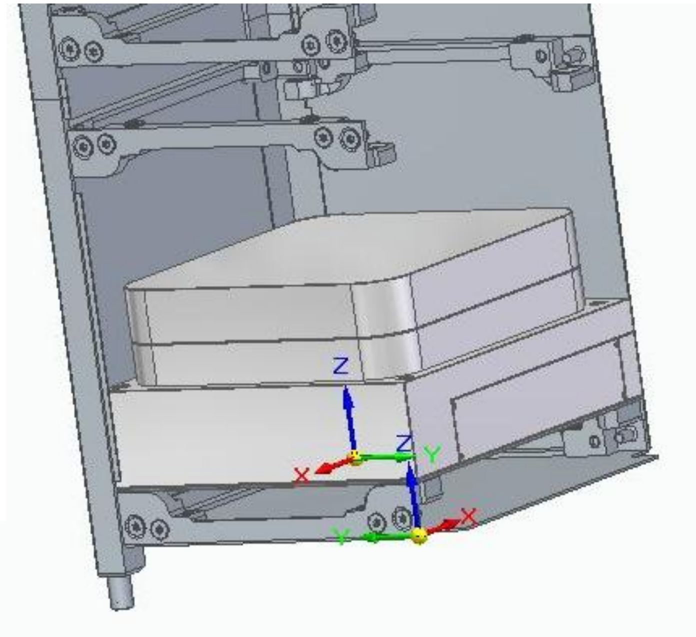


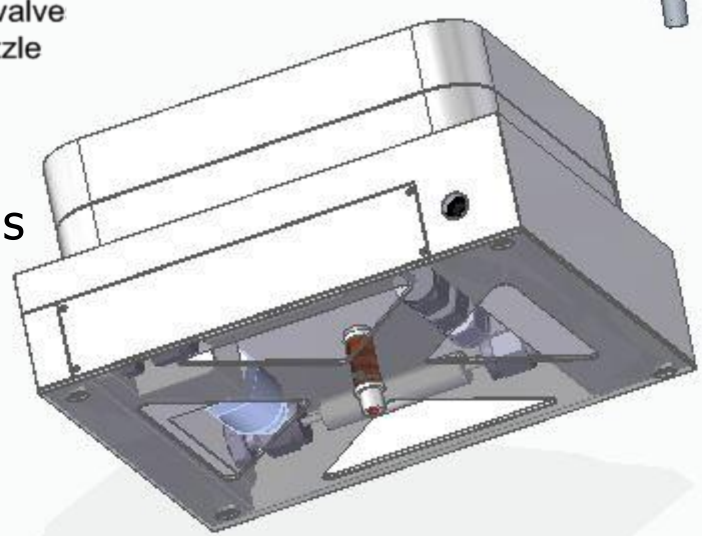
Components under test in air (2015/16 version)

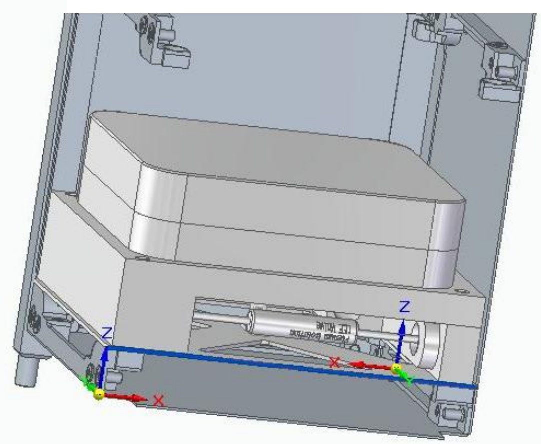
- **MirrorSat Propulsion System – Updated 2017**



Note:
Preliminary CAD – design not yet finalised





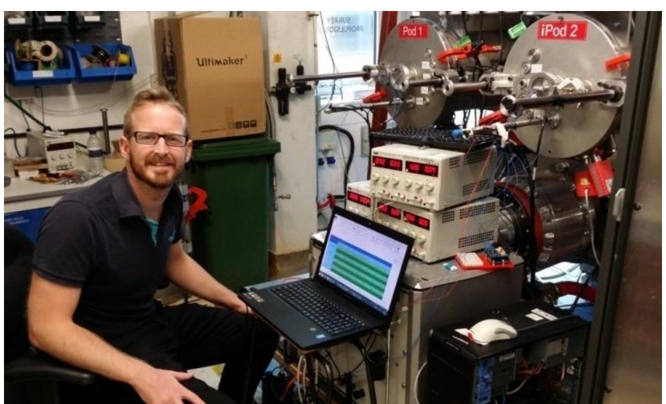


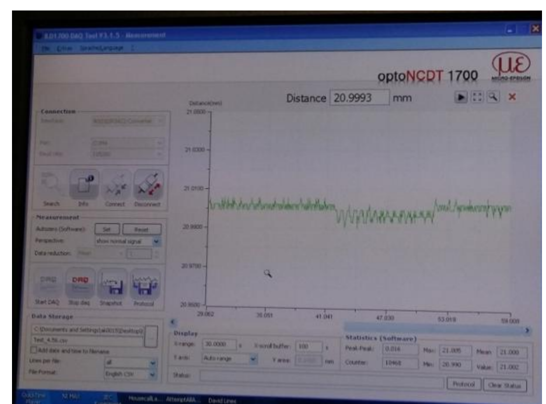
Nikolas Karefyllidis
(H/W design)

Dylan Fisher
(Electronics)

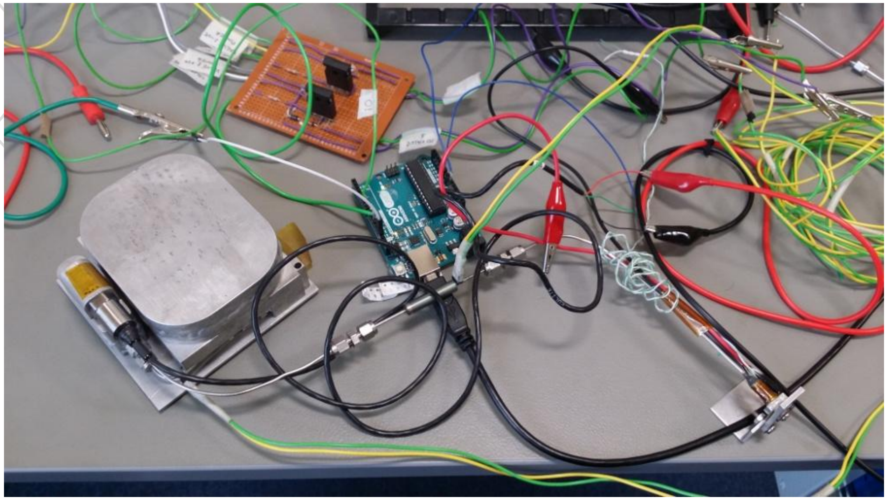
MirrorSat Spacecraft Bus

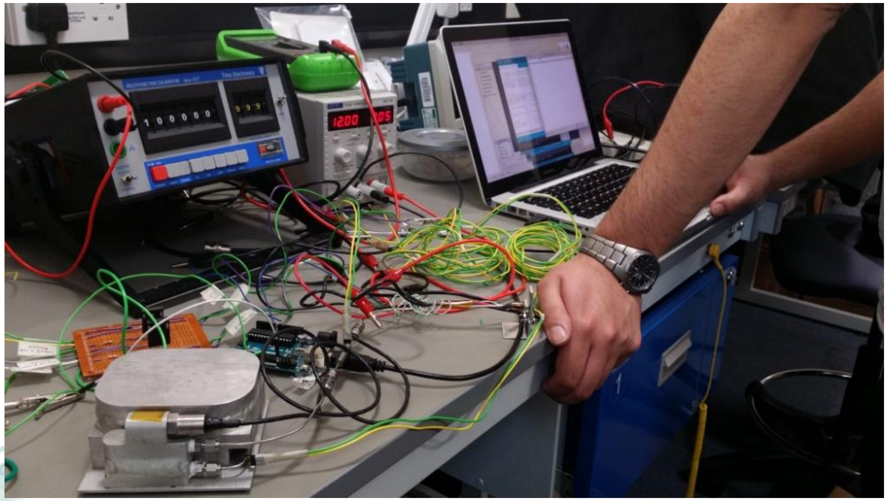
- **MirrorSat Propulsion Update 2017**
  - All system components built and tested – Propulsion tank, plenum chamber, (single) thruster/heater and valves – 2015 and 2016.
  - Two-part aluminium propellant tank welded successfully.
  - Butane filling very straight-forward from standard COTS cartridges.
  - 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.
  -

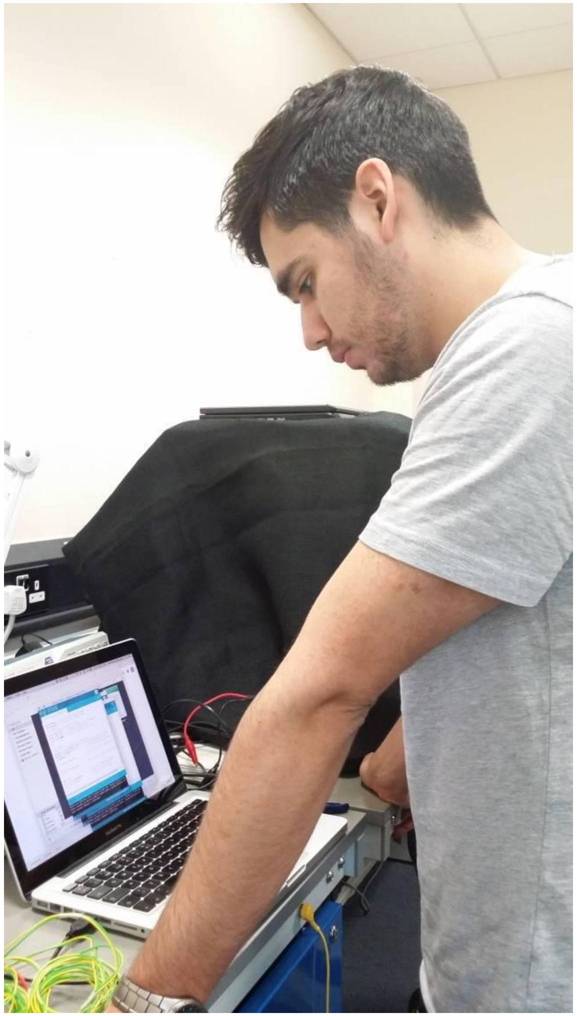




- **MirrorSat Propulsion Update 2017**
  - Propulsion tank, plenum chamber (old design), thruster/heater and valves re-tested 2016. New proto-flight system under development in 2017.

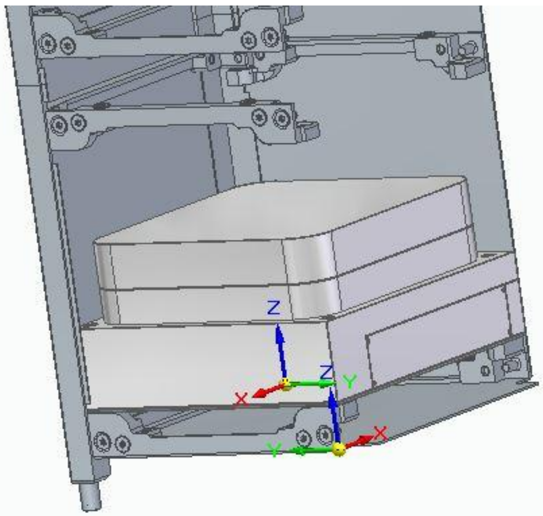






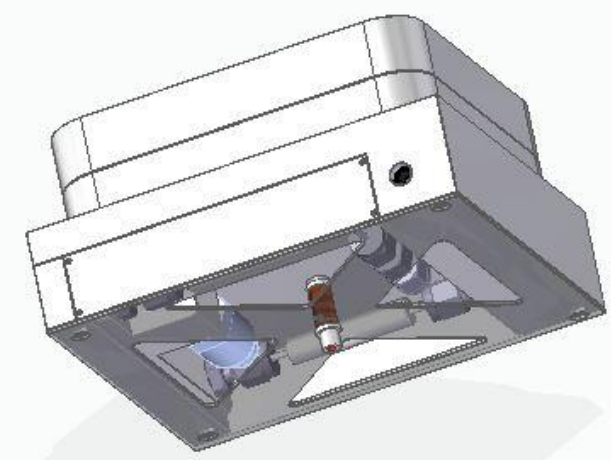
MirrorSat Spacecraft Bus

- **MirrorSat System Layout Update 2016/17 - Summary**
  - The Softkinetic DS325 LIDAR/Camera is now available again.
  - The dual redundant “Industrial” RPi board has successfully been implemented, revision 2 is under way
  - Propulsion system has been modified to a single axis thruster



Note: Preliminary CAD – design not yet finalised

Question: Can more thrusters be added so that 3 DOF translation is re-instated?



  - ISIS structure has been suitably modified for mechanical interface to MirrorBox
  - The Power System is the Gomspace P31U

AAReST CoreSat

NowCalTech Design with Technical Support from Surrey

Spacecraft Design

- **CoreSat Requirements**
  - Must be able to **point accurately** (< 0.1^{o} 3σ error all axes)
  - Must be **stable in attitude** (< 0.02^{o}/s for 600s) during payload operations.
  - Must be able to slew at >3^{o}/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^{o} 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

- **2015 CoreSat System Layout**
  (-X/+X facet view)

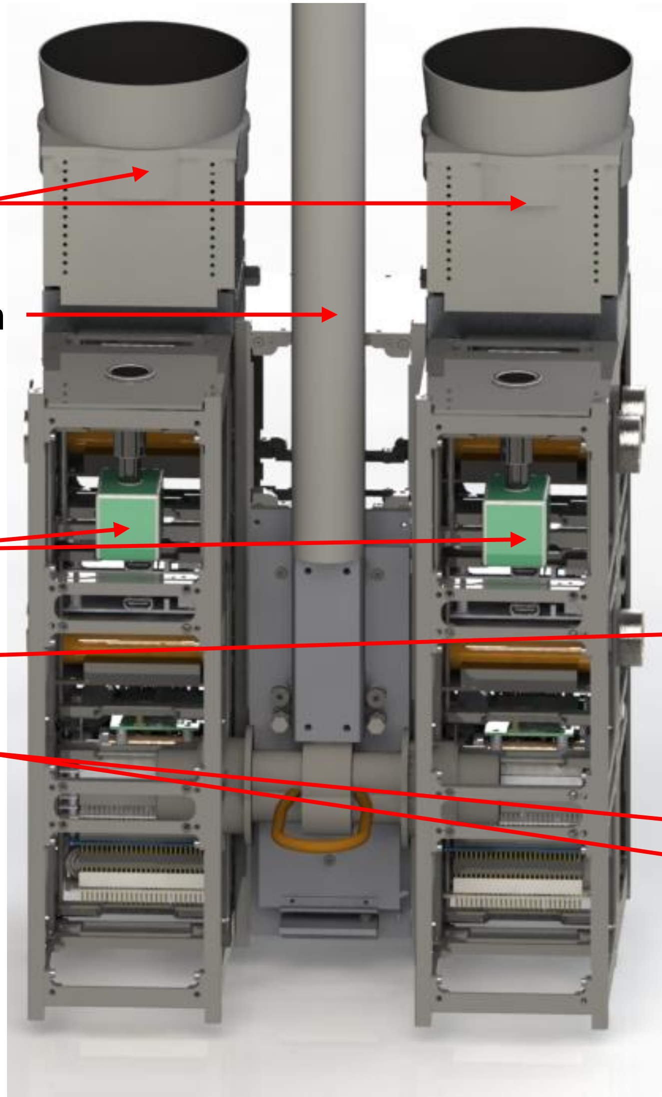
Payload (RMP)

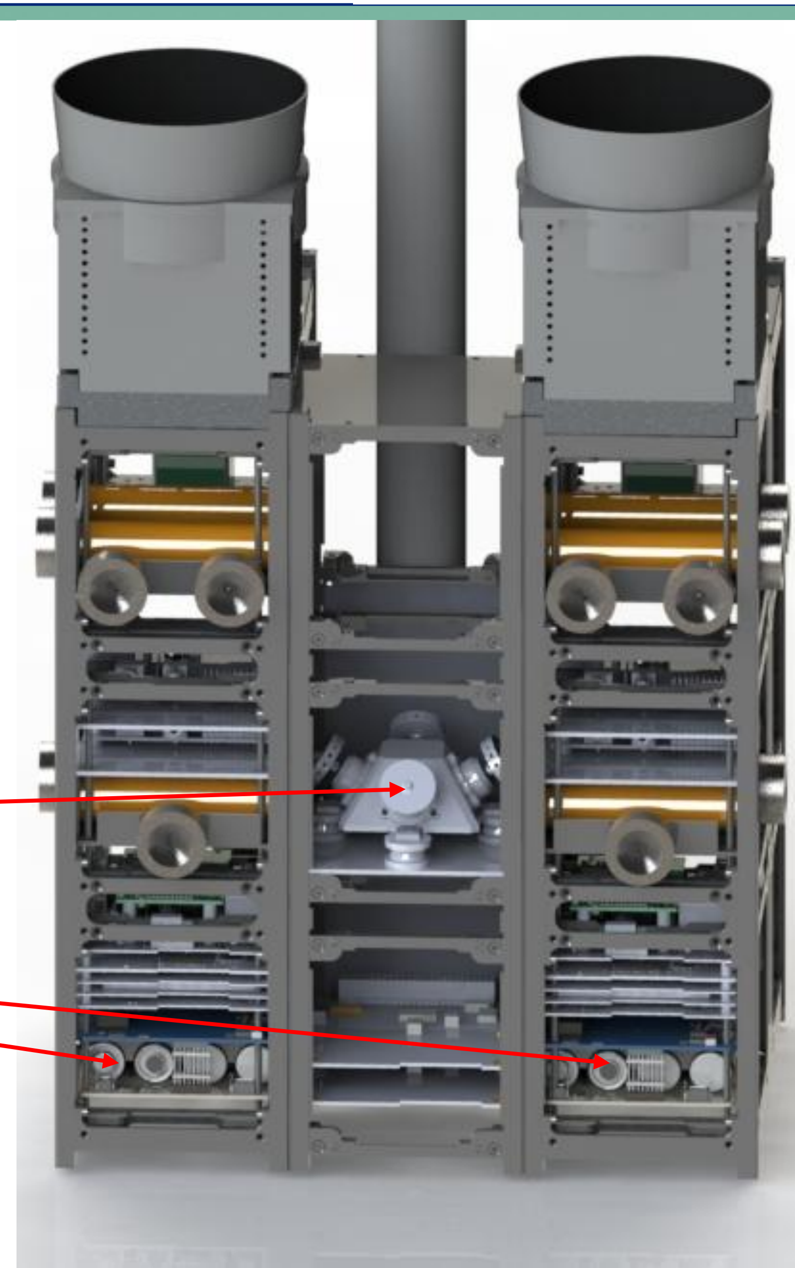
Composite Boom

CubeStar Cameras

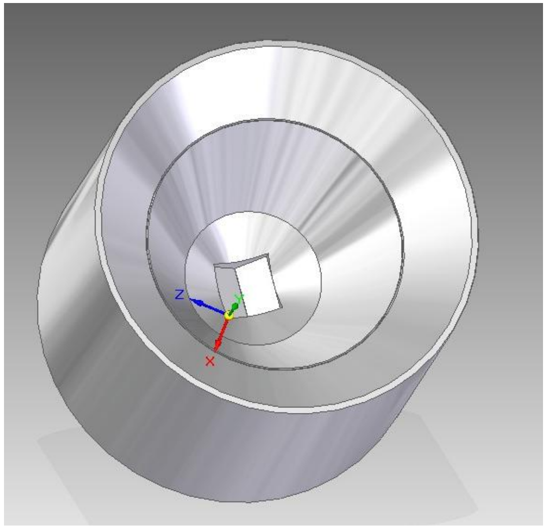
ADCS – 4 RWA

Battery – BP4

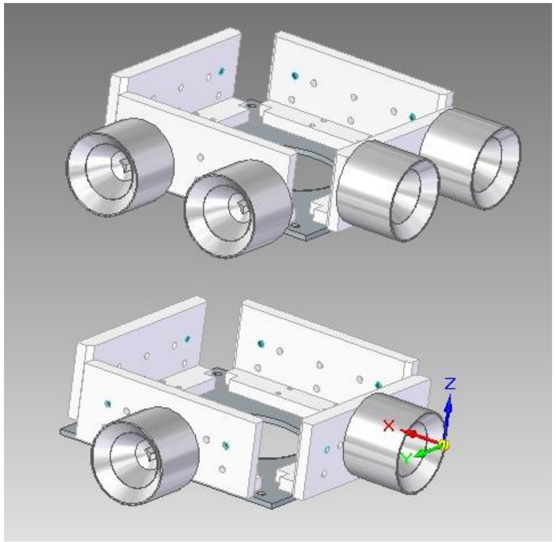




- **CoreSat Permanent Magnet Docking System**
  - One key change to the design for 2017 is to make the Docking Ports on the CoreSat **all permanent magnets** (rather than a mixture of permanent and EM as before).
  - This requires care choice of polarity, so as to minimise the magnetic moment in the far field (i.e. Reacting against the Earth's magnetic field), but maximise the RDV pull-in range and provide adequate latching.
  - Neodymium disc magnet stacks are proposed:



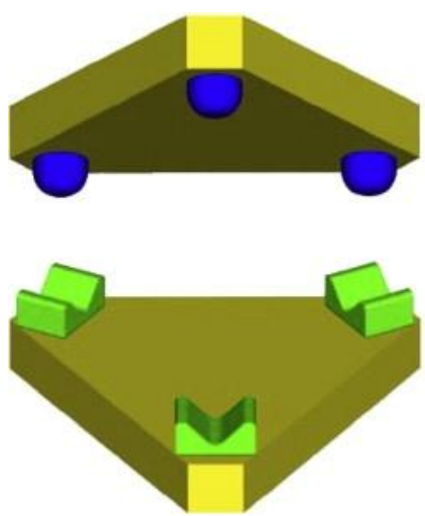
Note:
Preliminary CAD – design not yet finalised

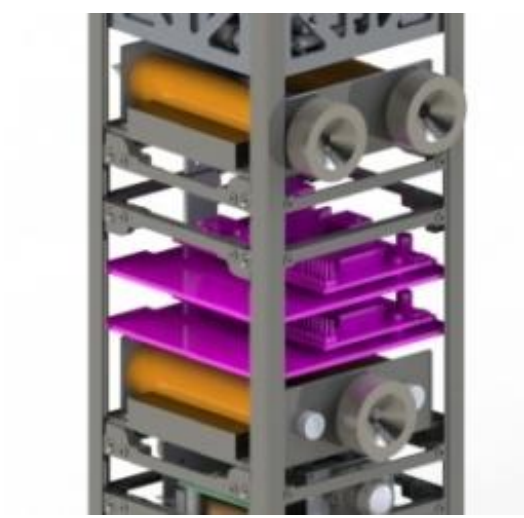


AAReST RDV & Docking

RDV/Docking

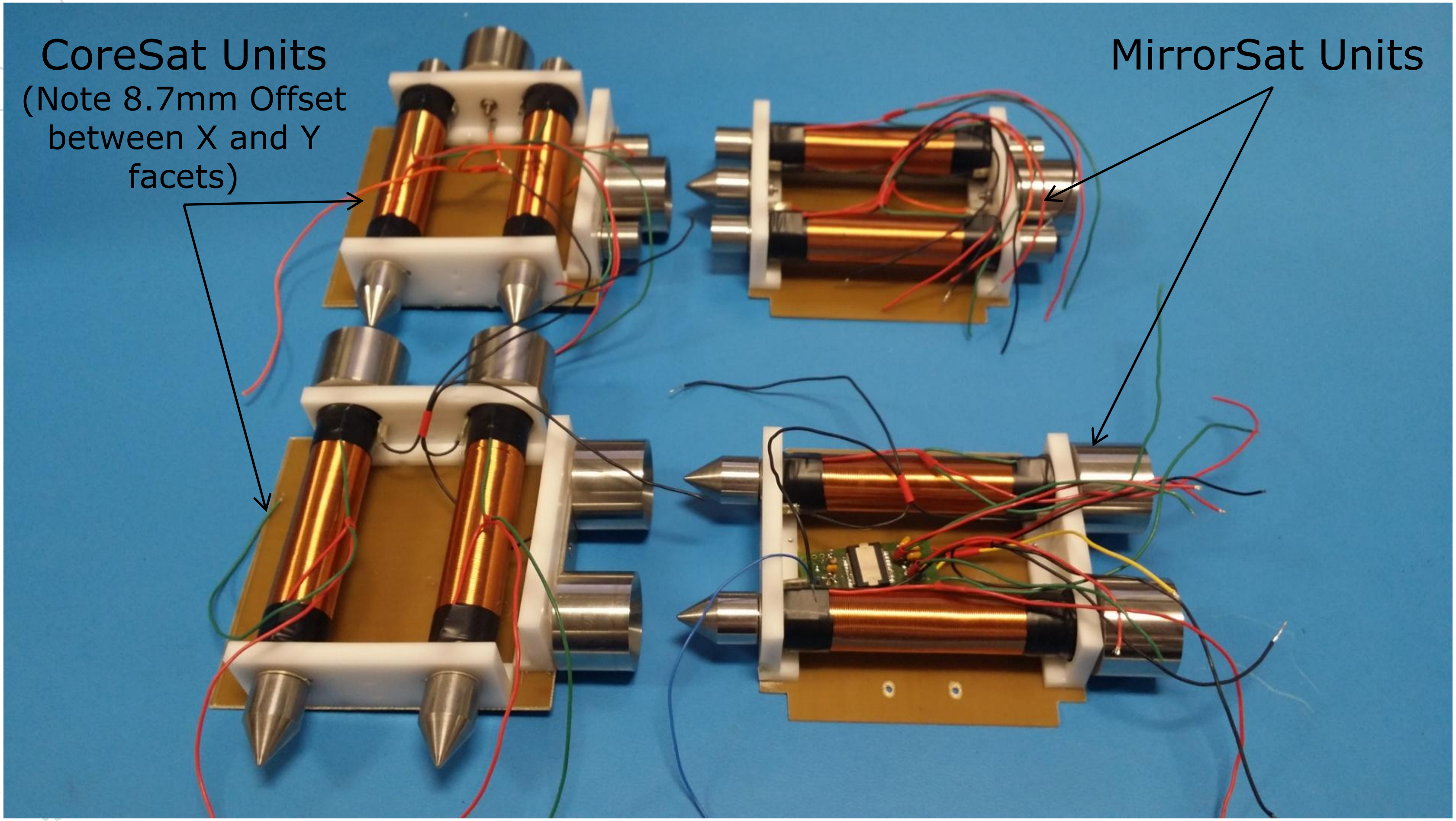
- **EM Docking System Concept (essentially unchanged)**
  - SSC Electro-Magnetic Kelvin Clamp Docking System (EMKCDS)
  - Comprises four PWM controlled, H-bridge-driven, dual polarity electro-magnets, each of over 800 A-turns
  - These are coupled to three “probe and drogue” (60º cone and 45º cup) type mechanical docking ports
  - Kinematic constraint is established using the Kelvin Clamp principle (3 spheres into 3 V-grooves arranged at 120º)





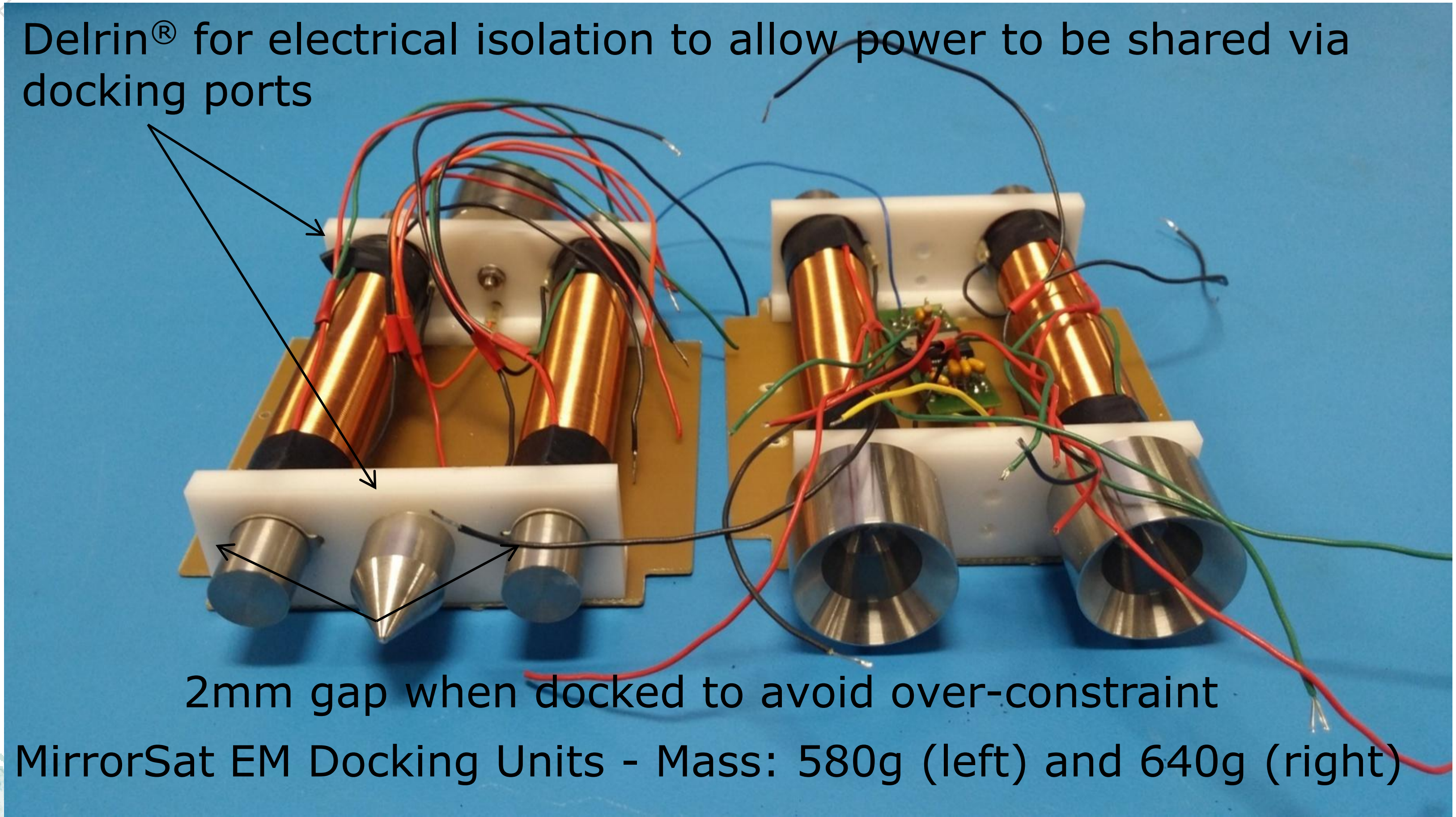
RDV/Docking

- **2015 EM Docking System Prototype**
  - Prototype Docking Port hardware designed and built:
  - Note: 2017 CoreSat Units will now be permanent magnets



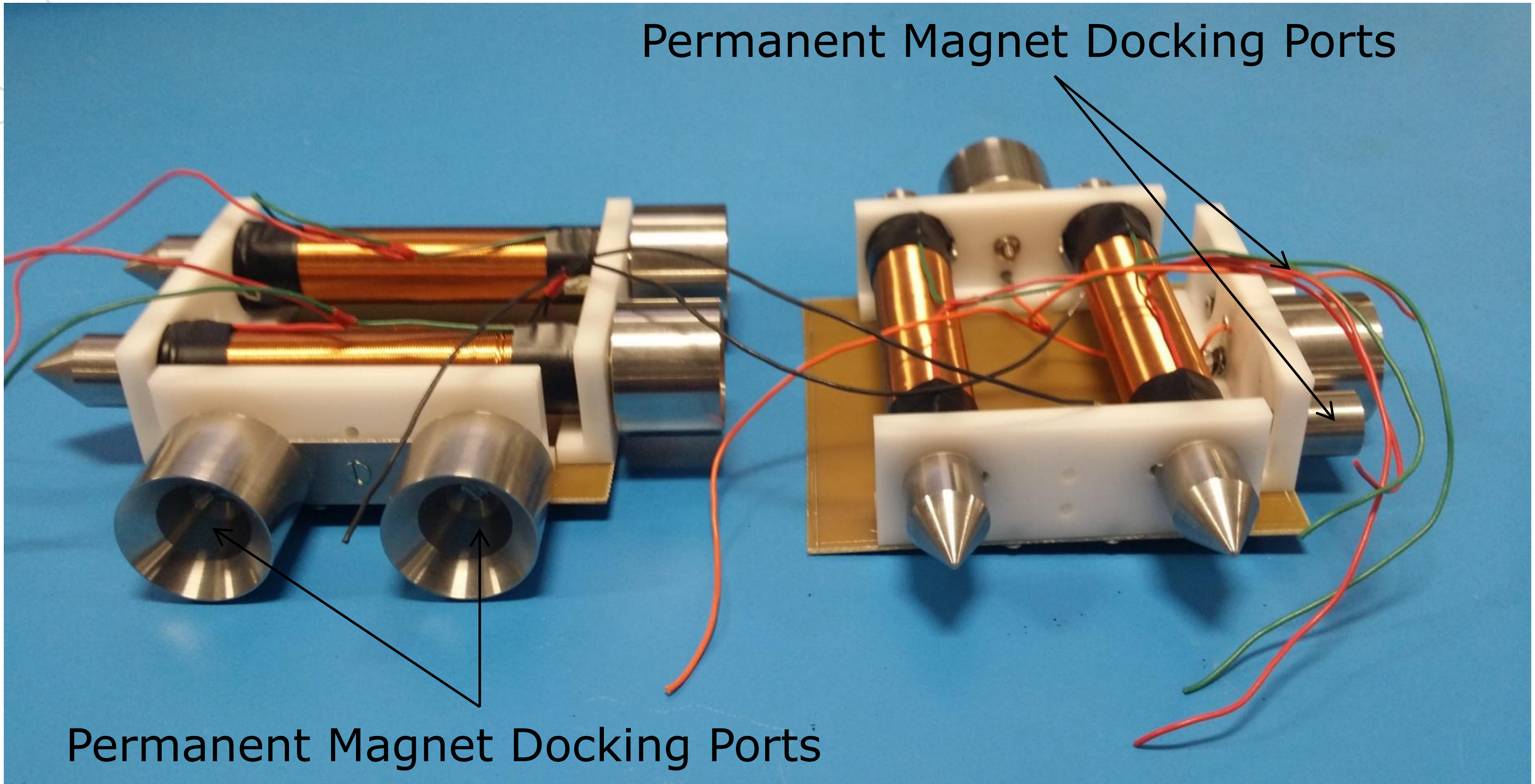
RDV/Docking

- **2015 EM Docking System Prototype**
  - Note 2017 Units will have reduced flux extenders and/or plastic end caps to avoid premature contact
  - Proposal: Remove cups from MirrorSat Units to free up space for an extra solar panels.



RDV/Docking

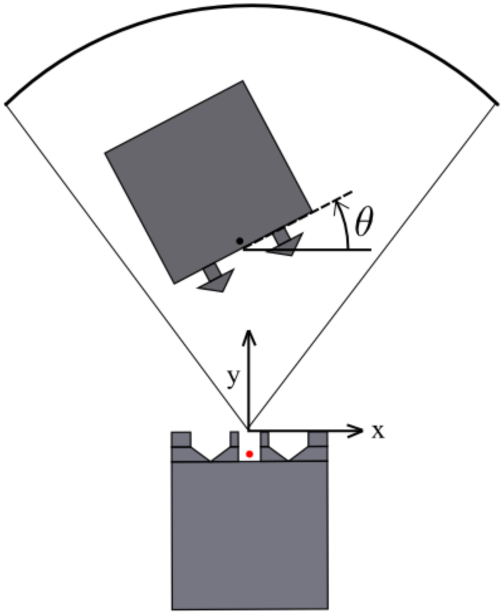
- **2015 EM Docking System Prototype**
  - Note: 2017 CoreSat Units will now be all permanent magnets
  - Freed electromagnets will be dedicated to the IIST MirrorSat



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

RDV/Docking

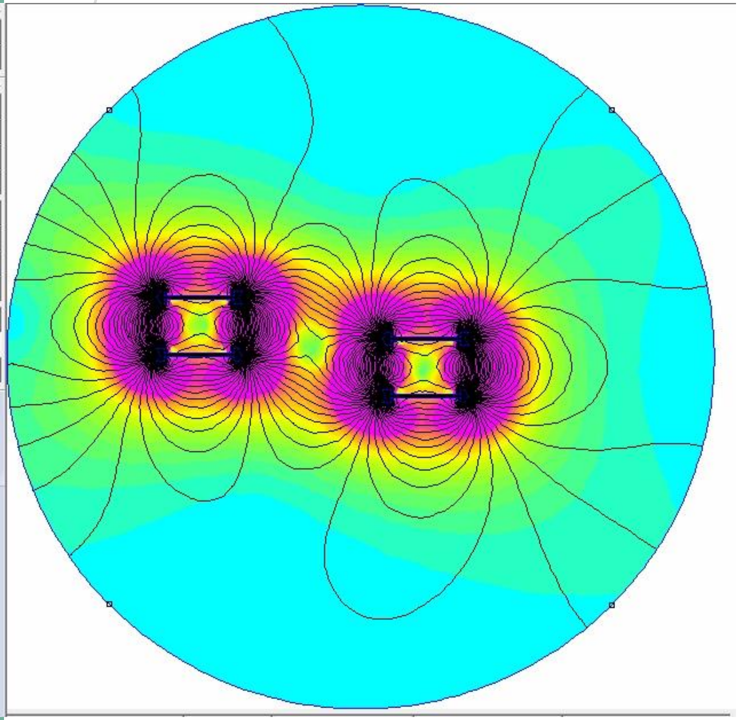
- **EM Docking System Testing**
  - CalTech and SSC initial Air-Bearing Table experiments show:
    - Capture distance is between 20-30cm for two pairs
    - Automatic self-alignment works, but choice of polarities is important to avoid miss-alignment/false-capture.
    - Attractive force is highly non-linear!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

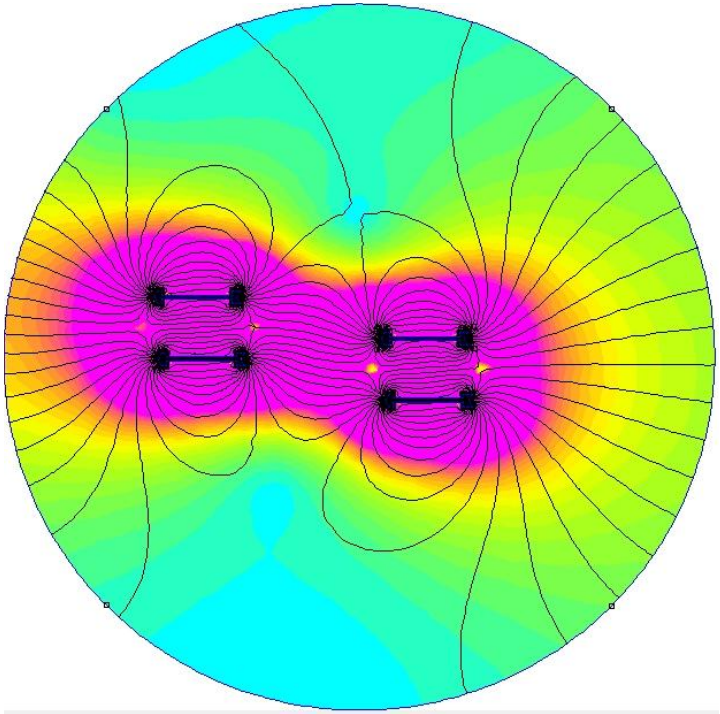


*Radius from centre of one face to centre of 'docking plane'; **Half angle

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.

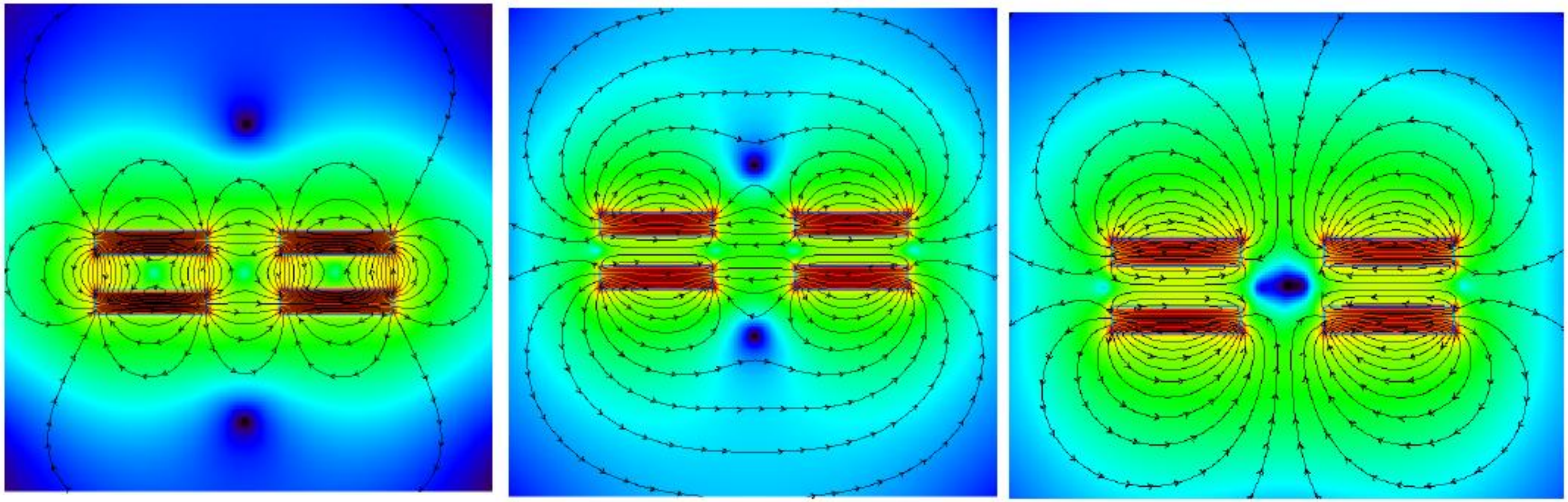
- PWM control is used to vary the current to compensate for the distance effect.

- 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

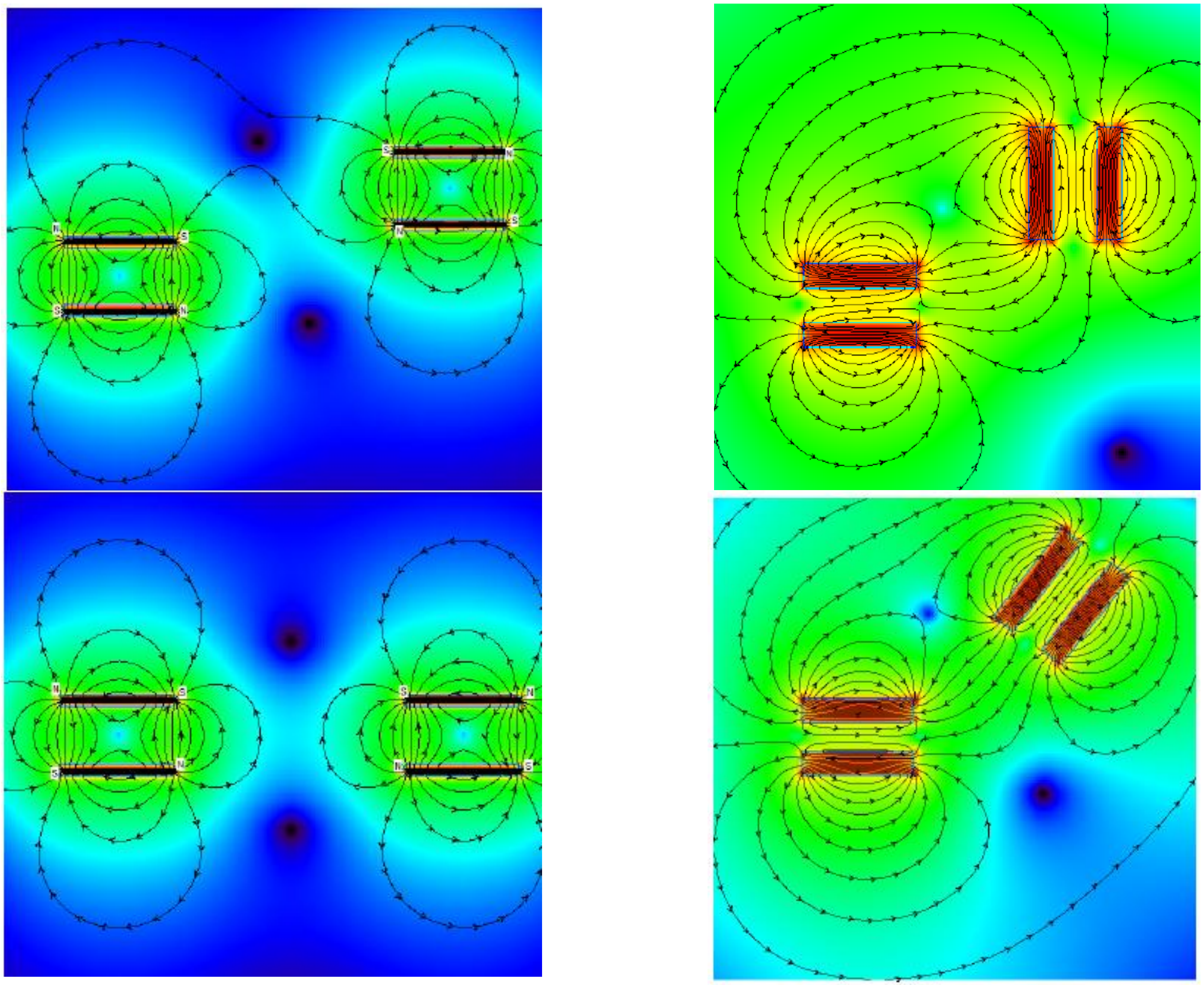
- **EM Docking System Tests 2015**
- (MSc Project:)
  - A simple 2D simulation was set up using the Vizimag software to help visualise the characteristics of the solenoids placed at various distances, polarity configurations and angular offsets.



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 Tests 2015**

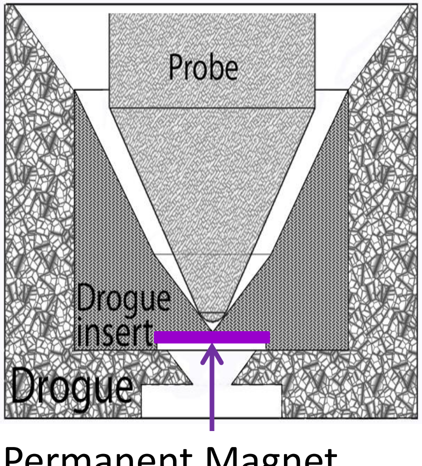


RDV/Docking

- **EM Docking System Tests 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.

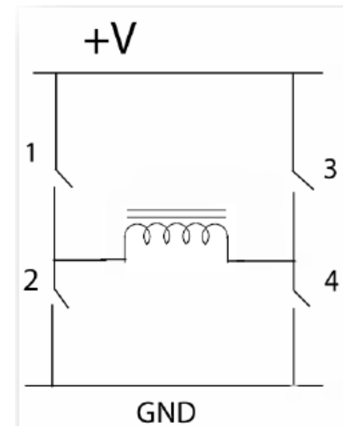
RDV/Docking

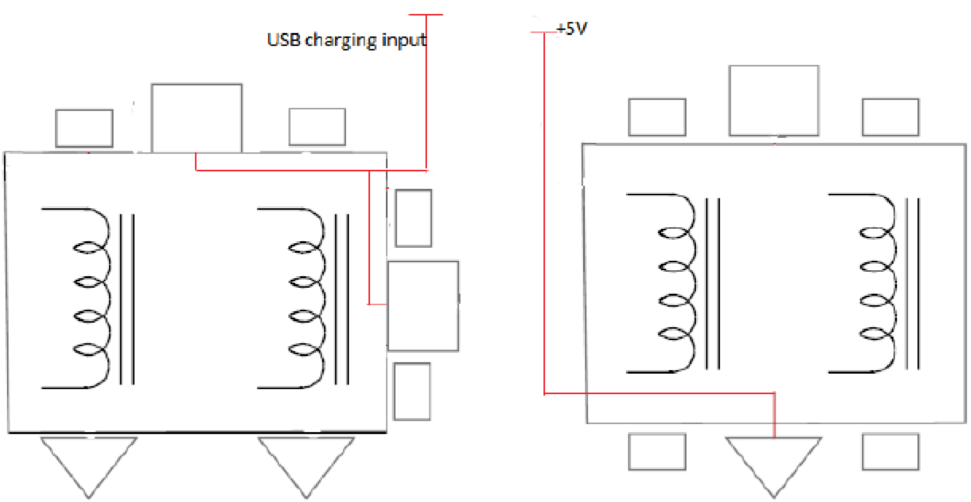
- **EM Docking System Tests 2015**
  - A new two-part drogue has been developed, which aids manufacture and assembly.
  - A built in neodymium permanent magnet (6mm dia., 1mm thick) provides the latching action to hold the spacecraft together when the electro-magnets are turned off.
  - We found the 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).
  - 2017 version needs no separate latching magnet.

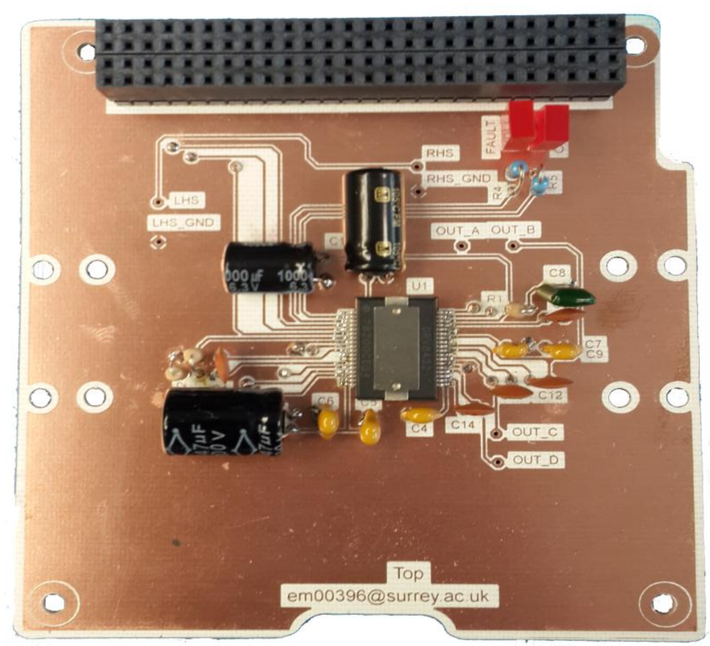


RDV/Docking

- **EM Docking System Tests 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:



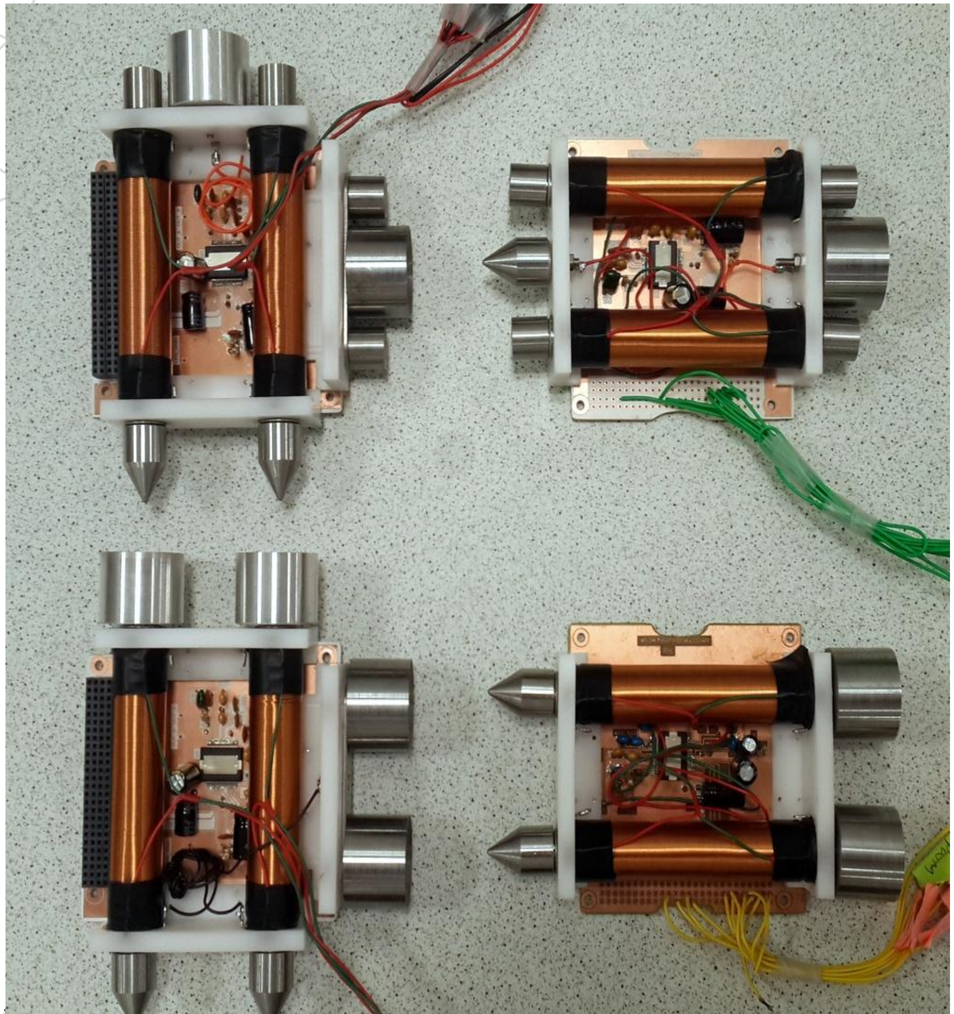


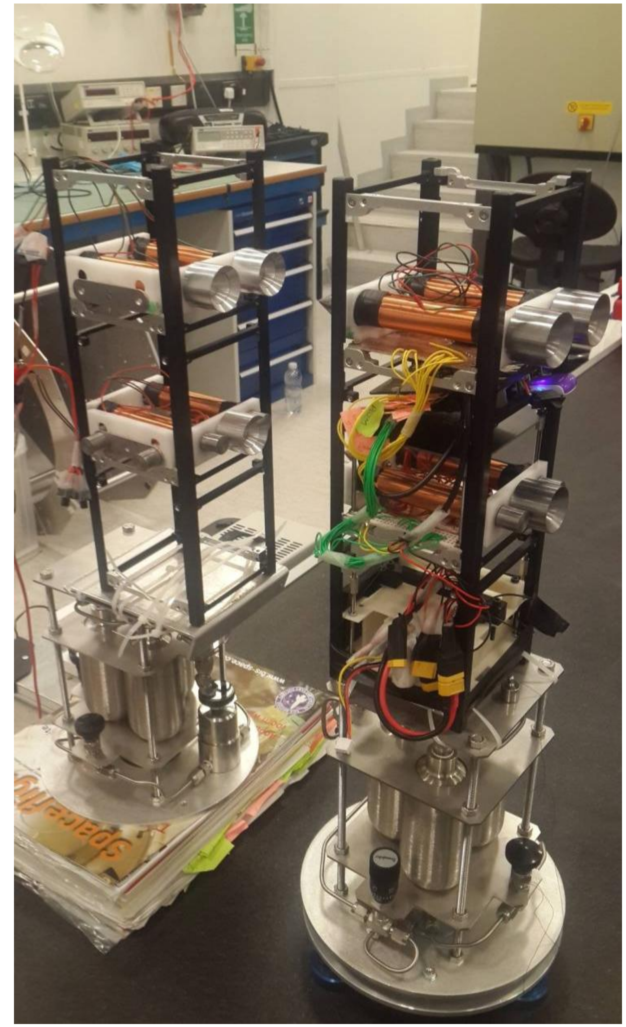


2017 – Design for 2-way power transfer?

RDV/Docking

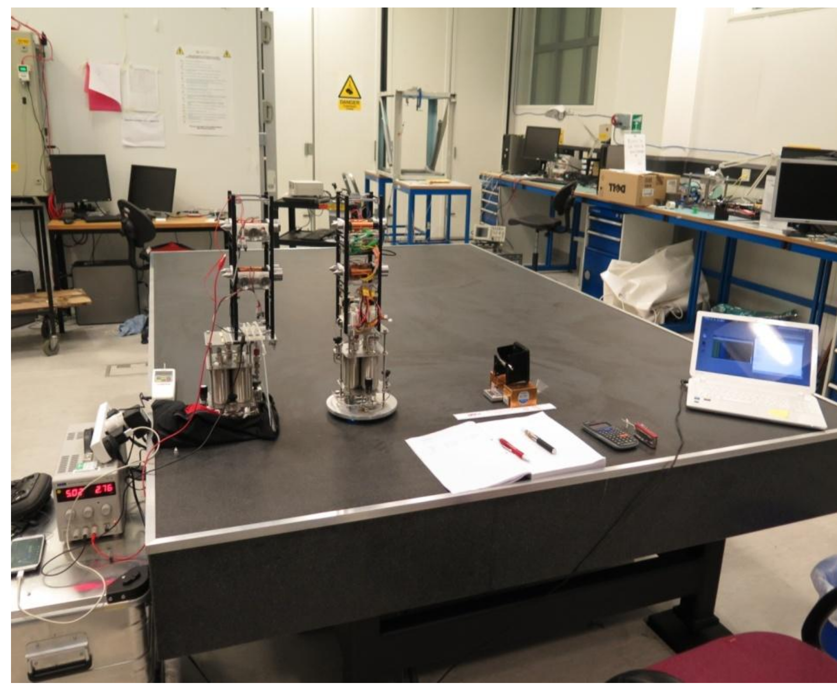
- **EM Docking System Tests 2015**
  - Re-designed Docking Ports and 2D Air Bearing Test Rig





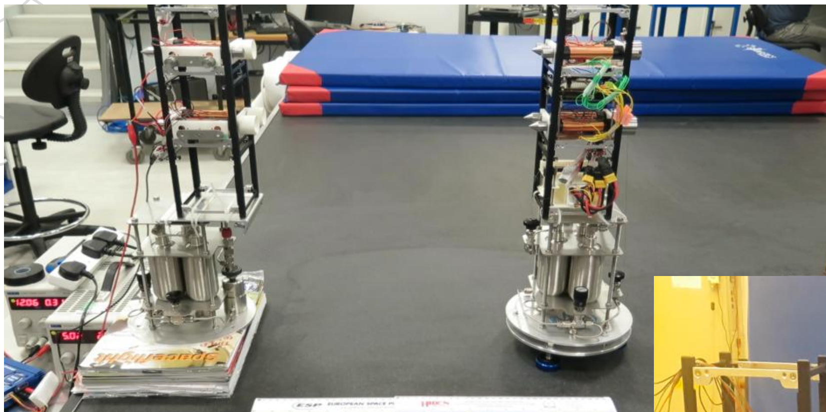
RDV/Docking

- **EM Docking System Tests 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.

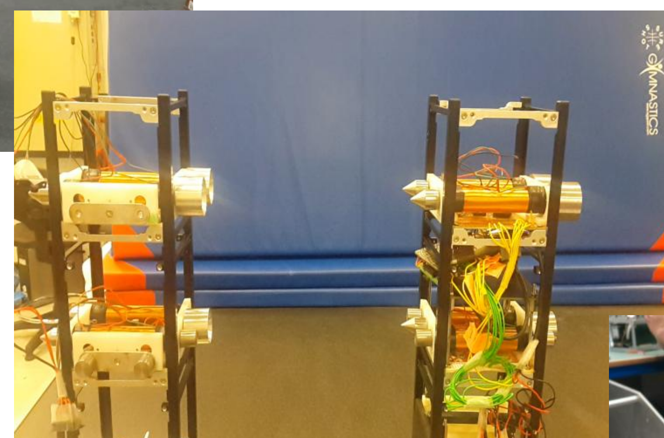


RDV/Docking

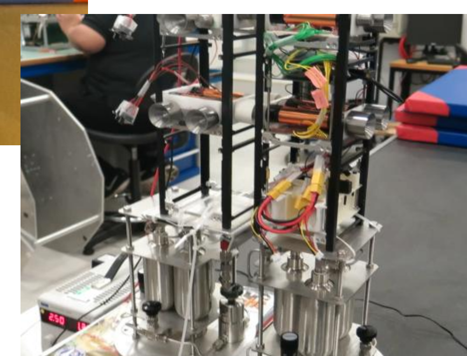
- **EM Docking System Tests 2015**
  - Videos: 50cm Docking; 20cm Docking; Repel and Hold at Distance



Docking from 50cm



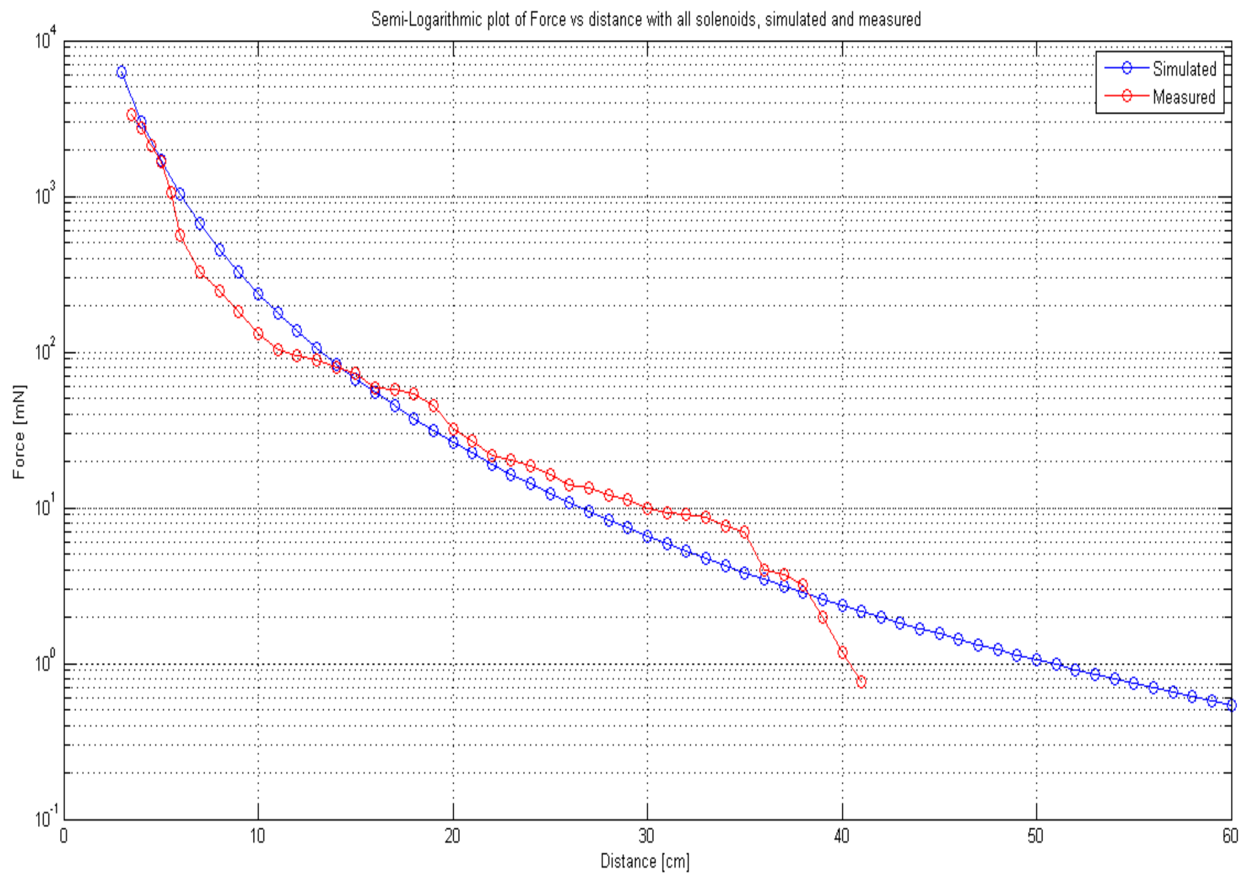
Docking from 20cm



Repel and Hold

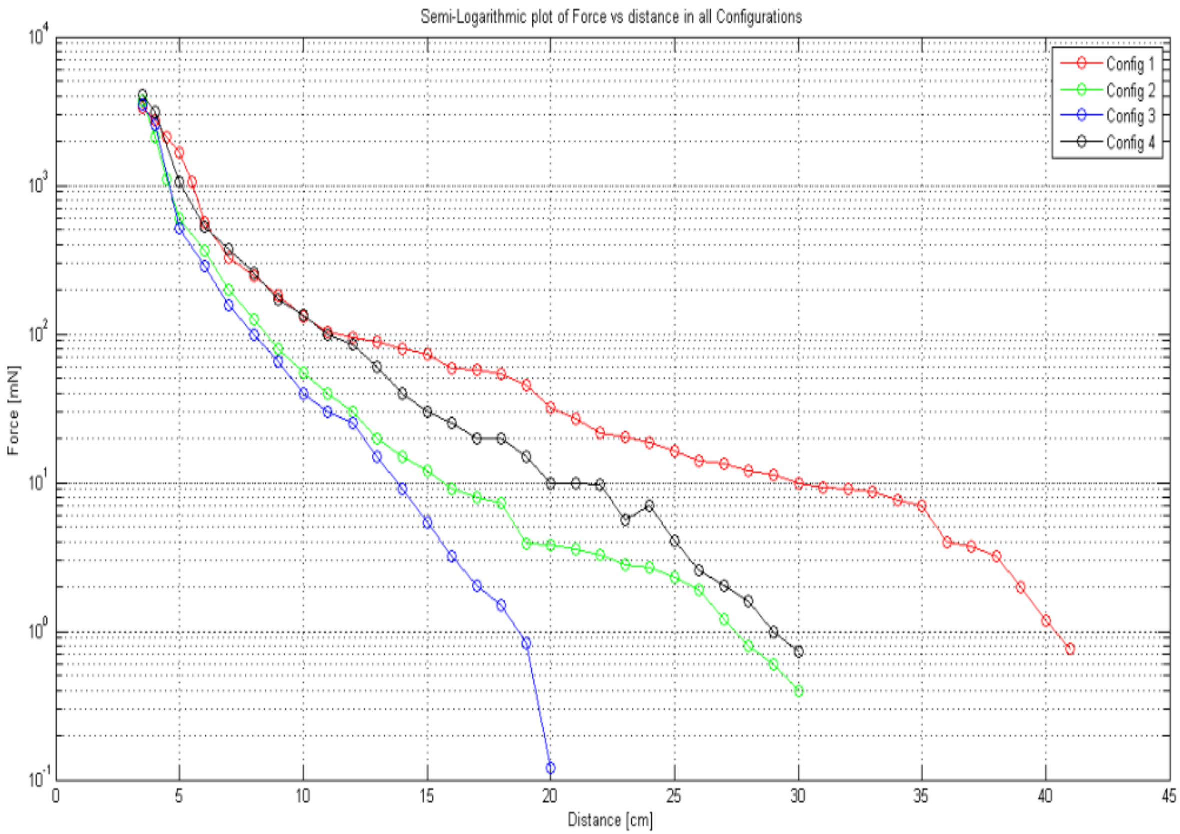
RDV/Docking

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



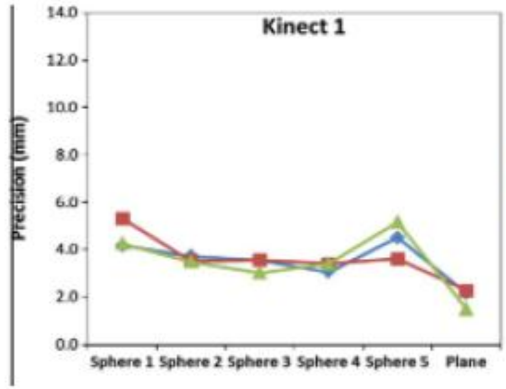
RDV/Docking

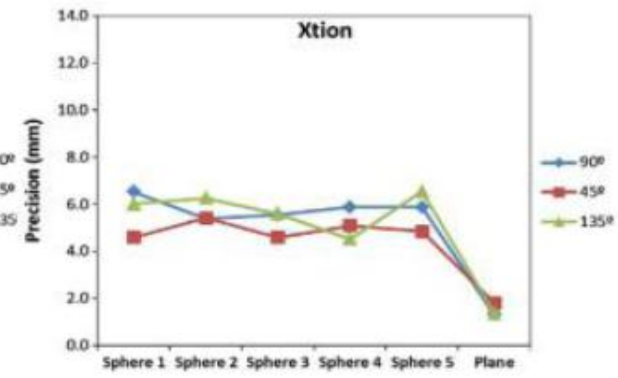
- **EM Docking System Tests 2015**
  - Attraction forces simulated using the 'Gilbert model'
  - Measured attraction forces in different solenoid polarity configurations.
  - Measured at a 0 degree offset and within a 5 degree half cone to the target.



RDV/Docking

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

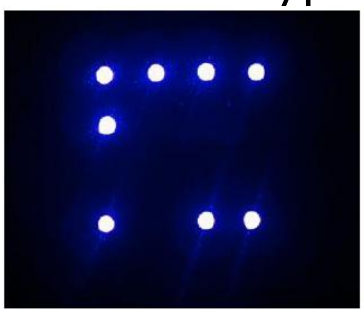


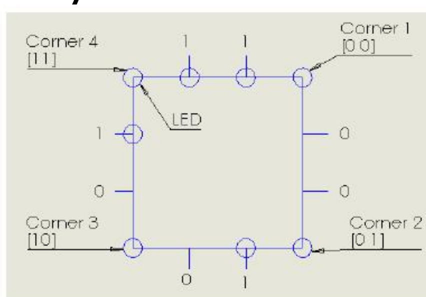


Power Consump-tion	Distance of Use	Field of View	Sensor	Depth Image Size
<2.5W	0.8-3.5m	58/45/70 Degrees H/V/D	RGB & Depth	VGA (640x480): 30fps QVGA(320x240): 60fps
Resolution	**OS Support**	**Programming Language**	**Dimensions**	**Software**
SXGA (1280*1024)	Win 32/64:XP, Vista, 7, 8 Linux Ubuntu 10.10:X86,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

RDV/Docking

- **RDV & Docking Sensor Tests 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.

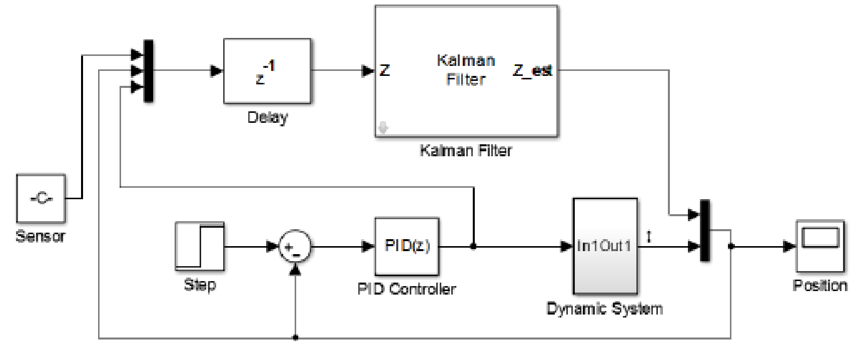


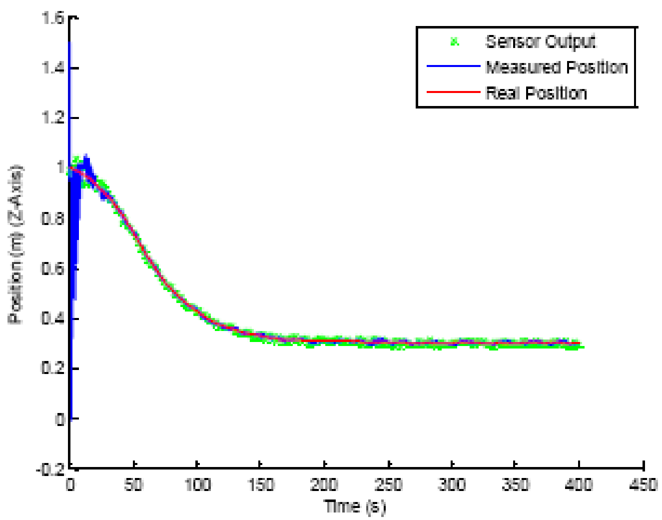


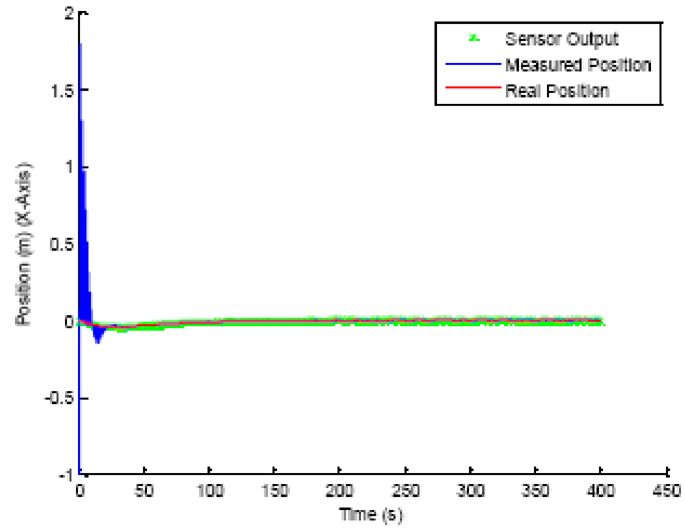
Axis	Range Interval (m)	Root Mean Square Error(mm)	Maximum Error (mm)	Standard Deviation (mm)	Confidence (%)
Z Axis	0-0.30	3.106	1.949	4.166	100
	0.30-0.80	5.787	11.265	3.687	100
	0.80-1.15	20.958	39.843	13.250	100
X Axis	0-0.30	1.9	0.2794	0.684	83
	0.30-0.80	1.7	2.851	0.585	91
	0.80-1.15	0.95	1.466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

RDV/Docking

- **RDV & Docking Sensor Tests 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:
  - Address solar blinding issue (via narrow pass-band filter high-intensity LEDs?).
  - Combine with Docking System.





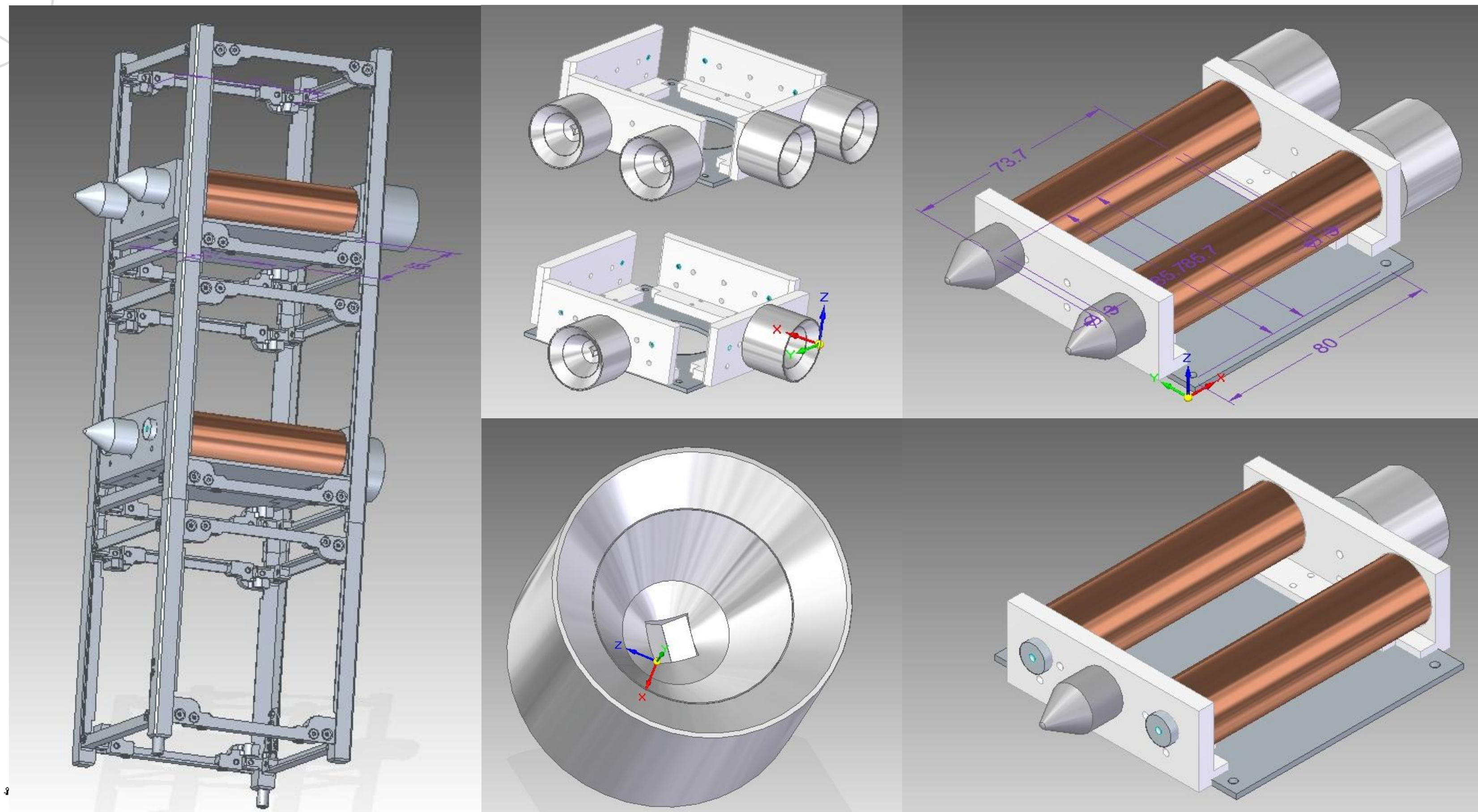


RDV/Docking

- **EM Docking System Update 2017**
- Summary (2015/16 MSc work): Enda McKenna and Patrick Maletz:
  - 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 (2017 MSc & CEOI Sponsored FastTrack Research):
  - 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

- **EM Docking System Update 2017**
  - Proto-Flight EMDS in development. PMDS now on CoreSat.
  - New Air-Bearing Tests planned
  - Integration of RDV sensors with EMDS Control



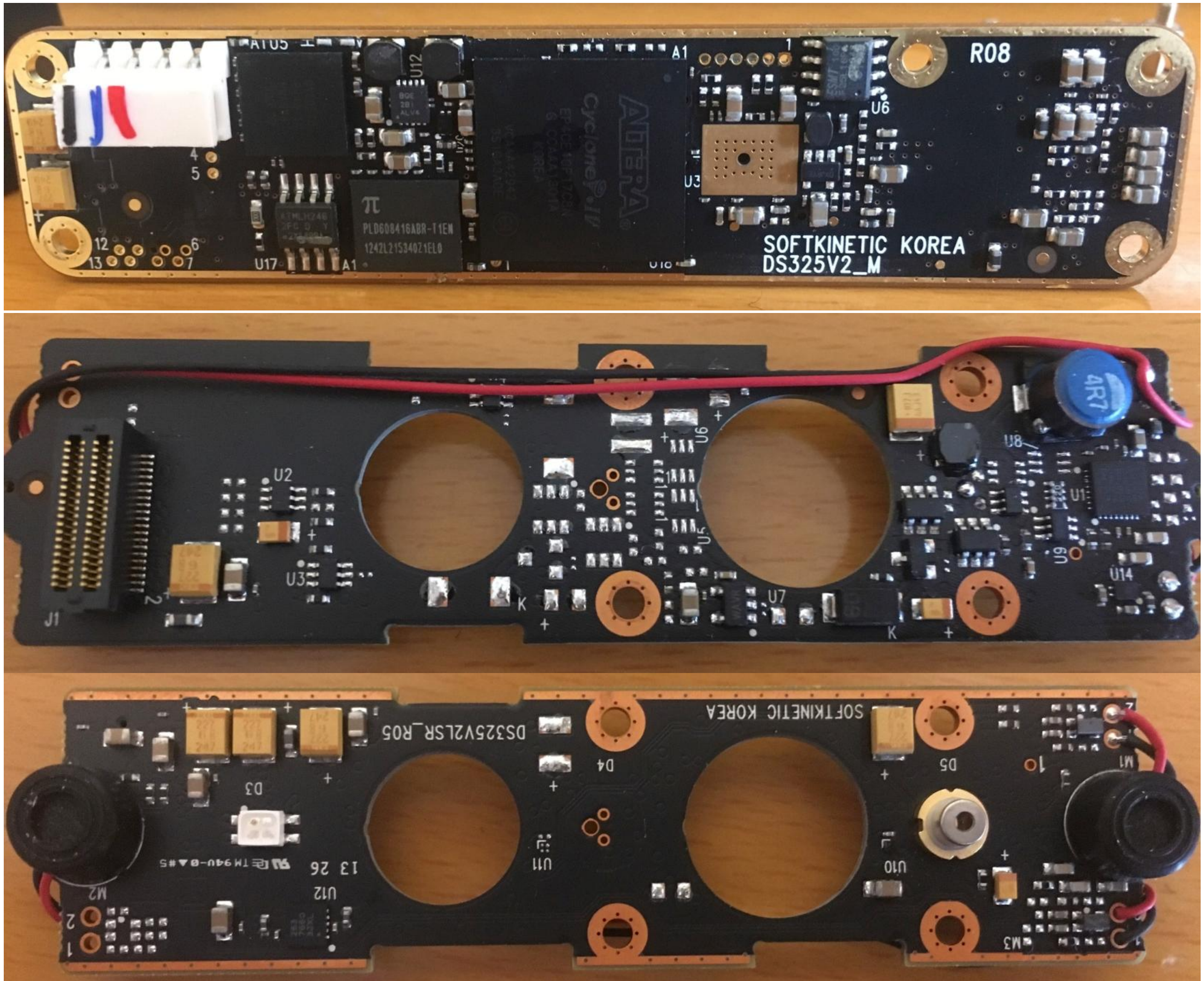
RDV/Docking

Preferred sensor – now back in production (2017)

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

RDV/Docking

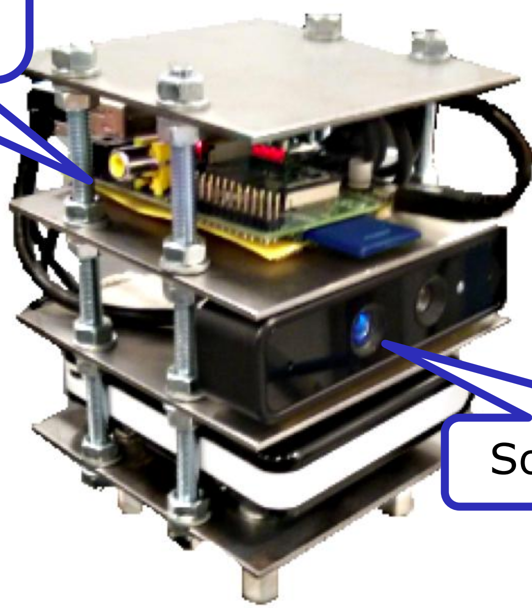
Stripped and modified for spaceflight use (2017)



RDV/Docking

• RDV & Docking Sensor Air Bearing Tests

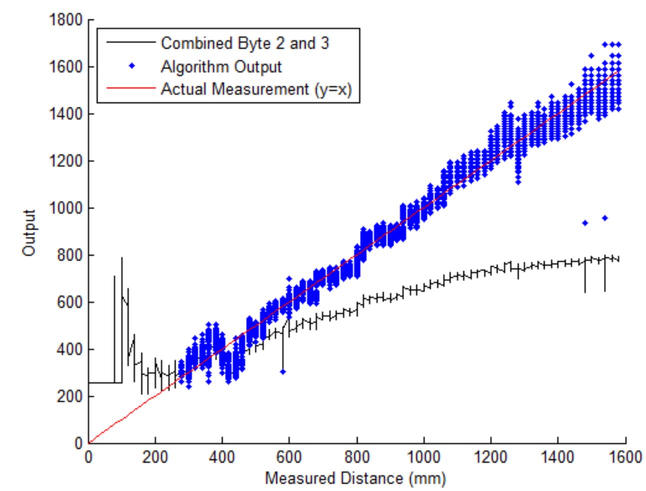
COTS RPi-B
4 GB SD-Card
WiFi Dongle



SoftKinectic DS325

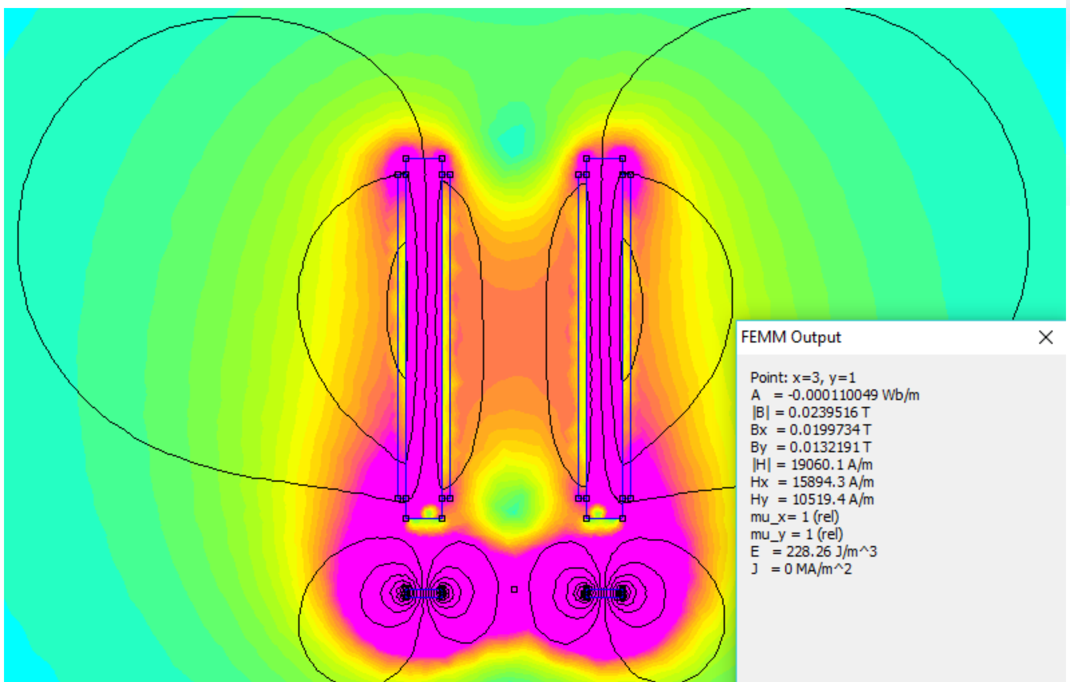
- OpenNI2DS325 driver used initially but tests showed it to be inaccurate.

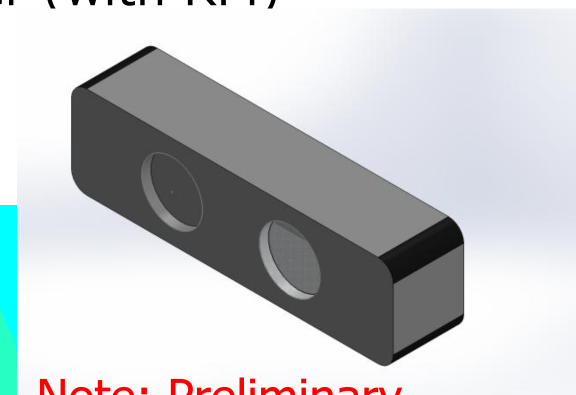
- Driver was reverse engineered and new algorithms were developed to convert raw sensor data into depth measurements leading to much more accurate results.



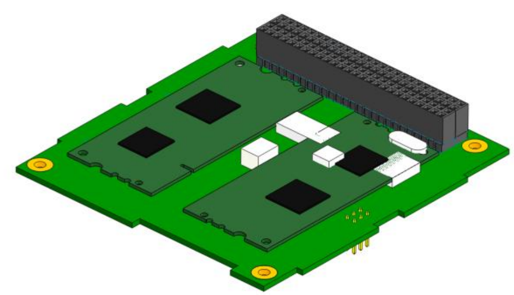
RDV/Docking

- **RDV & Docking Sensor Update 2017:**
  - New BSc and MSc Student Projects:
    - LIDAR Physical Modifications
    - FM of the Payload Interface Computer (with RPi)
    - Magnetic Control Algorithms
    - Electrical and Grounding Scheme



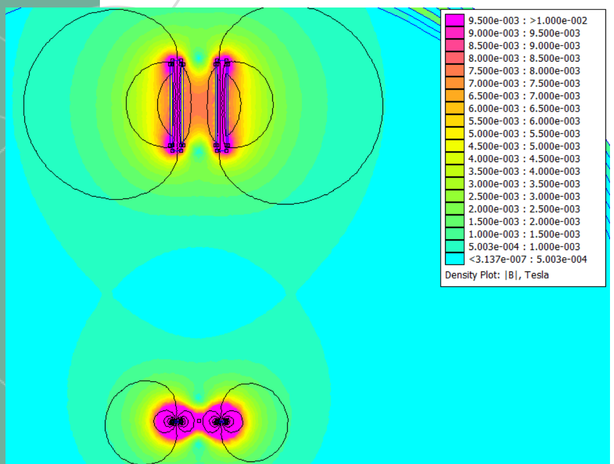


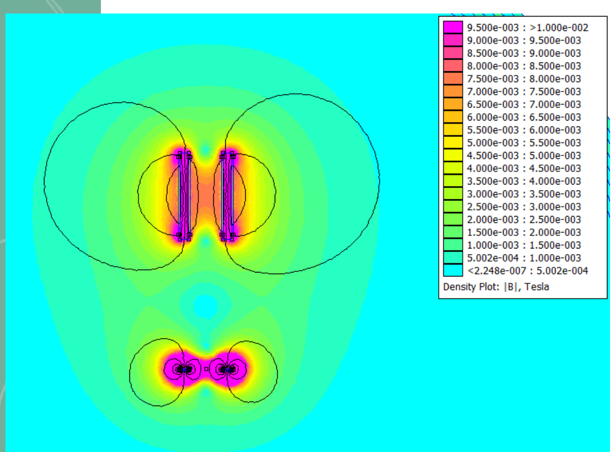
Note: Preliminary Magnetic Field FEA – analysis not yet finalised



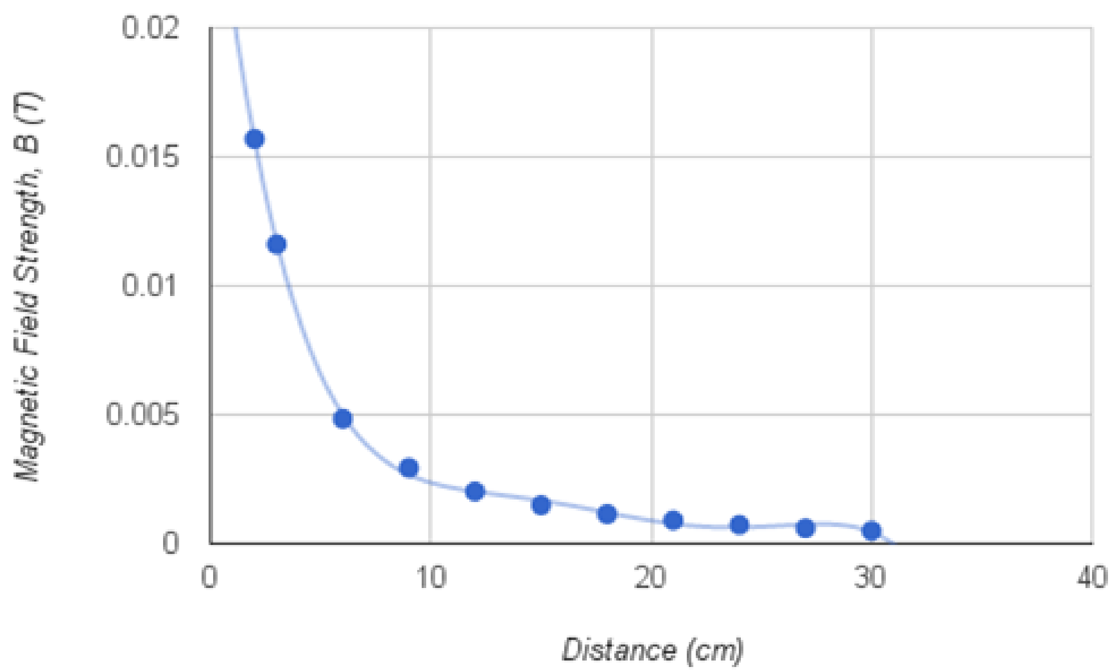
RDV/Docking

- **RDV & Docking Sensor Update 2017:**
  - 15 & 30 cm depths investigated



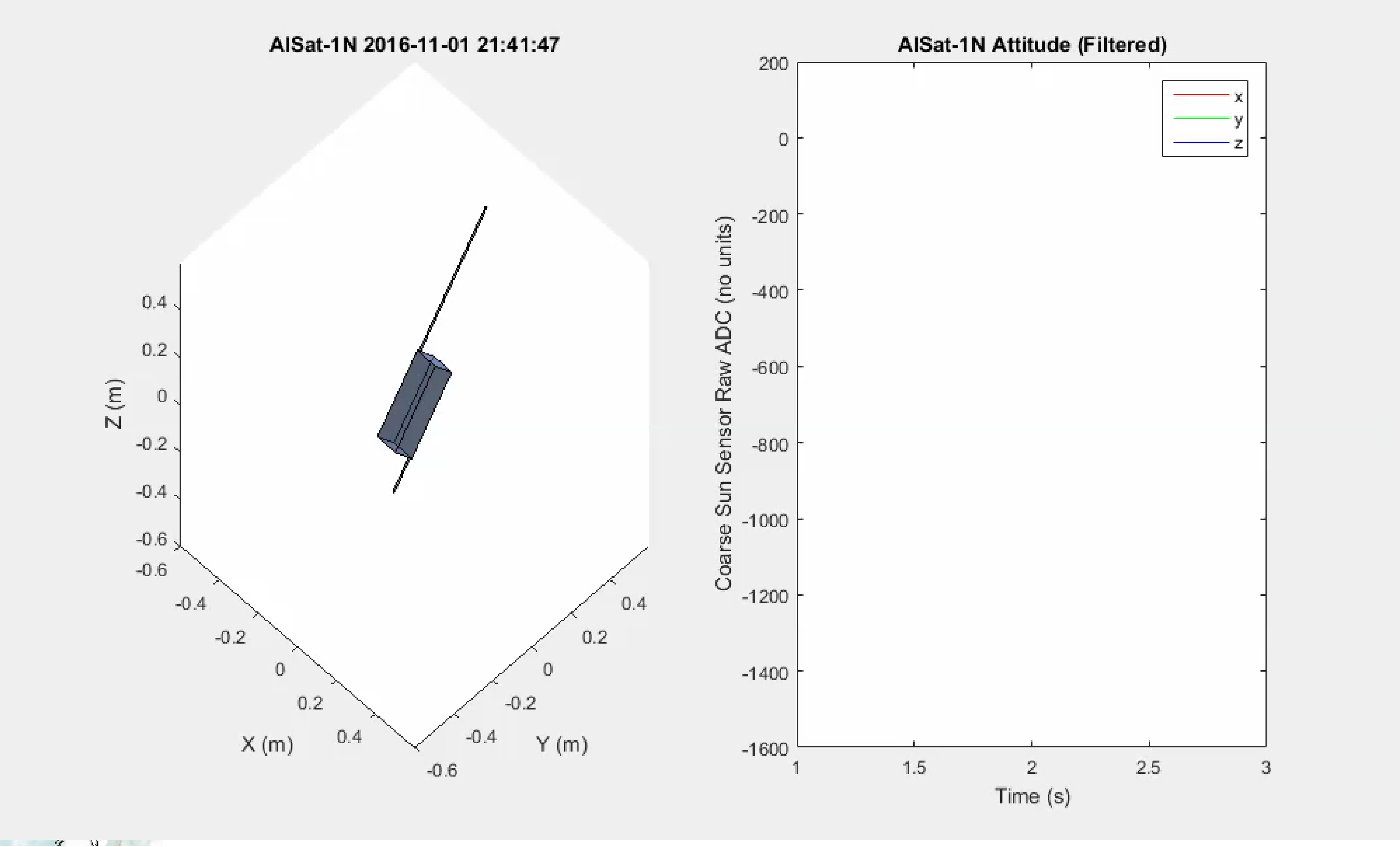


- Magnetic field strength of permanent magnets done
- BUT, with have Earth's B field, solar panels, power lines, actuators, etc (!)

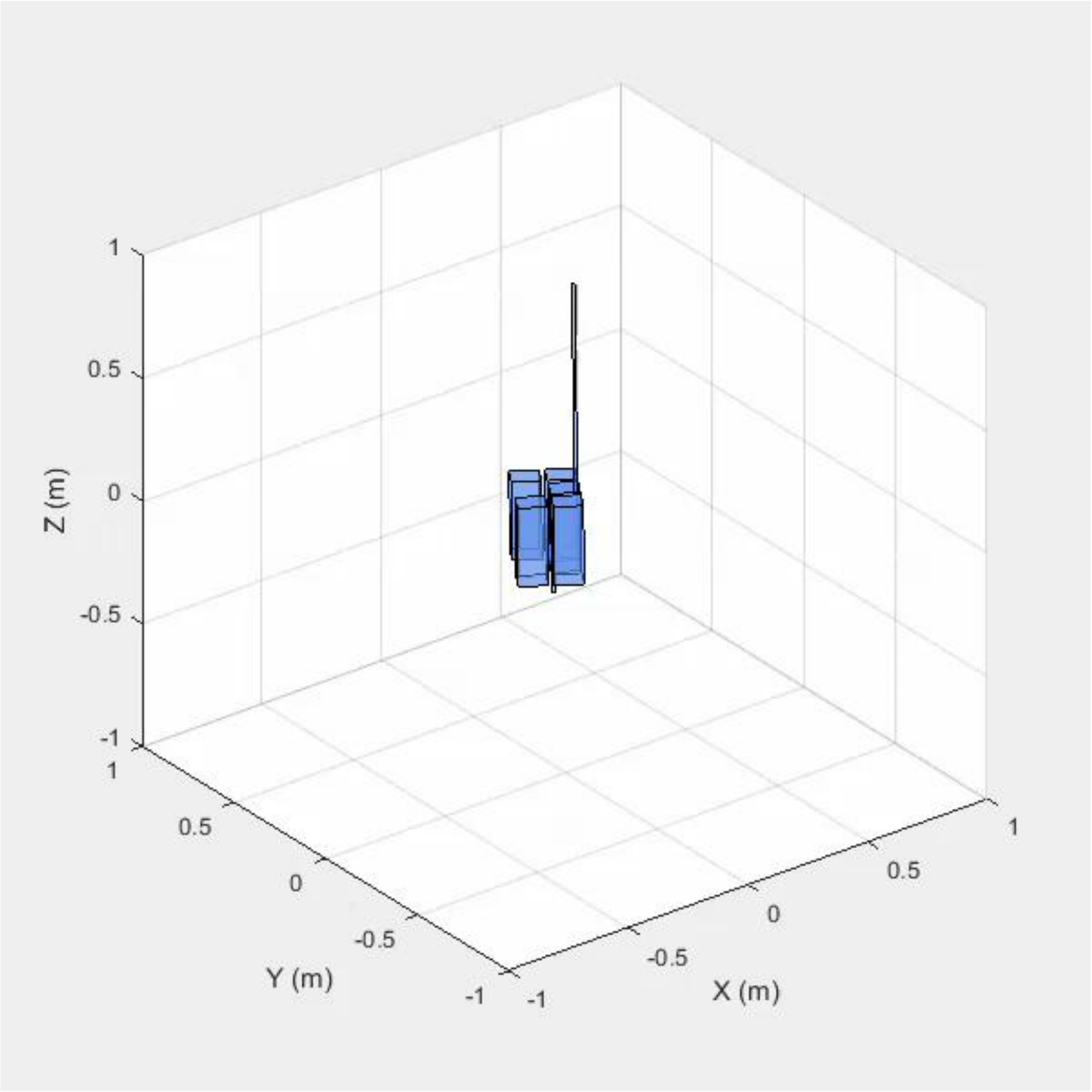


RDV/Docking Simulation

Tools in Development – Demonstrated for AlSat-1N ADCS Simulation (2017)



RDV/Docking Simulation

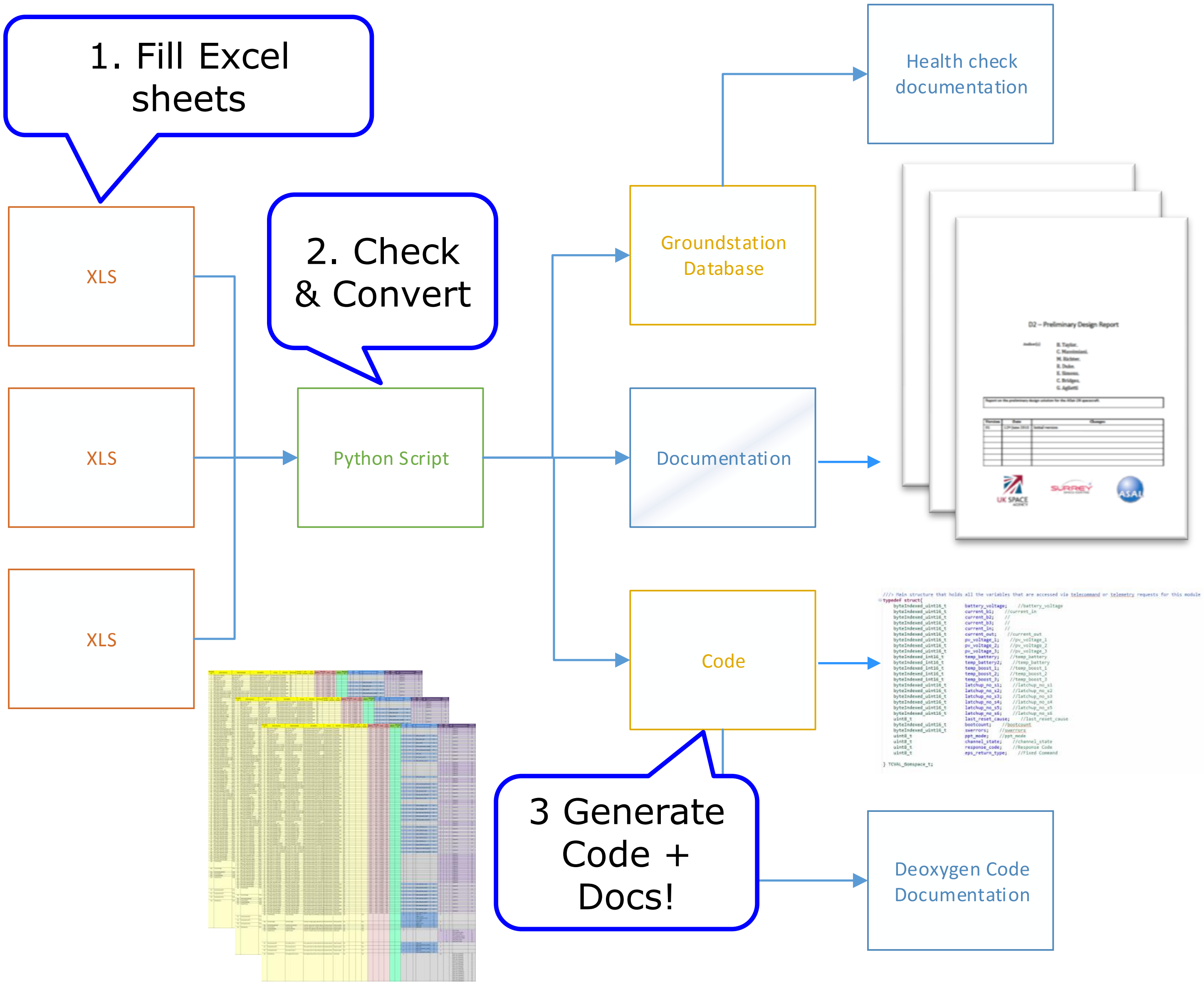


AAReST OBDH & Comms.

Surrey ADCS Software

- **Modular:** 'Plug & Play' with common core & optional threads for hardware & mission specific functions
  - Exploit BSPs + previous flight code bases + FreeRTOS O.S.
  - Improvements for one project easily shared amongst others
- **Mission Independent:** Aligning software & reducing differences between missions
  - Results in sharing of developer resources & operator training making the software enough to handle flexible/multiple mission environments
- **Rapid Development:** Auto code generation (AGC) for TT&C handlers and provide data structures to rapidly code.
- **Maintainable:** Using common uni. programming languages & standard code structures
  - Reduced time for new developers to get up to speed in an environment where short term research contracts are in use

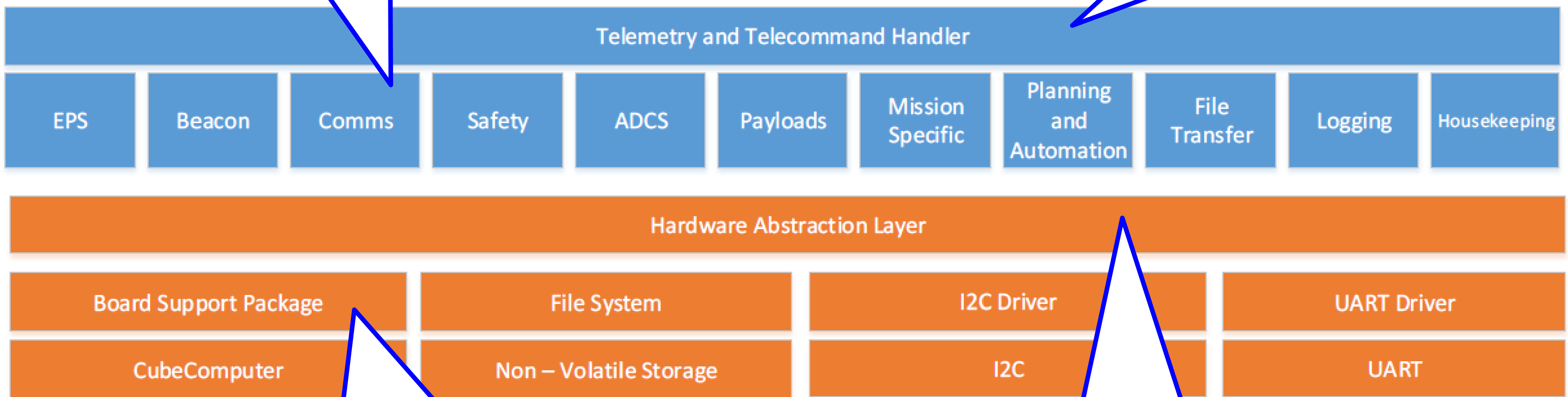
Surrey ADCS Software



Surrey ADCS Software

Separate Modules
(Threads)
Uses AGC output
Multi-Devs/thread

Flexible Router
Decodes for compatibility check +
Forwards on packets

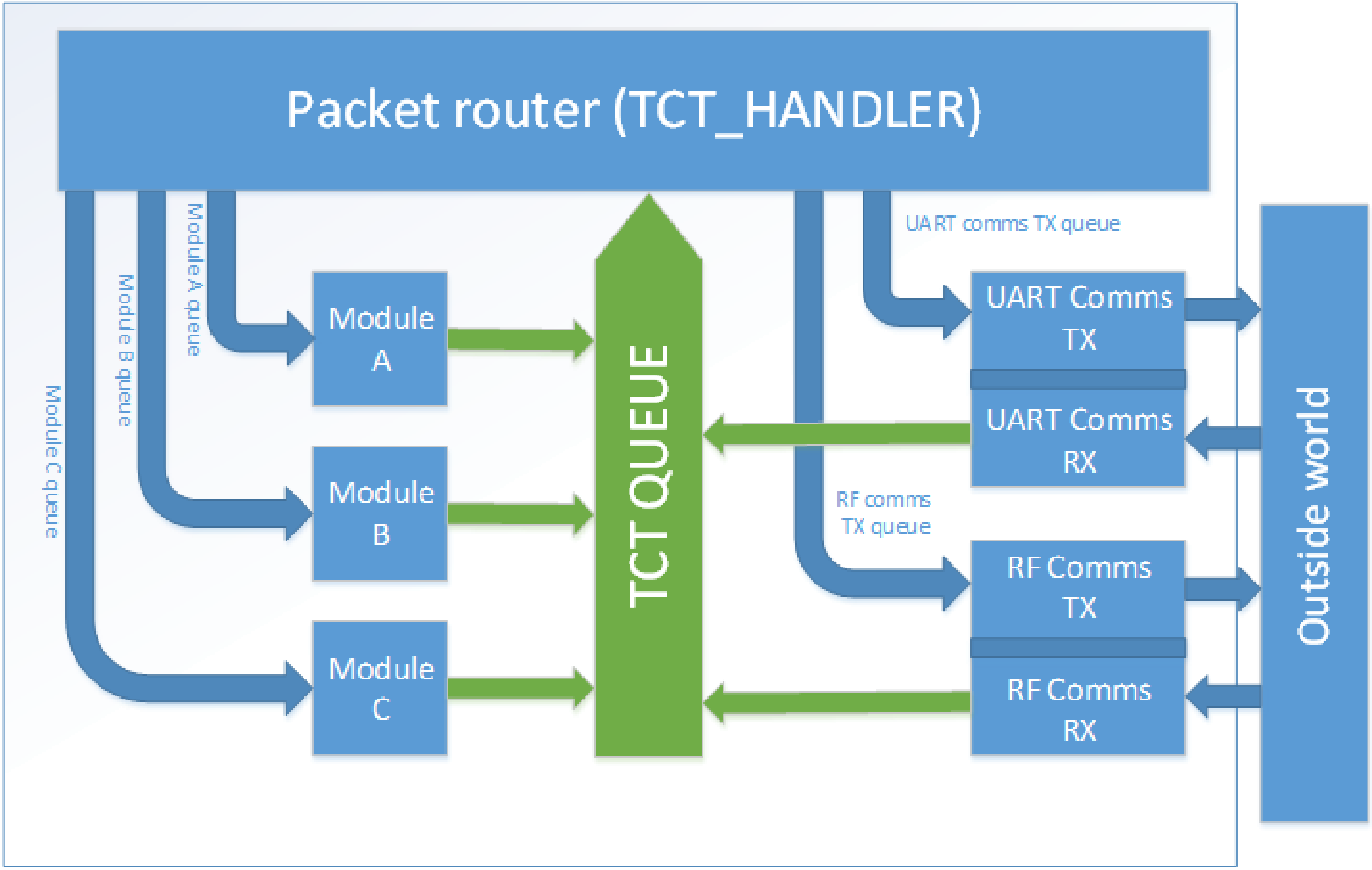


Existing BSPs
IC Level
Subsystem Level
Mission Level

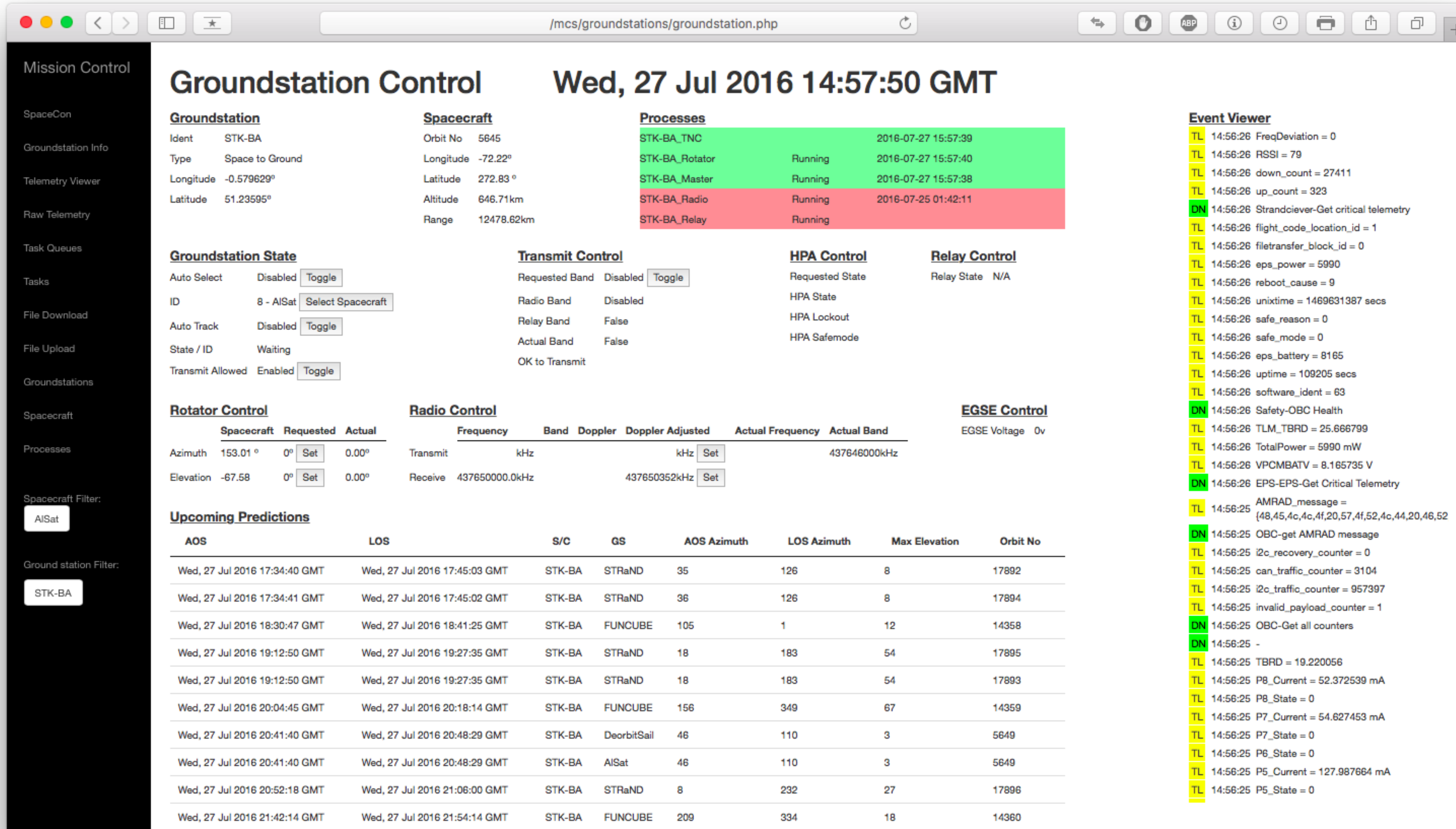
HAL
Mutex Handling
Error return/handling

Surrey ADCS Software

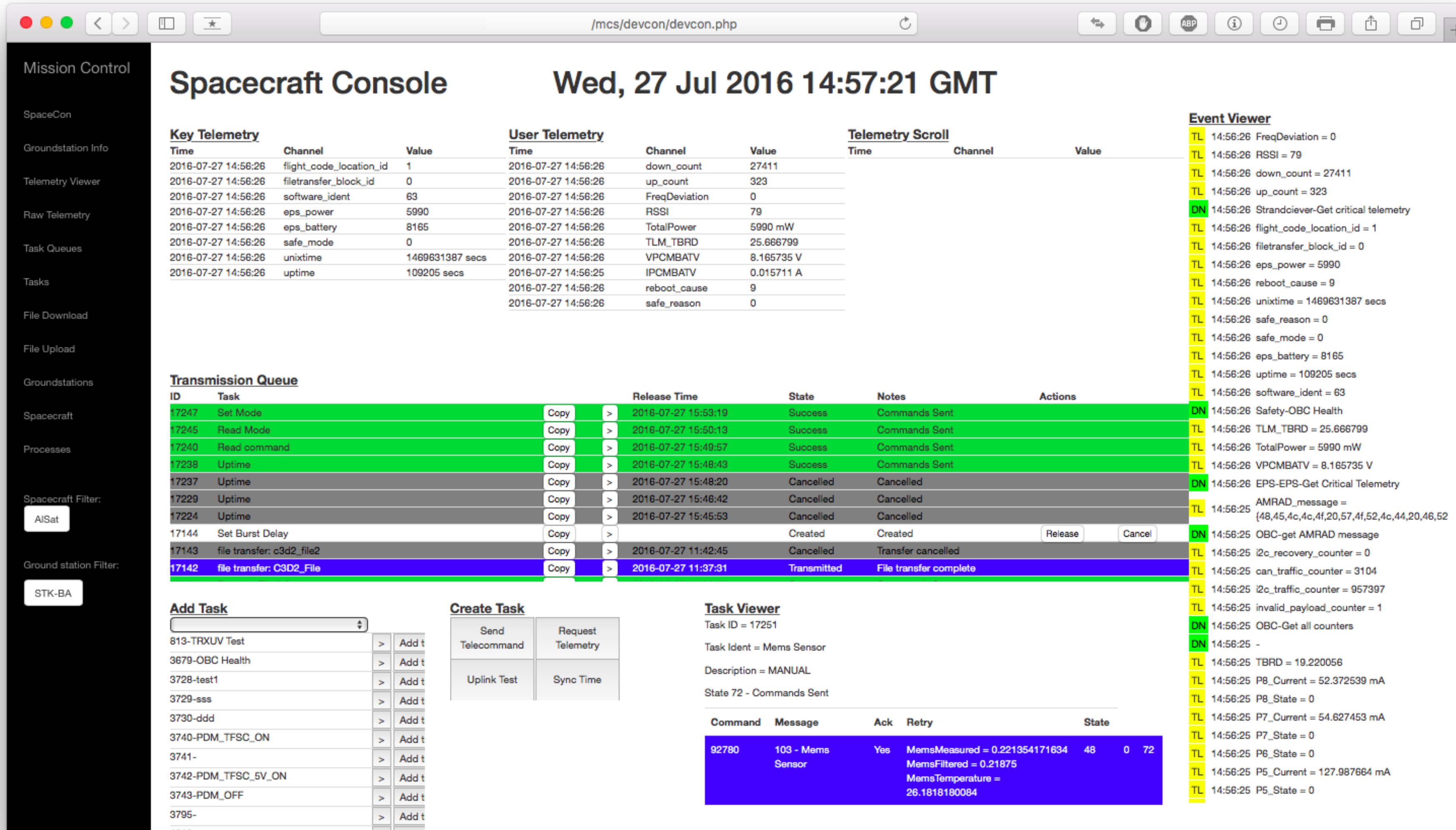
- Each module has an incoming queue, but places all outgoing message on the tct_handler queue
- Incoming messages from ground via UART or RF are treated identically



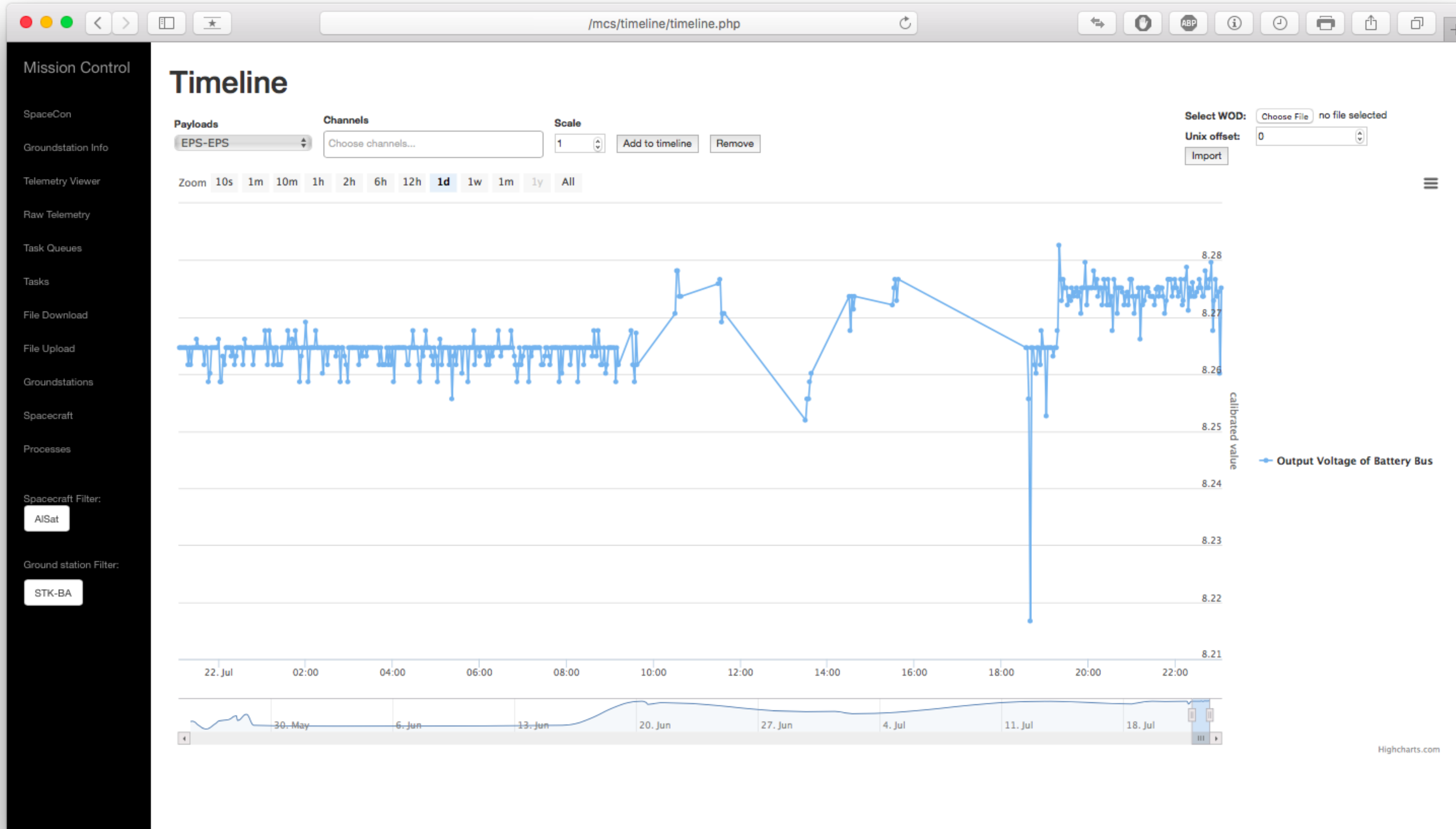
Surrey Ground Software



Surrey Ground Software



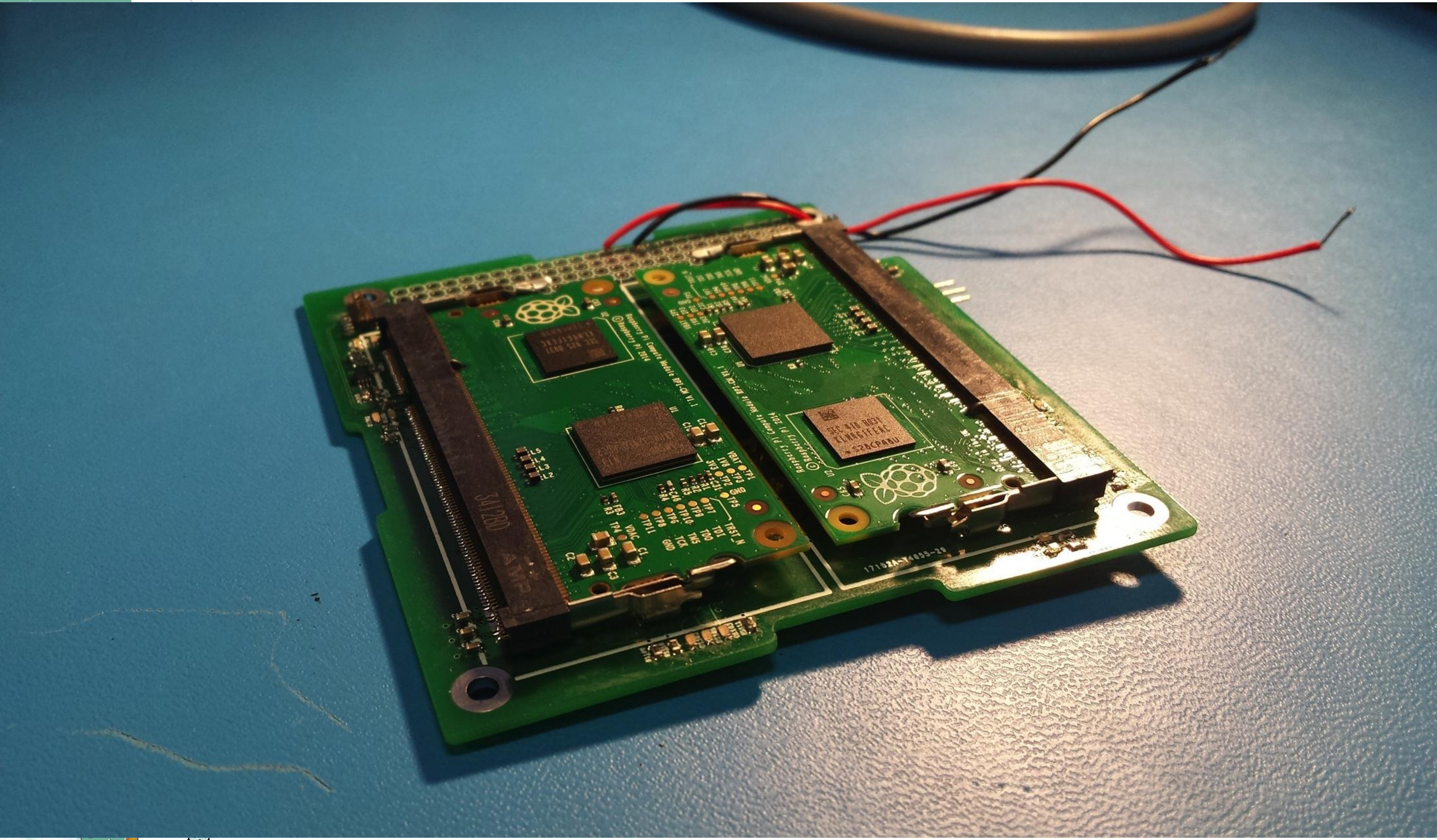
Surrey Ground Software



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

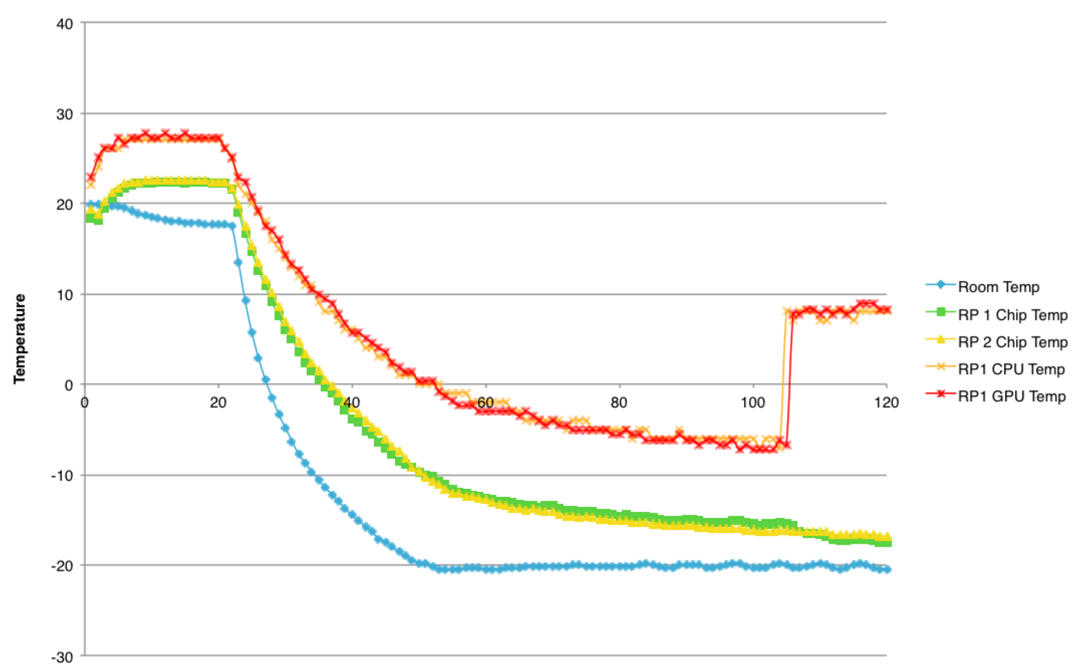
2014-2015 RPi Board Built



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.

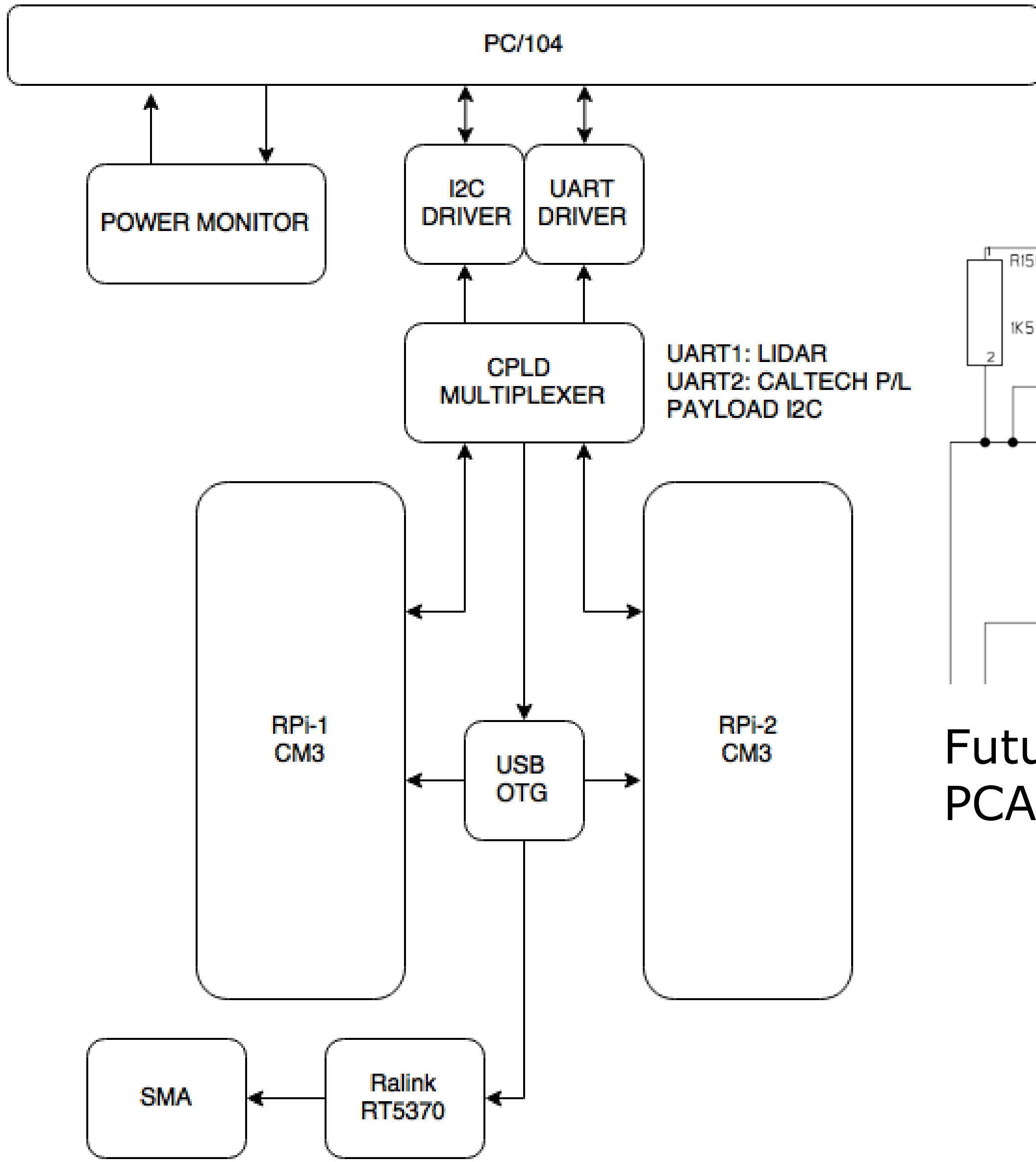
  - E.g. direct on-chip hardware control:
  - CPU & GPU Temp stable at 62° C
  - Turn ON/OFF at hot & cold (see right).
  - Core voltage & CPU freq. stable too.

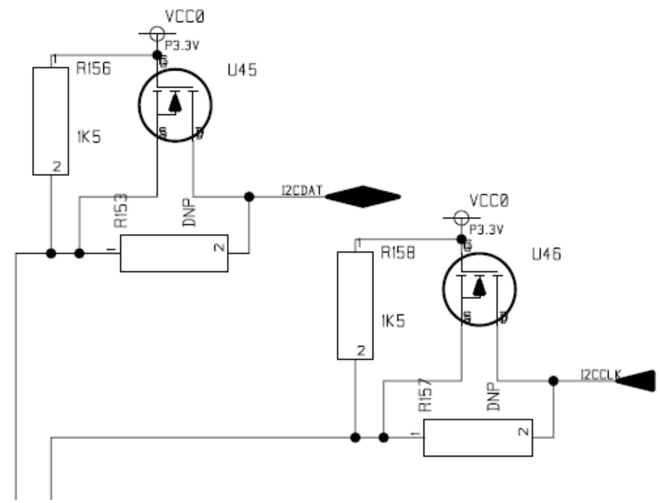


2017 RPi Board Spec.

- Key Specs:
  - Once ICD for payloads are finalised, the interfaces can be fixed
  - 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 CPLD as:
    - Power up sequencing
    - 'Heartbeat' Watchdog on RPi-Computes
    - Switch Power via UART / ADC
  - Payload data/frame processing
  - Multi-objective EM Control (XY-plane & Z plane) during RDV

2017 RPi Board Spec.





Future design part:
PCA9512A

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, the University of Surrey and IIST 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 Surrey MSc/BSc projects and 1 PhD.
- Funding remains an issue for the UK – however, a recent proposal to the UK (CEOI/UKSA NSTP2 FastTrack)was accepted to develop and demonstrate the RDV sensor technology.

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Thank-You

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