AAReST Spacecraft DDR:

Spacecraft Bus, Propulsion, RDV/Docking and Precision ADCS

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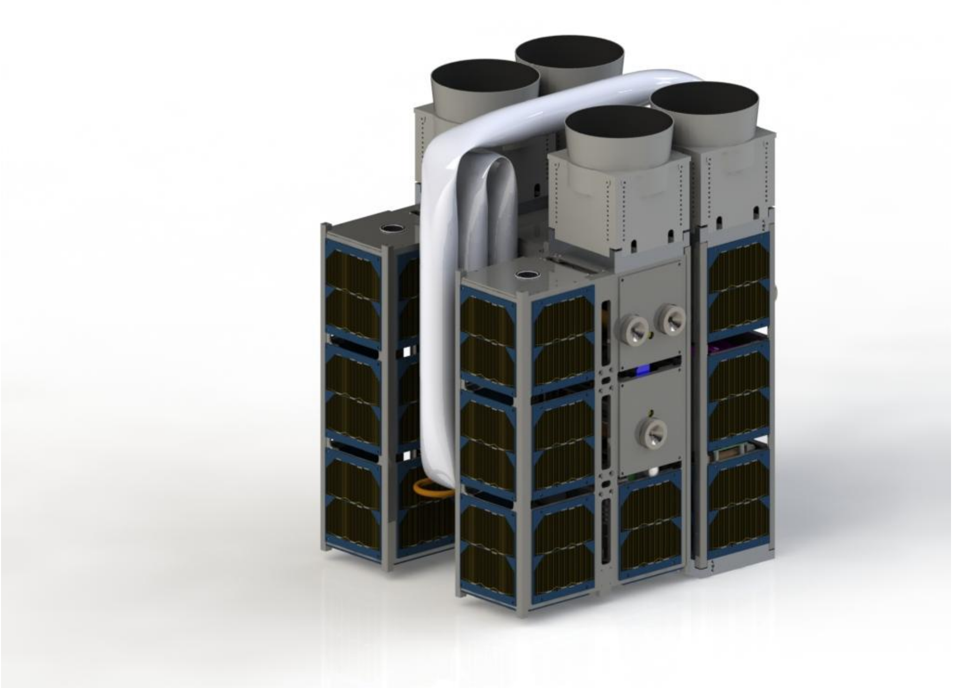
Spacecraft Design Overview

- **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.

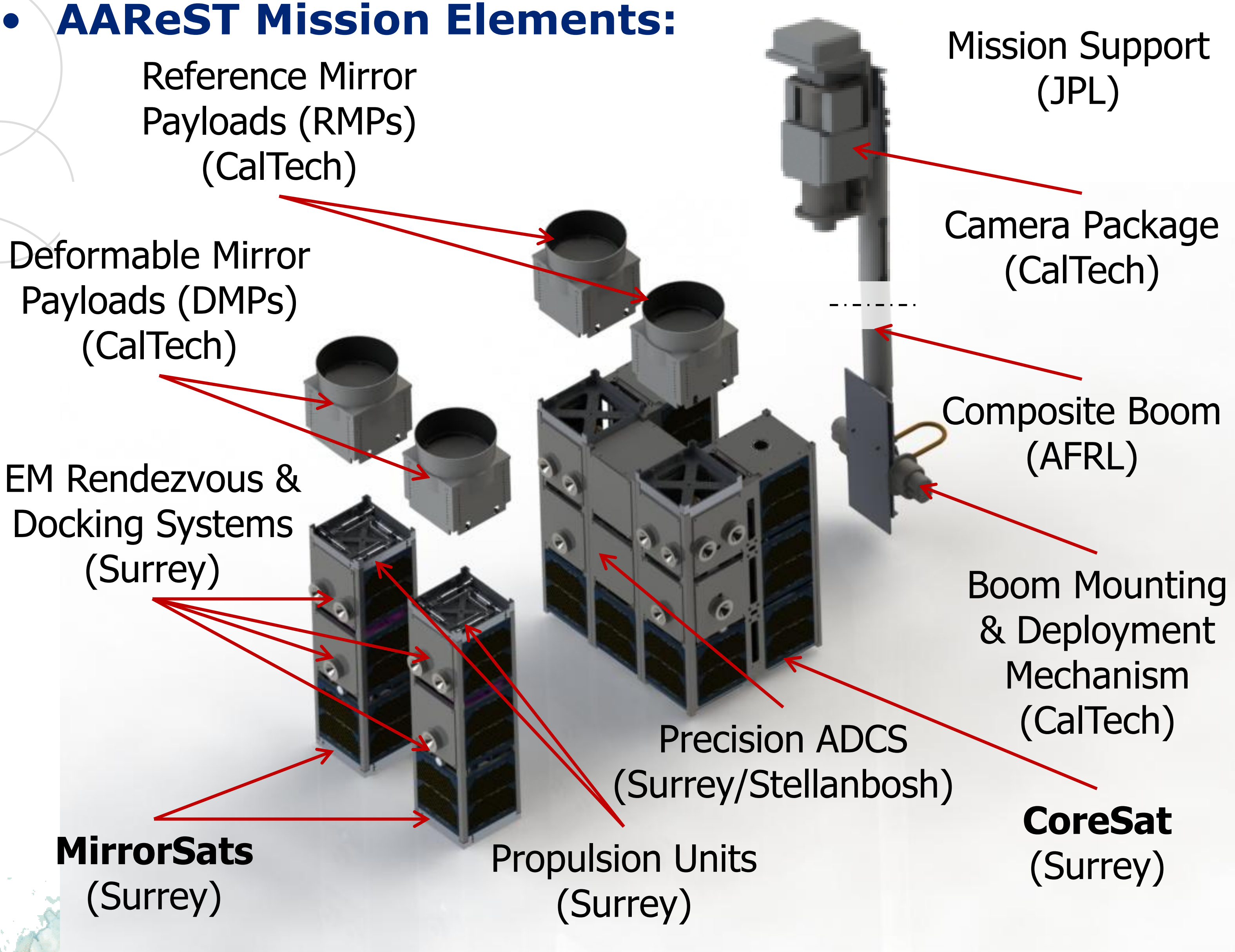


AAReST: Launch Configuration

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

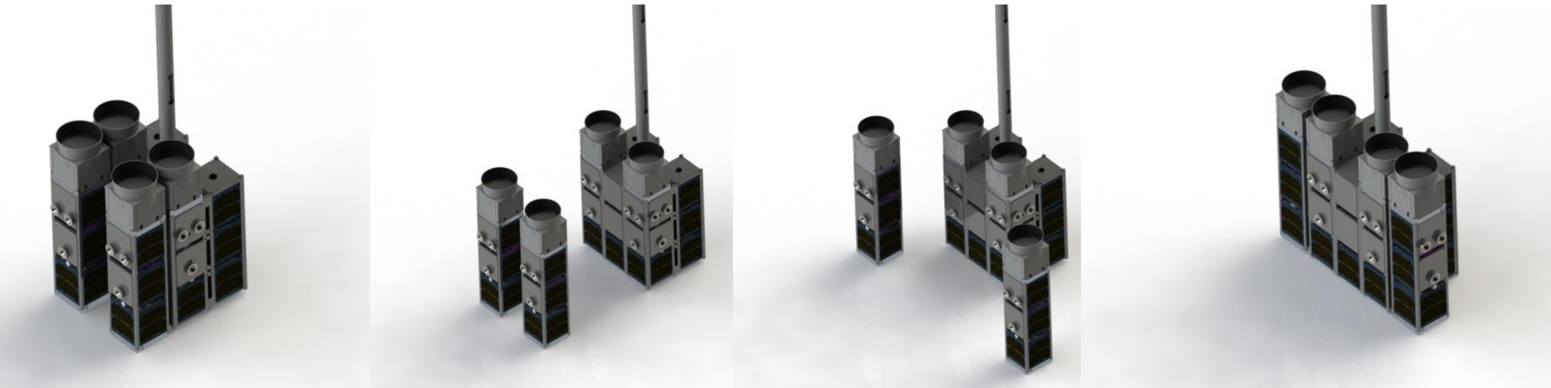
Spacecraft Design Overview

- **AAReST Mission Elements:**



Spacecraft Design Overview

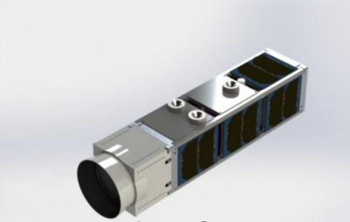
- **Flow-Down to Spacecraft Technology Objectives (Mission Related):**
  - Must involve *multiple* spacecraft elements (*CoreSat* + 2 *MirrorSats*).
  - All spacecraft elements must be *self-supporting* and "*intelligent*" and must cooperate to provide *systems autonomy* – this implies they must be each capable of independent free-flight and have an ISL capability.
  - Spacecraft elements must be *agile* and *manoeuvrable* and be able to *separate* and *re-connec*t in different configurations – this implies an effective AOCS, and RDV&D capability.



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

Spacecraft Design Overview

- **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

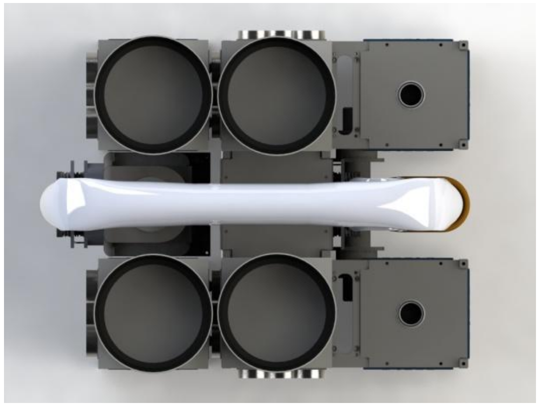

CoreSat (Internal View)

SURREY SPACE CENTRE

Spacecraft Design Overview

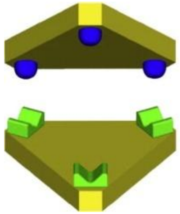
UNIVERSITY OF SURREY

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



Spacecraft Design Overview

- **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 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.



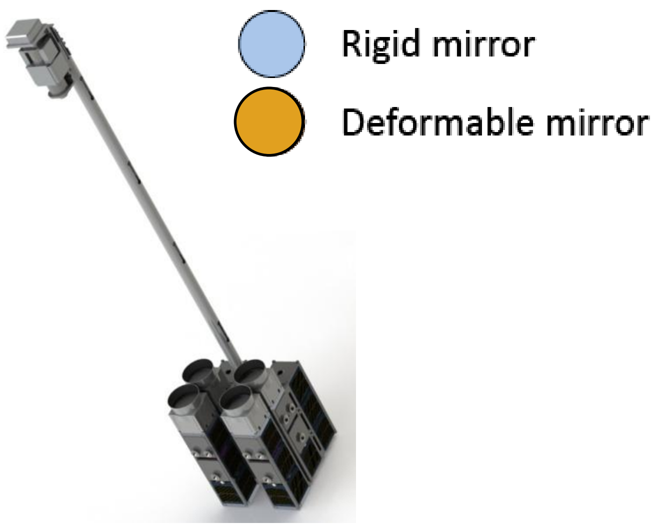
Compact Configuration

Transition

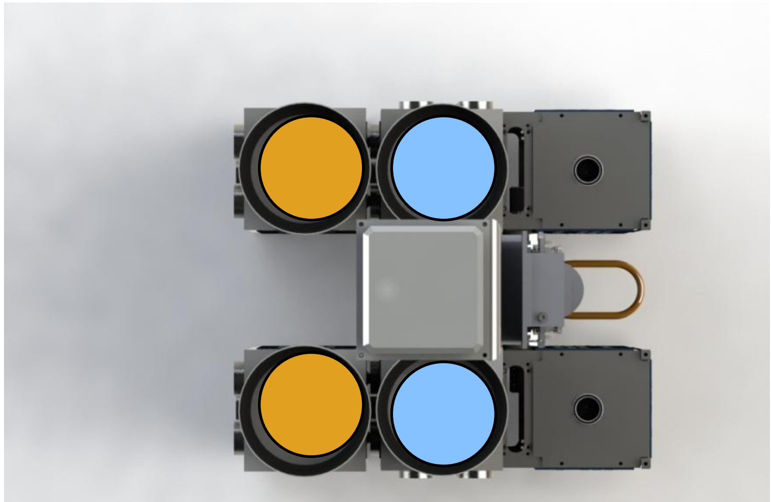
Wide Configuration

Spacecraft Design Overview

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



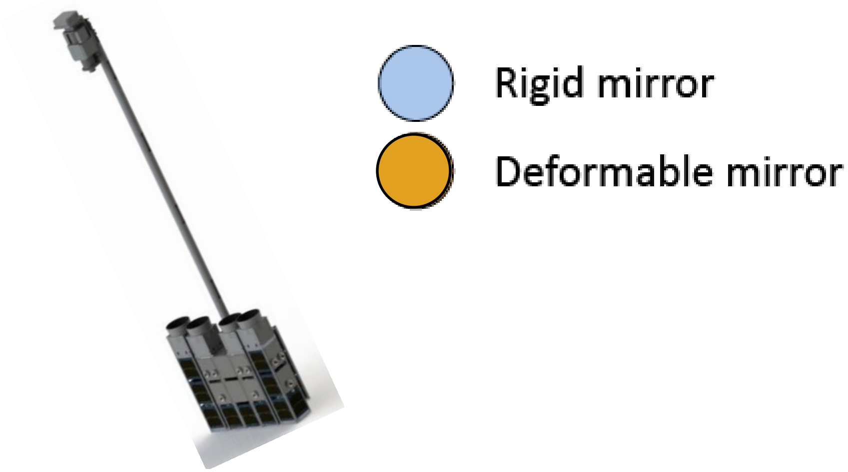
Compact Configuration Imaging Mode



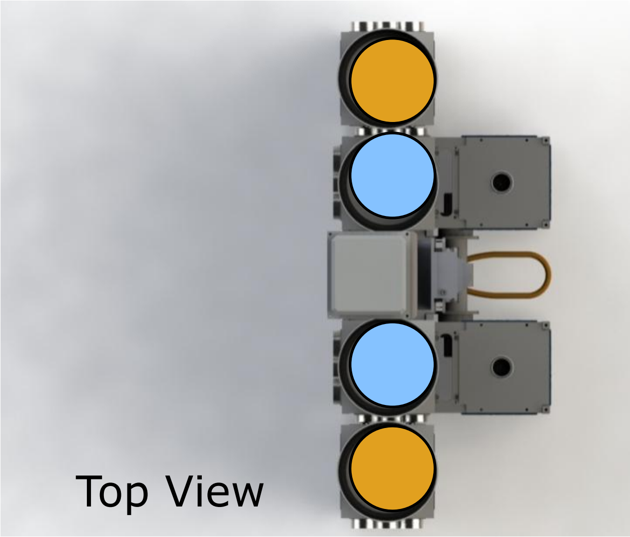
Top View

Spacecraft Design Overview

- **Spacecraft and Mission Concept**
  - **Science Mission Phase 3**: (Key Science Objective 2)
    - Autonomously deploys and re-acquires “MirrorSat” (manoeuvres within c. **10cm-20cm** distance)
    - Demonstrates electromagnetic docking technology
    - Demonstrates ability to re-focus and image in compact mode
  - **Science Mission Phase 4**: (Key Science Objective 3)
    - Autonomously deploys MirrorSat(s) and re-configures to “wide mode” (manoeuvres within **c. 30cm-100cm** distance)
    - Demonstrates Lidar/camera RDV sensors and butane propulsion
    - Demonstrates ability to re-focus and image in wide mode



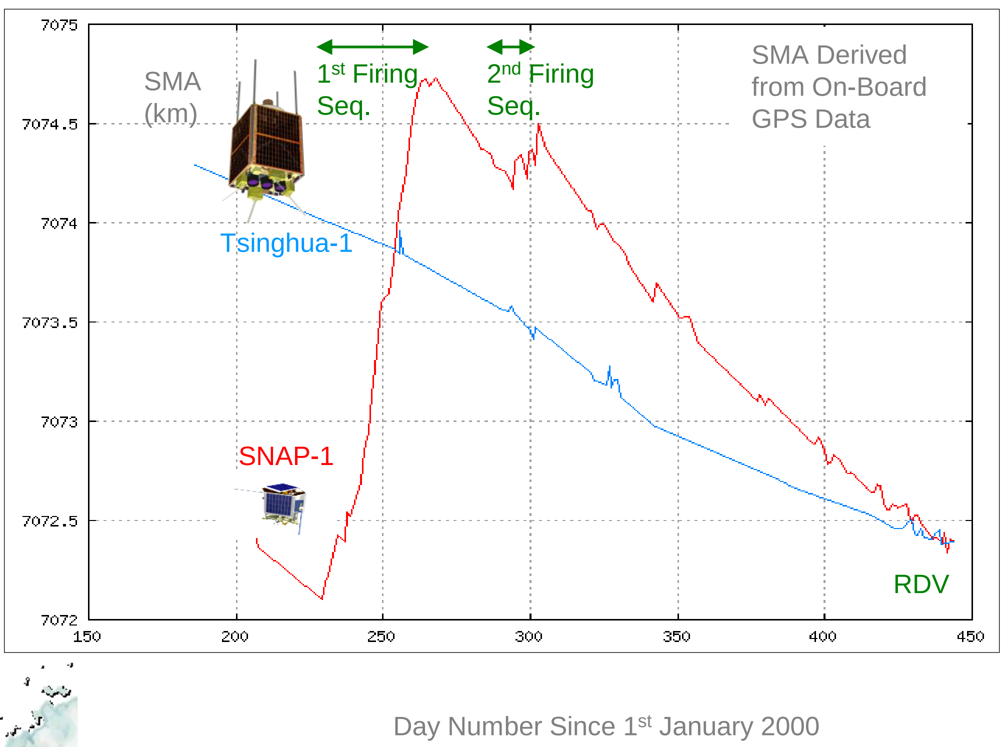
Wide Configuration Imaging Mode



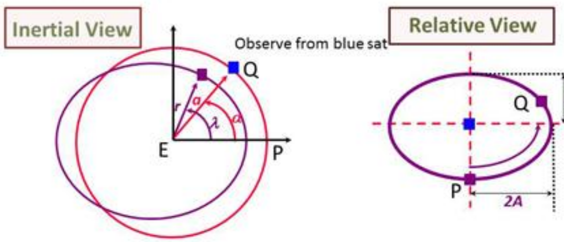
Top View

Spacecraft Design Overview

- **Spacecraft and Mission Concept**
  - **Science 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

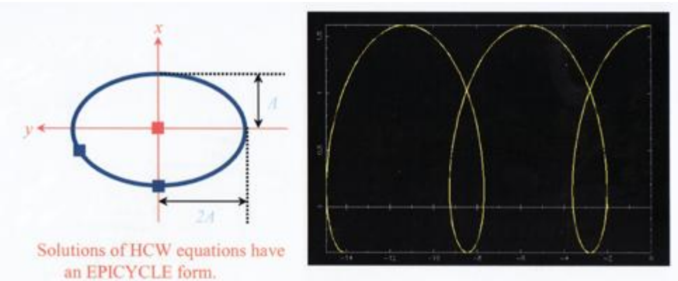


How we see slightly eccentric orbit from a neighbouring circular orbit.



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

A: Epicycle amplitude



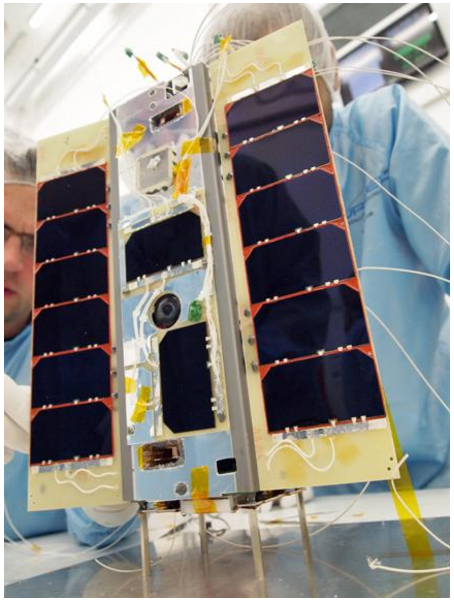
$$x(t) = (4 - 3\cos nt)x_0(\dot{x}_0 / n)\sin nt + 2\dot{y}_0(1 - \cos nt)/n$$

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

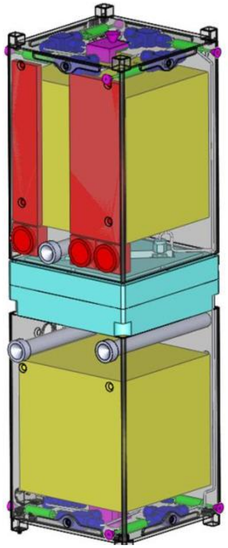
Spacecraft Design Overview

- **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/CubeSail missions currently under development.

SNAP-1 (2000)



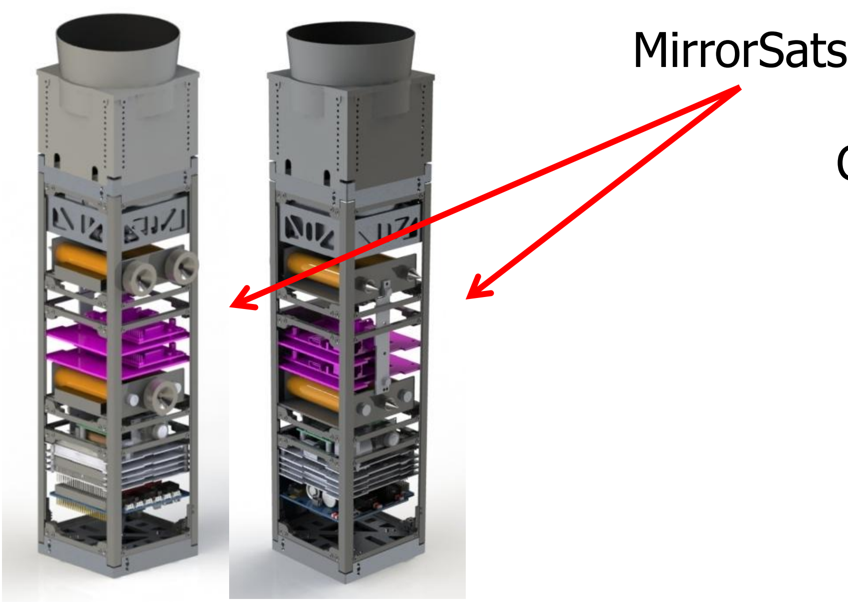
STRaND-1 (2013)

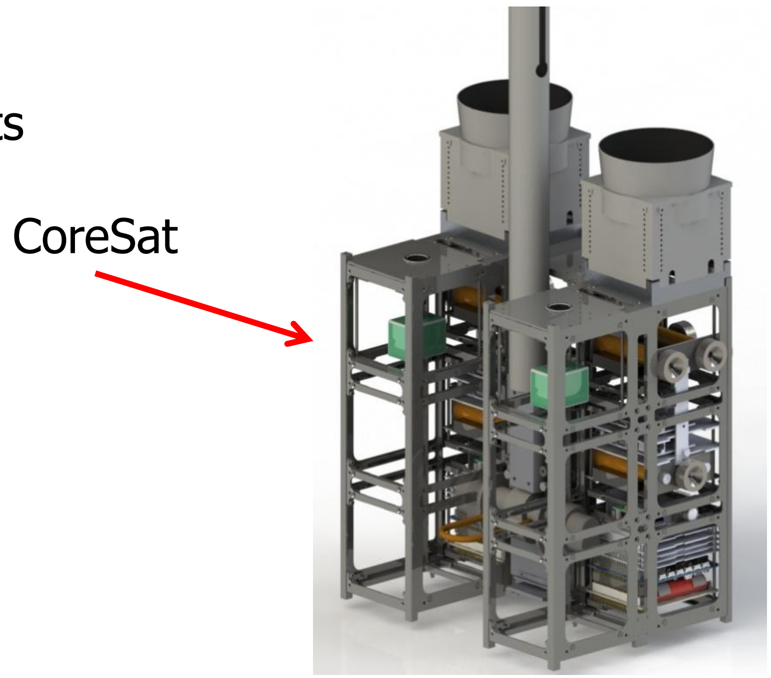


STRaND-2 Concept

Spacecraft Design Overview

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



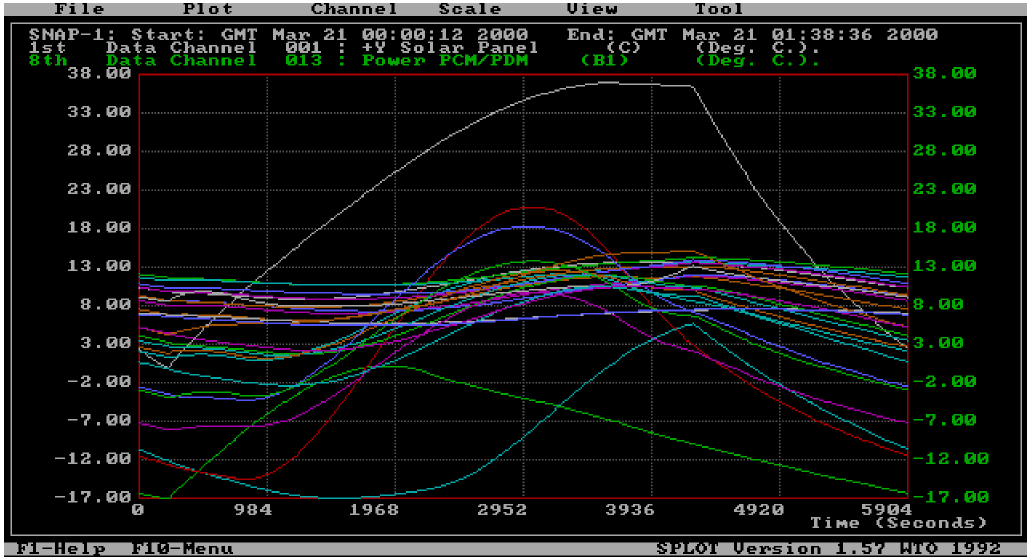


DDR Configuration Sept. 2014

Spacecraft Design Overview

Spacecraft Bus – Thermal Design Approach

- CubeSats use (mainly) passive thermal control.
- Scheme will be as per STRaND-1.
- Typ. Operating range for equipment -40 ^{o}C to +85 ^{o}C.
- Danger is running too cold at the end of eclipse.
- GomSpace battery is rated -5 ^{o}C to +45 ^{o}C (heater option).
- Once the orbit is verified, a Thermal Model will be created.
- Current reference orbits: 650km SSO and ISS.
- Spacecraft will be tested in SSC's CubeSat TVAC Chamber.



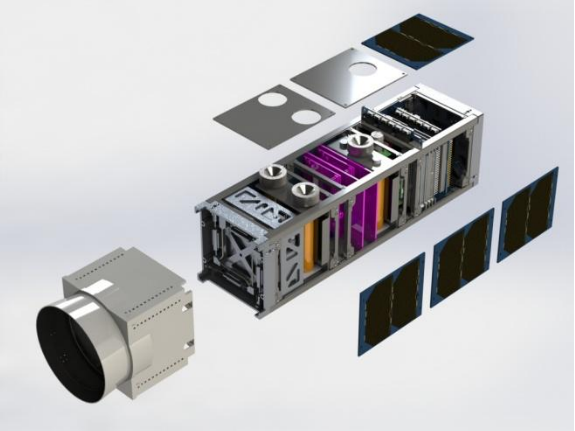
Spacecraft Design Overview

- **Updates since PDR (Sept. 2013)**
  - **Structure** and mechanical interfaces refined and new MCAD produced.
  - **Propulsion system** re-designed, manufactured and part tested. Electrical interface and control is still TBD.
  - **Docking ports** re-analysed, EM models produced, drivers selected, new materials selected for the electromagnets and modified design manufactured.
  - New **Softkinetic DS325 LIDAR** implemented and tested.
  - RDV operations over Wi-Fi tested on Air-Bearing Table.
  - **Raspberry-Pi OBC** implemented and tested (including TVAC); new (2014) Industrial Grade version acquired and under-test.
  - **ISIS VHF/UHF** Communications systems tested and qualified in orbit (QB-50) and Surrey Groundstaton upgraded for VHF/UHF with Software Defined Radio solutions as well as hardware RF/Modem chains.
  - Sample Reaction wheel manufactured and tested; multiple new **QB50 ADCS** systems built and tested, and two examples flown in orbit.

MirrorSat Spacecraft Bus

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 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.

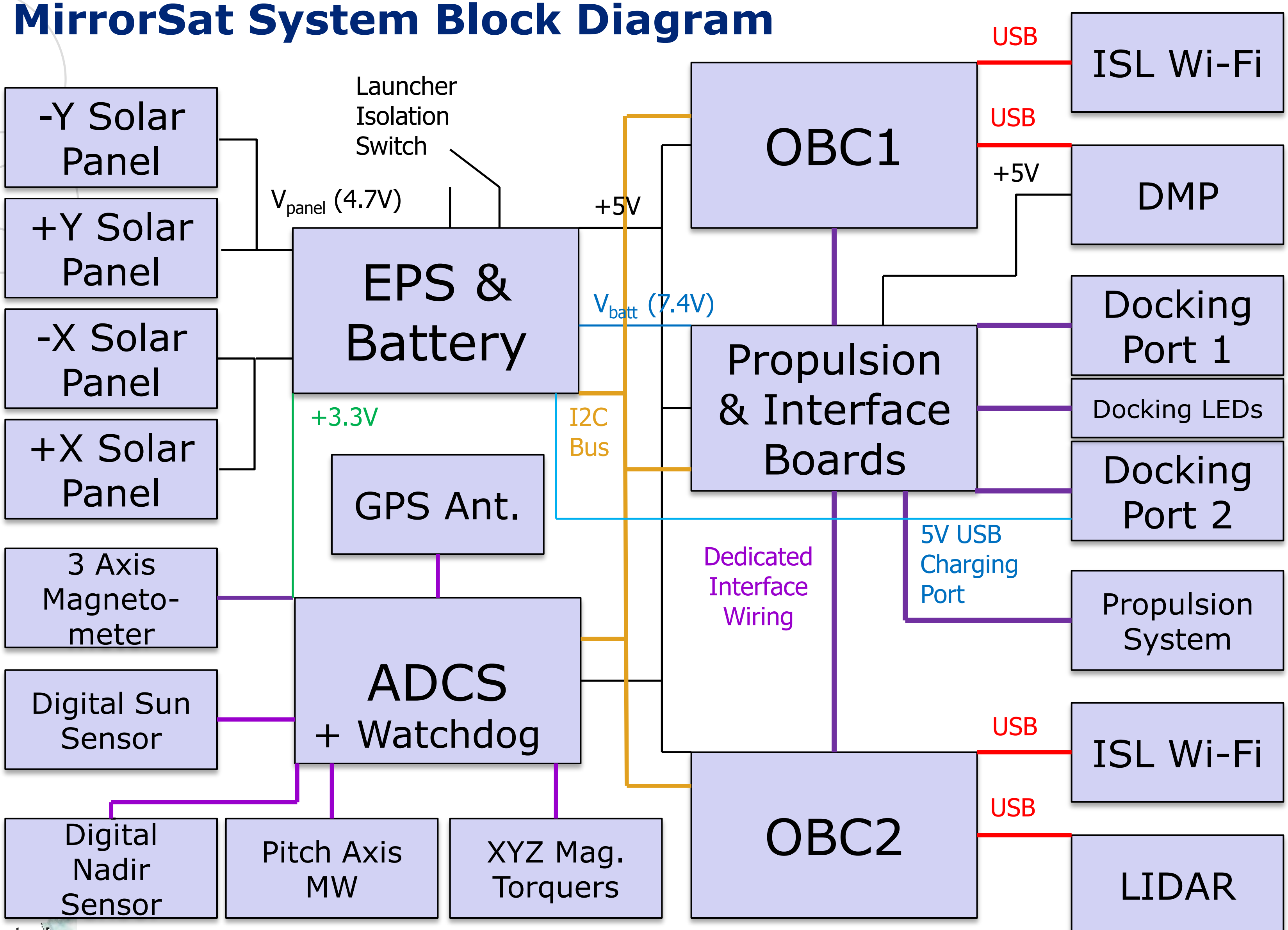


MirrorSat Spacecraft Bus

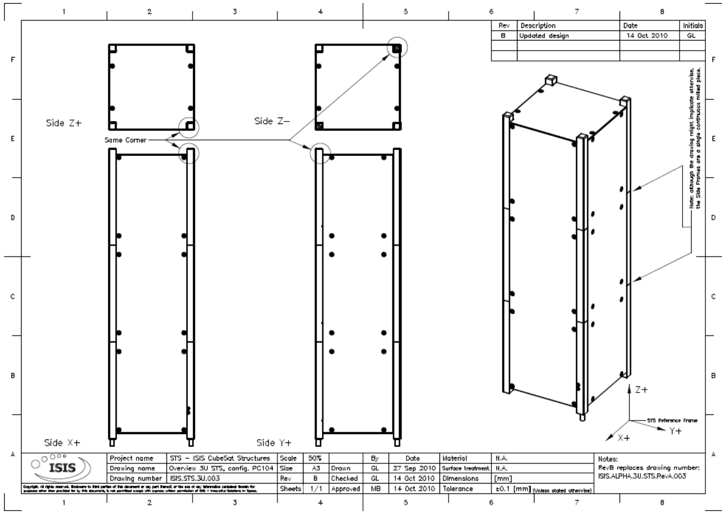
- **MirrorSat Sub-Systems**
  - **DMP Payload** (CalTech supplied)
  - **Structure** (modified COTS 3U CubeSat – ISIS)
  - **Thermal** (passive thermo-optical controlled)
  - **Power** (self supporting + power boosted when docked)
  - **ADCS** (3-axis control – to at least SNAP-1 standard: 1 MW)
  - **GPS Rx**. (for long range ops. >10m)
  - **OBC1 – Comms-Payload** (Raspberry-Pi, Wi-Fi, DMP Support)
  - **ISL Comms/Data** (2.4 GHz Wi-Fi; USB 2.0)
  - **OBC2 – RDV OBC** (Raspberry Pi – RDV/Docking/LIDAR)
  - **Docking Sensor** (Softkinetic DS325 LIDAR/Camera for RDV)
  - **Docking Illumination/Optical RDV** (IR LEDs; Nadir Sensor)
  - **EM Docking System**(20-30cm range; $\pm$ 45^{o} capture cone)
  - **Launch Retaining Structure** (Frangibolt + docking port)
  - **On-Orbit Retaining Structure** (passive magnet)
  - **Propulsion** (9 thruster ~6DOF butane ~10 m/s ΔV)

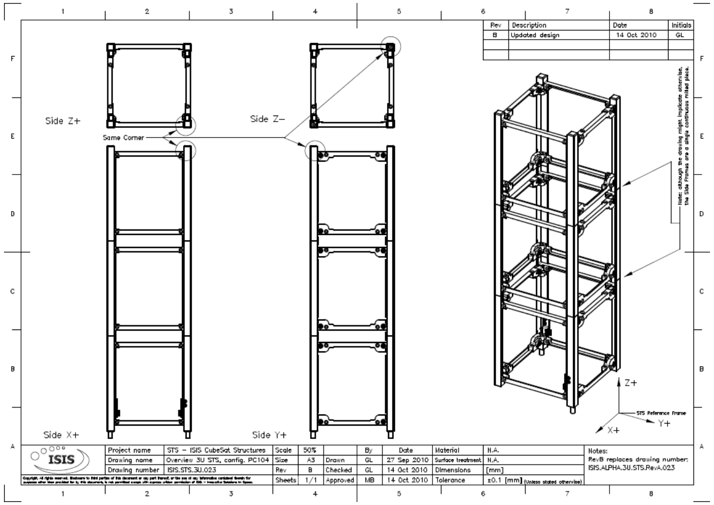
MirrorSat Spacecraft Bus

- **MirrorSat System Block Diagram**



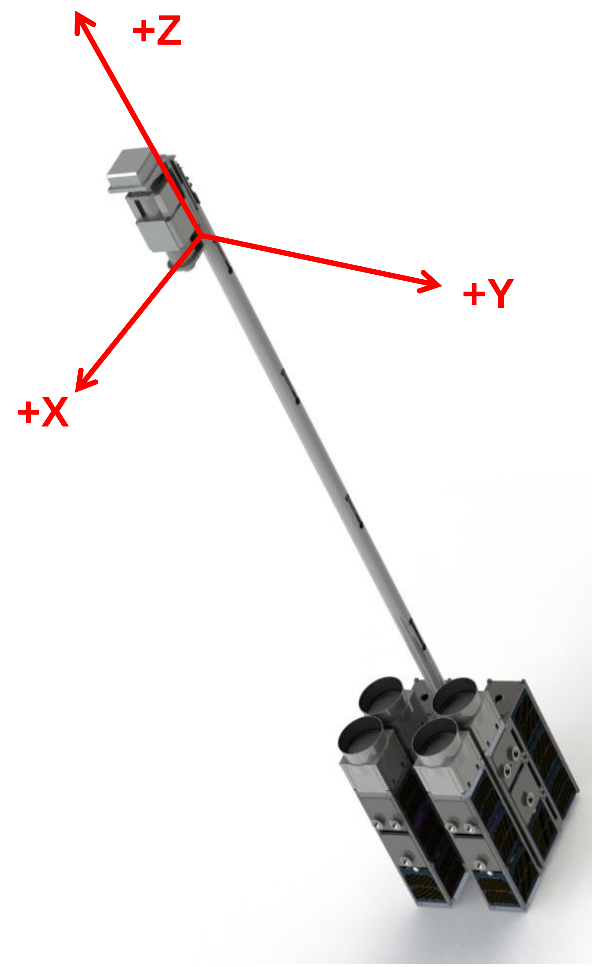
- **MirrorSat Structure**
  - Modified COTS **ISIS 3U CubeSat Structure** (270g for 3U)





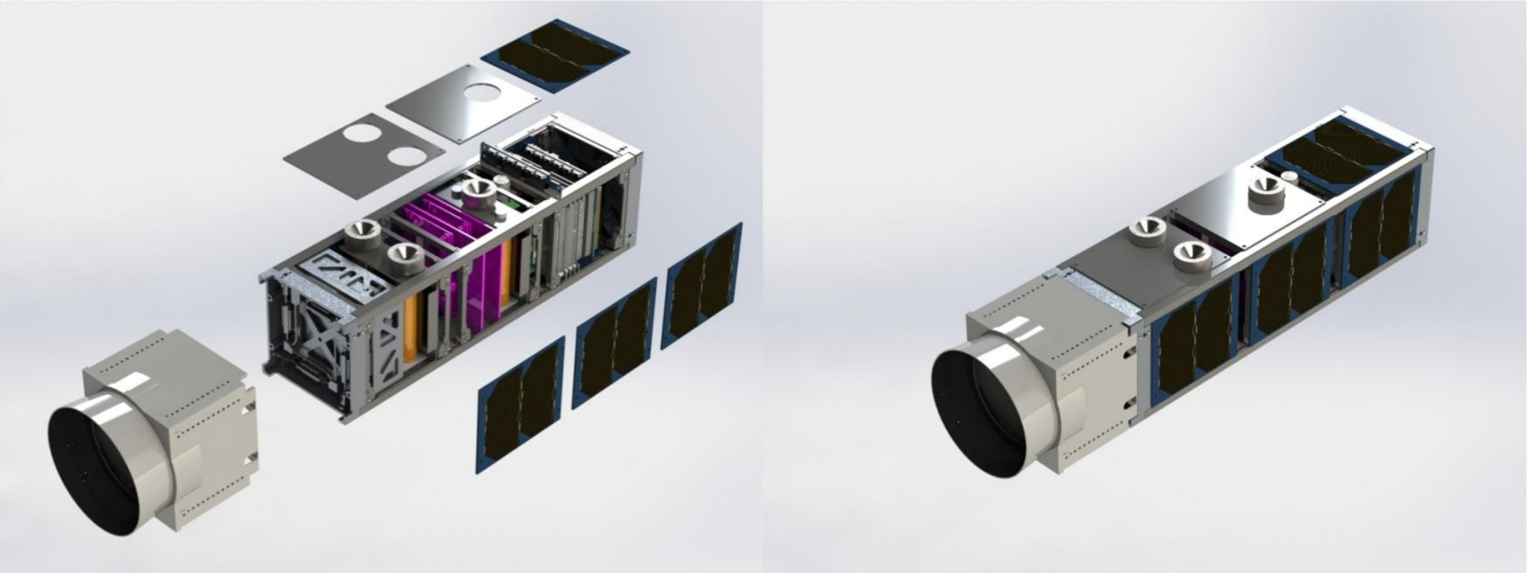
MirrorSat Spacecraft Bus

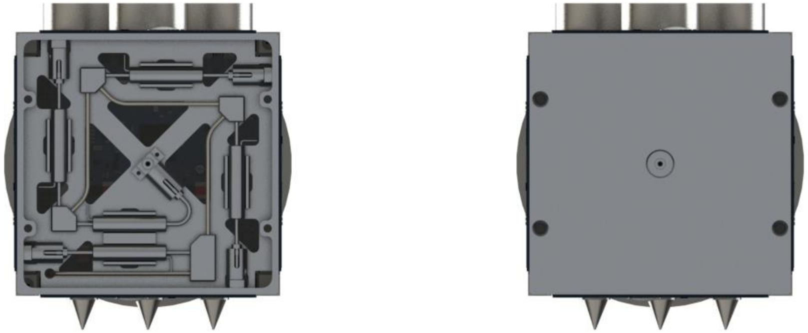
- **MirrorSat Structure**
  - Renderings showing X (Docking) Facets, Y (Main Solar Panel) Facets and +Z (DMP) Facet (EMC screens not shown)



MirrorSat Spacecraft Bus

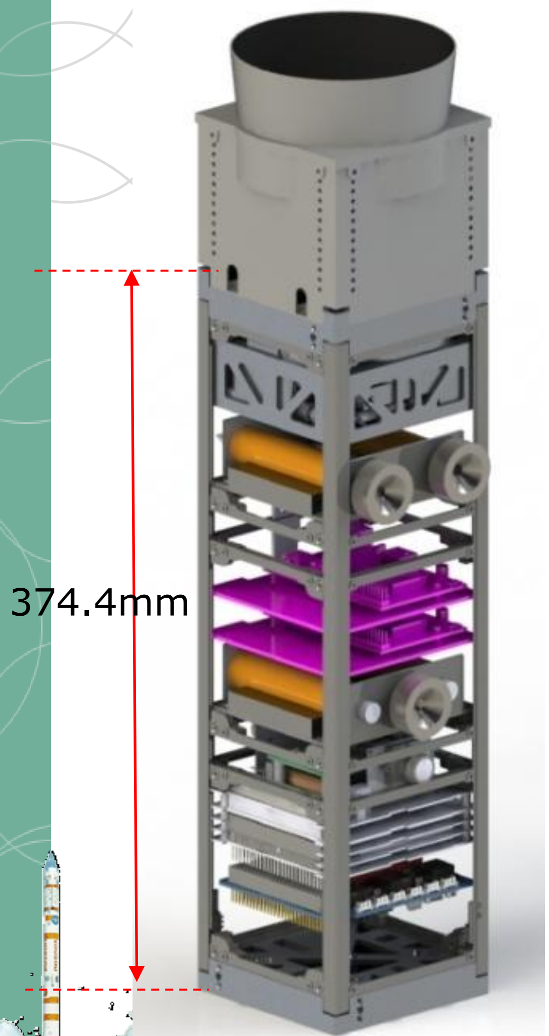
- **MirrorSat Structure**
  - Propulsion units fit on either end of the ISIS 3U structure and the DMP payload fixes to the upper (+Z) propulsion unit.
  - Electrical interface: USB 2.0 with switchable 5V (1A limit)

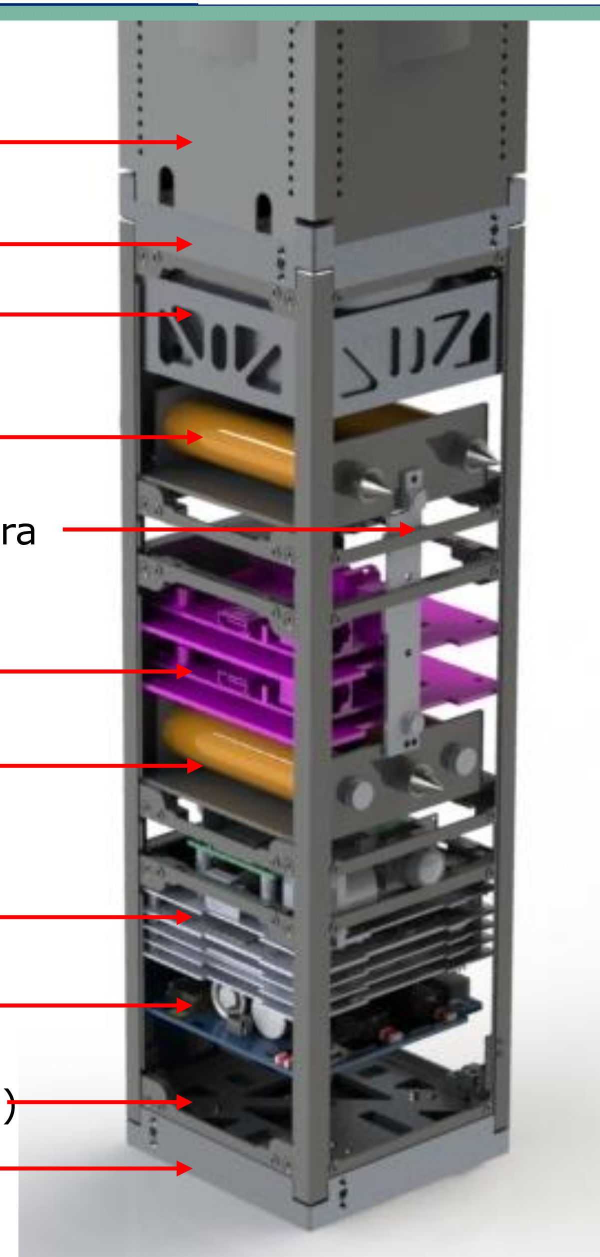




MirrorSat Spacecraft Bus

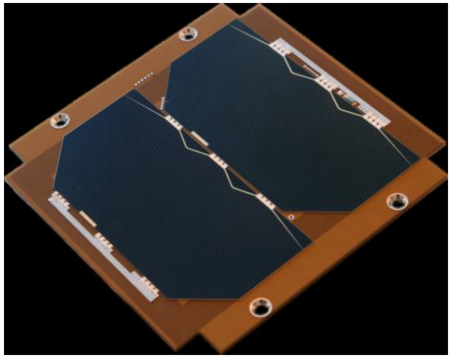
- **MirrorSat Structure**
  - System Layout





MirrorSat Spacecraft Bus

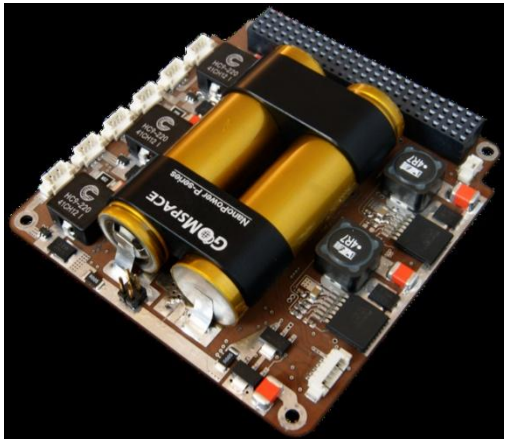
- **MirrorSat Solar Panels**
  - **COTS GOMSPACE NanoPower P110 Series**
  - Compatible with ISIS structure
  - AzurSpace 3G30A space qualified triple junction cells at ~30% efficiency with CMX 100 cover glass (100um); 26-29g per PCB; 1.1mm thick; blocking diode, Sun Sensor and Temperature Sensor included 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.
  - Average power for the free-flying MirrorSat in sunlight is ~4W; orbit average power ~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.

MirrorSat Spacecraft Bus

- **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 control, telemetry and telecomand.

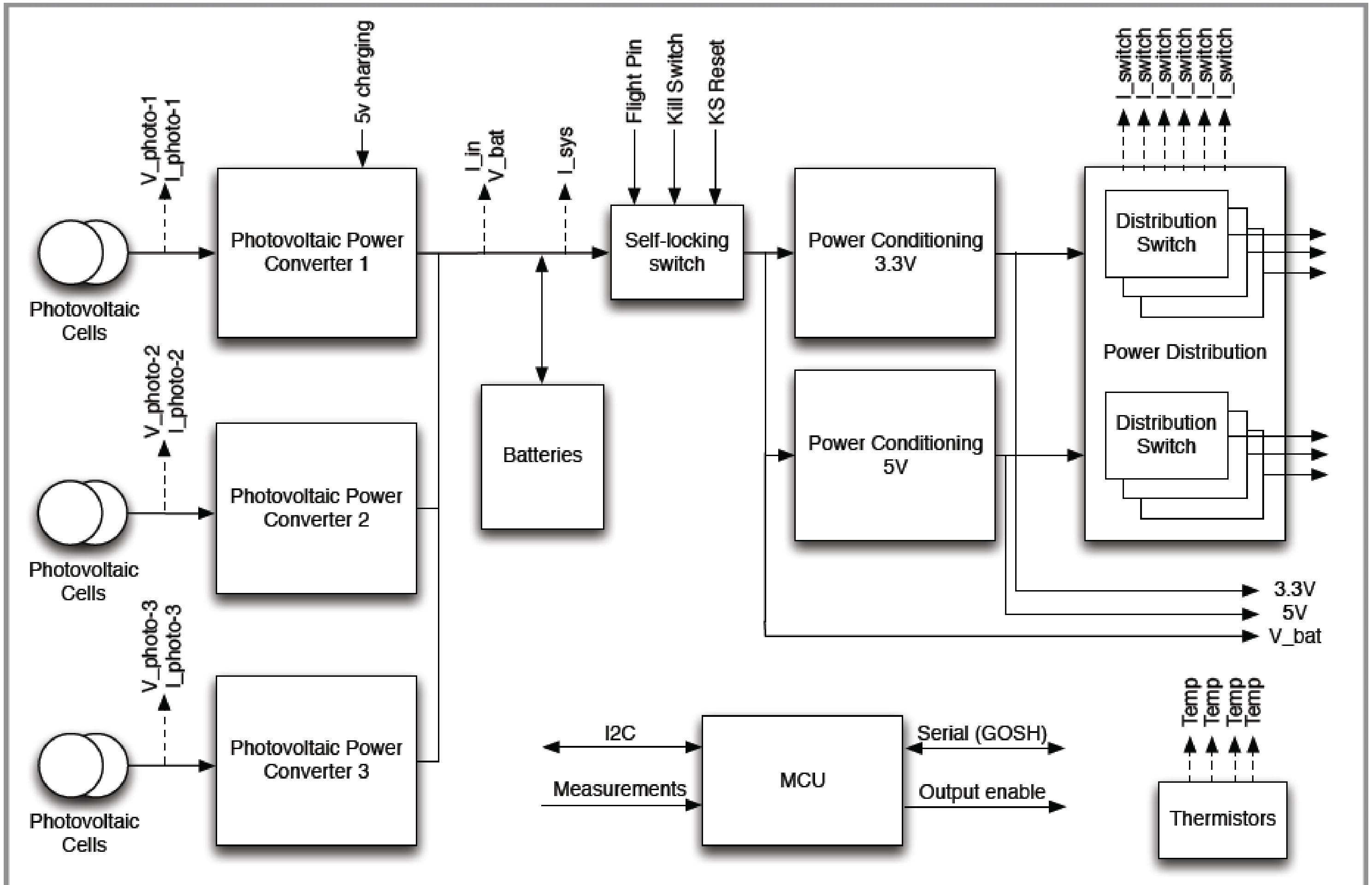


MirrorSat Spacecraft Bus

- **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

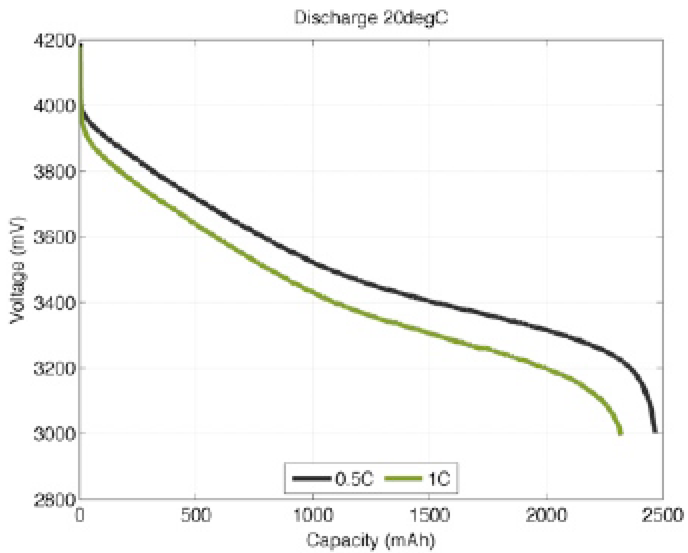


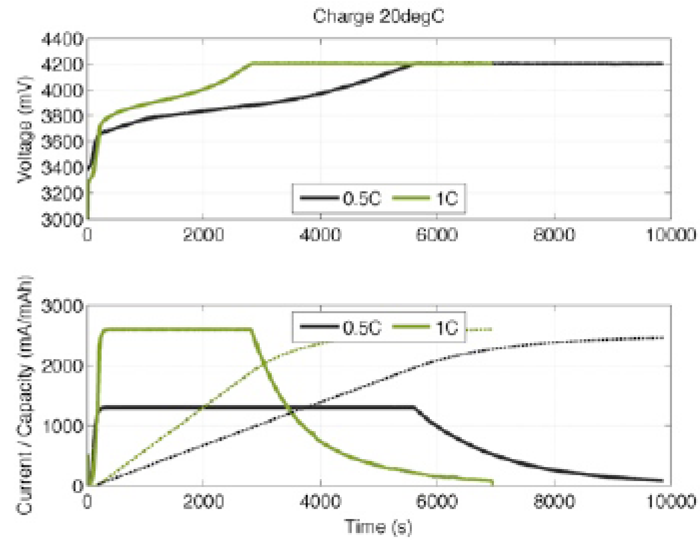
- **MirrorSat EPS**
  - **Housekeeping (I2C):**
    - Four temperatures
    - Current into and out of photovoltaic power converters
    - Photovoltaic input voltage for each input converter
    - Battery voltage
    - Total current into the output bus converters.
    - Current out of all power output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

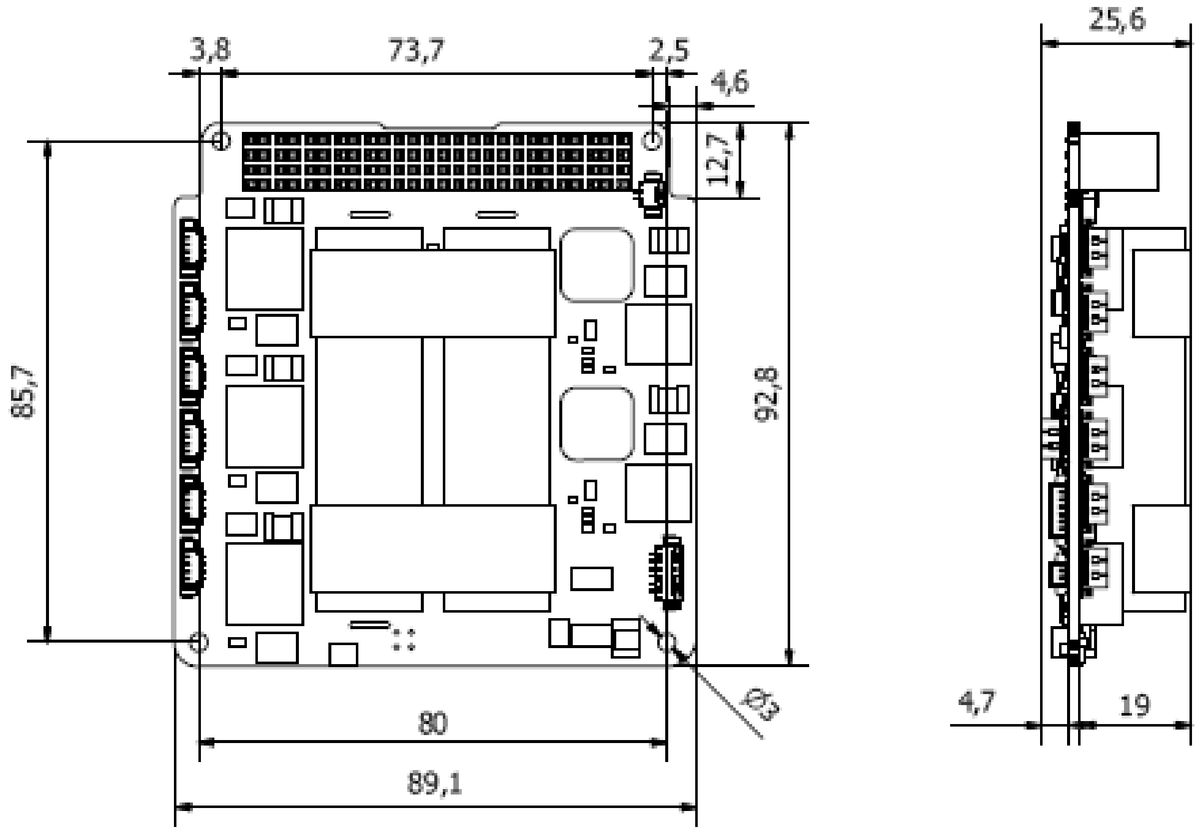
- **MirrorSat Battery**
  - **2600mAh Li-Ion:** (note short cycle life at 100% DoD)

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

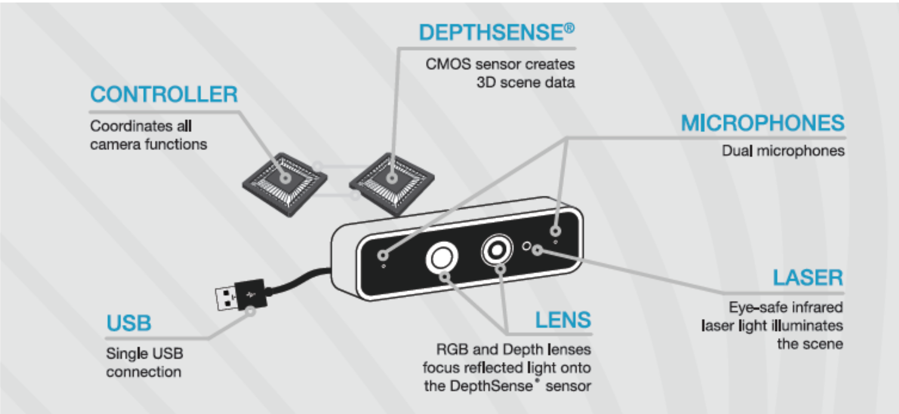


MirrorSat Spacecraft Bus

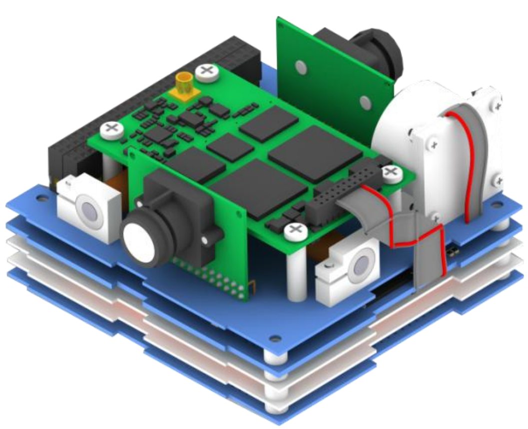
- **MirrorSat Power Budget (not updated)**
  - Systems connections/ power budget:
    - **EPS:** 125 mW on; 60 uA off (700 day min. discharge)
    - **ADCS:** (**CubeControl**; **CubeSense**; **CubeComputer**) – ADCS **3.3V sw.**; ADCS **5V sw.**; GPS **3.3V fixed**; GPS **5V fixed**; total consumption < 2W expected 0.5W (tbc).
    - **OBC1:** (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+OBC1+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)

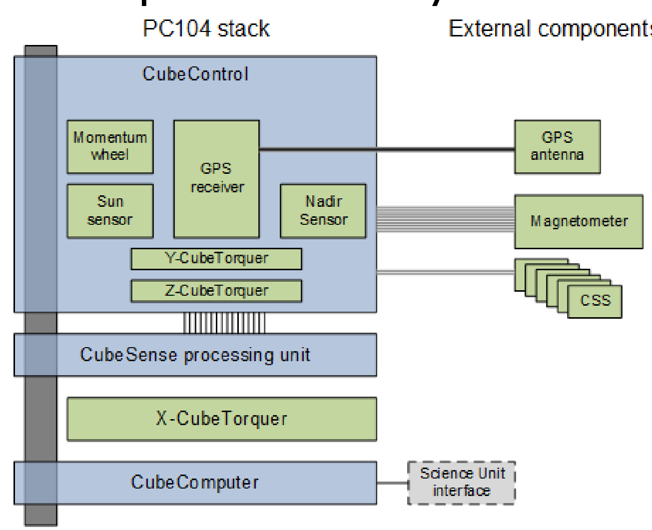
MirrorSat Spacecraft Bus

- **MirrorSat OBCs; Control/Communications/Data Link**
  - These systems and their current status will be presented by Dr. Chris Bridges shortly.



- **MirrorSat ADCS**
  - This system and its current status will be presented by Prof. Vaios Lappas shortly.

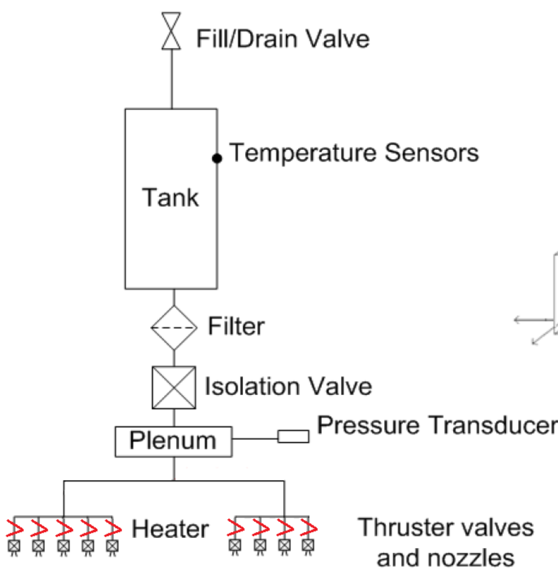


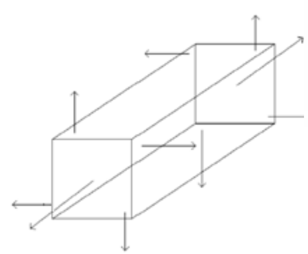


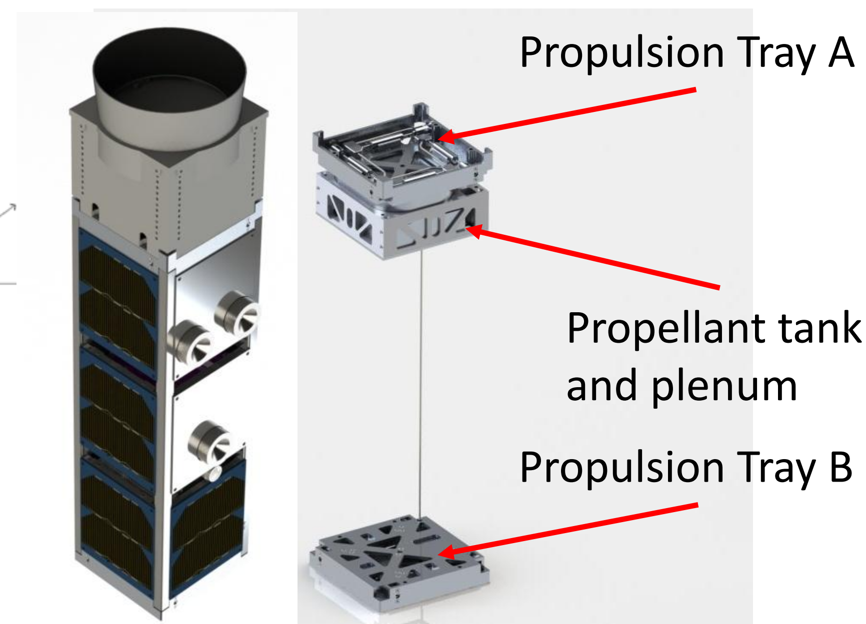
MirrorSat Propulsion System

MirrorSat Spacecraft Bus

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





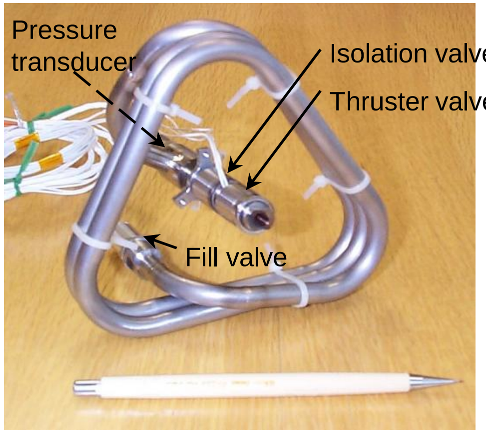


MirrorSat Spacecraft Bus

- **MirrorSat Propulsion**
  - 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
  - Z-axis Torque ~0.5-1 mNm; X/Y–axis Torque ~2-4 mNm.
  - Z-axis angular acceleration ~0.7-1.4 rad.s^{-2}; X/Y–axis angular acceleration ~1-2 rad.s^{-2};
  - Min. angular Speed step ~2 mrad.s^{-1} (~0.1° s^{-1}).
  - System mass estimated at 880 grams (800 grams dry mass)
  - Resistojet's 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 grams butane**
Total impulse	**22.3 Nsec**
Thrust range	**25 to 100 milli N**
Module mass	**455 grams**
ΔV imparted	**2.1m/s (actual)**



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

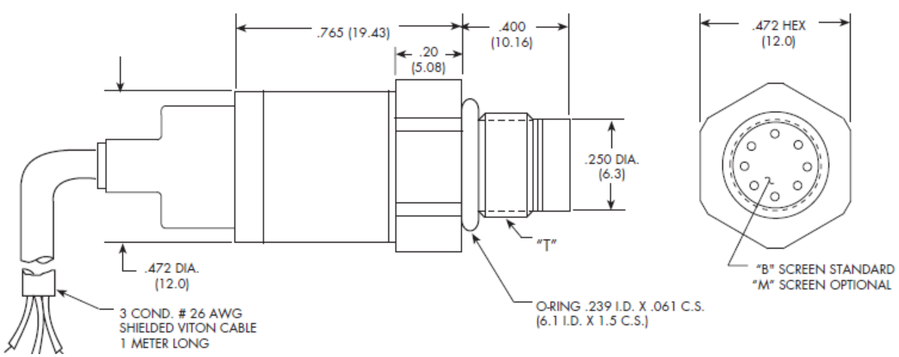
- 1/16th inch stainless steel swagelok tubing rated to 560 bar

- 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

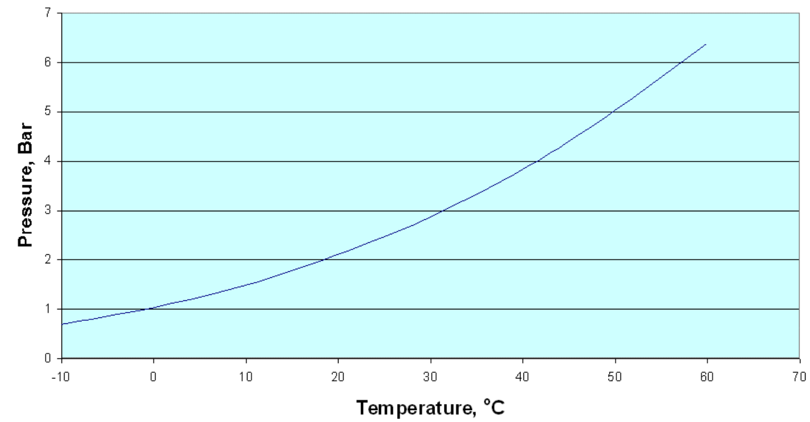
- Kulite ETM-634-312M pressure transducer used for monitoring plenum pressure and feedback input to valve
- Smallest high performance amplified transducer worldwide
- Operating temperature range of -55° C to 185° C
- Pressure range 0 – 15 Bar absolute with burst pressure of 45 bar
- Rated excitation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



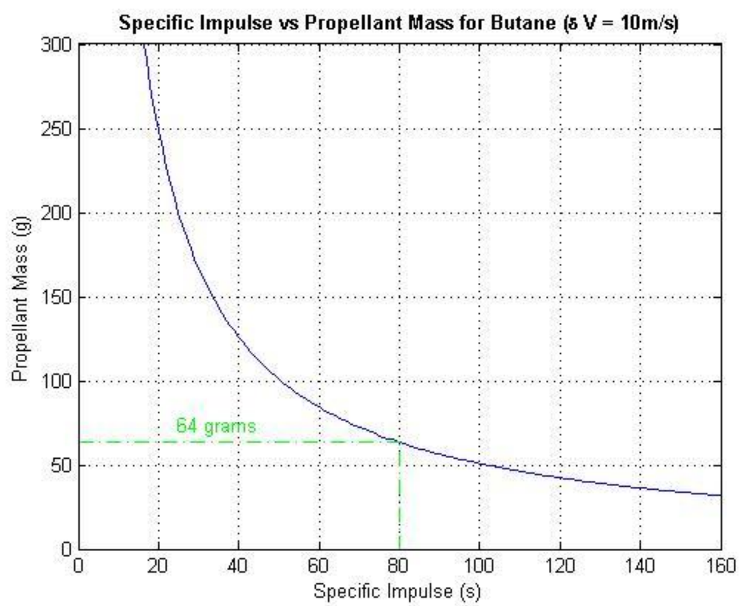
- Output impedance of 200 Ohms (Typ.)
- Analogue voltage output
- Full scale reading of 4.5V $\pm$ 1%
- Mass of 15g
- Stainless steel diaphragm

Propellant Tank

- 150 ml tank stores 80g 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)



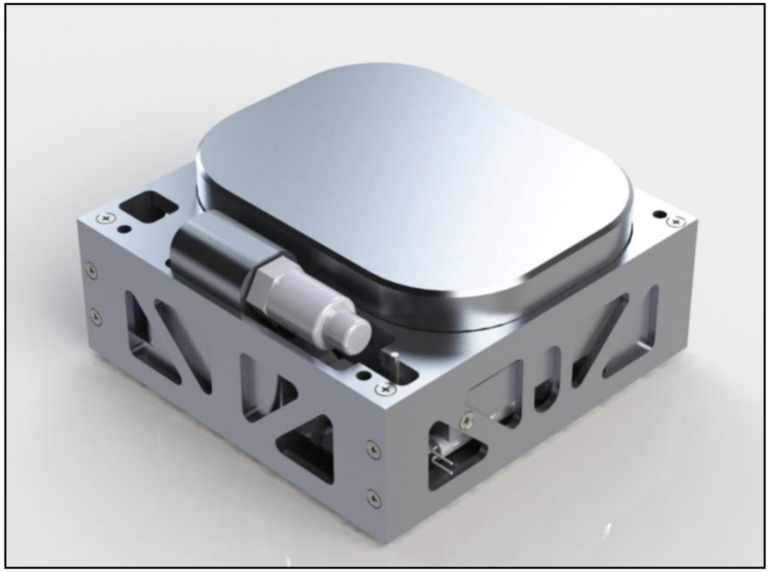
Vapour pressure vs temperature for butane gas
Source: D.Gibbon SSTL



- 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 80Isp
- AAReST carries 80g propellant which amounts to a 20% contingency

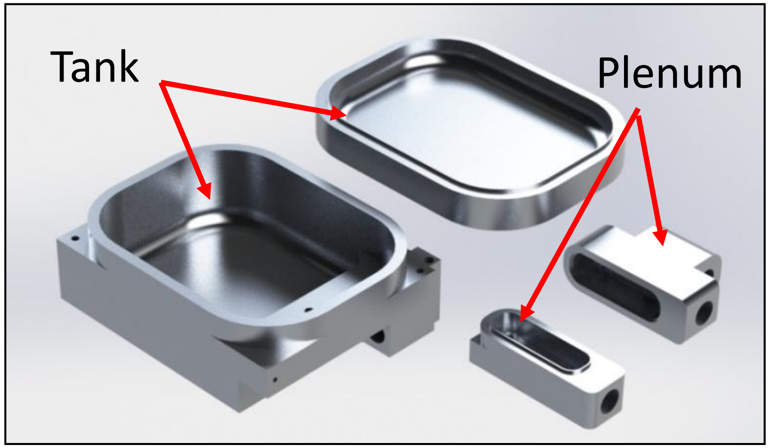
Plenum

- 7 ml plenum used to expand butane and control pressure: 0.5 -1 bar depending on desired thrust
- Pressure regulated mode for fixed thrust or impulse bit. Thrust not dependent on tank temperature
- Plenum used to feed thruster at nominally constant pressure
- IEP valve pulsed at up to 500 Hz to maintain desired plenum pressure

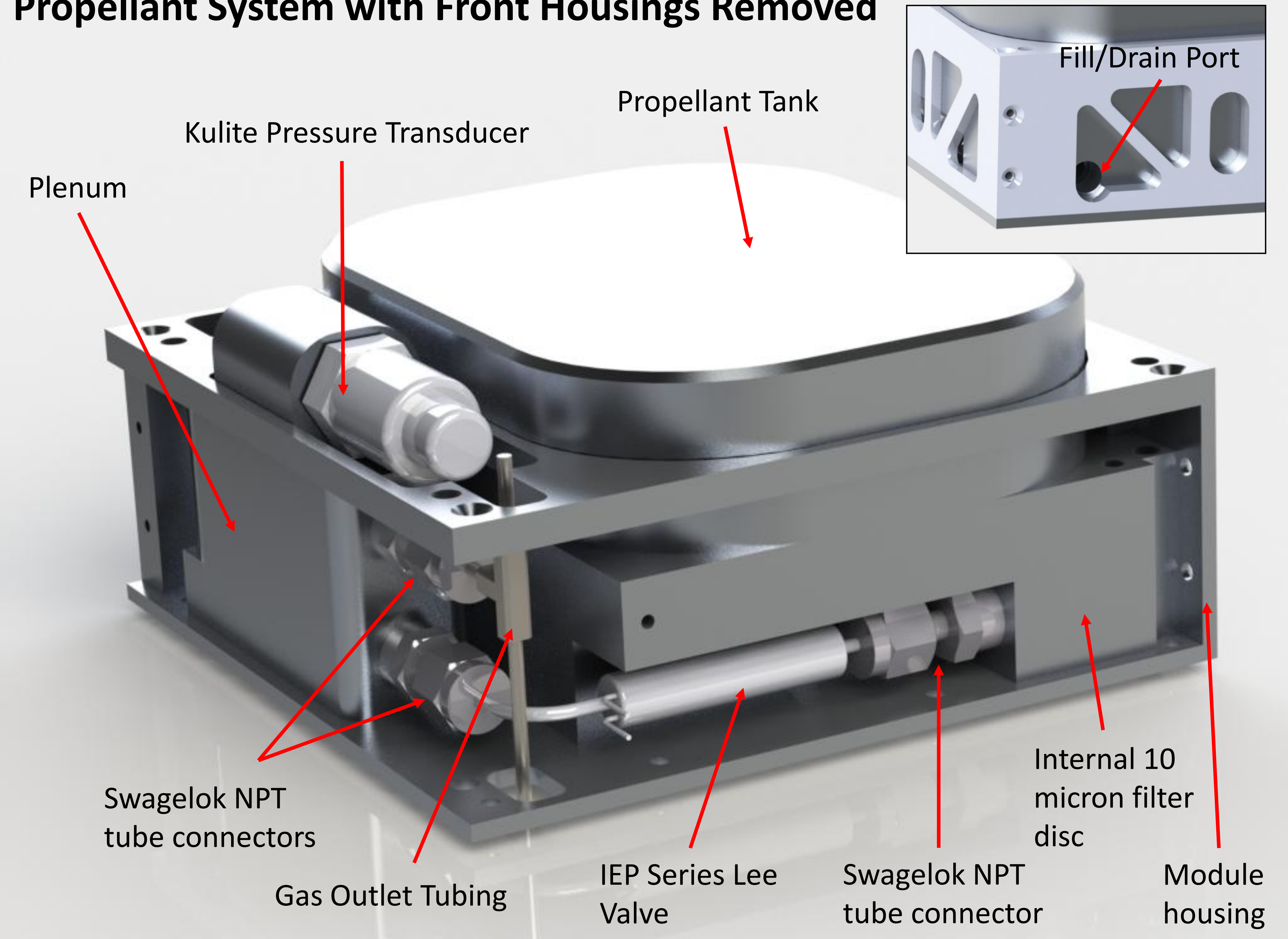


Manufacture

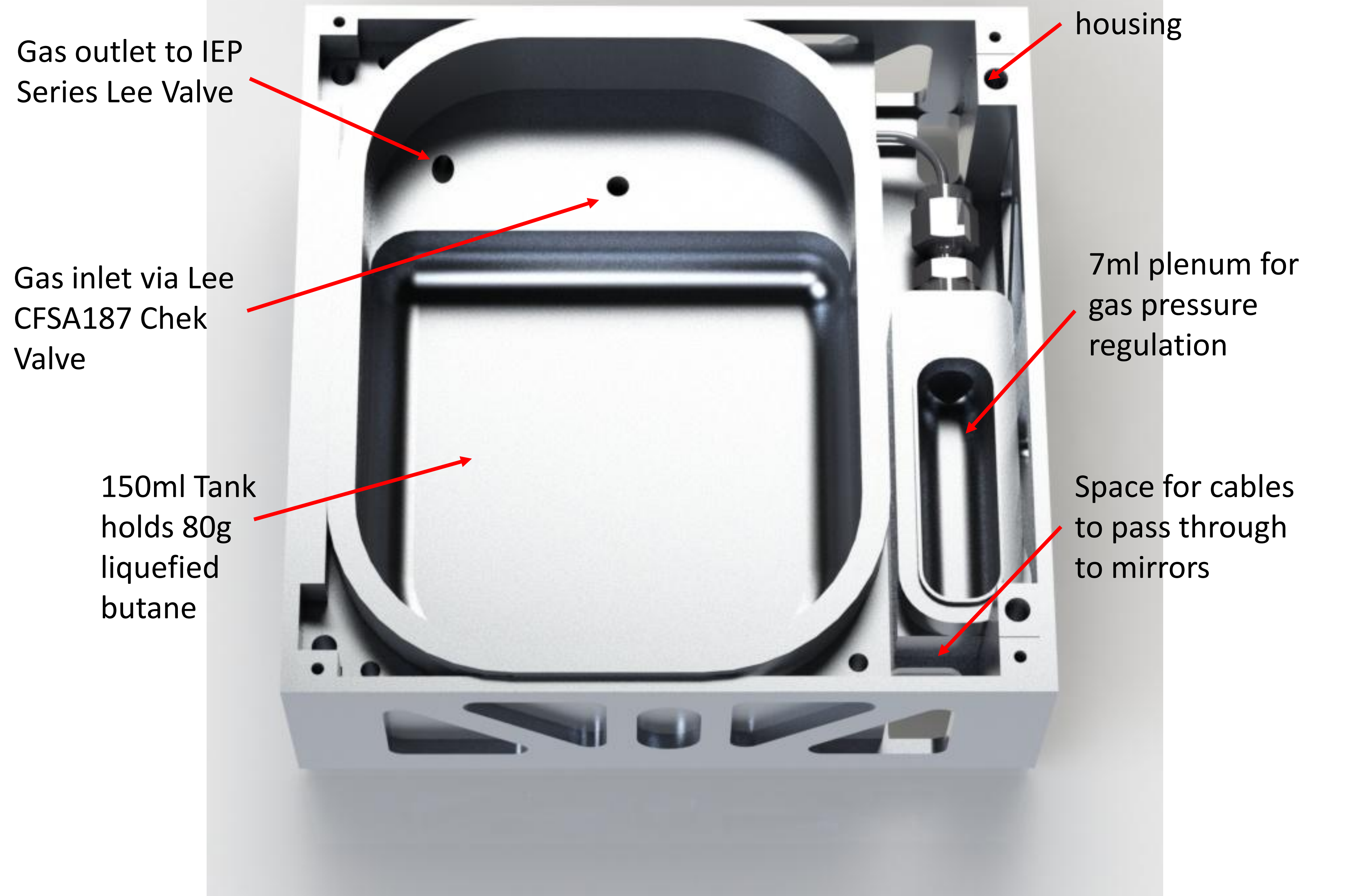
- Traditional machined in two parts and electron-beam welded
- Machined from Aluminium 7075-T6
- Housings machined from Delrin plastic for weight saving
- All components machined in-house for cost saving



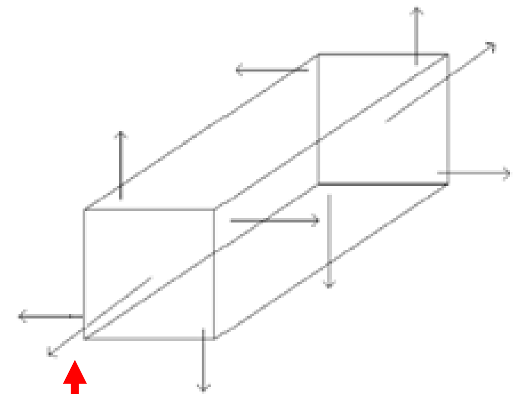
Propellant System with Front Housings Removed



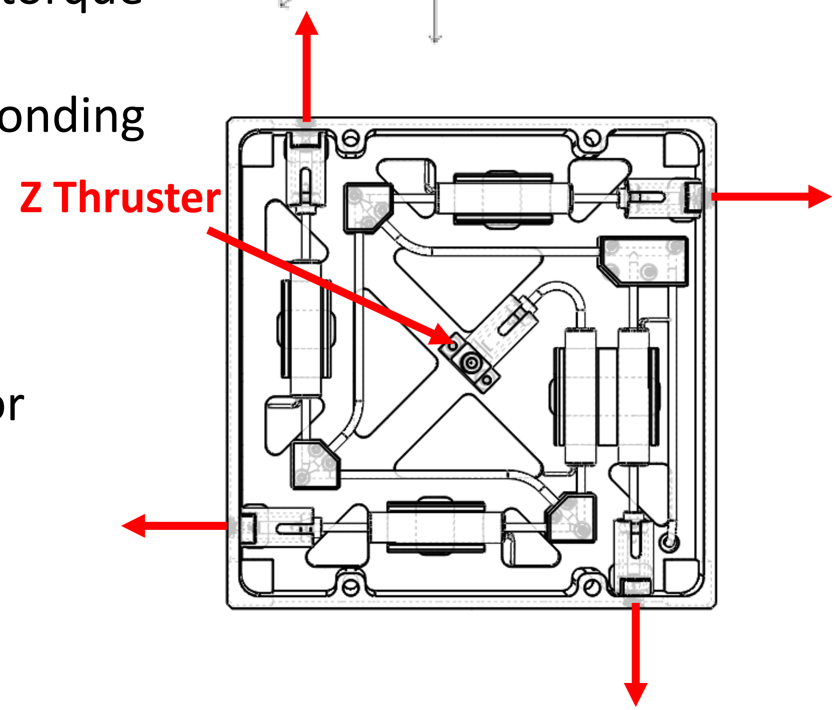
Propellant System with Lids removed

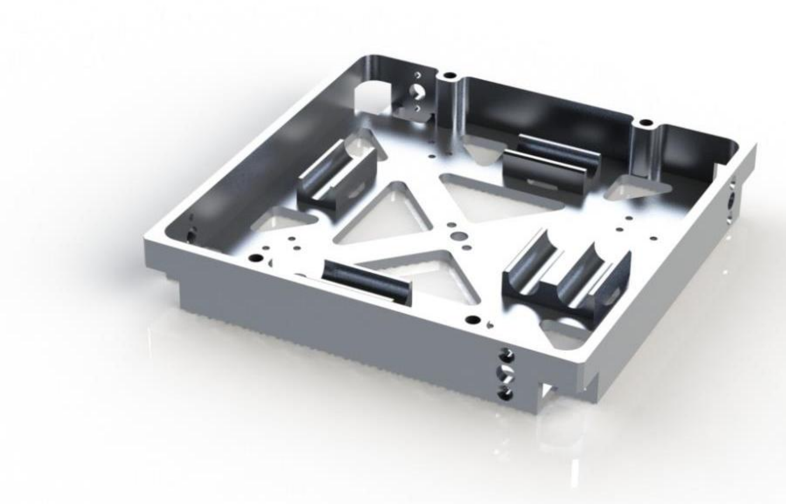


Thruster Mounting Configuration



- 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

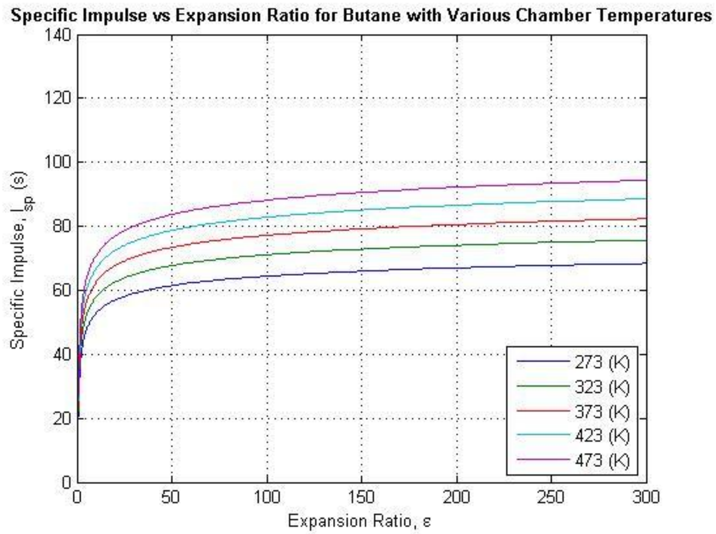


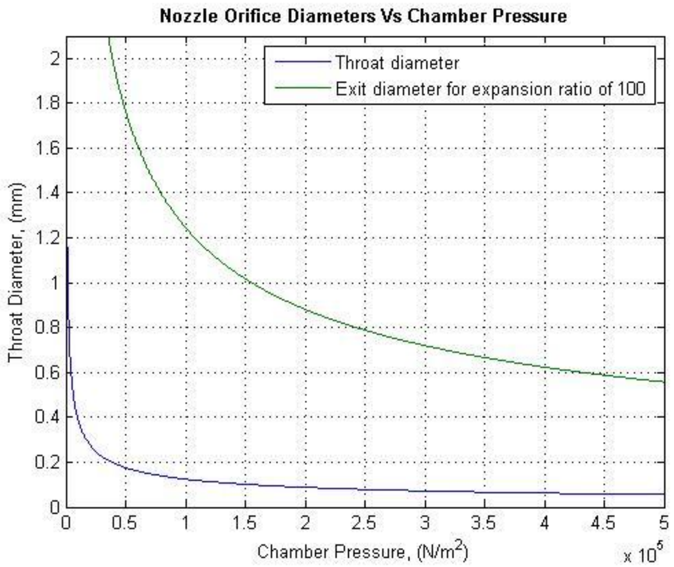


- Thrust trays machined from single piece of stock aluminium for extra rigidity
- Valve mounts built-in to structure

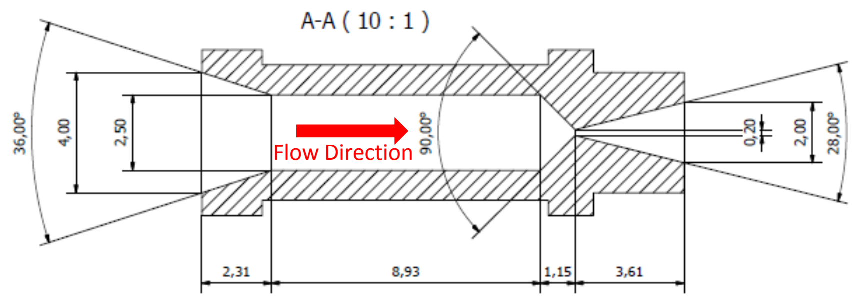
Thrusters

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



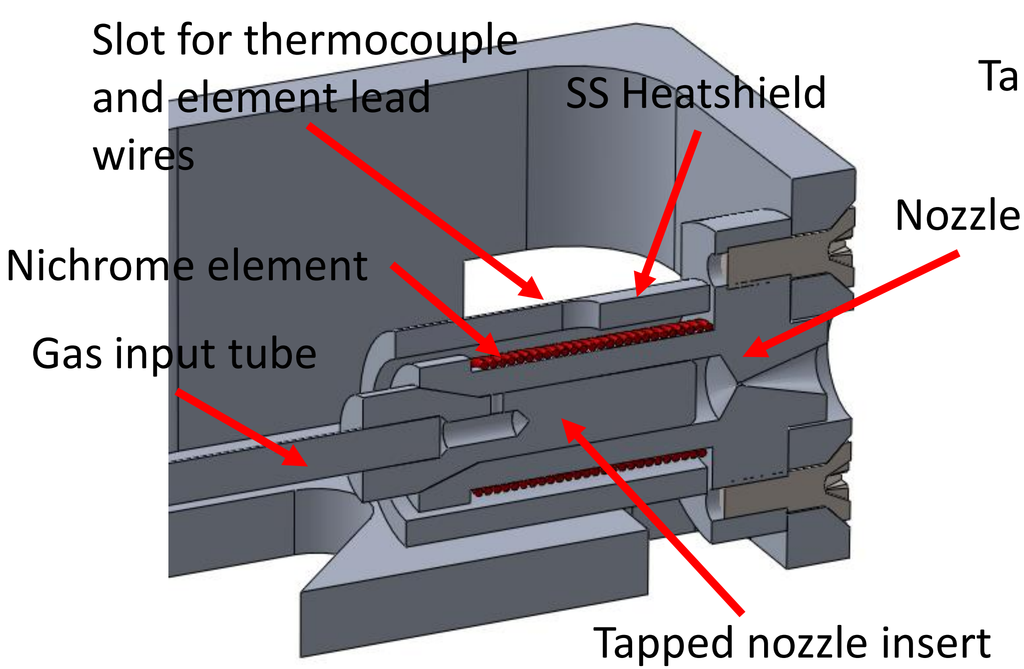


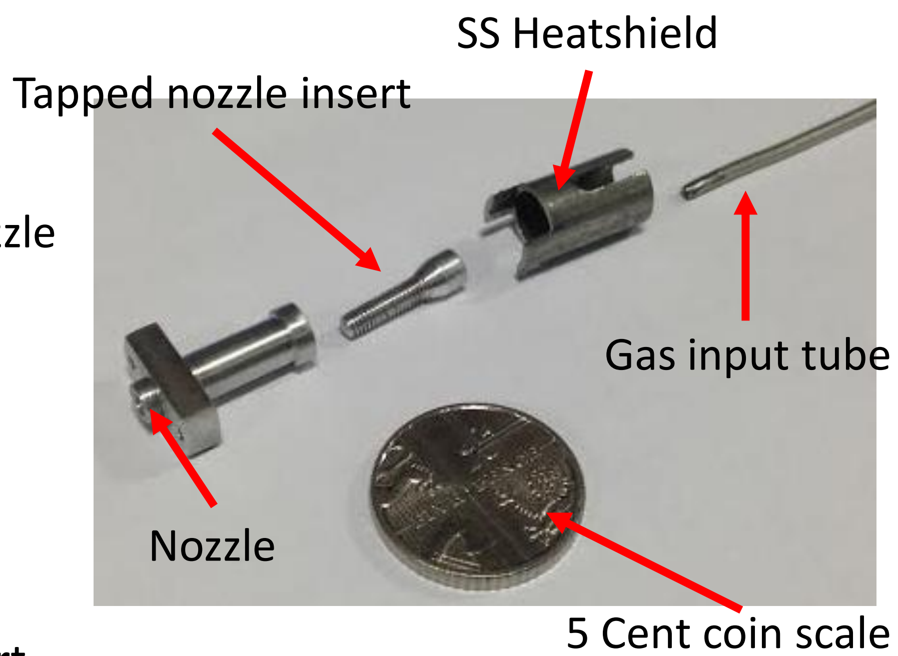
- Isentropic flow relations used to predict optimum throat geometry for nominal plenum pressure of 0.5 bar
- Nozzle throat diameter of 0.2mm and exit diameter of 2mm



Thrusters

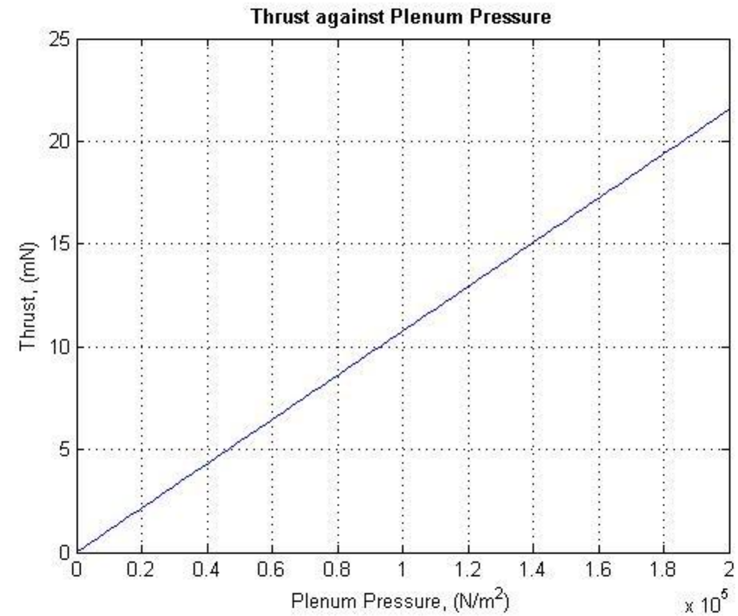
- 0.13mm diameter Teflon insulated nichrome wire used for heater elements
- Heating element bonded to thruster body with Duralco 133 Aluminium based epoxy resin for optimum heat transfer (Thermal conductivity of 5.8 W/m.K and maximum temperature of 316 ^{o}C)
- Stainless Steel heat shield to minimise radiative heat loss
- K-Type wire thermocouple for thruster temperature monitoring (0 – 250 ^{o}C)
- Tapped nozzle insert to deliver gas and provide a long gas flow path around screw for optimum heating





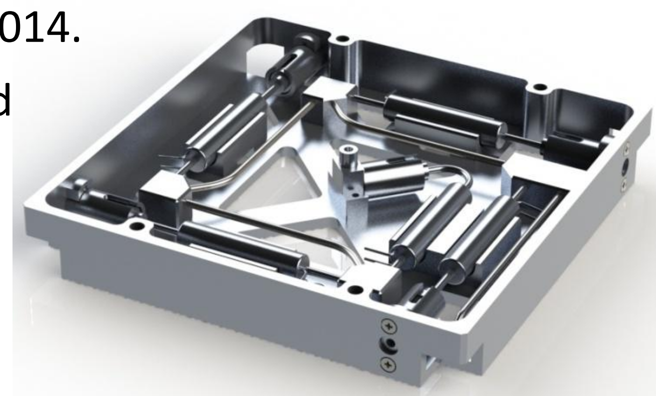
Thrusters

- Input pressure from plenum varied from 0.5-1 Bar according to desired thrust
- Produces a thrust of 5 – 10 mN range at ~80s Isp
- 80g butane propellant provides +10m/s ΔV - 6 m/s for ΔV manoeuvres, 4 m/s for attitude control and contingency



Current Status

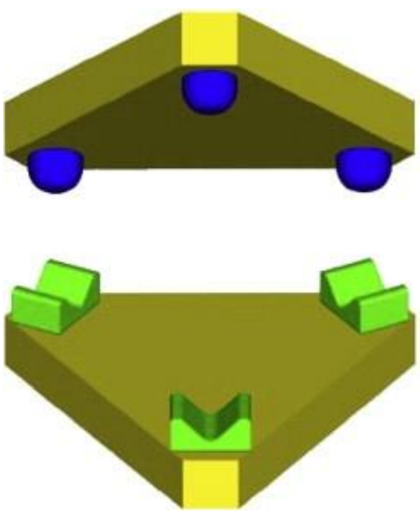
- Single thruster built and tested;
- Plenum Chamber/ Propellant Tank due Mid-September 2014.
- Assembly and test by Q3 2014.
- Next year: design and build electronic controller.
- Demonstrate performance in vacuum chamber



RDV & Docking System

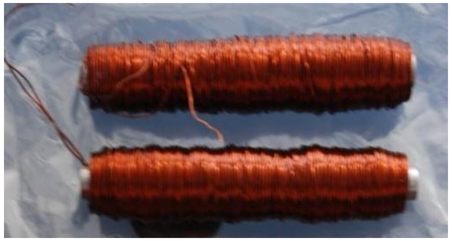
RDV/Docking

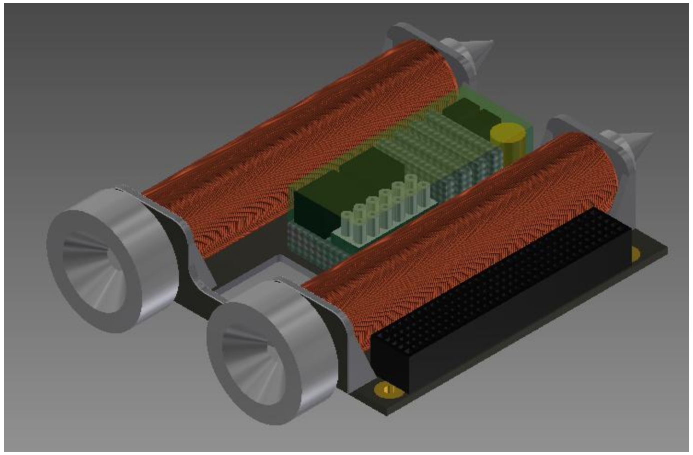
- **MirrorSat EM Docking System**
  - SSC Electro-Magnetic Kelvin Clamp Docking System (EMKCDS)
  - Comprises four PWM controlled, H-bridge-driven, dual polarity electro-magnets, each of over 900 A-turns
  - These are coupled to three “probe and drogue” (60^{o} cone and 45^{o} cup) type mechanical docking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

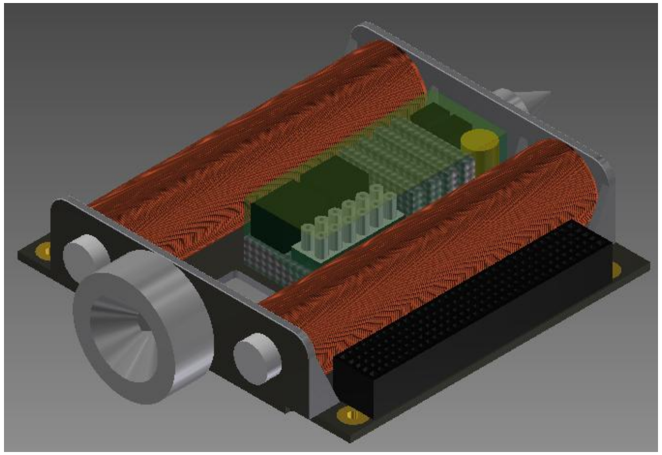


RDV/Docking

- **MirrorSat EM Docking System (PDR Design)**
  - The four Electro-magnets are each implemented with 91m of 24 AWG wire (0.51mm diameter ~84 milliohm per meter).
  - 9 layers of 160 turns (= 1440 turns) is wound on a 100mm long, 10mm dia. Rod of heat-treated Supra50 (ultra-low remanance) Ni-Fe alloy, giving approximately 7.7 ohm impedance at 5V (~650 mA per coil) = 3.25W per coil.
  - Total power for 4 coils is 13W (2.6A at 5V)
  - Mass = 326g total (4 coils) + 220g (ports)
  - FoM = 11.4 ampere-turns per gram.
  - Diameter of wound EM = 20mm.







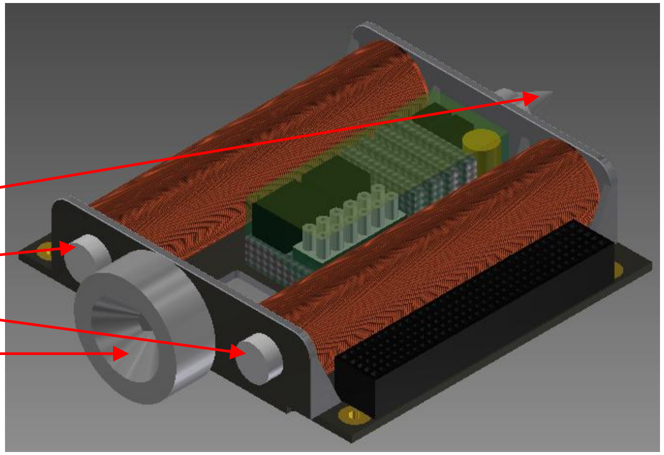
RDV/Docking

- **MirrorSat EM Docking System (PDR Design)**
  - The Central Cone is connected to the 5V, 1A “USB” charger input of the EPS.
  - The Central Cup is connected to a 5V, 1A switched output of the EPS, so that the two MirrorSats could dock together and share power. Both Central Cup and Cone contain a small **permanent magnet** to provide passive magnetic latching.
  - All other cones/cups are at EPS ground potential.
  - The EM extensions either side of the Central Cone and Central Cup extend the magnetic flux output, but remain separated by a 2mm gap upon full capture – this prevents kinematic over-constraint.
  - The Controller Board is connected to the OBC1 I/O and provides the PWM H-Bridge drivers (L293D).

Central Cone (5V, 1A input to EPS)

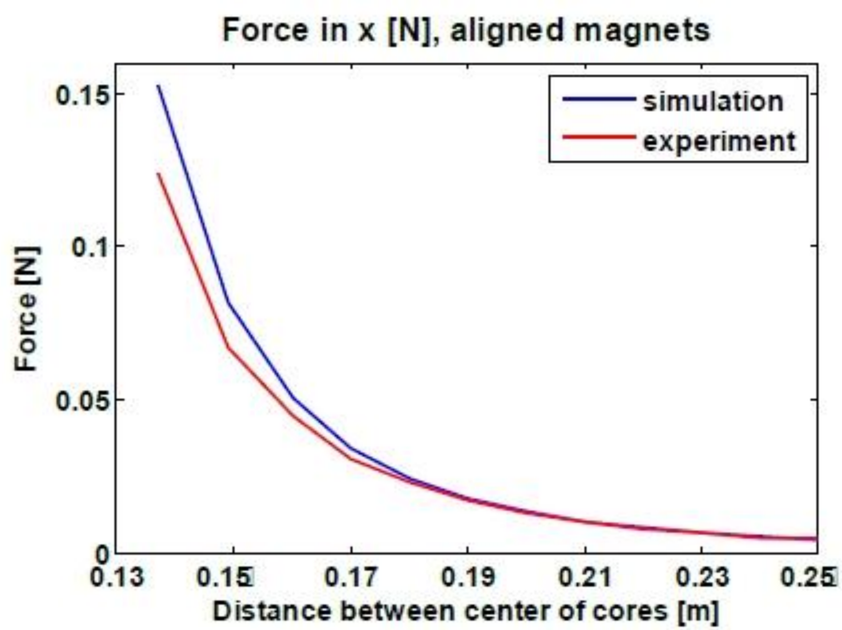
Magnetic Flux Extenders

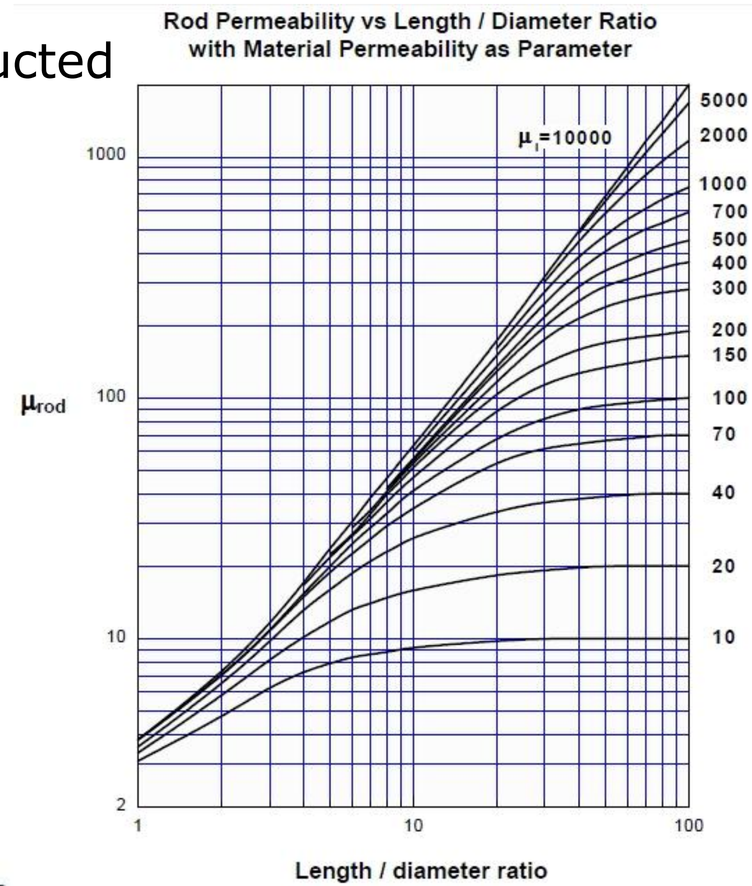
Central Cup (5V, 1A output from EPS)



RDV/Docking

- **EM Docking System (Current Status)**
  - The magnetic core materials were re-evaluated and **pure iron** was selected as a repleacement for the Supra-50 alloy as this has both a better permeability performance and is a less expensive material.
  - A new Magnetic Model was constructed to evaluate the force performance of the docking port. Results were compared with experimentally measured data on a test rig.





RDV/Docking

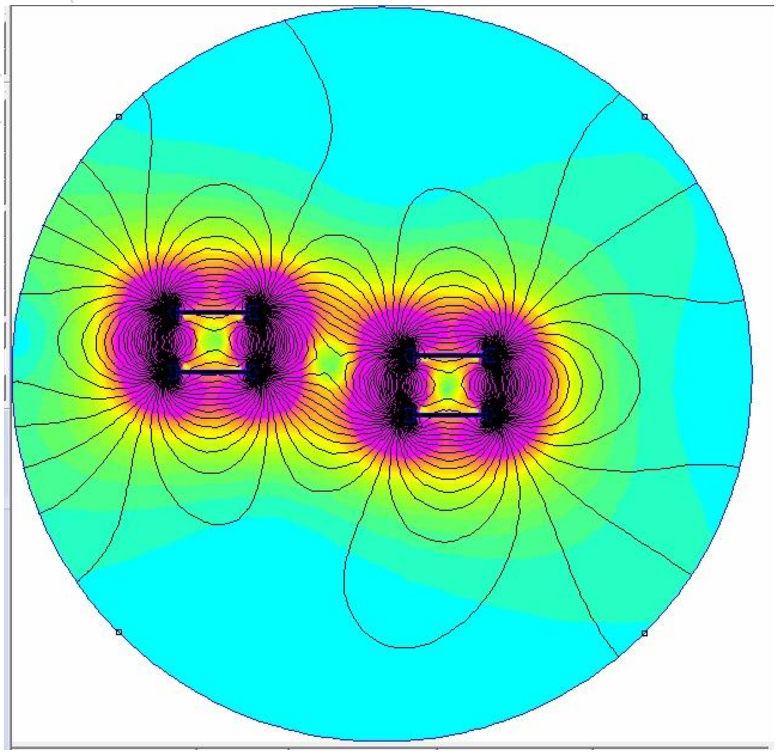
- **EM Docking System (Current Status)**
  - On Axis Force Between Solenoids (Model):
  - (Pure Iron core:10x1cm; 1440 turns; I=650 mA; 4 pairs)

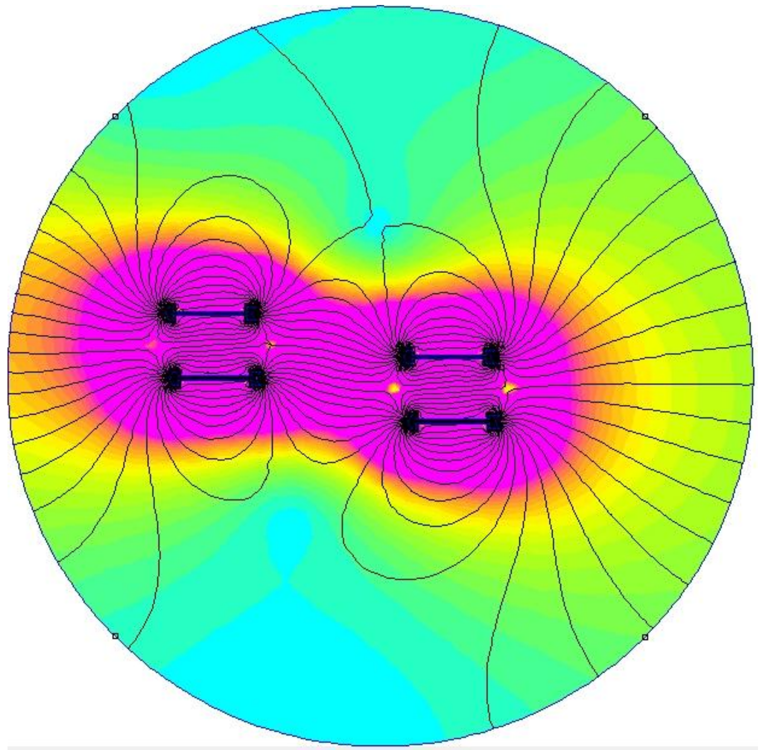
Distance/cm	Force/N	Acc./ms^{-2}	Time to Impact*/s
0.2 (min)	6.07	1.21	< 0.06
0.5	1.62	0.324	< 0.17
1.0	0.564	0.113	< 0.42
2.0	0.181	0.036	< 1.05
5.0	0.036	0.0072	< 3.73
10	0.009	0.0018	< 10.5
15	2.68 mN	0.000536	< 23.7
20	1.140 mN	0.000228	< 41.9
25	0.569 mN	0.000114	< 66.2
30	0.334 mN	0.000067	< 94.6
35	0.207 mN	0.000041	< 131
40	0.135 mN	0.000027	< 172
45	0.097 mN	0.000019	< 218

*Simple $\frac{1}{2}at^2$ linear model as an approximate guide: Assumes 5kg s/c – note: c.f. 5-10mN thruster

RDV/Docking

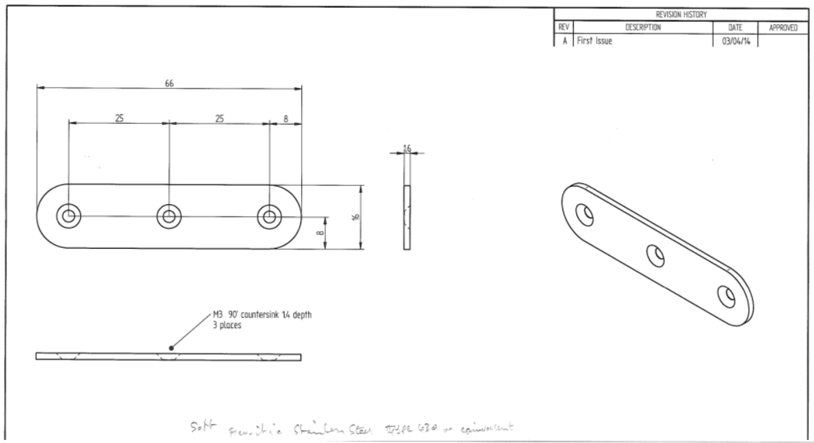
- **EM Docking System (Current Status)**
  - FEM of magnetic flux linking confirmed previous experimental findings:

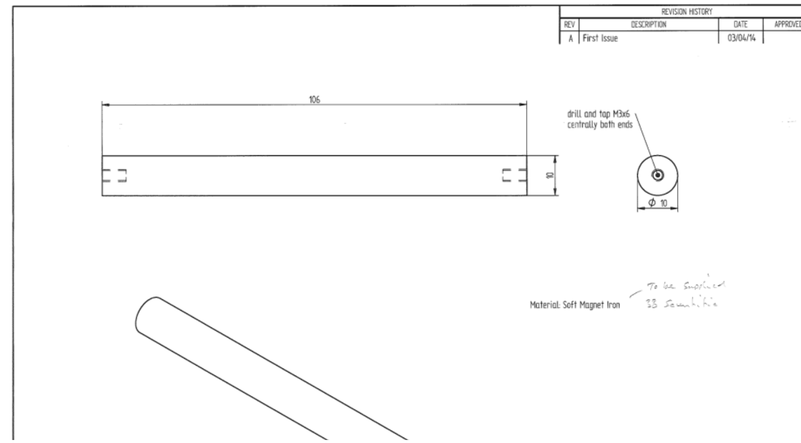


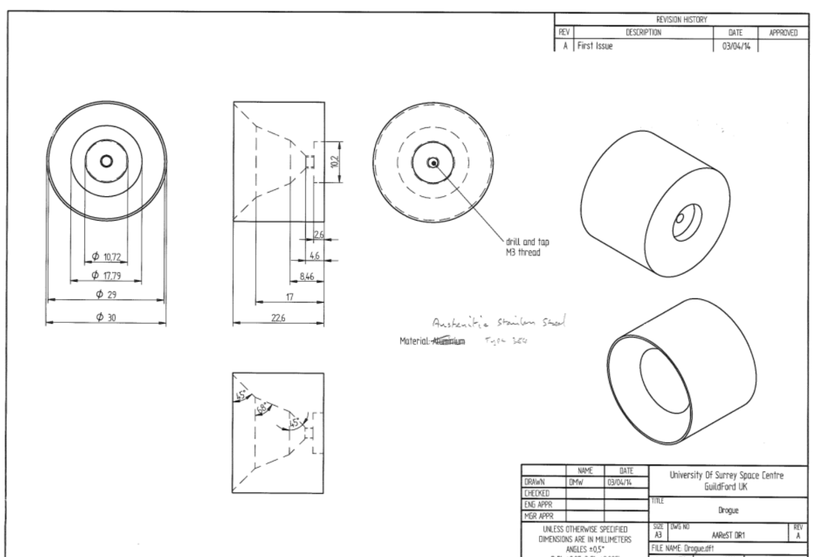


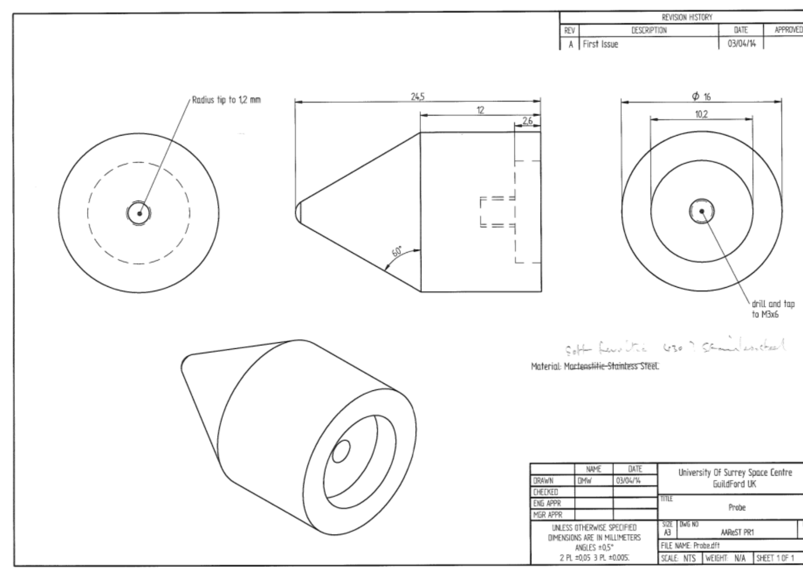
RDV/Docking

- **EM Docking System (Current Status)**
  - New Docking Port hardware designed(with electrical pick-up):



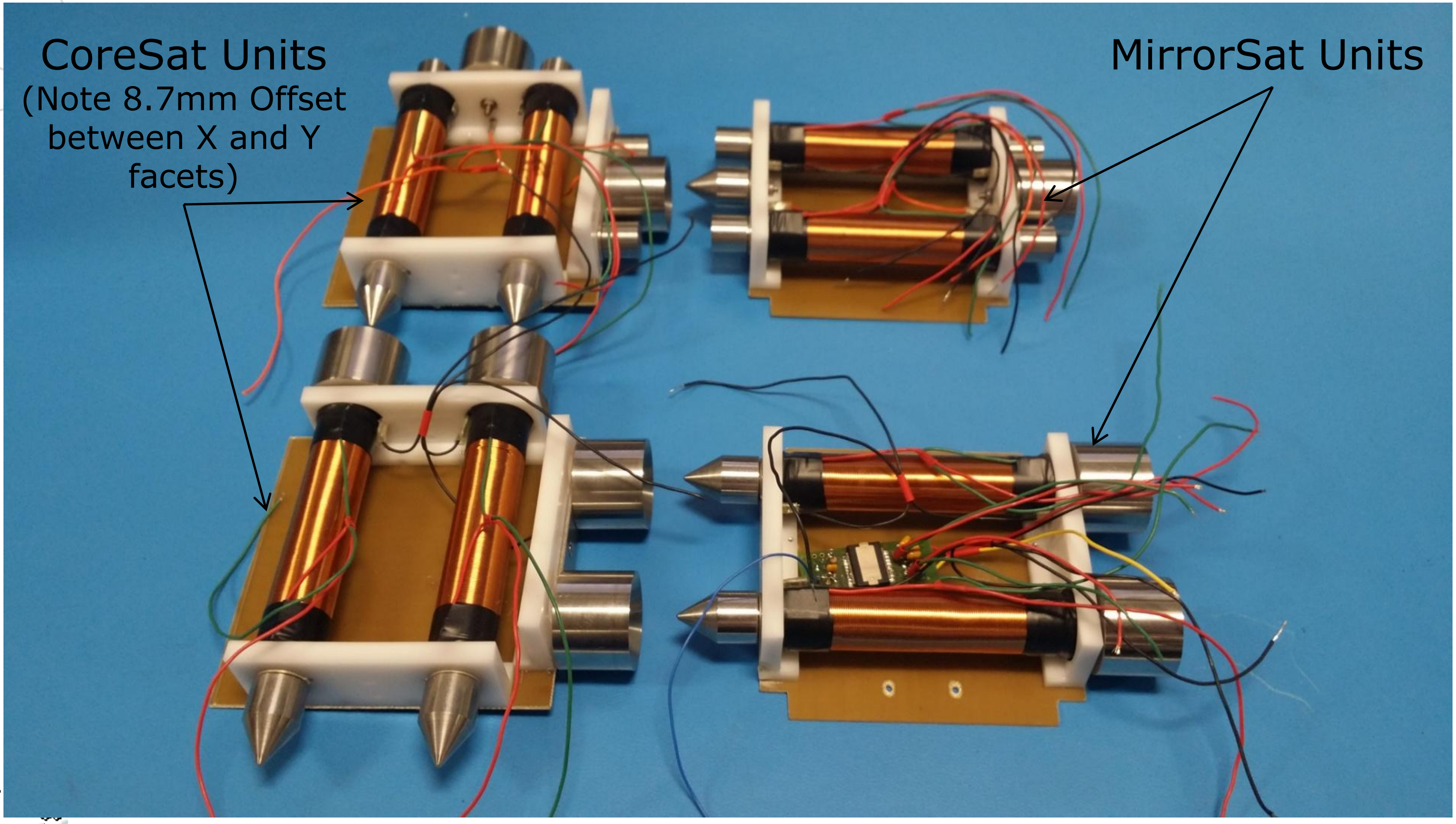






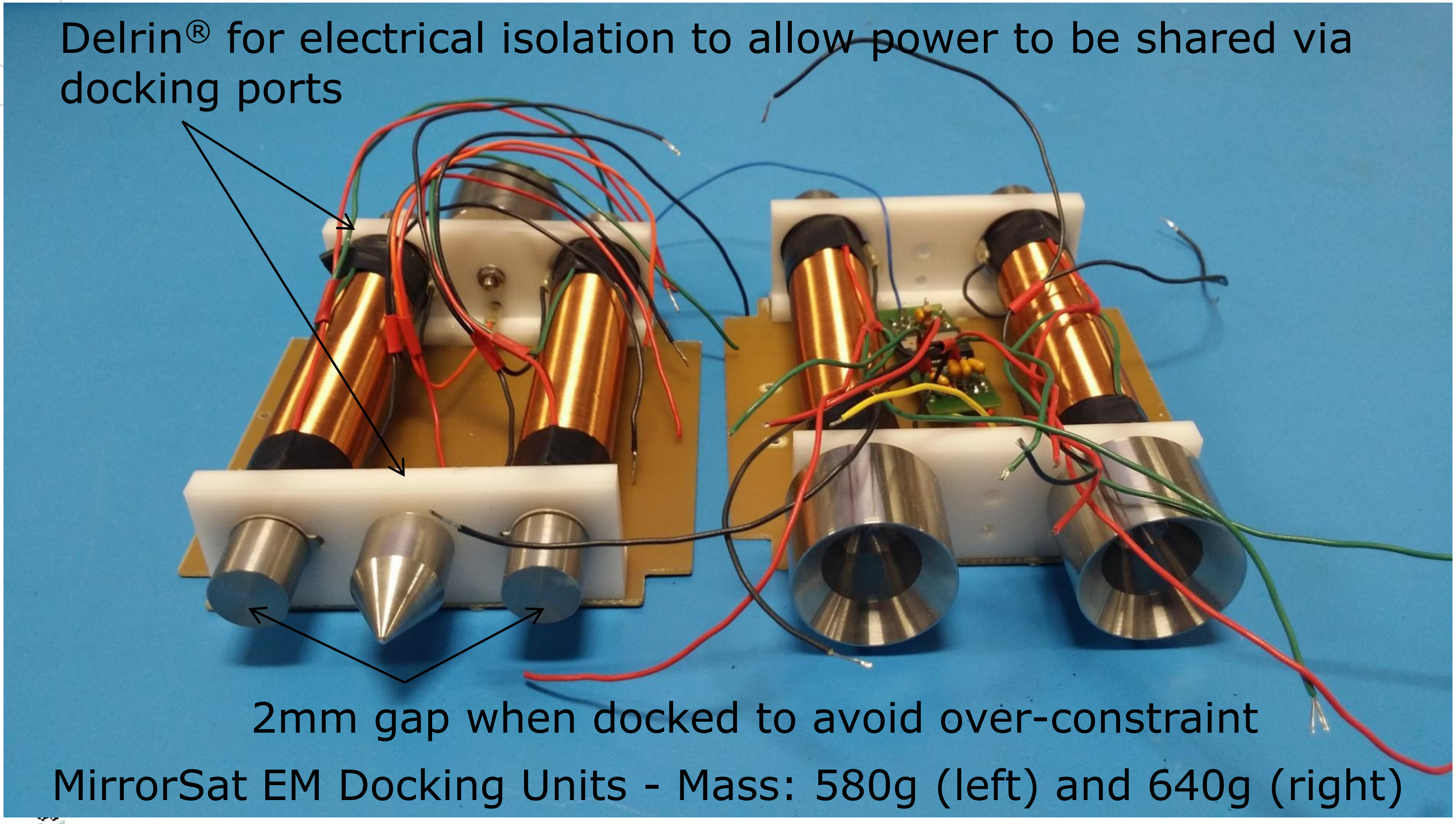
RDV/Docking

- **EM Docking System (Current Status)**
  - New Docking Port hardware designed and built:



RDV/Docking

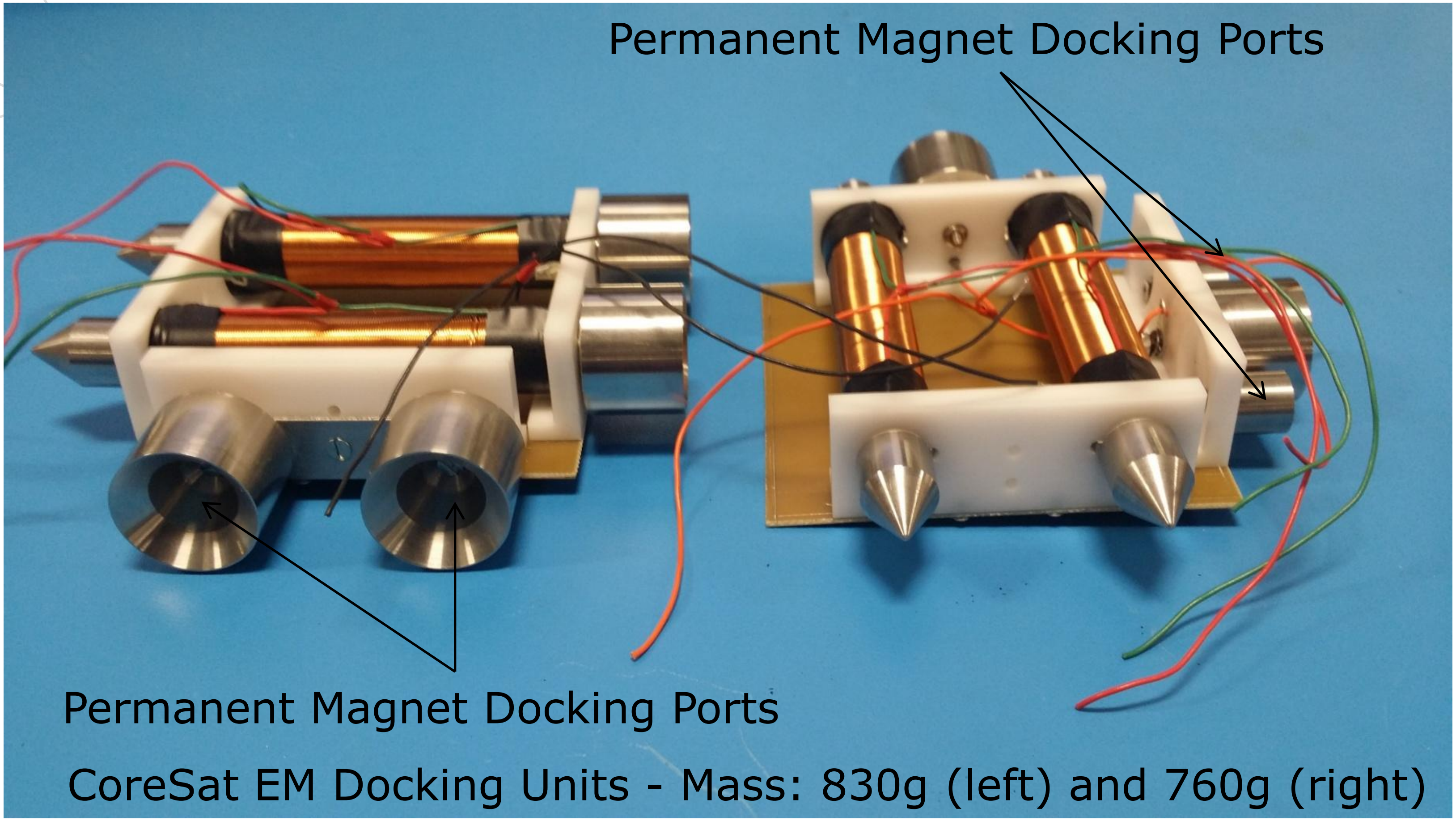
- **MirrorSat EM Docking System (Current Status)**
  - New Docking Port hardware designed and built:



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

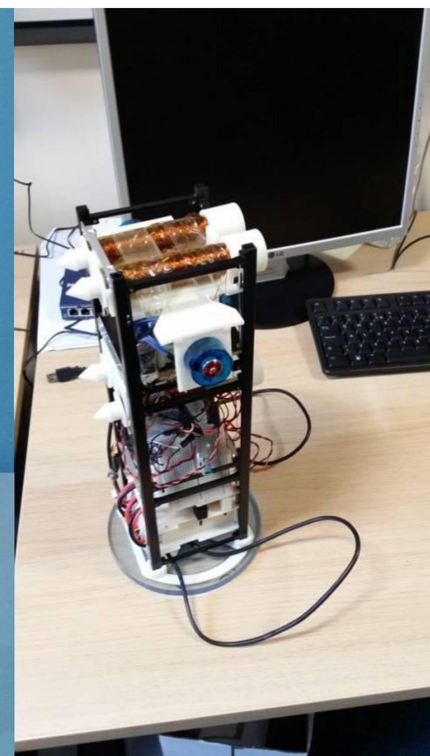
MirrorSat Spacecraft Bus

- **MirrorSat EM Docking System (Current Status)**
  - New Docking Port hardware designed and built:



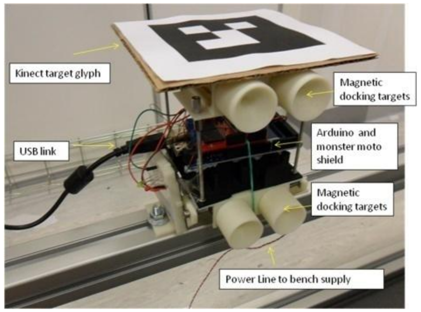
MirrorSat Spacecraft Bus

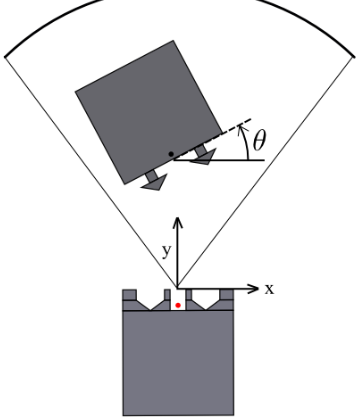
- **MirrorSat EM Docking System (Current Status)**
  - New Docking Port hardware designed and built:
  - Next Steps: Refine Kelvin Clamp V-Grooves;
  - Assemble into S/C structure and test on SSC Air-Bearing Table.
  - EM test results by Q3 2015.



RDV/Docking

- **MirrorSat EM Docking System**
  - CalTech and SSC Air-Bearing Table experiments show:
    - Capture distance is between 20-30cm for two pairs
    - Automatic self-alignment works, but choice of polarities is important to avoid miss-alignment/false-capture.
    - Attractive force is highly non-linear!
  - Capture and alignment experiments show:
    - Within 30 cm offset*, 45 degree cone**
      - Tolerate +/- 30 degree roll/pitch/yaw
      - Reasonable Relative Velocity
    - Within 15 cm offset, 45 degree cone
      - Tolerate +/- 20 degree roll/pitch/yaw
      - Reasonable Relative Velocity
    - Within 5cm offset, 45 degree cone
      - Tolerate +/- 10 degree roll/pitch/yaw
      - Reasonable Relative Velocity
  - **Status:** Prototyped. New form/controller ready by Q3 2015.

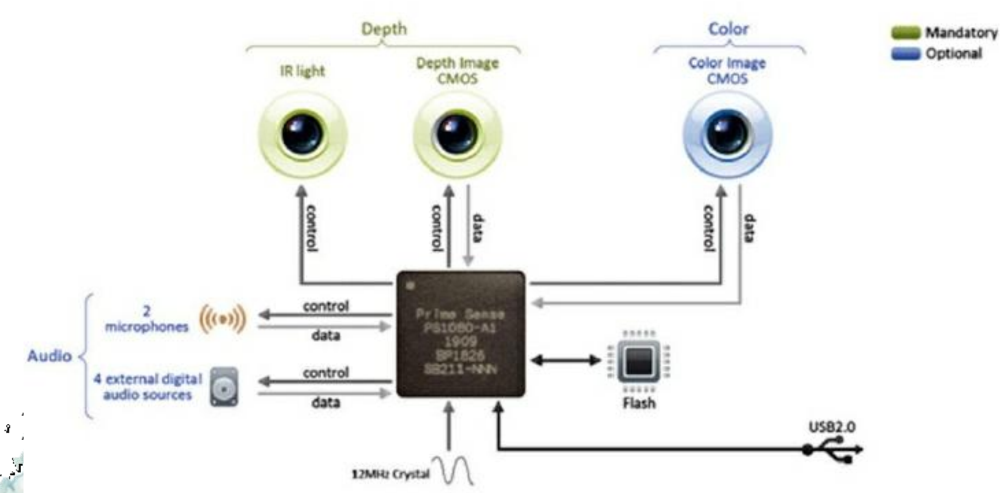


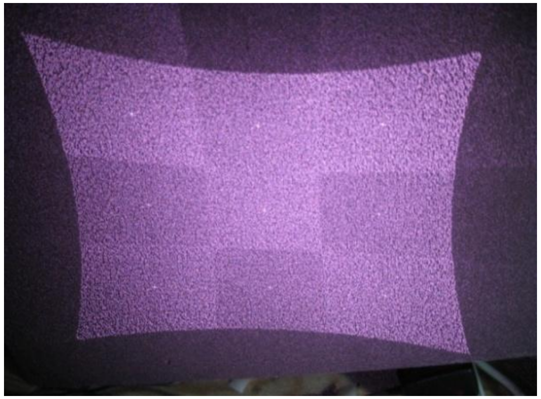


*Radius from centre of one face to centre of 'docking plane'; **Half angle

RDV/Docking

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





LIDAR NIR Projected Speckle Pattern

RDV/Docking

- **Next Phase**
  - SSC PhD student David Williams, should return Q2 next year after a period of temporary withdrawal to complete the the EM Docking System work.
  - SSC Robotics Group (Prof. Yang Gao, Dr Mini Saaj), Embedded Systems Group (Dr Chris Bridges), and Astrodynamics Group (Dr Phil Palmer) will use the STAR Lab Robotics Facilities and SSC Air-Bearing Tables to further develop the RDV/Docking, orbit control algorithms and sensor systems – through MSc Projects.
  - We shall also enlist Marin Kobilarov at JHU to provide further support to this work.
  - **Aim**: by CDR to have prototype system at spacecraft level, which can demonstrate autonomous RDV and Docking in 2D.

CoreSat Spacecraft Bus

CoreSat Spacecraft Bus

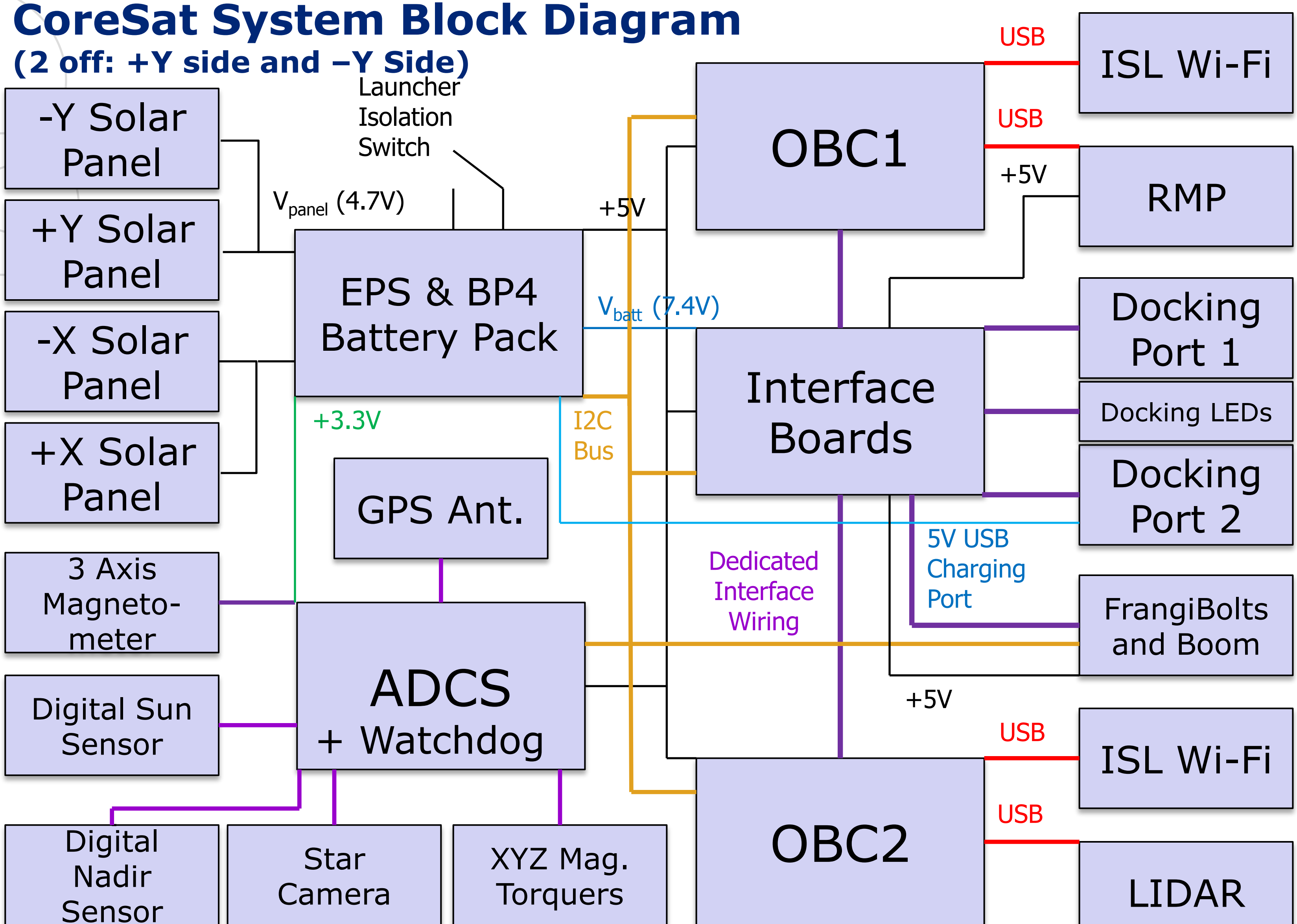
- **CoreSat Requirements**
  - Must be able to point accurately (< 0.1^o 3σ error all axes)
  - Must be stable in attitude (< 0.02^o/s for 600s) during payload operations.
  - Must be able to slew at >3^o/s for RDV manoeuvres.
  - Must be able to mechanically support 2 Reference Mirror Payloads (RMPs) 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)

CoreSat Spacecraft Bus

- **CoreSat Sub-Systems**
  - **RMP Payload** (CalTech supplied – 2 off)
  - **Structure** (modified COTS 3U and two 6U CubeSat – ISIS)
  - **Thermal** (passive thermo-optical controlled)
  - **Power** (self supporting + power out to docked MirrorSats)
  - **ADCS** (High Precision 3-axis control <0.1^{o} error: 3 RW)
  - **GPS Rx**. (for long range ops. >10m)
  - **OBC1 – Comms-Payload** (Raspberry-Pi, Wi-Fi, FMP Support)
  - **ISL Comms./Data** (2.4 GHz Wi-Fi; USB 2.0)
  - **RF Comms.** (VHF U/L at 1200 bps; UHF D/L at 9600 bps)
  - **OBC2 – RDV OBC** (Raspberry Pi – RDV/Docking/PrimeSense)
  - **Docking Sensor** (Softkinetic DS325 LIDAR/Camera for RDV)
  - **Docking Illumination/Optical RDV** (IR LEDs; Nadir Sensor)
  - **EM Docking System**(SSC EMKCDS 20-30cm range; 45^{o} capture cone + passive magnetic docking port)
  - **Launch Retaining Structures** (Frangibolts + docking port)
  - **On-Orbit Retaining Structure** (passive magnet)

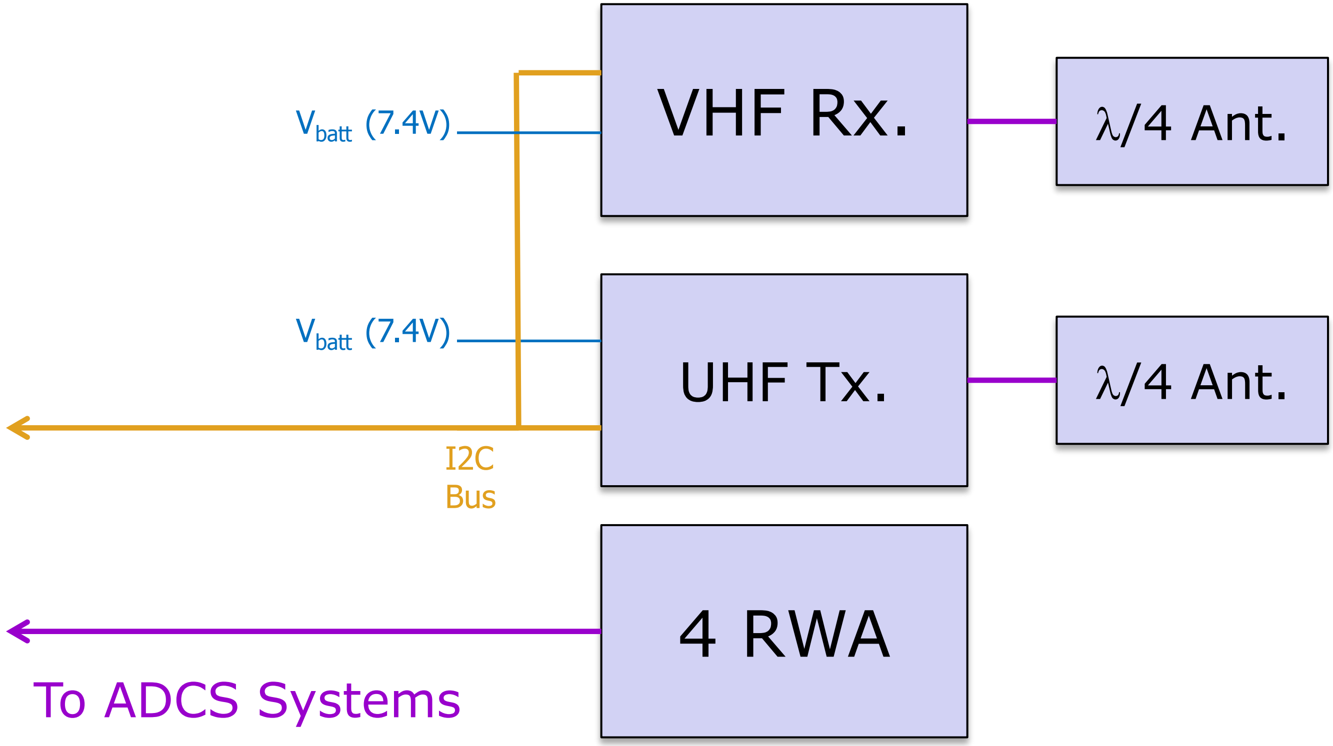
CoreSat Spacecraft Bus

- **CoreSat System Block Diagram**
  (2 off: +Y side and –Y Side)



CoreSat Spacecraft Bus

- **CoreSat System Block Diagram (Central Core)**



Note: There is space to fit a redundant VHF Rx. and UHF Tx. This would provide risk mitigation provided the power budget can support the extra systems.

Note: It may be possible to cross-strap the 4RWA to both ADCS systems.

CoreSat Spacecraft Bus

- ## CoreSat Structure
  - Modified COTS **ISIS 3U** (270g) **+ two 6U** (600g) **CubeSat Structures** mounted on 200mm x 300mm Al honeycomb (TBD), with RUAG Space PAS 175 Launcher Interface (TBD)
  - Structures are modular:

Include with Shipment

- Primary Structure:
  - 2x Side Frames, Black Hard Anodised
  - Ribs, Blank Alodyned
  - 2x Kill Switch Mechanisms
  - Supplied with inserted Phosphor Bronze HeliCoils
  - Fasteners
- Secondary Structure:
  - 6x Aluminium Shear Panels, Blank Alodyned
  - M3 Threaded Rods, M3 Hex Nuts, M3 Bus Spacers
  - Boards are supported using M3 Washers

Performance

Primary structure mass:

- 1U STS: 100 grams	- 4U STS: 345 grams
- 2U STS: 190 grams	- 5U STS: 420 grams
- 3U STS: 270 grams	- 6U STS: 600 grams

Secondary structure mass per 1-Unit Stack: 100 grams

(Aluminum shear panels & PCB stacking elements)

Inside Envelope (1U)(l x w x h): 98.4 x 98.4 x 98.4 mm

Outside Envelope (1U)(l x w x h): 100 x 100 x 113.5 mm

Qualification

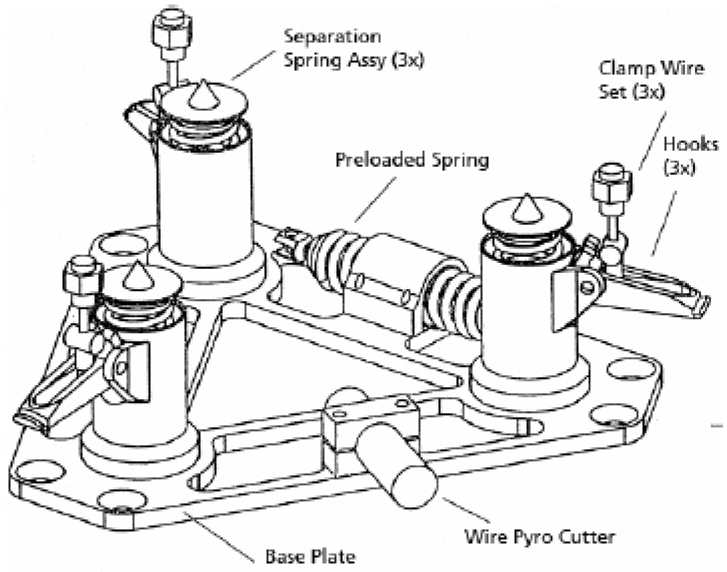
Design Qualification Loads:

- Static +21.6 [g], three axes
- Sine Vibration 4.0 [g], 5 – 100 [Hz]
- Random Vibration 14.1 [grms], NASA GEVS

Thermal Range (min – max): -50 to 90 °C

CoreSat Spacecraft Bus

- **CoreSat Launcher Interface**
  - RUAG Space PAS 175 Launcher Interface (low shock - < 200g)



PAS 175 and PAS 400 Key Data

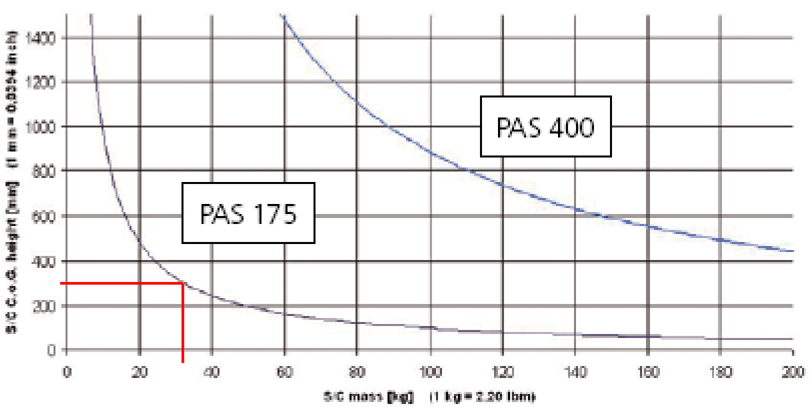
PAS 175

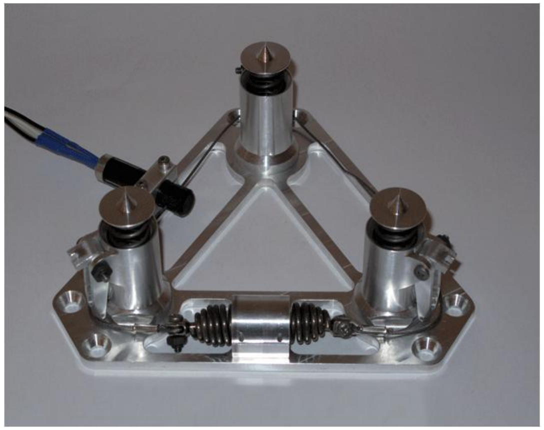
S/C interface: 3 points / 175 mm diameter
Total height: 40 mm
Base plate dimension: 184 mm x 162 mm
Total mass: 0.35 kg
Total separation energy: 0.86 Nm

PAS 400

S/C interface: 3 points / 400 mm diameter
Total height: 40 mm
Base plate dimension: 416 mm x 370 mm
Total mass: 1.0 kg
Total separation energy: 0.86 Nm

PAS 175 & PAS 400 Load Capability





CoreSat Spacecraft Bus

- **CoreSat Launcher Interface (Update)**
  - Alternately: Dassault MicroSat Launcher Interface (SSTL standard) – (TBD on cost/launch availability).

Mechanical :
Mass : 3 kg + 4 to 10 springs (120 gr. each)
Ejected mass with the microsatellite : 1 kg
Bulk : height = 91 mm, diameter = 348 mm
Hollow : internal diameter 250 mm
Interface : 12 screws on the launch vehicle and the satellite

Electrical :
Detonator initiation : D.C. current 5 A, 10 ms at least
Detonator's category : 1 A, 1 W, 5 minutes
Resistant to static electricity, and to lightning

Environmental constraints :
Functioning range : -90° C to + 100° C
Resistant to sinusoidal and random vibrations, to humidity, to vacuum

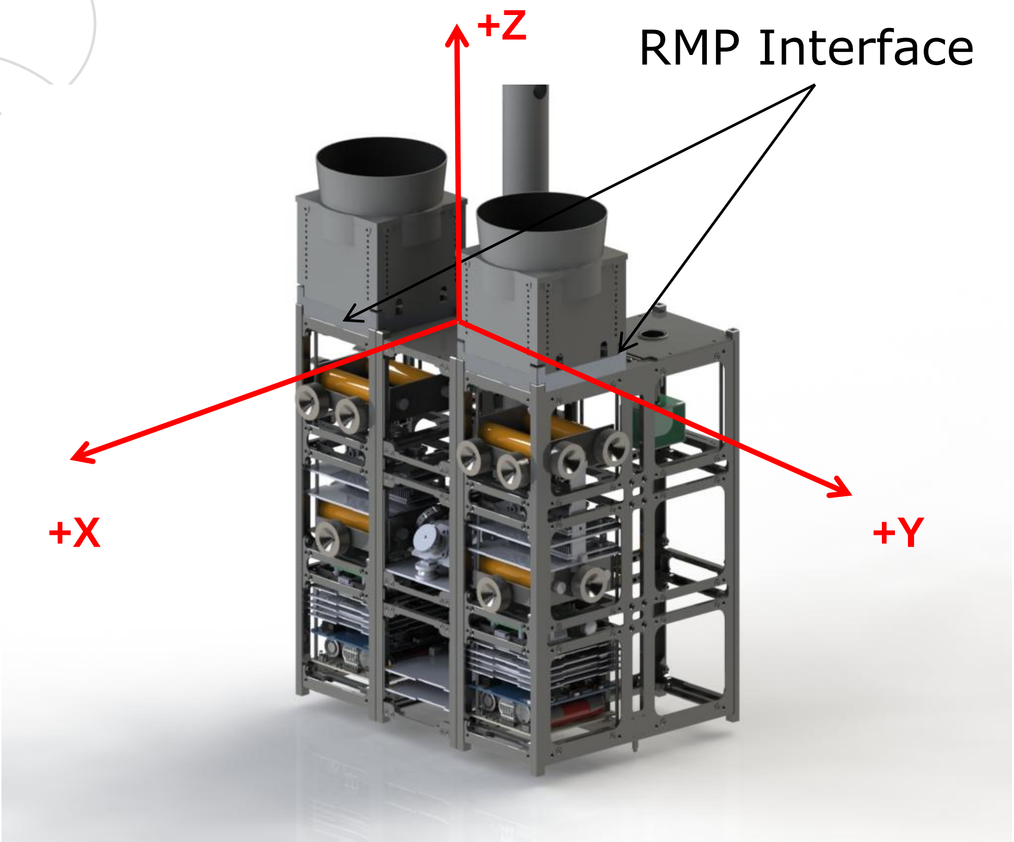
Functional :
Microsatellite mass : 100 kg
Moving speed : ~ 1 to 3 m/s (depending on the mass)
Redundancy of pyrotechnic initiation
Reliability ? 0.99995
No debris ejection, no venting

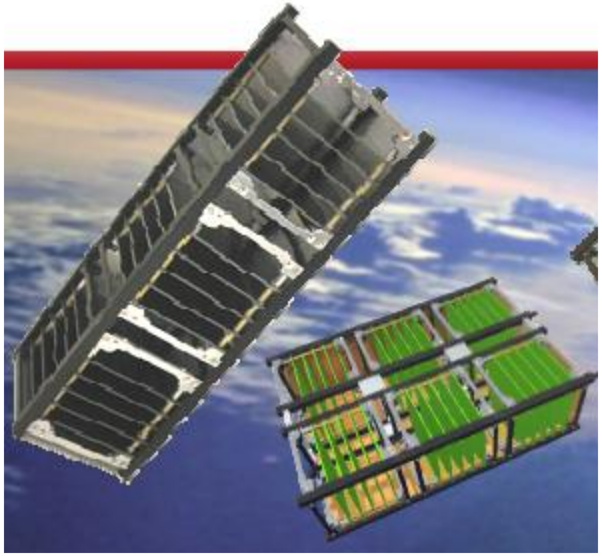
Tightness :
< 1.10^{-3} atm.cm.s^{-1}

Life duration :
7 years

CoreSat Spacecraft Bus

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



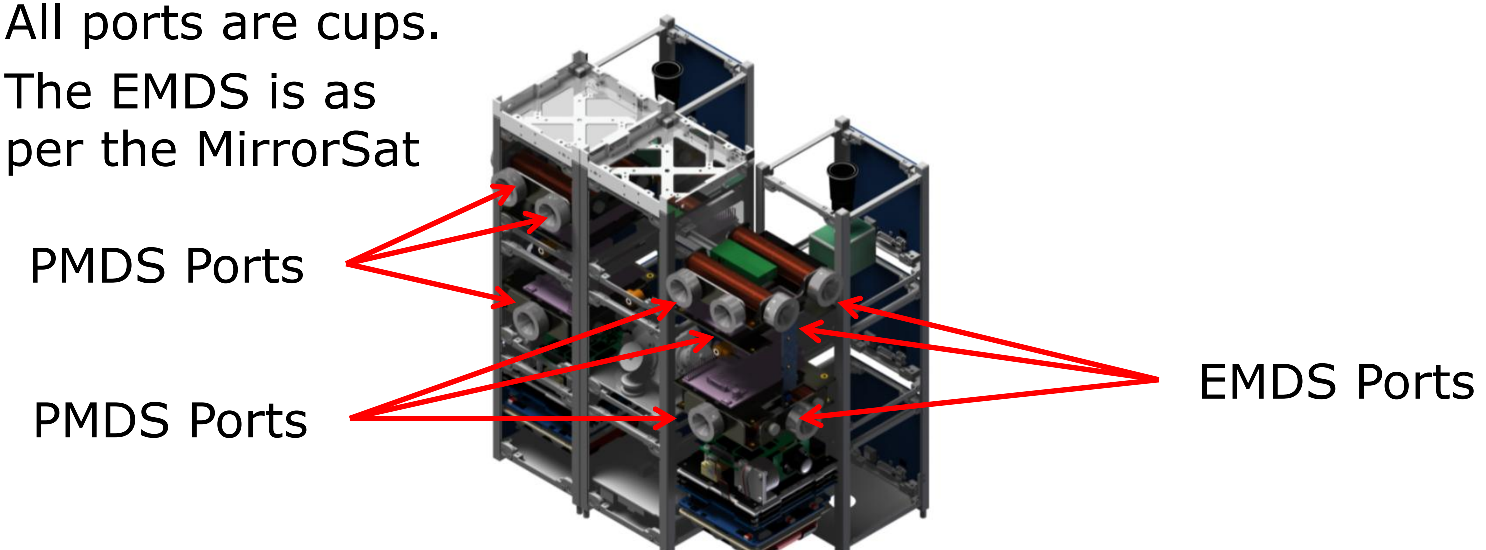


CoreSat Spacecraft Bus

- **CoreSat Structure**
  - The (two) Reference Mirror Payloads (RMPs)fix to the dummy "propulsion" units on the +Z facet.
  - The RMP electrical interface (each): USB with switchable 5V (1A limit)
  - The Boom fixes to the lower 2U of the 3U central module, between the two 6U structures.
  - The Boom electrical interface: I2C with switchable 5V (1A limit)

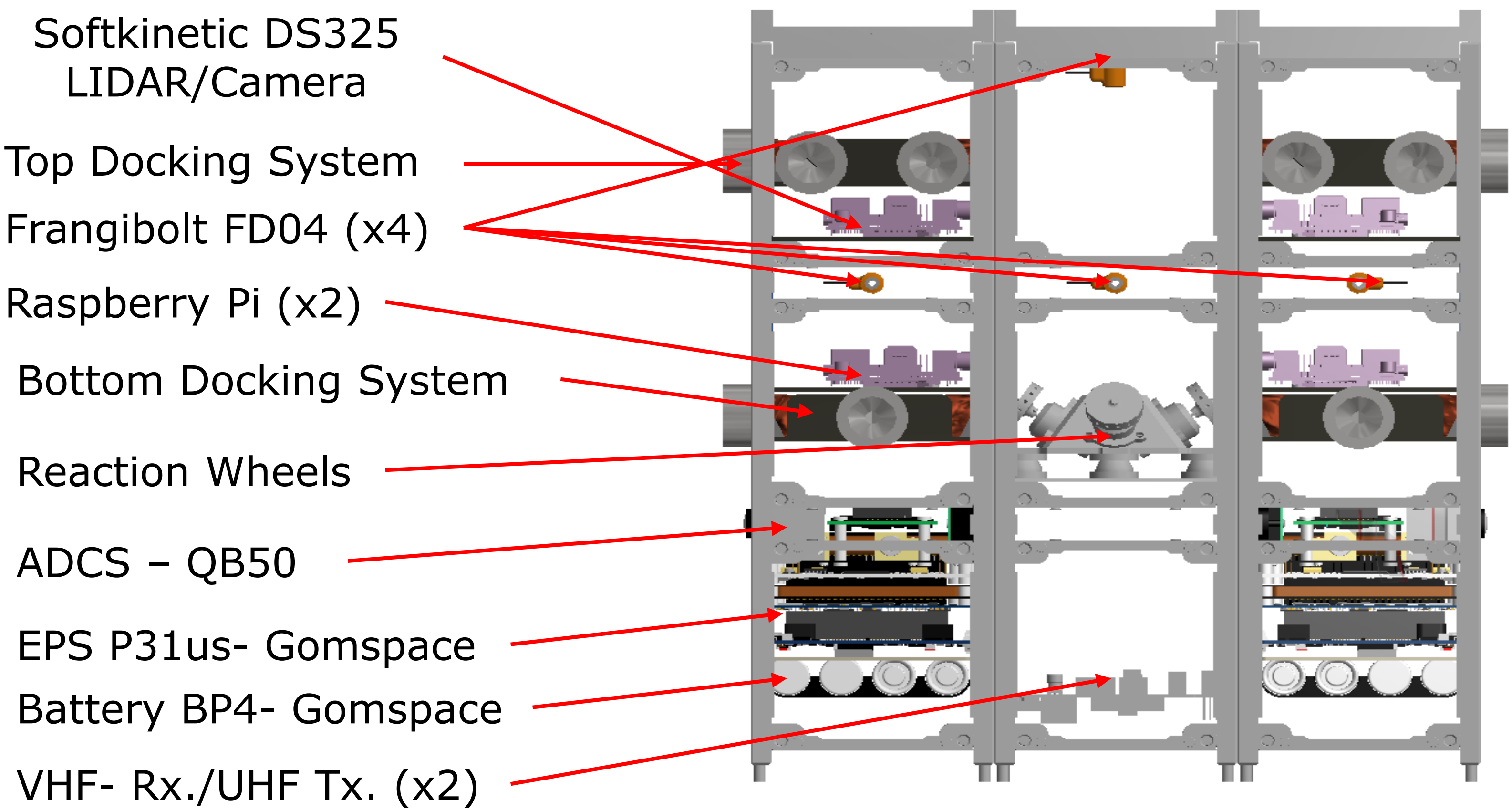
CoreSat Spacecraft Bus

- **CoreSat Structure**
  - The **Passive Magnetic Docking System** (PMDS) ports on the +X facet are at the same height as the active EMKCDS ports on the MirrorSats, so that when docked in the **Compact Mode** (i.e. as launched), the DMP and FMP payloads sit at the <u>same</u> height.
  - The **Electro-Magnetic Docking System** (EMDS) ports on the +Y and –Y facets of the CoreSat are **8.7mm** higher up the structure, so that, when docked in the **Wide Mode**, the DMPs are 8.7mm higher than the FMPs.
  - All ports are cups.
  - The EMDS is as per the MirrorSat



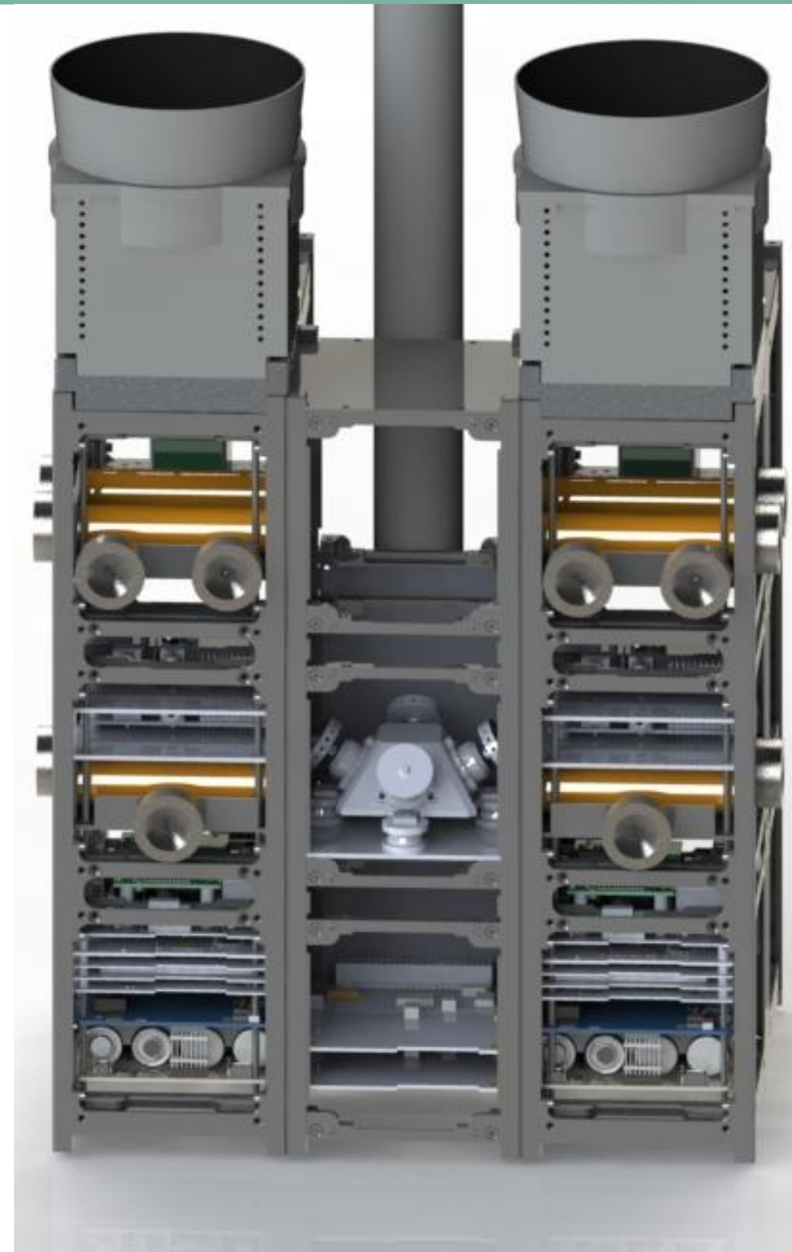
CoreSat Spacecraft Bus

- **CoreSat Structure**
  - System Layout (+X facet view)
  - Note: side facet (+Y, -Y) EMDS Ports are 8.7mm higher than shown
  - Fangibolts hold down the two MirrorSats and the Camera.



CoreSat Spacecraft Bus

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

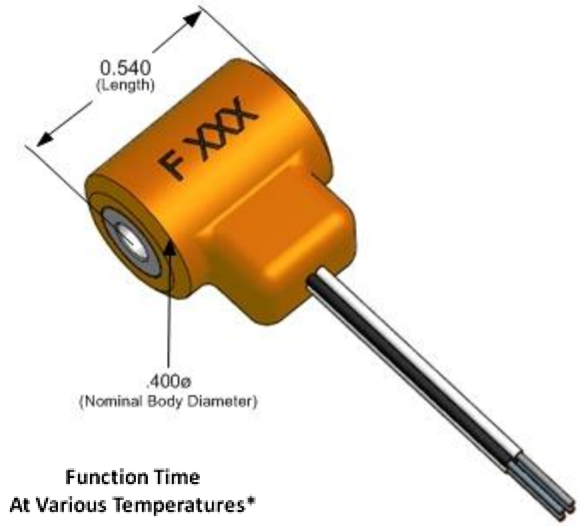


CoreSat Spacecraft Bus

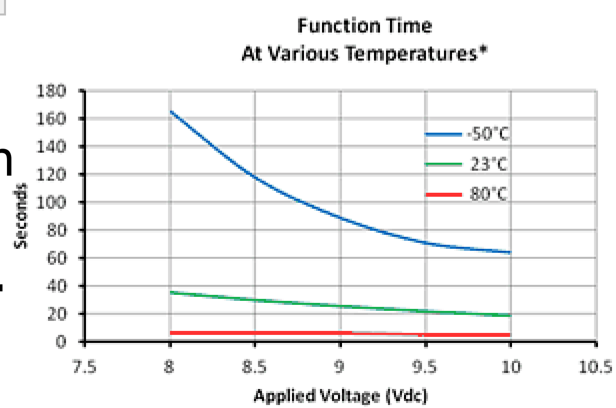
- **CoreSat Hold-Downs**
  - Four TiNi Aerospace FD04 Frangibolts
  - 1 Holds the Camera, 1 the Mirror Covers, 2 others hold the MirrorSats. (Note: dimensions in inches)

Mass:	0.25 oz (7 g)
Power:	15 W @ 9 VDC
Operational Voltage:	9 ± 1 VDC
Current Draw:	1.6 A @ 9 VDC
Resistance:	5.5 ± 0.5 Ω
Bolt Tensile Strength:	Typical 500 lbf (2,224 N)
Max Load Support and Release:	150 lbf (667 N)
Function Time:	Typical 20 sec. @ 9 VDC
Reusable:	By Re-Compressing Actuator
Life:	50 Cycles MIN
Operational:	-50° C to +80° C

*Specification subject to revision; Please contact TiNi Aerospace for detailed drawing (ICD).



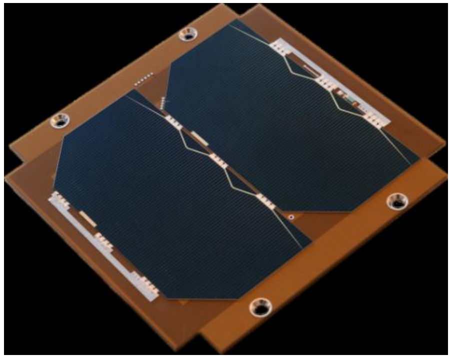
  - The Boom will be held by a burn wire similar to that used to deploy the STRaND-1 antennas.

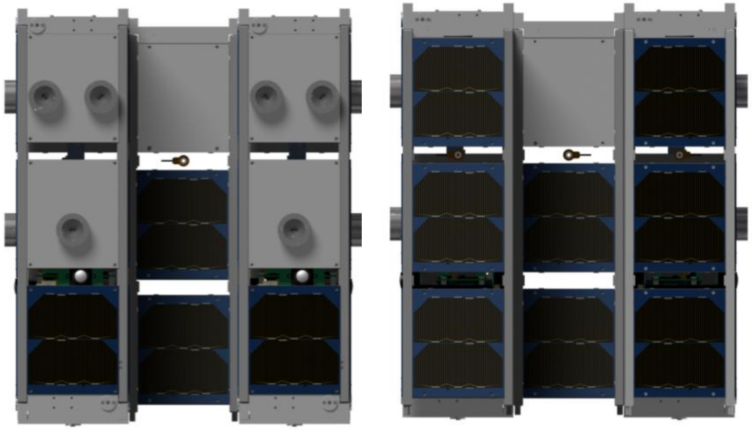


*Nominal values for estimation purposes only. Actual function time depends on application (joint) design and circuit used (primary or secondary).

CoreSat Spacecraft Bus

- **CoreSat 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 PCB; 1.1mm thick; blocking diode, Sun Sensor and Temperature Sensor included on each PCB.
  - **+X facet** (PMDS side) has **4 PCBs** wired in series pairs – generating 500mA at 9.4V each (**9.4W**) max. when MirrorSats and Camera are deployed. 1 pair goes to the +Y EPS (4.7W), the other to the –Y EPS (4.7W).
  - **-X facet** has **8 PCBs**: 2x 2s2p = 1000mA at 9.4V (9.4W) to each EPS = 18.8W max.
  - **Deploying** <u>two</u> panels double-sided panels 45º from the –X/-Y & -X/+Y corners would add ~10W without interfering with the RDV.

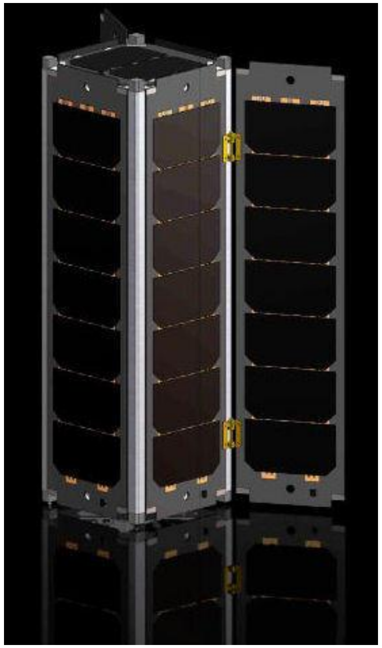




CoreSat Spacecraft Bus

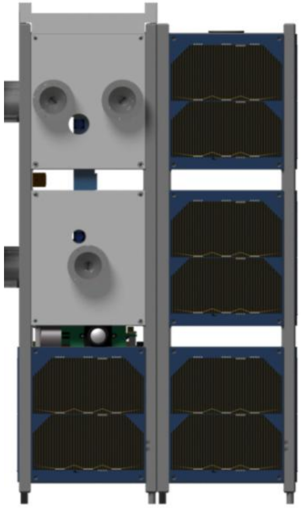
- **CoreSat Solar Panels**
  - **Deploying** two panels double-sided panels 135º from the –Y and +Y panels at the –X/-Y & -X/+Y corners would add ~10W without interfering with the RDV.
  - **Clydespace** have developed such a panel with integral hold-down and burn wire for CubeSat, which will be demonstrated on **UKube-1**.
  - Next Step - detailed power/operational scenario simulations for chosen orbits. Results Q3 2015

Parameter	**Units**	**3U Side Panel**
BOL Voc at -40°C	(V)	21.46
BOL Vmpp at -40°C	(V)	19.54
BOL Vmpp at 80°C	(V)	14.08
BOL Vmpp at 28°C	(V)	16.45
BOL Power at -40°C	(W)	8.63
BOL Power at 80°C	(W)	6.26
BOL Power at 28°C	(W)	7.29
Mass 1.6mm PCB no MTQ	(g)	135



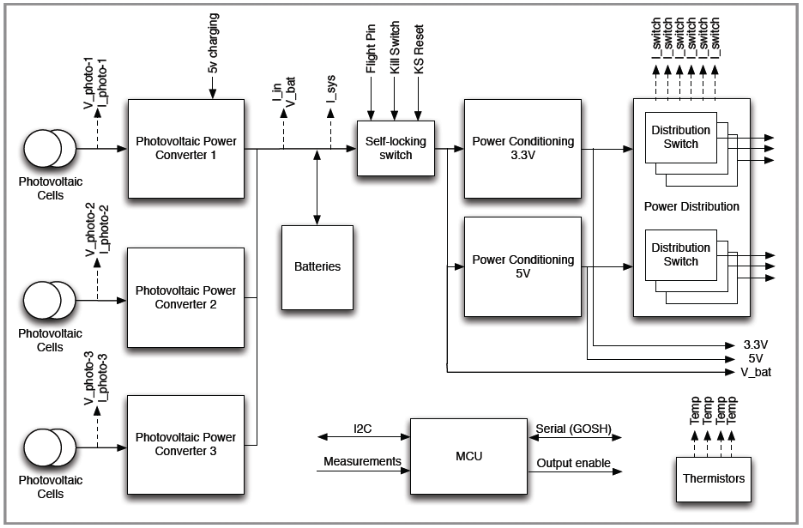
CoreSat Spacecraft Bus

- **CoreSat Solar Panels**
  - **Y facets** have **4 PCBs** (2s2p) = 1000mA at 9.4V (9.4W) linking to the associated +Y or –Y EPS
  - Average power for the CoreSat ~12W for; orbit average power ~7.5W (depending on final orbit choice and attitude scenario).
  - When docked, in Wide Mode, the MirrorSats cover 1 PCB on each of the Y facets which significantly reduces the power available from the Y facets to 4.7W.
  - The ideal scenario is to maintain the –X facet Sun Pointing, this then gives over 18W orbit average power assuming a 6am-6pm SSO
  - As 2 series PCBs is the basic unit for the CoreSat the PV voltage is 9.4V and thus the P31us EPS is required with the BP4 four Li-ion cell battery pack.
  - The dual EPS/Battery approach means that they can be cross-strapped via their USB charging ports (5V, 1A) to provide redundancy and power sharing.



CoreSat Spacecraft Bus

- **CoreSat EPS**
  - **COTS GOMSPACE NanoPower P31u-S EPS** (30W)
    - Two EPS/Battery sets are flown – one on the +Y side and one on the –Y side.
    - PVCP1 charging port is crossed strapped via switchable 5V, 1A lines
    - PVPC2 is connected to the Y facet panels (1A); PVCP3 is connected to X facet panels (1A or 0.5A).
    - Solar Array Voltage = 9.4V; V_Bat = 13.2V nom.



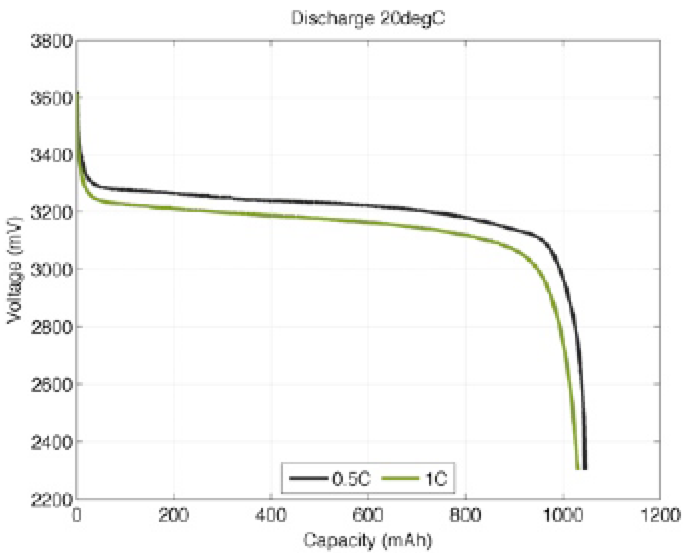
- ## CoreSat EPS
  - **COTS GOMSPACE NanoPower P31u-S EPS** (30W)

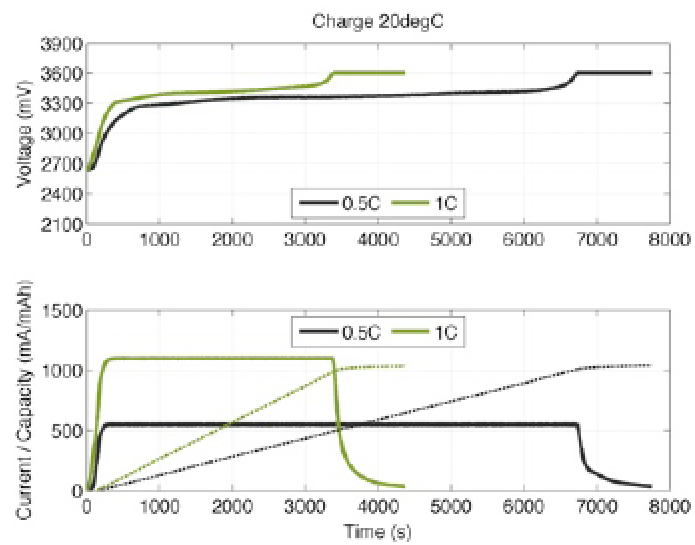
Parameter	Condition	Min	Typ	Max	Unit
Battery - Voltage - Current, charge - Current, discharge *(*Only on Pxx-S)*	Battery connection (depends on battery configuration) (depends on battery configuration)	6.0 (*12.0)	7.40 (*14.9)	8.40 (*16.80) 6.00 12.00	V V A A
PV inputs - Voltage - Current, charge *(*Only on Pxx-S)*	Photo-voltaic inputs (Customer selectable)	0 (*0) 0.00	4.2 (*8.4)	8.5 (*17) 2.00	V V A
5V_in - Voltage - Current, cont.	Battery charge input (beware of inrush) 5V => 0.9A charge, 4V => 0A charge @5V	4.10	5.00 0.9	5.00 1.1	V A
OUT-1,2,3,4,5,6 - Voltage - Current limit	Latch-up protected outputs Configurable Current cut-off limit (Cust. select)	0.5	3.3/4.98 Select	3.0	V A
+5V - Voltage - Current, cont.	5V regulated output (always on) Total current including output channels !!!		4.98	4.00	V A
+3.3V - Voltage - Current, cont.	3.3V regulated output (always on) Total current including output channels !!!	3.28	3.3	3.32 5.00	V A
V_BAT - Voltage - Current out *(*Only on Pxx-S)*	Raw battery voltage (depends on battery configuration)	6.0 (*12.15)	12	8.40 (*16.80)	V A
Power consumption	Power consumed by NanoPower		125		mW
Off current	Current consumed with separation switch OFF		35	60	uA
Shelf-life	Period until batteries are fully discharged when separation switch is OFF. (depends on battery configuration)	700	1400		Days

CoreSat Spacecraft Bus

- **CoreSat Battery**
  - **1100mAh 3.3V cell Li-Ion:** (note long cycle life)

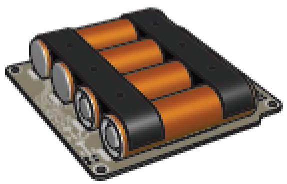
Parameter	Condition	Min	Typ	Max	Unit
Lithium-Ion Cell					
- Voltage		2.0	3.3	3.6	V
- Charge current			1500	4000	mA
- Discharge current			5000	30000	mA
- Charge temperature		-30		60	ºC
- Discharge temperature		-30		60	ºC
- Storage temperature	80% recovery after 1 year	-10		20	ºC
- Internal impedance				20	mOhm
- Mass			39		g
- Cycle life (20% capacity loss)	DOD: 100%, Temp 25degC Charge/discharge: 1C/1C		8000		cycles

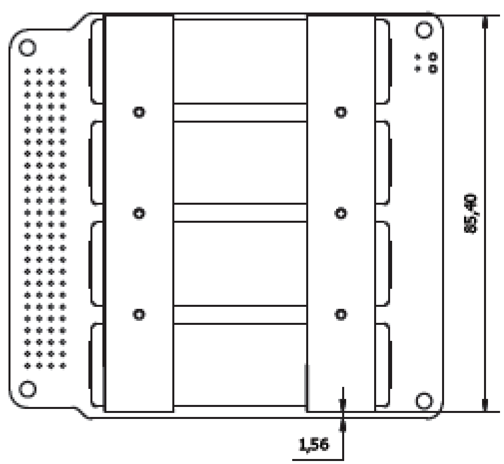


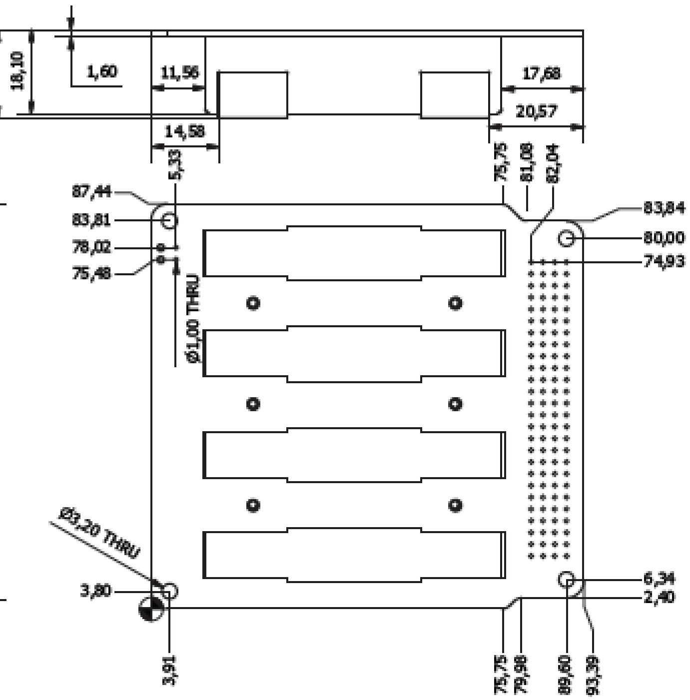


CoreSat Spacecraft Bus

- **CoreSat EPS and Battery**
  - **Dimensions:** (90g EPS + 240g battery = 330g mass)







Parameter	Condition	Min	Typ	Max	Unit
Space height	Spacer size between QuadBat and NanoPower	6.2	6.5	6.8	mm

Model	Mass	Dimensions
NanoPower BP-4	240.0 g	94x88x20 mm

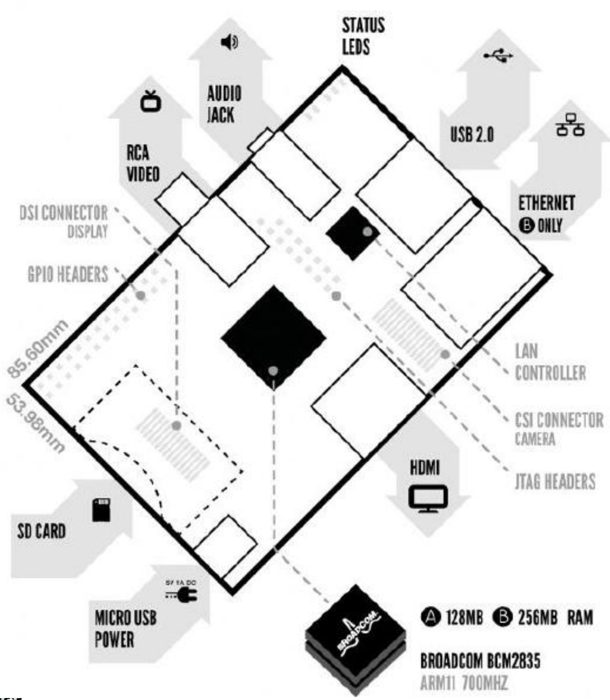
Model	Mass
NanoPower P31 without batteries. With low stack connector	90 g
NanoPower P31. With 2600mAh batteries. With high stack connector*	200 g

CoreSat Spacecraft Bus

- **CoreSat Power Budget**
  - Systems connections/ power budget (per side):
    - **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).
    - **Wheels (2) and Star Camera:** 5V, 3.5W
    - **OBC1:** (R-Pi; Wi-Fi) **5V sw.**; consumption 3.5W max.
    - **RMP: 5V sw.**; consumption 2W continuous.
    - **Camera: 5V sw.;** 2.5W (share)
    - **OBC2+Softkinetic DS325+LEDs**: **5V sw.**; 5V fixed; 6W
    - **EM Docking: 5V fixed**; 3.25W per coil = 13W max.
    - **MirrorSat Charge: 5V sw.;** 5W max.
    - **VHF/UHF Rx./Tx.:**V-bat; 0.35W Rx.; 2W tx.
  - MINIMUM Power Config. (EPS+OBC1+Wi-Fi+ADCS) <9W (contingent of software implementation) – aiming at 4-5W.
  - MAXIMUM Power Config. (RDV/Docking/Manoeuvre) <30W
  - MAXIMUM Power Config. (P/L Operation) <18-20W

CoreSat Spacecraft Bus

- **CoreSat OBCs; Control/Communications/Data Link**
  - The CoreSat's primary controller and communications link to the CoreSat is via the Raspberry-Pi (B) based **OBC1** and the COTS Wi-Fi link.
  - R-Pi has two USB master ports – one will be used for the Wi-Fi "dongle" and the other will be dedicated to the FMP payload.
  - ISL data rate is programmable – effective range ~1 km

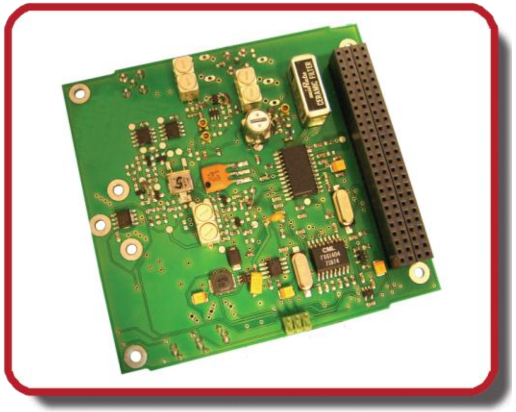


CoreSat Spacecraft Bus

- **CoreSat OBC2, PrimeSense Lidar, EMKCDS, PMDS**
  - **OBC2** is also based on the Raspberry Pi (B) with 512 MB SDRAM and is a copy of OBC1 in terms of hardware.
  - Its primary uses are to provide I2C interfaces and control of docking system, OBC2+**Softkinetic DS325** sensors (via USB), LED illumination and propulsion system.
  - The second USB port is currently free.
  - Note: the CoreSat LIDARs look in the +Y and –Y directions.
  - The **EMKCDS** is as per the MirrorSats except that the ports (cups) are on the Y facets.
  - The CoreSat +X facet carries two sets of docking cups with fixed permanent magnets (**PMDS**) to hold the MirrorSats in Compact Mode.
  - The magnets are arranged with alternate polarities to minimise magnetic disturbances.
  - The +X, +Y and -Y facets all carry LEDs for illumination and MV based RDV.

CoreSat Spacecraft Bus

- **CoreSat RF Comms**
  - Intend to use same (or similar) approach to STRaND-1 – i.e. Use Amateur Radio Satellite Service VHF U/L and UHF D/L.
    - Use of AR opens up the data for outreach.
    - AX.25 protocol, 9.6kbps in common use.
  - Frequency filing for AAReST not yet started.
  - ISIS VHF/UHF RF + VHF and UHF quarter-wave antennas:
    - Mass: ~ 85g
    - Dimensions: 96 x 90 x 15 [mm]
    - Power: <2.0W (transmitter on), <0.35W (receiver only)
    - Interfaces: 104 pin CubeSat Kit stackthrough connector :
      - ✓ 5-18V DC power supply
      - ✓ I2C bus interface
      - ✓ Raw FSK demodulator output
      - ✓ Direct modulator input
      - ✓ RF input: MMCX 50 ohm
      - ✓ RF output: MMCX 50 ohm



CoreSat Spacecraft Bus

- **CoreSat RF Comms**
  - **ISIS UHF transmitter**
    - Frequency range: 400-450MHz (Synthesized)
    - Transmit power: Typical 500mW.
    - Modulation: Raised-Cosine Binary Phase Shift Keying (BPSK)
    - Data rate selectable: 1200, 2400, 4800, 9600 bit/s. Higher values on request
    - Protocol: AX.25 (Other protocols available upon request)
  - **ISIS VHF Receiver**
    - Frequency range: 130-170MHz (Synthesized)
    - Modulation: Audio Frequency Shift Keying, 1200Hz/2200Hz (Bell202)
    - Data rate: 1200 bit/s.
    - -100dBm Sensitivity for BER 10E-5
    - On-board AX.25 command decoding

AAReST Spacecraft DDR:

RDV LIDAR, Bus Computing, WiFi

& Ground Comms

Dr. Chris Bridges

Surrey Space Centre
University of Surrey
Guildford, UK, GU2 7XH

AAReST Spacecraft DDR:

MirrorSat ADCS and CoreSat Precision ADCS

Prof. Vaios Lappas

Surrey Space Centre
University of Surrey
Guildford, UK, GU2 7XH

MirrorSat Spacecraft Bus

- **MirrorSat MEL**

System	Mass, kg with 10% margin
ISIS 3U Structure	0.3
Solar Panels (8)	0.3
P31u EPS/Battery	0.2
ADCS GPS Wheel	0.5
OBC1 OBC2 Wi-Fi	0.2
EMKCDS	1.3
Lidar LEDs Lenses	0.1
Propulsion (dry mass)	0.8
Harness Connectors	0.2
DM Payload	0.7
Sub-system total	**4.6**
System margin (30%)	1.4
Dry mass	**6.0**
Propellant	0.08
Launch mass	**6.1**

System	Power, W
P31u EPS/Battery (95% eff.)	2.2
ADCS GPS Wheel	2.0
OBC1 OBC2	7.0
Wi-Fi	1.0
EMKCDS	13.0
Lidar LEDS	2.3
DM Payload	2.0
Propulsion	9.0
Battery Heater	7.0
Sub-system total	**45.5**
System margin	4.6
Total peak power	**50.0**
Practical Max.	30 (60%)

CoreSat Spacecraft Bus

- **CoreSat MEL:**

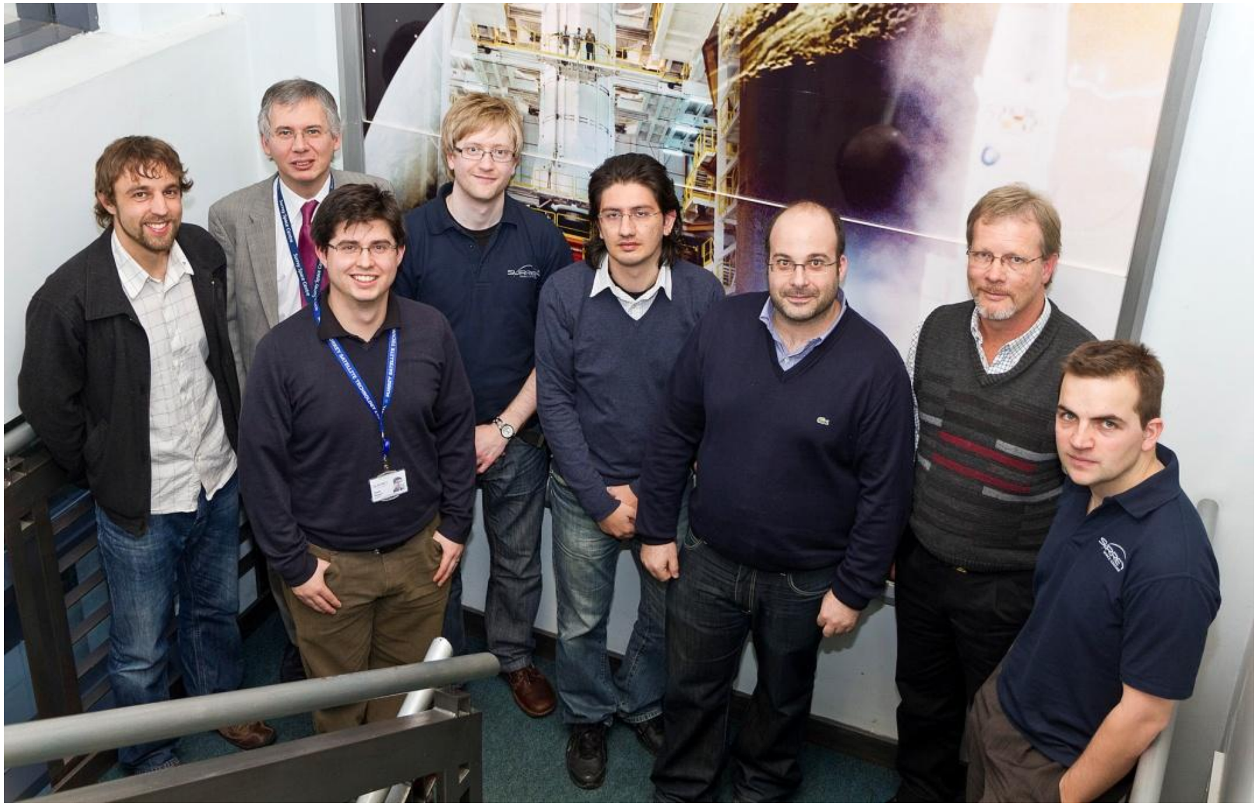
System	Mass, kg with 10% margin
ISIS 3U + 2 6U Struc.	1.6
Solar Panels (20)	0.6
P31uS EPS/BP4 (x2)	0.7
ADCS GPS (x2)	1.0
3RW + IMU	1.0
OBC1, 2 Wi-Fi (x2)	0.4
EMDS, PMDS (x2)	1.7
Lidar LEDs Lens (x2)	0.2
Star Camera (x2)	0.2
Harness Connectors	0.4
FM Payload (x2)	1.3
Camera + Boom	4.0
VHF/UHF (x2)	0.2
Frangibolts (x4)	0.1
Attach Fitting/ Panel	1.8
Sub-system total	**15.2**
System margin (30%)	4.6
Launch mass	**19.8 (all up mass = 32.0kg)**

System	Power, W
P31uS EPS/Batt (95% eff.)	4.5
ADCS GPS (x2) RW (max)	8.0
OBC1 OBC2 (x2)	14.0
Wi-Fi (x2)	2.0
EMKCDS (x2)	26.0
Lidar LEDS (x2)	4.6
Star Camera (x2)	1.0
FM Payload (x2)	4.0
Camera	5.0
MirrorSat Charge Supp. (x2)	10.0
VHF/UHF (x1)	2.4
Frangibolts (x1 at a time)	9.0
Battery Heater (x2)	14.0
Sub-system total	**104.5**
System margin	10.5
Total peak power demand	**115.0**
Practical Max.	60 (52%)

Mass and Volume constraints are fine, however the spacecraft are **severely power limited** both by total capacity of the EPS and very low power generation rate – operations sequencing and orientation w.r.t. the Sun will be critical factors in the mission operations plan

Acknowledgements

- We wish to acknowledge and thank the people at Surrey who contributed to this presentation, in particular: David Lines, and Lourens Visage at the Surrey Space Centre, and Herman Steyn at Stellenbosch University, South Africa. We also acknowledge the support of the STRaND, QB-50, CubeSail, DeorbitSail and SMESat Teams at Surrey.



Thank-You

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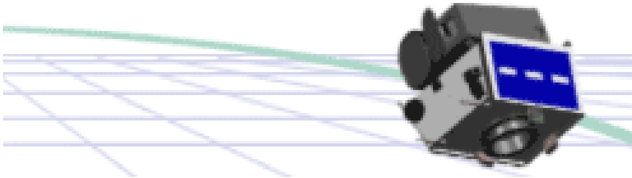
AAReST Spacecraft DDR:

RDV LIDAR, Bus Computing, WiFi

& Ground Comms

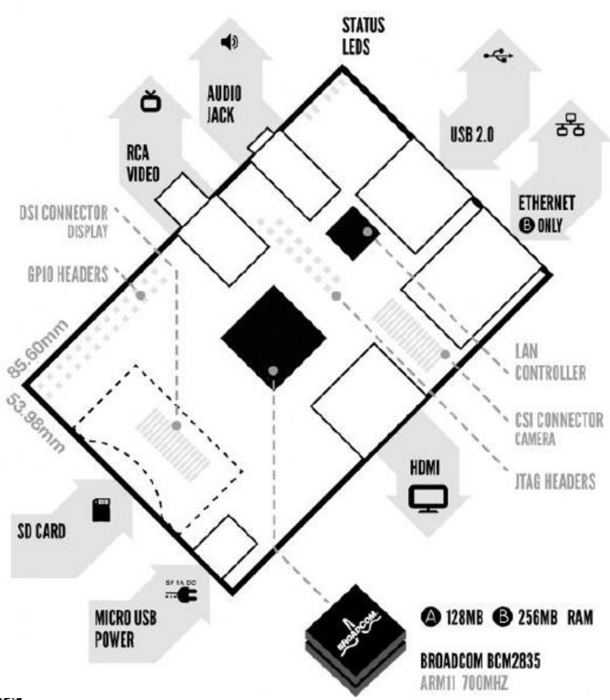
Dr. Chris Bridges, OBDH Group

Surrey Space Centre
University of Surrey
Guildford, UK, GU2 7XH



Prev. Sat Spacecraft Bus

- **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



Prev. Sat Spacecraft Bus

- **MirrorSat Wi-Fi Comms**

Hardware Features and Performance	
Physical Interface	USB 2.0
Antenna	Built-in smart antenna
Permissible Working and Storage Environments	Working Temperature: 0 ℃ to +40 ℃
	Storage Temperature: -40 ℃ to +70℃
Wireless Features and Performance	
Standards	IEEE 802.11n; backward compatible with IEEE 802.11g and IEEE 802.11b
Transmission speed	11b: 1/2/5.5/11Mbps
	11g: 6/9/12/18/24/36/48/54 Mbps
	11n: up to 150 Mbps

Wireless Features and Performance	
Frequency range	2.4 to 2.4835 GHz
Working channel	1 to 13
Transmit power	20dBm (max)
Software and Security	
Security features	WPA-PSK/WPA2-PSK
	WPA/WPA2
	64/128/152 bit WEP encryption
Operating System Support	Natively supported by the Raspbian "Wheezy" Linux operating system distribution onwards.

Based on a COTS WiFi

Antennas (2 off) mounted on X facets - TBD

Range: ~1 km

Mass: ~5 g

Power: ~1 W (EIRP)

Prev. Sat Spacecraft Bus

- **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

Prev. Sat Spacecraft Bus

- **OBC2**
  - OBC2 is also based on the Raspberry Pi (B) with 512 MB SDRAM and is a copy of OBC1 in terms of hardware.
  - Its primary uses are to provide I2C interfaces OBDH and control of docking system, Soft Kinetic sensors (via USB), LED illumination and propulsion system.
  - The second USB port links to a redundant WiFi link.

Status:

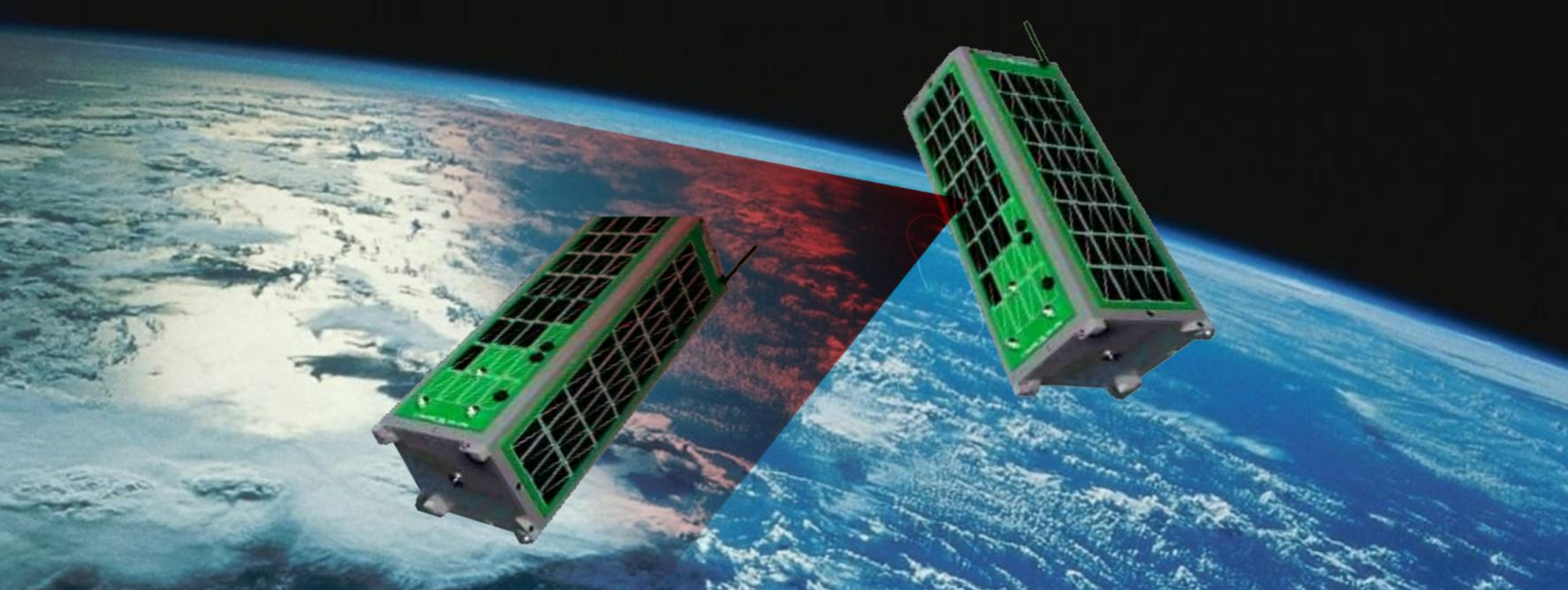
- The **RPi OBC** and **WiFi** are new developments at SSC.
- Hardware is in the lab, and software is in development.
- Prototypes completed Q3 2014.

De-Risking:

- Should the RPi not prove suitable, an additional **CubeComputer** will replace both, and a **Delta Mobile DM300** WiFi unit (I2C) or **ZigBee** will be substituted for the comms.
- Recent tests show this is unlikely to be needed.

RDV LIDAR Update

Dr Chris Bridges
Mr Richard Duke

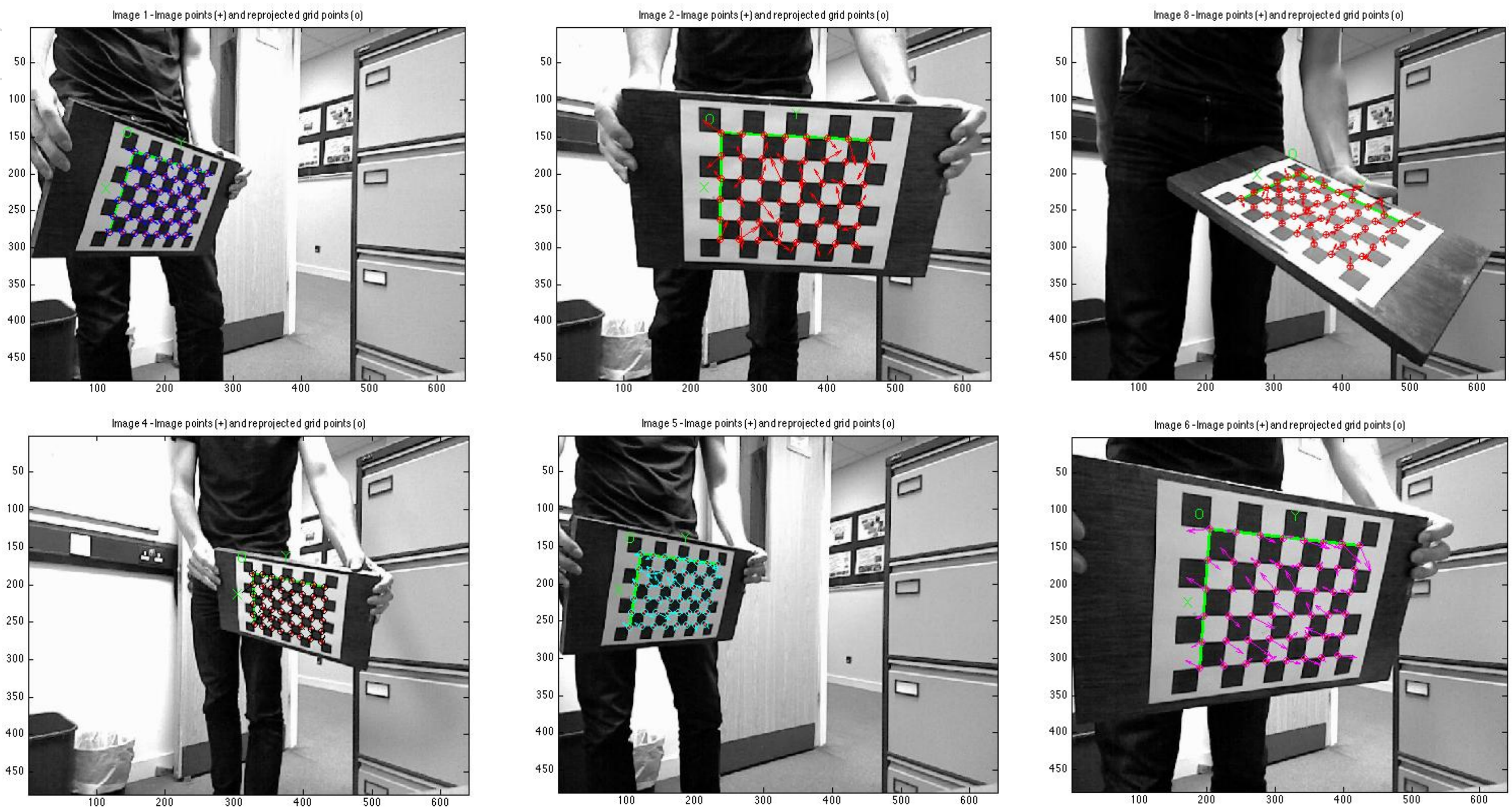


Prev. RDV LIDAR Work

- **PrimeSense LIDAR > SoftKinectic DS325**
  - Open Access Development Software has been identified and utilised and expanded upon to operate the KINECT™ as an independent sensor.
  - **Microsoft Kinect SDK**: This is the official platform for development. Includes numerous high and low level operational functions such as gesturing or retrieving depth sensor images. Limited to Windows.
  - **OpenKinect**: This is an open-source solution to the Microsoft Kinect SDK, where source code of all interfaces and libraries is available from a git repository. Available on Windows, Linux, and Mac OS computers and is extensively used, given the availability of source.
  - **OpenNI**: Being the prime LIDAR developers & provide a middleware API to perform high level operations called for gesturing, voice commands, & body motion/tracking.
  - For satellite embedded development, it is important to utilise existing C or C++ code than interpreted Java or Python code from source.

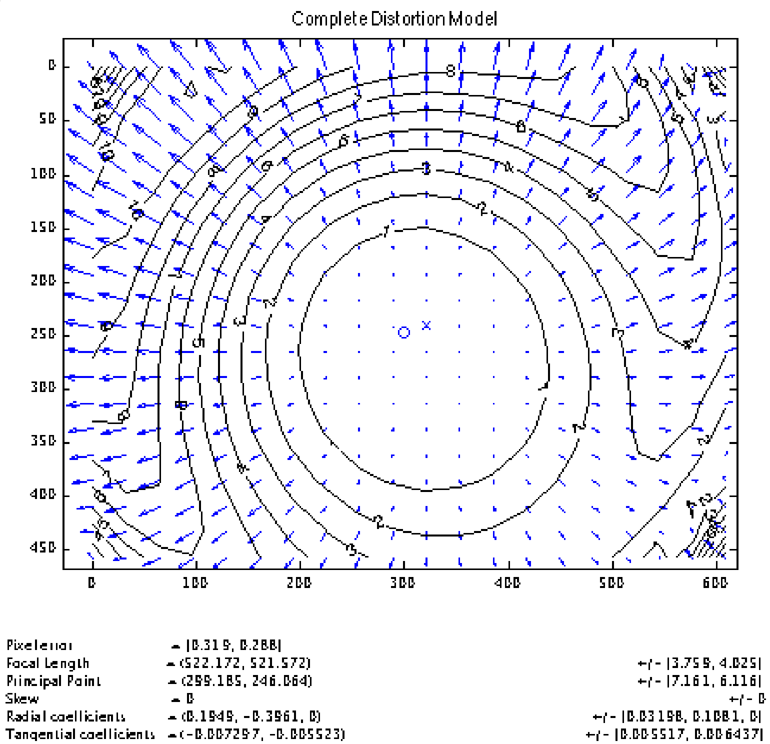
Prev. RDV LIDAR Work

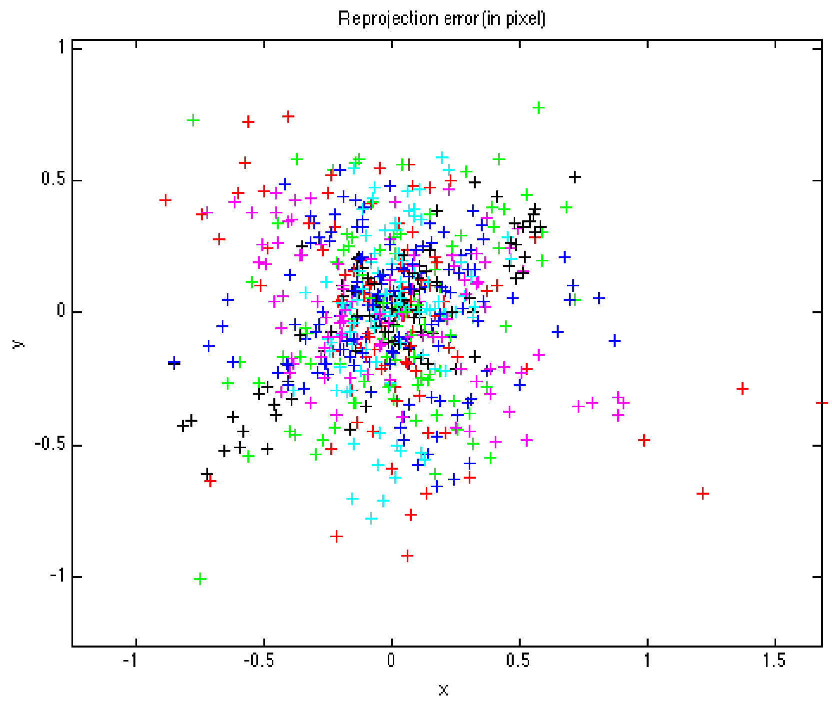
- **LIDAR:**
  - KINECT™ Lens Calibration Measurements have been taken to assess properties and to map distortions



Prev. RDV LIDAR Work

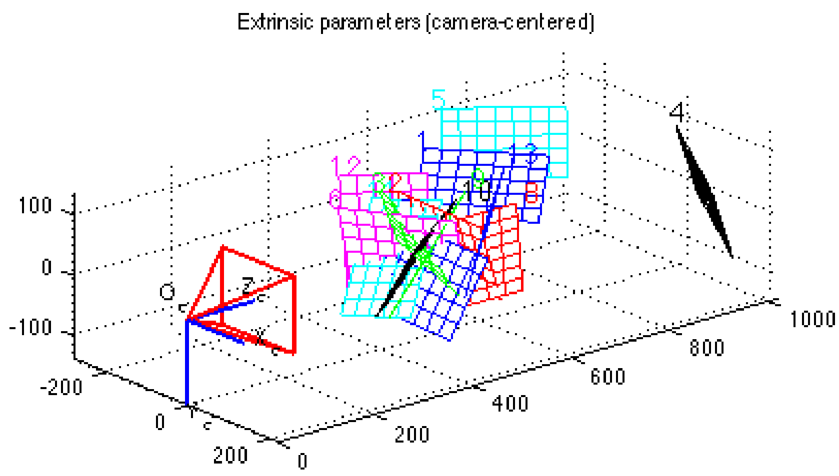
- **LIDAR:**
  - Optical centre was found to be slightly off (but known before flight)
  - Pixel error leads to a position error of 3 mm tangentially and up to 2 cm with depth

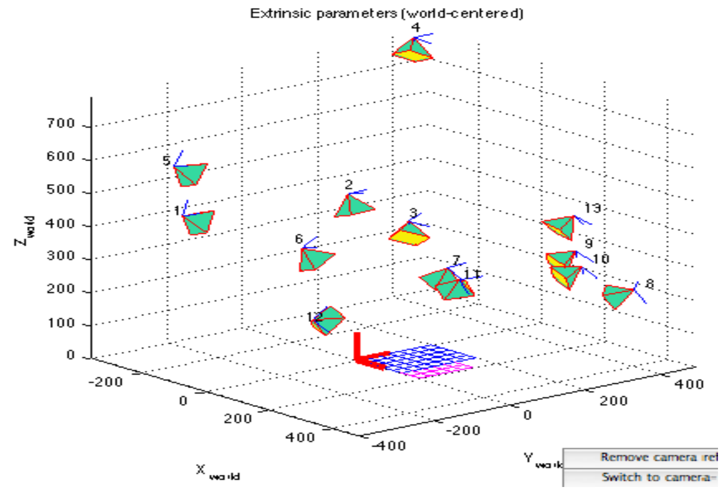


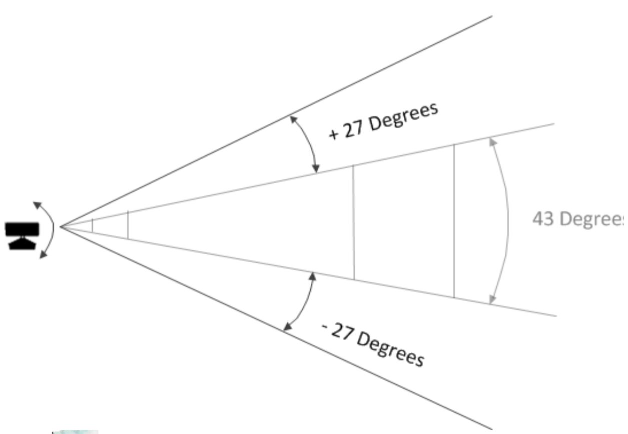


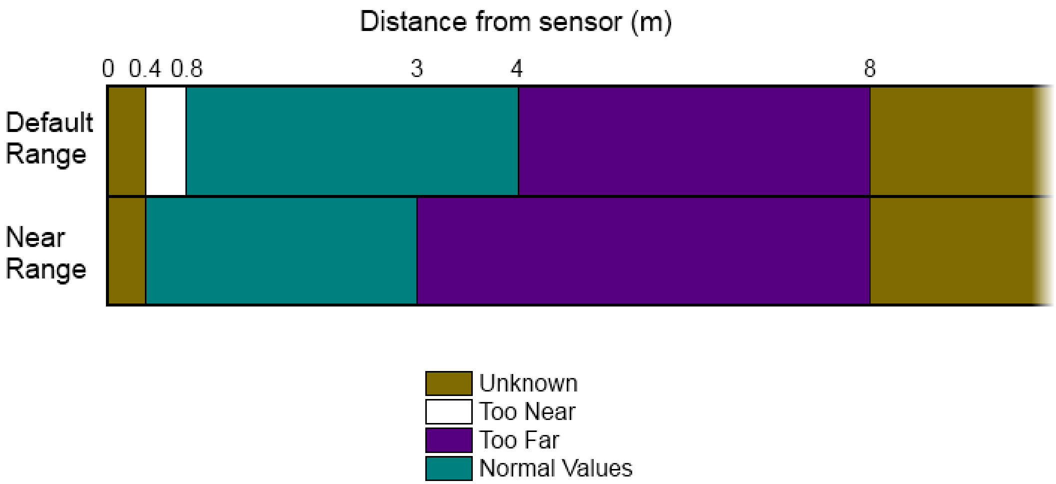
Prev. RDV LIDAR Work

- **LIDAR:**
  - Position and Pose was inferred from Imagery for two frames
  - Experiments show it is effective from 20-30cm out to ~10m



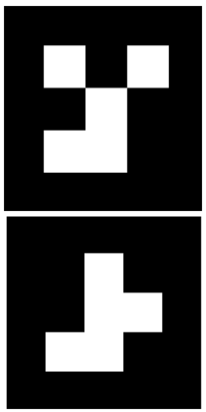


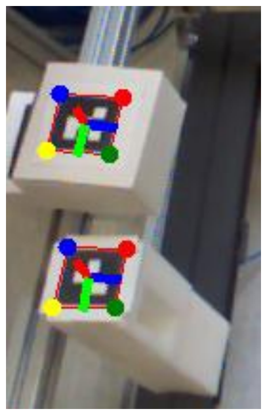


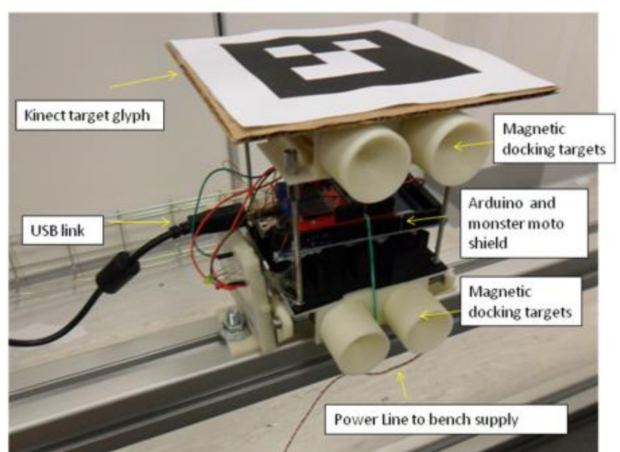


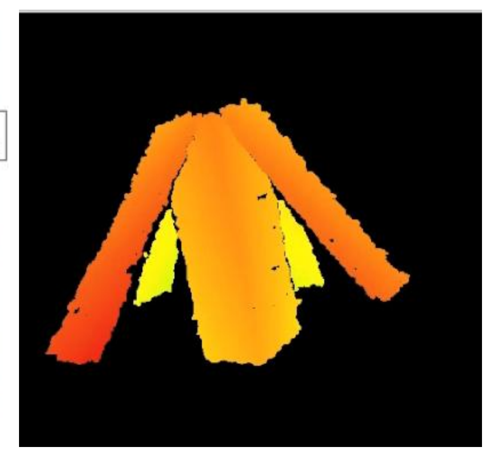
Prev. RDV LIDAR Work

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



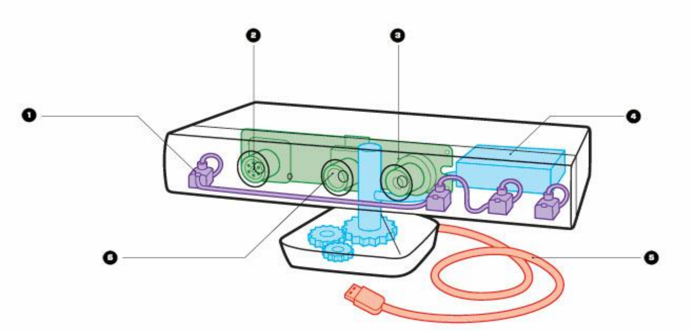






Prev. RDV LIDAR Work

- **LIDAR:**
  - System was broken down to explore key electronics



  - Remained functional after a vacuum test with a chamber pressure of 2.6 x 10^{-6} bar for 28 hours.
  - However other tests showed there is a **solar blinding** problem
  - **Solution**: perform the RDV in eclipse (i.e. within 30 mins) and/or use sensors on <u>both</u> the MirrorSat and the CoreSat

CAD Model of Broken Down Kinect

Under Test in Hermes Vacuum Chamber

RDV LIDAR & Bus Dev.

- MSc Project to solve:
  - 1st Try physical interfacing RPi, LIDAR Battery, WiFi > Desktop
  - Software driver/application dev.
  - Networking throughput

Primsense Capri **unavailable** (unless in 10's of thousands) > Softkinetic DS325

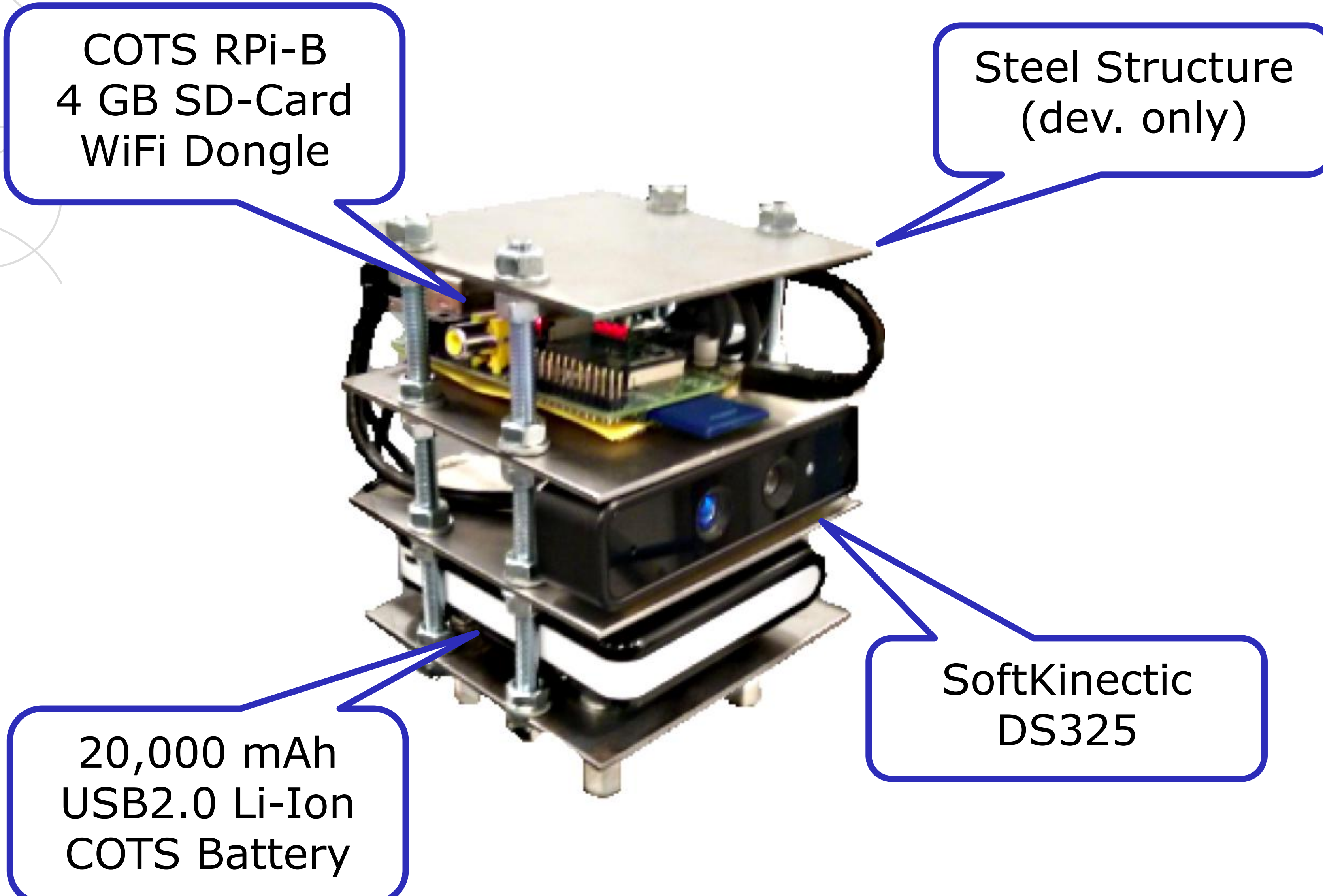
Primsense Capri	Softkinetic DS325
FoV: 57.5° x 45°	FoV: 87° x 58°
Range: 0.8 – 3.5m	Range: 0.15 – 1m
VGA Depth Map: 640 x 480	QVGA: 320 x 240
USB 2.0 powered	USB 2.0 powered

SURREY SPACE CENTRE

RDV LIDAR & Bus Dev.

UNIVERSITY OF SURREY

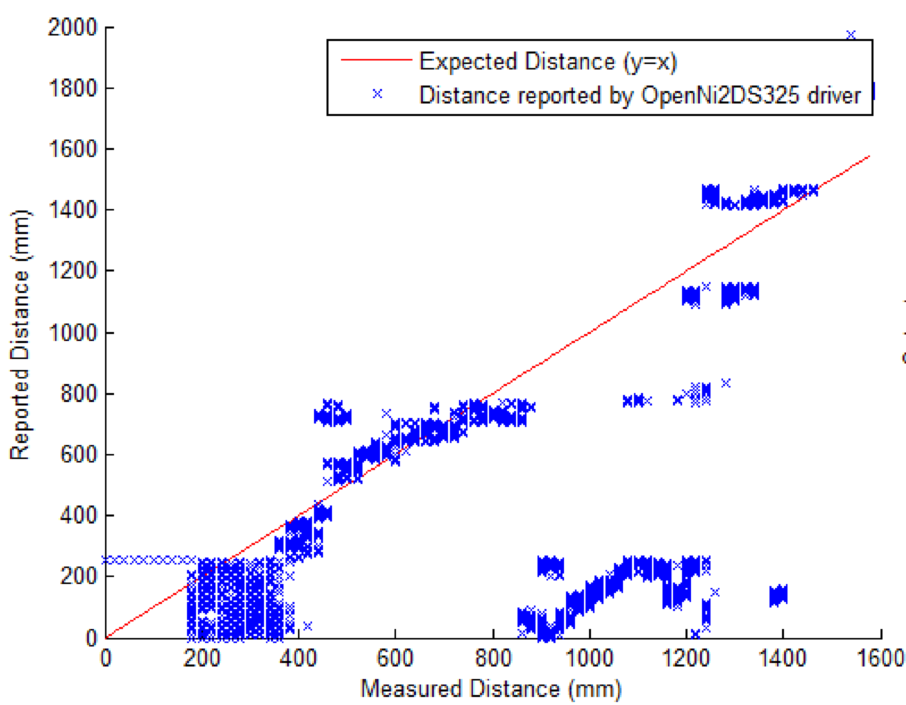
RDV LIDAR & Bus Dev.

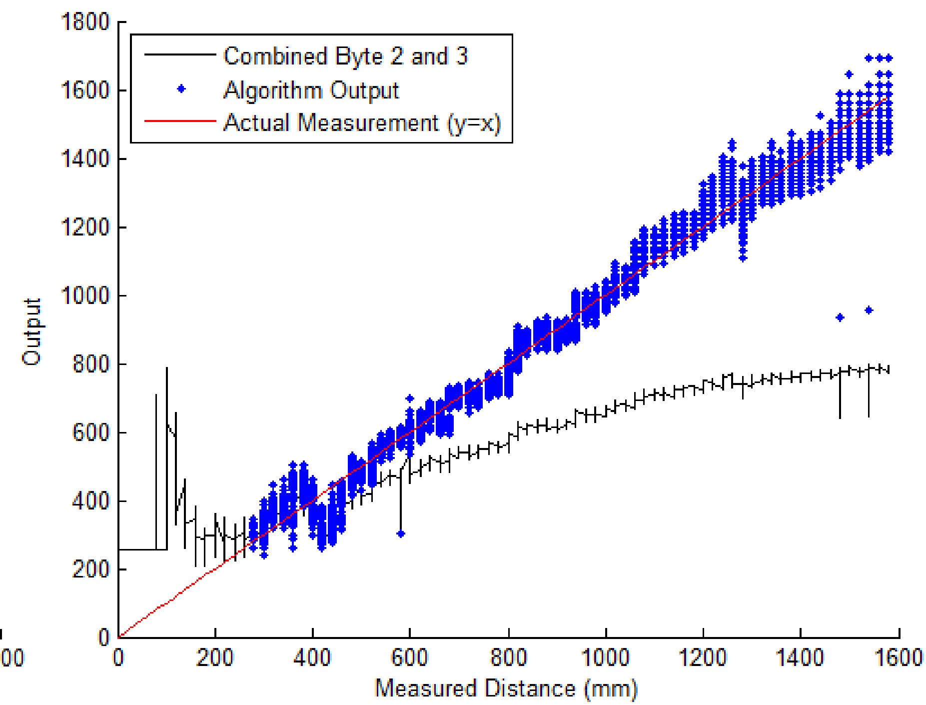


RDV LIDAR & Bus Dev.

RDV LIDAR & Bus Dev. SW

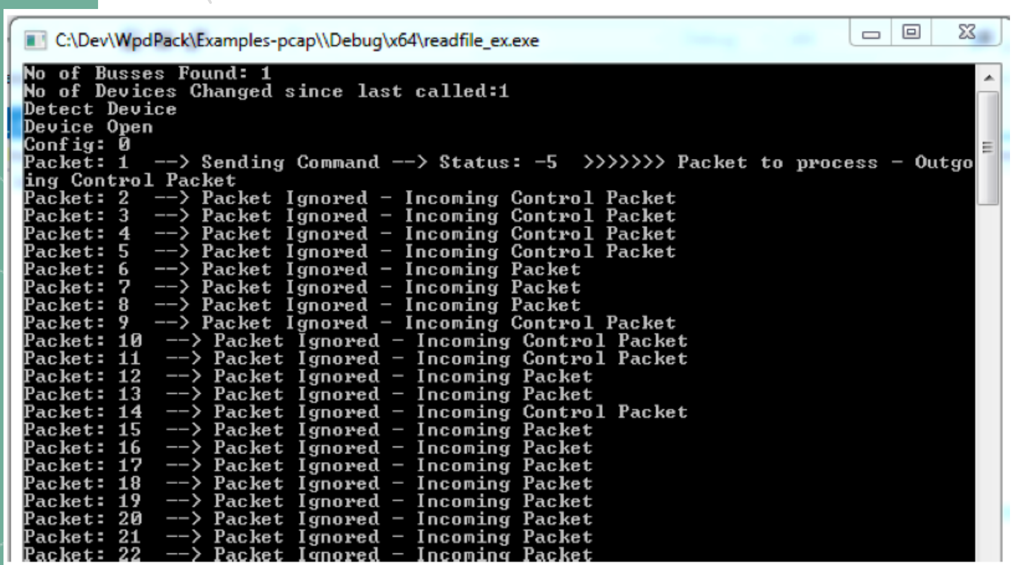
- OpenNI2DS325 driver used as more fully developed but later found to be very inaccurate.
- Reverse engineered driver to redevelop algorithm to convert raw data sensor data into depth measurements in kernel.





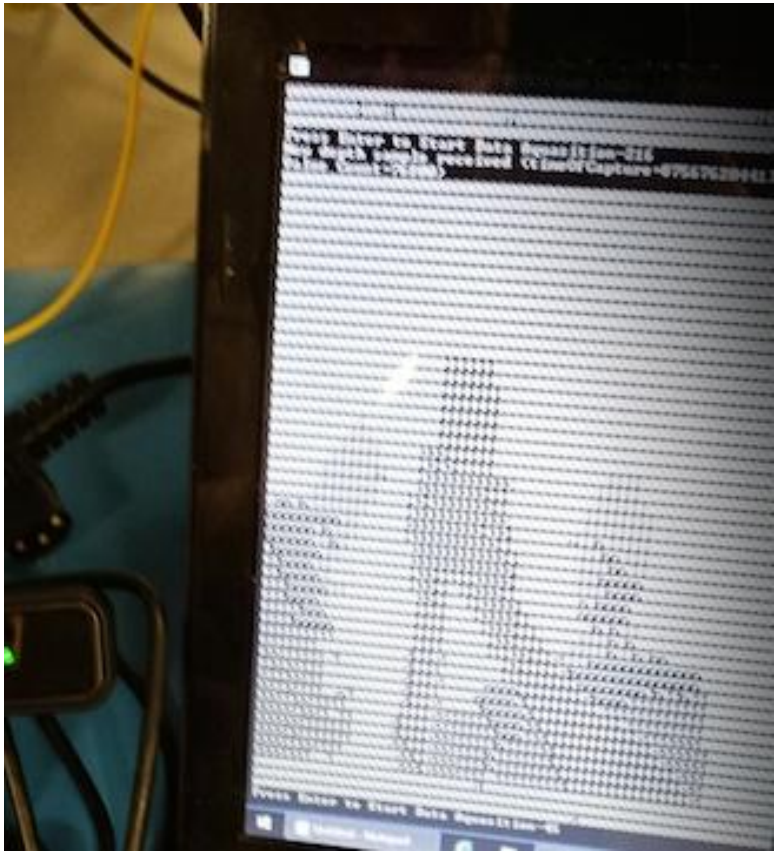
RDV LIDAR & Bus Dev. SW

- Embedded Linux Driver verified to operate LIDAR on RPis
  - USB Driver level: Isochronous & Bulk Transfer packets hacked
  - Dependencies: LibUSB, ssh, VNC (server); all **open-source**



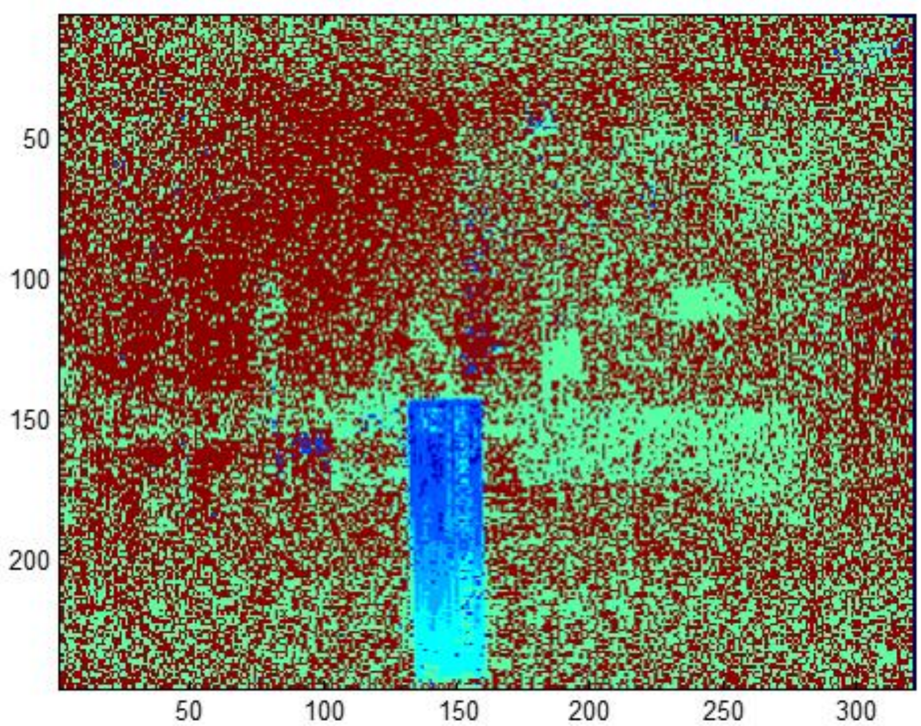
```
C:\Dev\WpdPack\Examples-pcap\\Debug\x64\readfile_ex.exe
No of Busses Found: 1
No of Devices Changed since last called:1
Detect Device
Device Open
Config: 0
Packet: 1  --> Sending Command --> Status: -5  >>>>>>> Packet to process - Outgoing Control Packet
Packet: 2  --> Packet Ignored - Incoming Control Packet
Packet: 3  --> Packet Ignored - Incoming Control Packet
Packet: 4  --> Packet Ignored - Incoming Control Packet
Packet: 5  --> Packet Ignored - Incoming Control Packet
Packet: 6  --> Packet Ignored - Incoming Packet
Packet: 7  --> Packet Ignored - Incoming Packet
Packet: 8  --> Packet Ignored - Incoming Packet
Packet: 9  --> Packet Ignored - Incoming Control Packet
Packet: 10  --> Packet Ignored - Incoming Control Packet
Packet: 11  --> Packet Ignored - Incoming Control Packet
Packet: 12  --> Packet Ignored - Incoming Packet
Packet: 13  --> Packet Ignored - Incoming Packet
Packet: 14  --> Packet Ignored - Incoming Control Packet
Packet: 15  --> Packet Ignored - Incoming Packet
Packet: 16  --> Packet Ignored - Incoming Packet
Packet: 17  --> Packet Ignored - Incoming Packet
Packet: 18  --> Packet Ignored - Incoming Packet
Packet: 19  --> Packet Ignored - Incoming Packet
Packet: 20  --> Packet Ignored - Incoming Packet
Packet: 21  --> Packet Ignored - Incoming Packet
Packet: 22  --> Packet Ignored - Incoming Packet
```

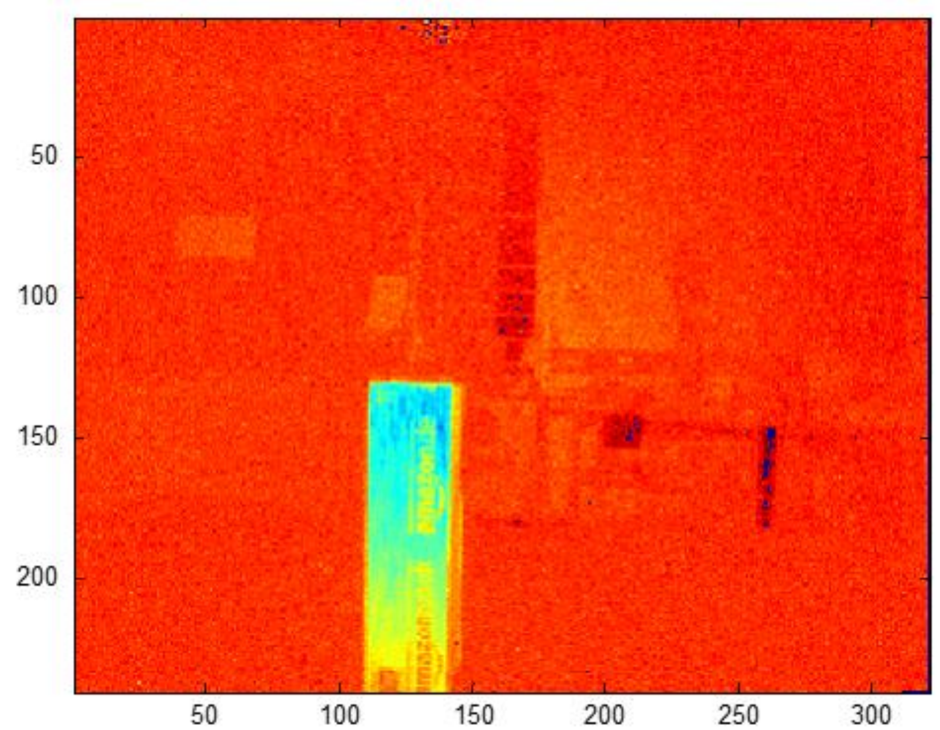
Ignoring control packets in processing
> stream depth data only



RDV LIDAR & Bus Dev. SW

- Embedded Linux Driver verified to operate LIDAR on RPis
  - USB Driver level: Isochronous & Bulk Transfer packets
  - Dependencies: LibUSB, ssh, VNC (server); all **open-source**
- Software now returns correct depth positions over WiFi UDP





RDV LIDAR & Bus Dev. SW

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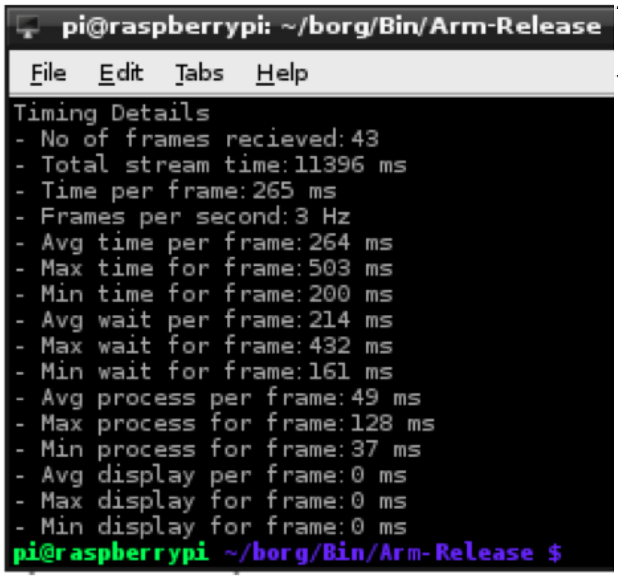
- Software now returns correct depth positions over WiFi UDP



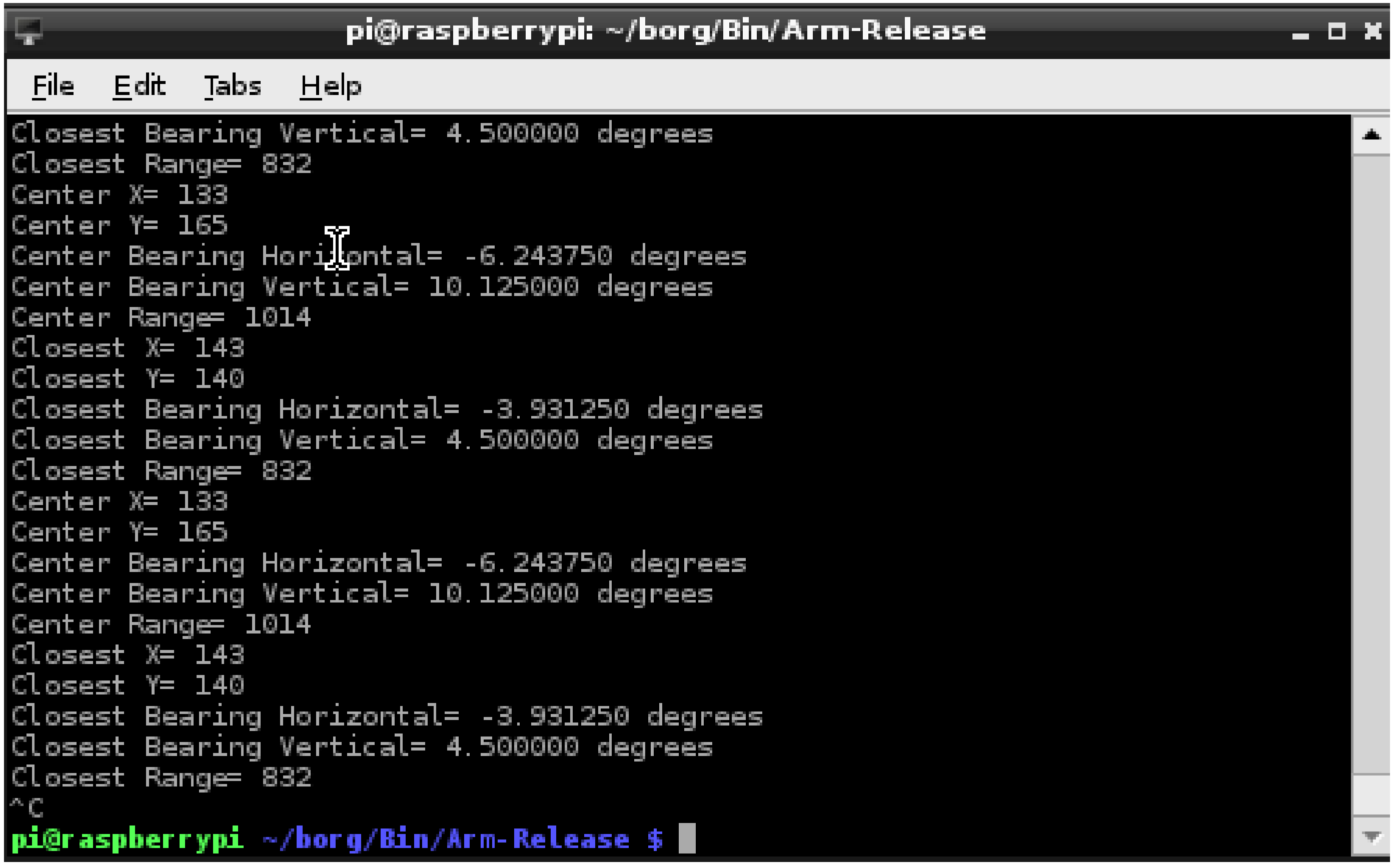
	No Output	Display Summary	Display All	Output to File	Processing Test
No of Frames	5918	3568	8	413	7347
Test Duration (s)	291	351	422	300	457620
Time per frame (ms)	49	98	52763	727	62
Frames per sec (Hz)	20	10	<1	1	16
Avg time per frame (ms)	48	97	52763	725	61
Max time per frame (ms)	206	1429	54173	2303	3125
Min time per frame (ms)	44	2	50708	351	24
Avg wait per frame (ms)	48	72	44	<1	37
Max wait per frame (ms)	206	611	359	60	246
Min wait per frame (ms)	44	<1	<1	<1	2
Avg process per frame (ms)	<1	<1	<1	3	23
Max process per frame (ms)	6	16	<1	51	79
Min process per frame (ms)	<1	<1	<1	<1	18
Avg display per frame (ms)	<1	24	52717	722	<1
Max display per frame (ms)	7	1278	54172	2275	2
Min display per frame (ms)	<1	2	50707	350	<1
Approx CPU usage (%)	50	100	100	100	80

Display takes a long time (!)

Processing at 16 Hz

RDV LIDAR & Bus Dev. SW

- Embedded Linux Driver verified to operate on RPi boards
- Software now returns correct depth positions over WiFi UDP
- Also returns relative range & pose estimates (also filtered)



RDV LIDAR & Bus Dev. SW

- Embedded Linux Driver verified to operate on RPi boards
- Software now returns correct depth positions over WiFi UDP
- Also returns relative range & pose estimates (non-filtered)

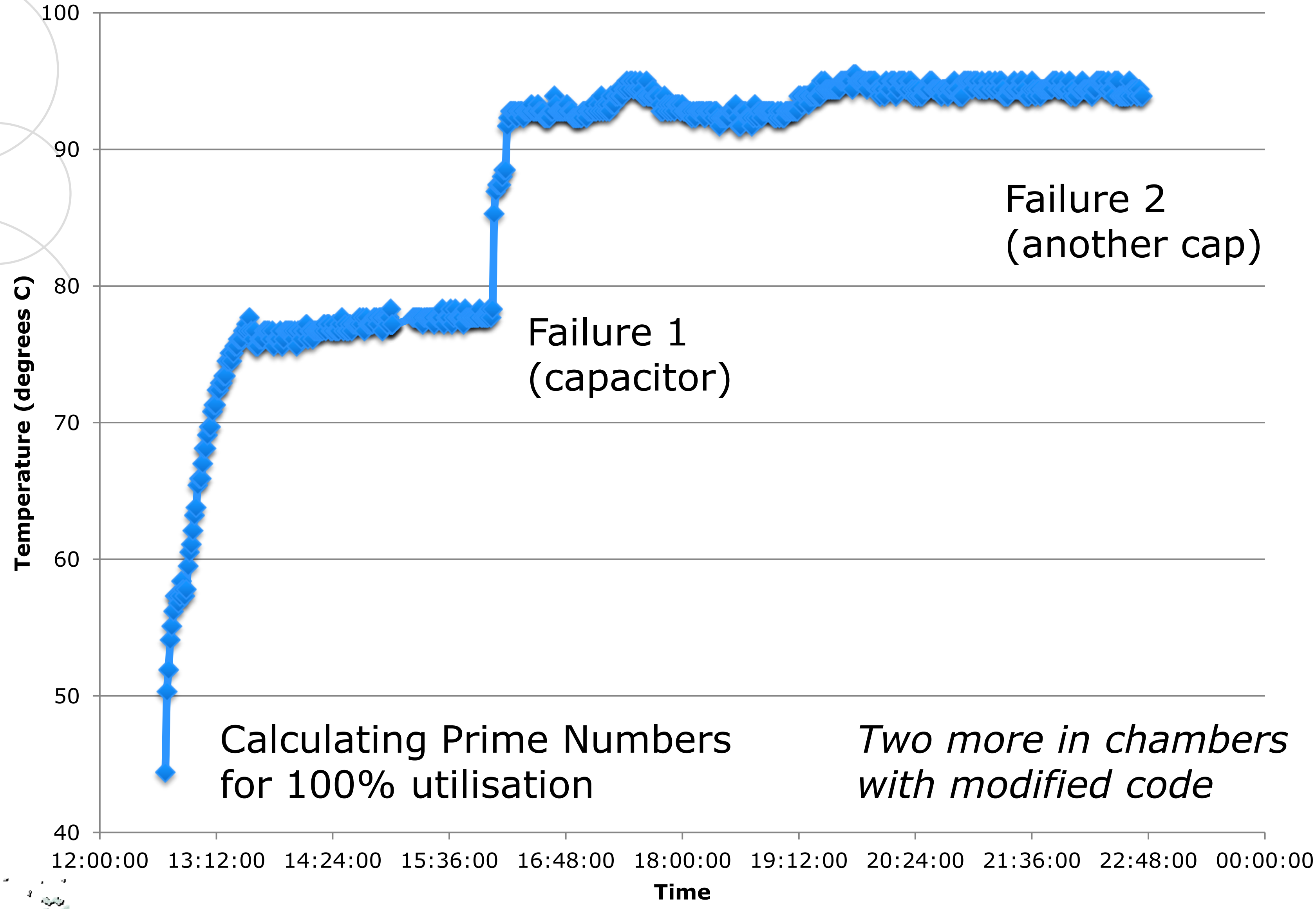
- Power Measurements of new system from PDR:

–MINIMUM Power Config. (EPS+OBC1+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)

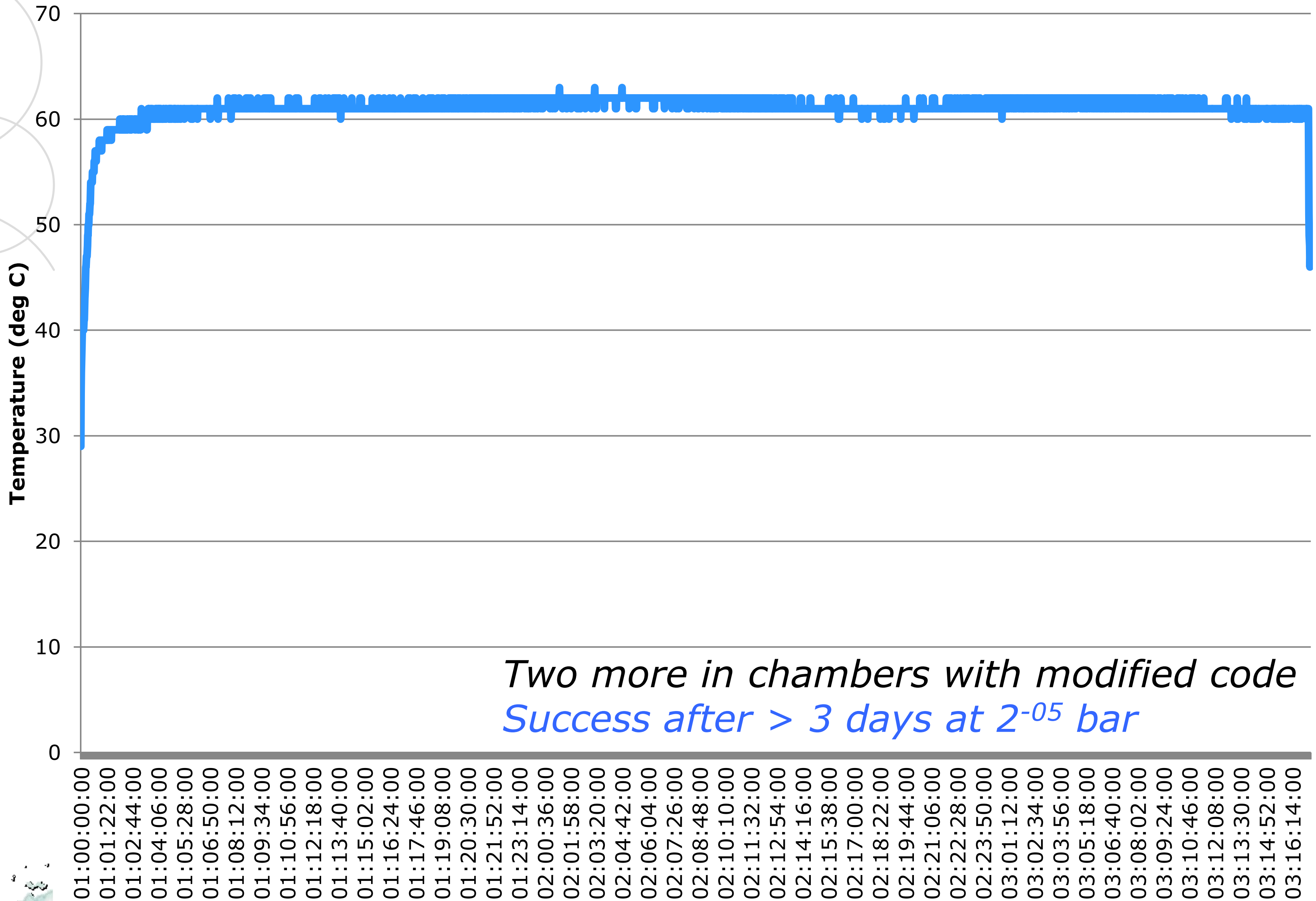
	Current (mA)
Raspberry Pi Bootup Max	0.56
Raspberry Pi TCP Streaming (Ave)	0.54
Raspberry Pi TCP Streaming (Peak)	0.60
DS325 (Ave)	0.43
DS325 (Peak)	0.44

Power @ 5V
2.8 W
2.7 W
3.0 W
2.15 W
2.2 W

RPi Model B Thermal Tests



RPi Model B Thermal Tests



Two more in chambers with modified code

Success after > 3 days at 2^{-05} bar

SURREY SPACE CENTRE

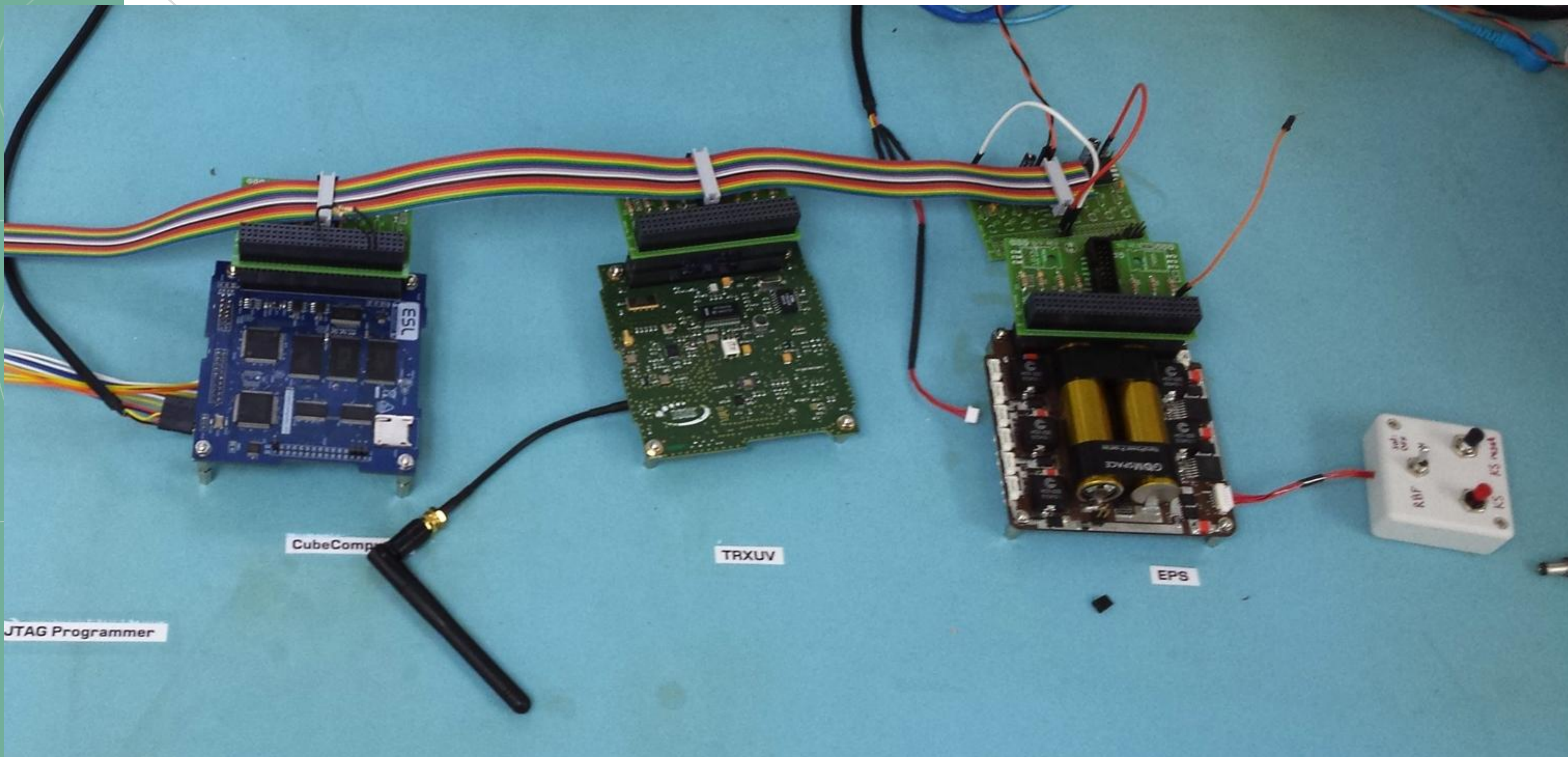
RPi-B > RPi Compute

UNIVERSITY OF SURREY

- 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

WiFi Dongle Teardown

Ground Comms.

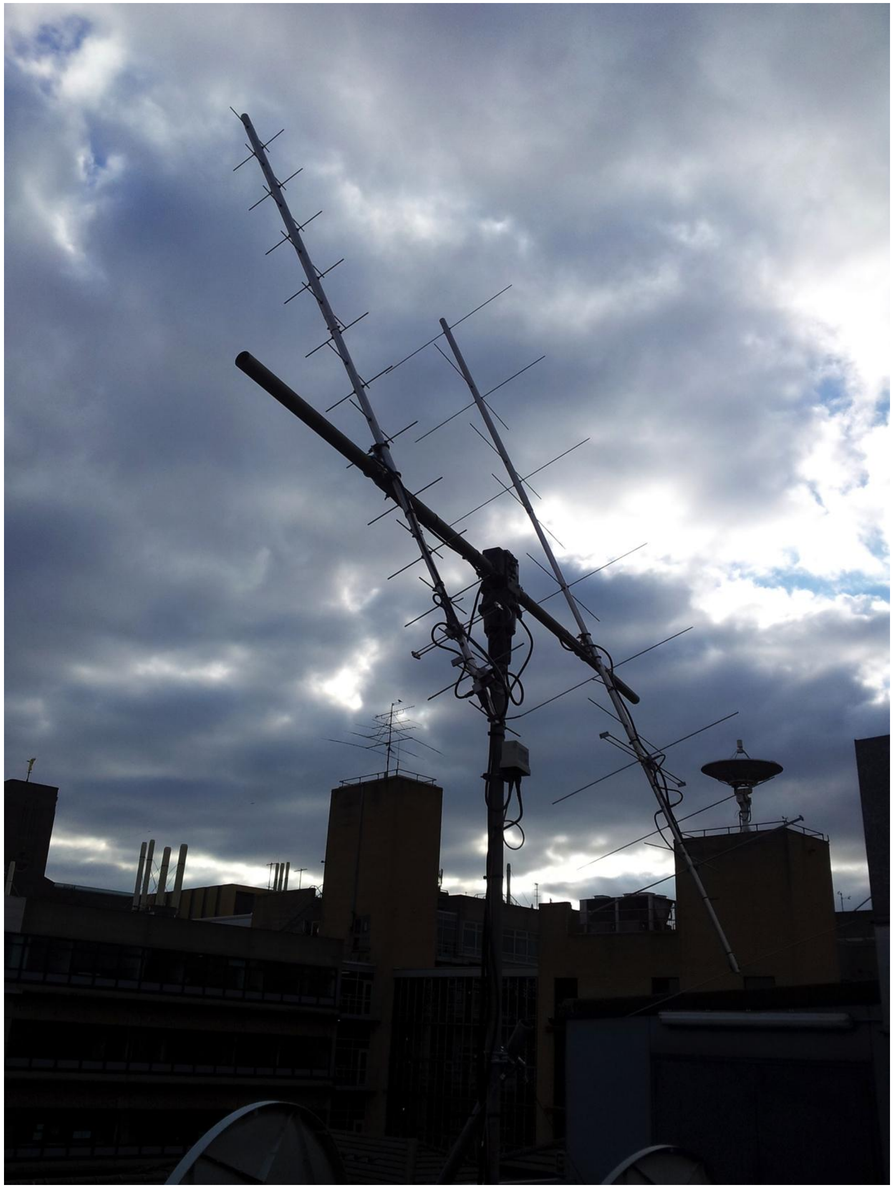


Above: Cleanroom 'Generic' FlatSat: OBC, Comms, GomSpace Power

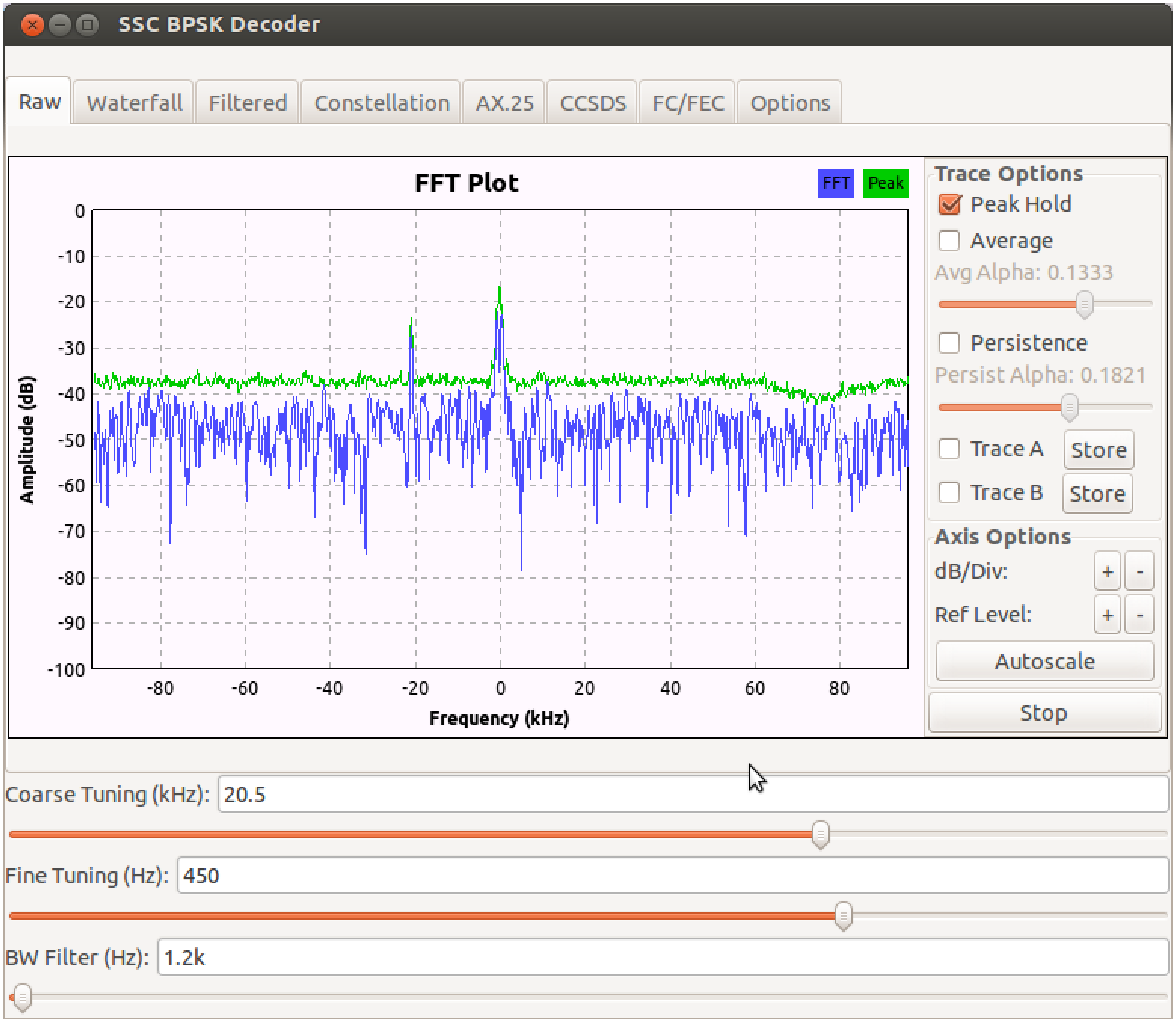
OBDH Team working with Prof. Lappas' Team on various missions for Earth < > Satellite communications with ISIS TXRUV

Ground Comms

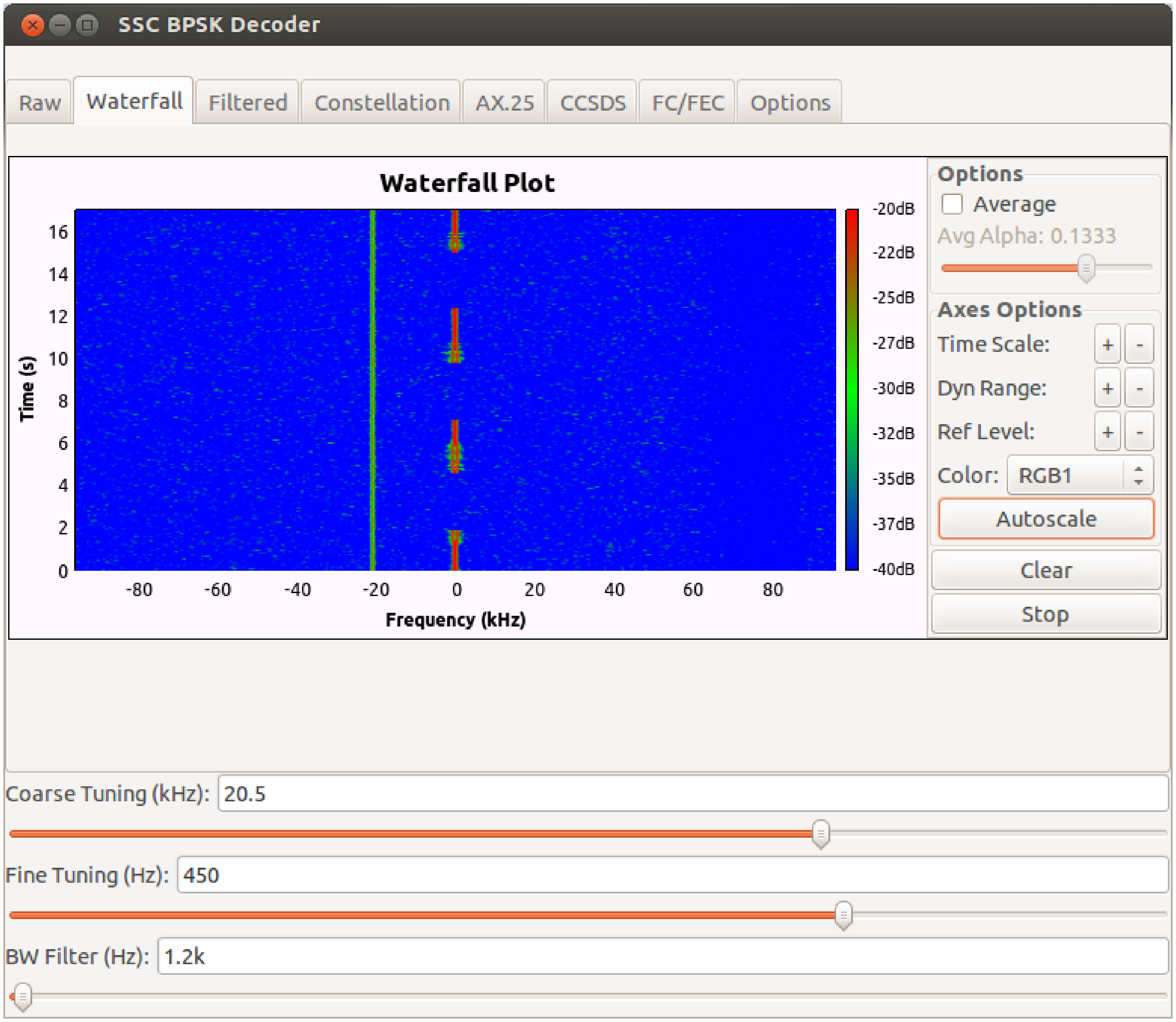
- Demonstrated 1k2 on VHF
  - From cleanroom to ground-station (same building)
  - No LNA, HPA required.
- Front-end
  - Dr Bridges' Team
  - Handles RF, Packetisation, error coding/checking
  - Acts as UDP Server
- Back-end
  - Prof. Lappas' Team
  - Sends/receives raw data over UDP as client
  - Multiple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



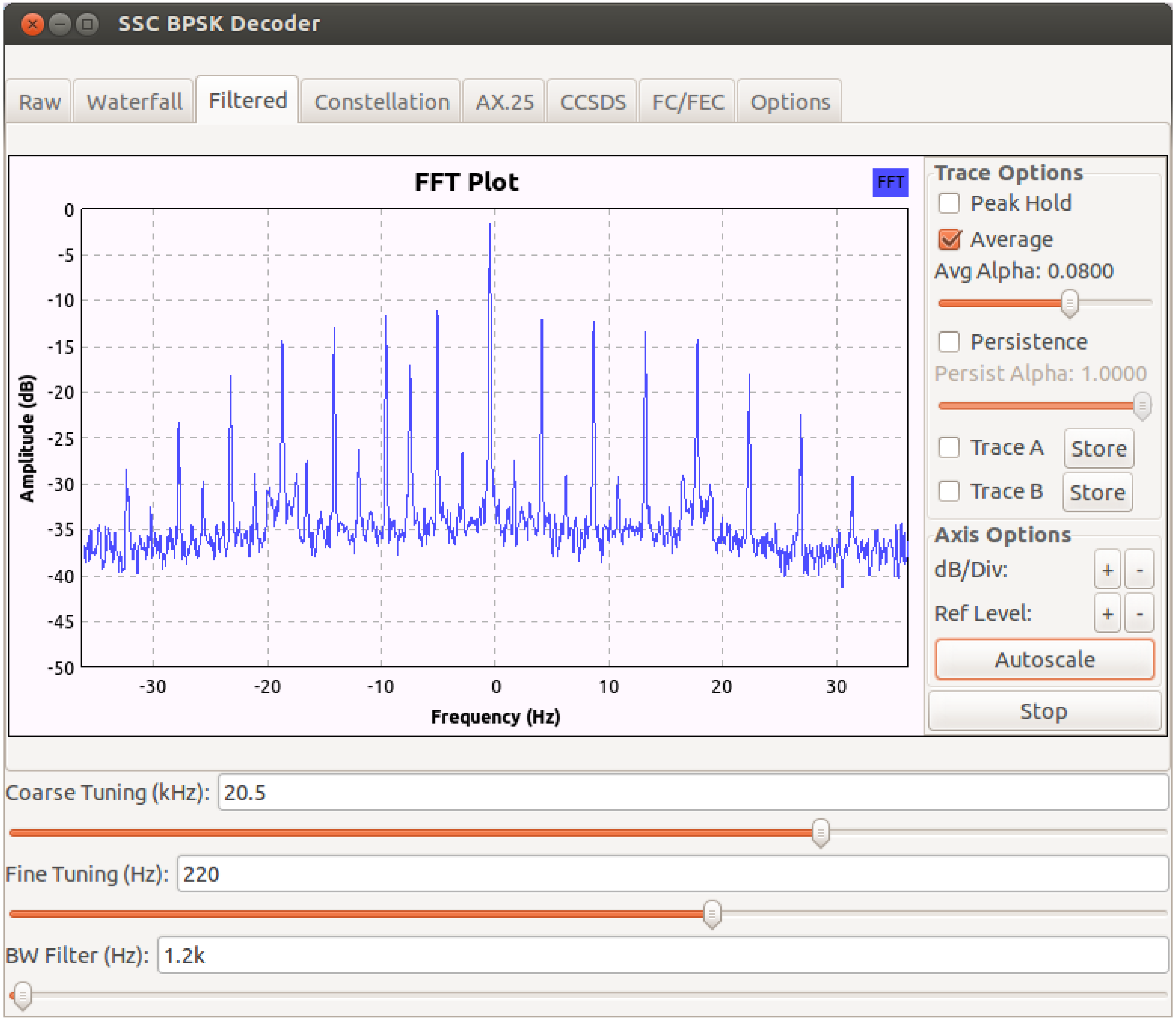
Frontend SDR-based GUI



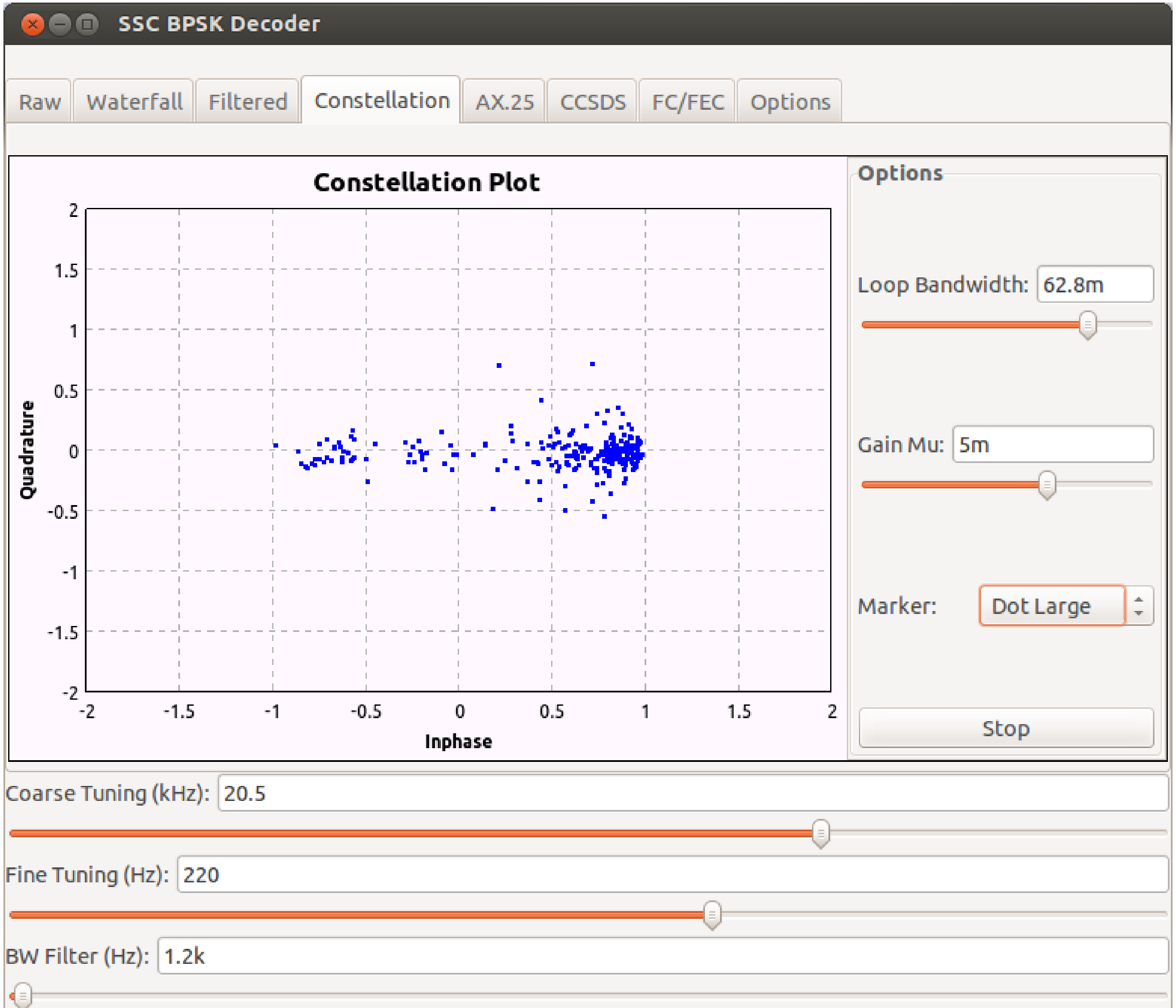
Frontend SDR-based GUI



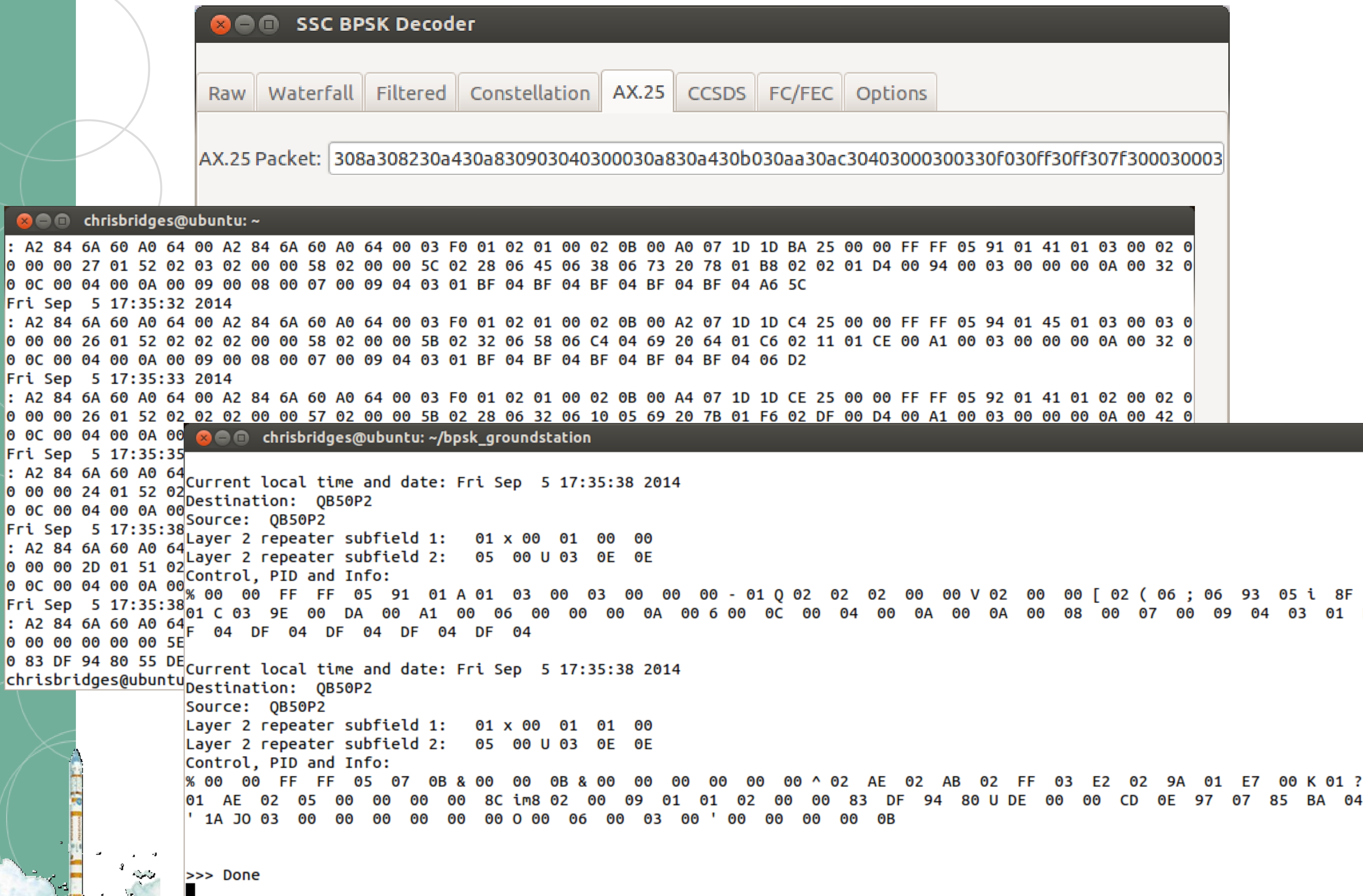
Frontend SDR-based GUI



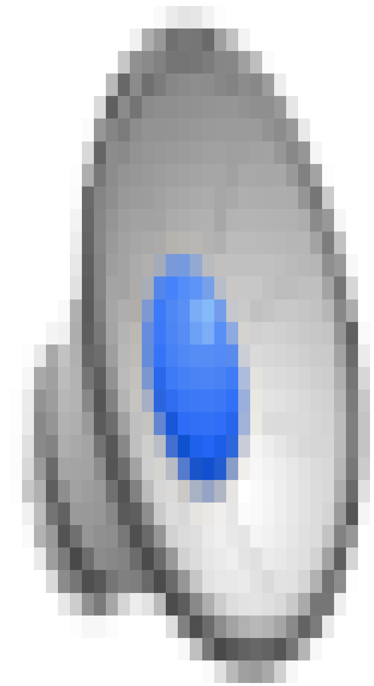
Frontend SDR-based GUI



Frontend SDR-based GUI



Frontend in action

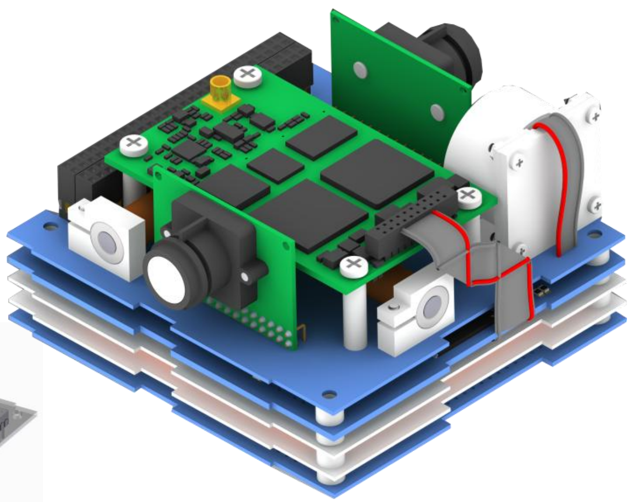


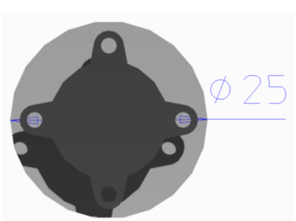
Future Work

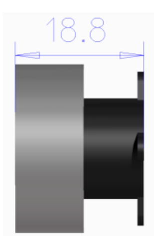
- LIDAR:
  - Lens Calibration (& potential replacement)
  - Solar Blinding Testing & Resolution
  - Testing with IR LEDs (& reflectors - TBD)
- RPi OBCs:
  - Rework industrial RPi Compute into PC/104 standard (schematics, PCB)
  - Functional Testing: I2C, USB > Power Measurements
  - Thermal Vacuum Testing under all modes of operation
  - If EPSRC funding is successful, TID/SEU with proton/neutron
- WiFi USB Module:
  - Thermal Vacuum with RPi units
- Ground Communications:
  - Add Doppler/fading/attenuation model to existing FlatSat
  - Commission USRP for FSK AX.25 transmit (uplink)
    - For Q4 2014 > CubeSail, DeorbitSail, QB50

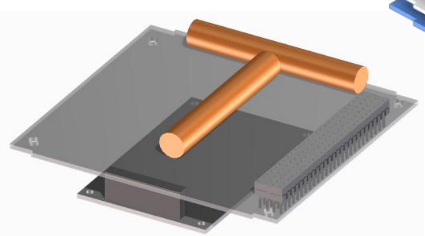
MirrorSat/CoreSat ADCS

- **MirrorSat ADCS**
  - New compact Integrated ADCS System being developed for QB50 by Prof. Steyn (Stellenbosch) and Prof. Lappas (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









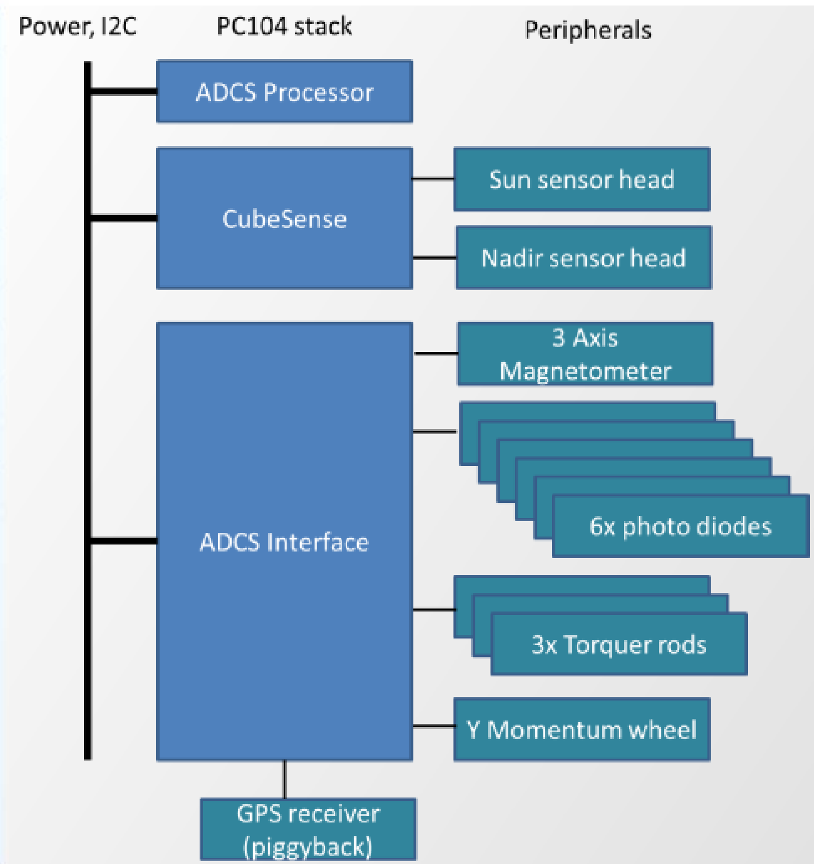
Spacecraft Bus

• MirrorSat ADCS Requirements

- 3-axis stabilized attitude control
- Accurate position, velocity & time from GPS
- < 1° roll, pitch, yaw stability (sunlit part of orbit)
- Low power: 2W (3-axis mode)

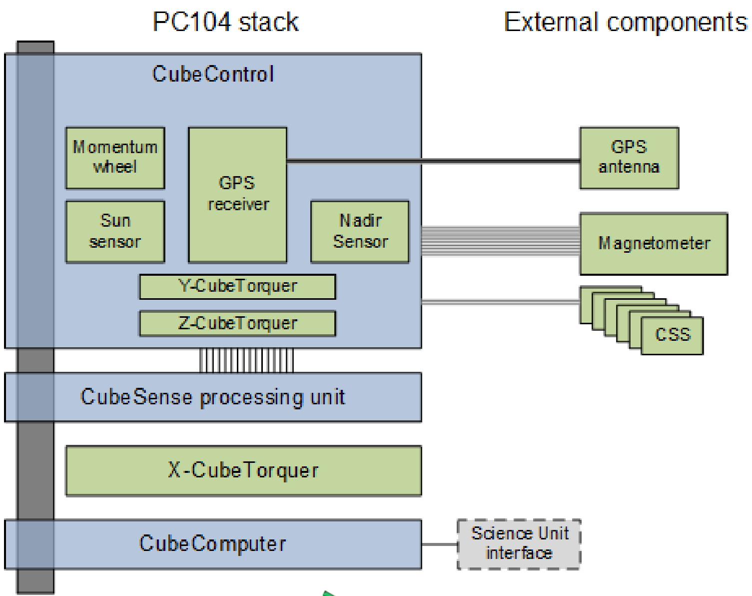
Processing

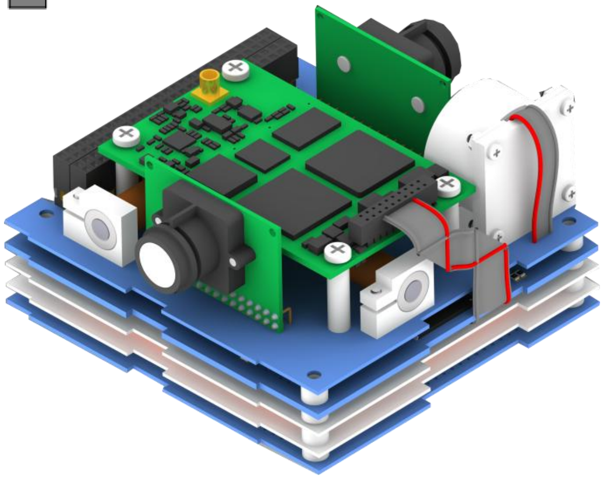
Processor	32-bit ARM Cortex-M3
Clock frequency	4-48 MHz
EEPROM	256 KB
Code Memory (flash)	4 MB
Data Memory (EDAC protected SRAM)	2x 1 MB
MicroSD support	Up to 2 GB
Communication	2x I^2C
	2x UART
Power use	< 200 mW



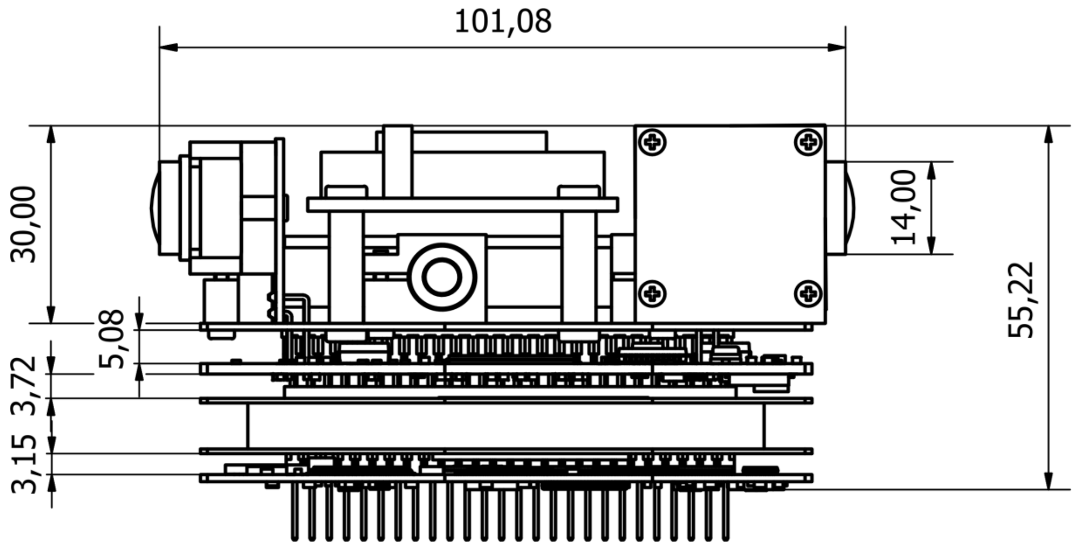
ADCS Hardware

- 3x PC104 boards
  - CubeComputer
  - CubeSense processing board
  - CubeControl
- Peripheral components
  - Fully integrated ADCS has momentum wheel, sun- and nadir cameras, GPS receiver and magnetorquers contained in stack
  - External GPS antenna, magnetometer and coarse sun sensor photodiodes
- In qualification (testing)
- 15 ADCS Units to be delivered in Nov 2013 (QB50)
- Flight heritage on STRaND-1



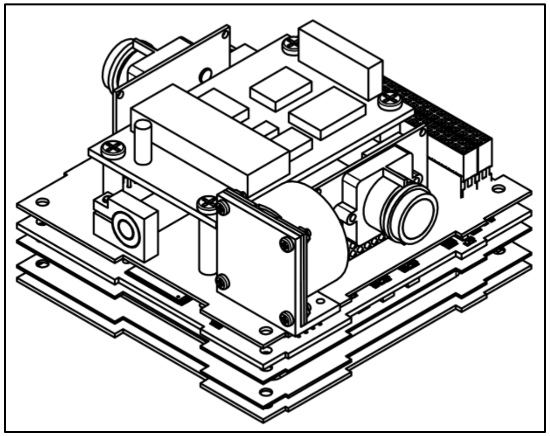


ADCS Interface specification



Mechanical interface

- Standard PC104 form factor for CubeComputer, CubeSense and CubeControl



Mass

< 450g for fully integrated system (incl. GPS receiver)

MirrorSat ADCS

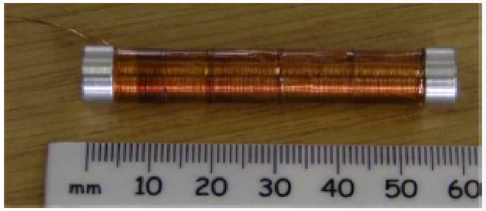
- **MirrorSat ADCS**
  - Z-axis coil 0.07 Am^2, 5V into ~100 Ohm (NanoPower P100U).

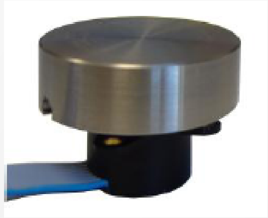
Sensors

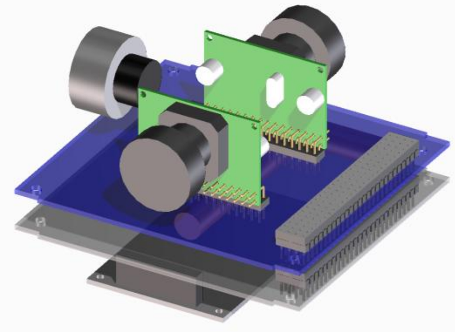
Coarse sun sensor	
Visibility	360°
Accuracy	< 10°
Sun & nadir sensor	
Mass	110 g
Power use	360 mW
Update rate	2 Hz
Sun sensor range	± 90°
Nadir sensor range	± 50°
Sun sensor accuracy	
within 40° of boresight	0.3°
full range	< 2°
Nadir sensor accuracy	0.18°

Actuators

Magnetic torquer rods	
Mass	22 g
Dimensions	60 x 8 x 8 mm
Maximum magnetic dipole moment	0.2 Am^2
Y momentum wheel	
Mass	45 g
Maximum momentum	1.7 mNms





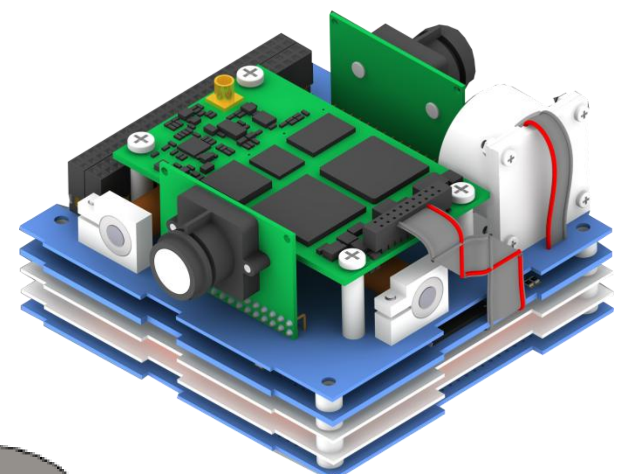


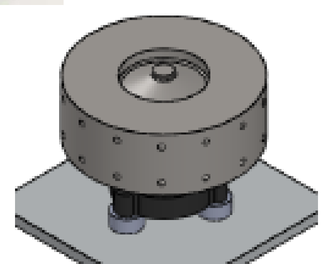
CoreSat ADCS

- **CoreSat ADCS**
  - Uses Compact Integrated ADCS system (as per MirrorSats), but replaces the single small pitch MW with three Surrey RWs (RPY) with dampers for increased control authority/low jitter control
  - Req’s: pointing (< 0.1^{o} error all axes), stability (< 0.02^{o}/s for 600s)
  - 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
  - Alternative COTS options exist (Sinclair, Stellenbosch) but noisy
  - For high precision pointing/stability we use Star camera + IMU

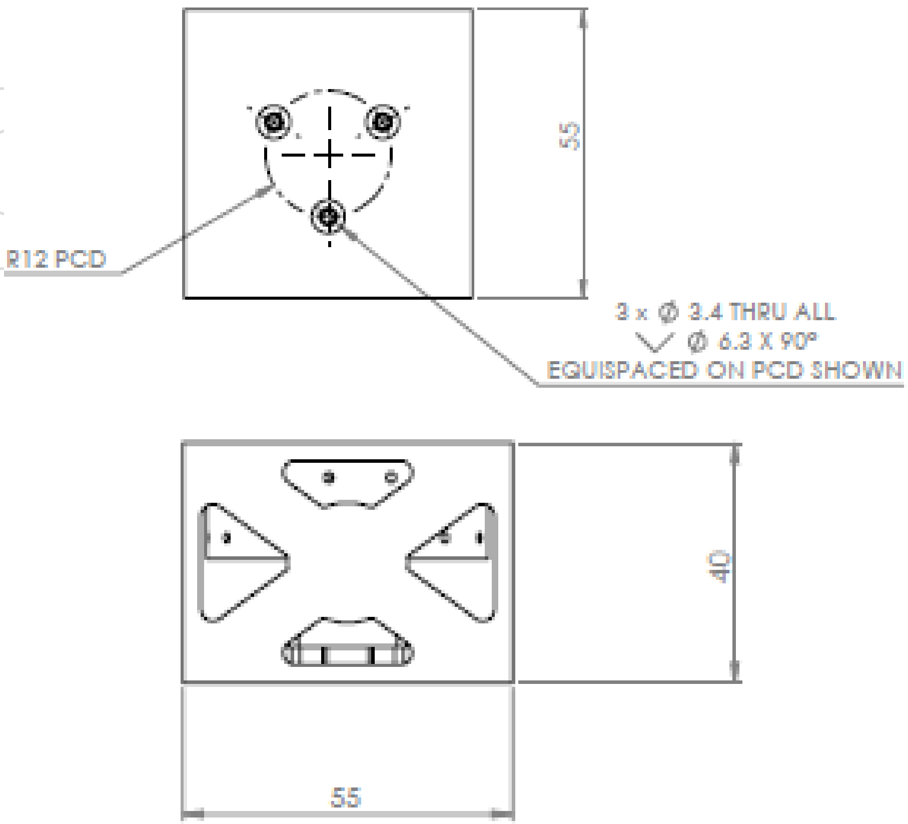
Supportsat ADCS

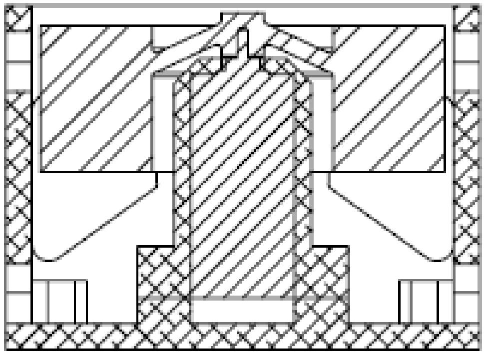
- CoreSat ADCS:
  - 2 x Mirrorcraft ADCS units (QB50) no MW
  - Magnetorquers from STRaND-1
  - 3 x RW for high res pointing with dampers for low jitter
  - 2 x miniature Star cameras (CubeStar)
  - 1 x IMU (gyros/acc's) from Surrey (SMESAT)



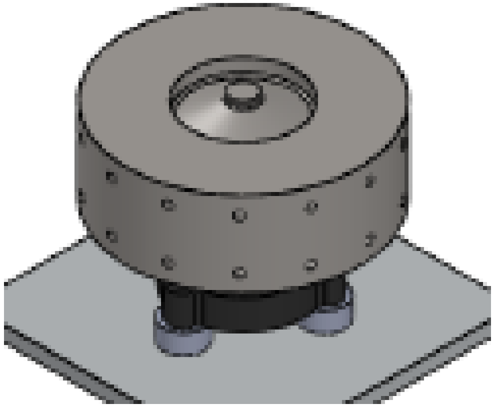


RW Design





SECTION A-A
SCALE 2 : 1



Micro-IMU

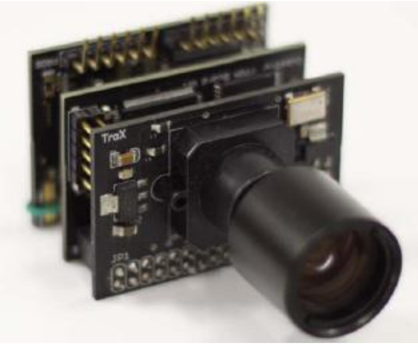
- Surrey Space Centre in house development
- Developed in EU FP7 SMESAT project (www.SMESAT.com)
- Based on Sensonor MEMS Gyros

STIM210 is a high-performance multi-axis gyro module including up to 3 gyroscopes (1, 2 or 3 axes)

- Low bias instability (0.5°/h)
- Low bias drift over temperature gradients (10°/h)
- Low noise (0.15°/√h)
- Short start-up time (1s)
- Integrated electronics

CubeStar

- Developed by Stellenbosch University (South Africa)
- Low cost, high performance, ultra miniature



Features

- Attitude quaternions or raw images can be output
- Onboard current monitors and power switches safeguard against radiation induced latchups.

Specifications (without Baffle)

Weight (g)	<100
Dimensions (mm)	46 x33x70
Power (mw)	320 nominal 500 peak
Operating Voltage (V)	3.3
Data Interface	I^2C / UART
Field of View (deg)	52 x 27
Star Catalogue Size	415

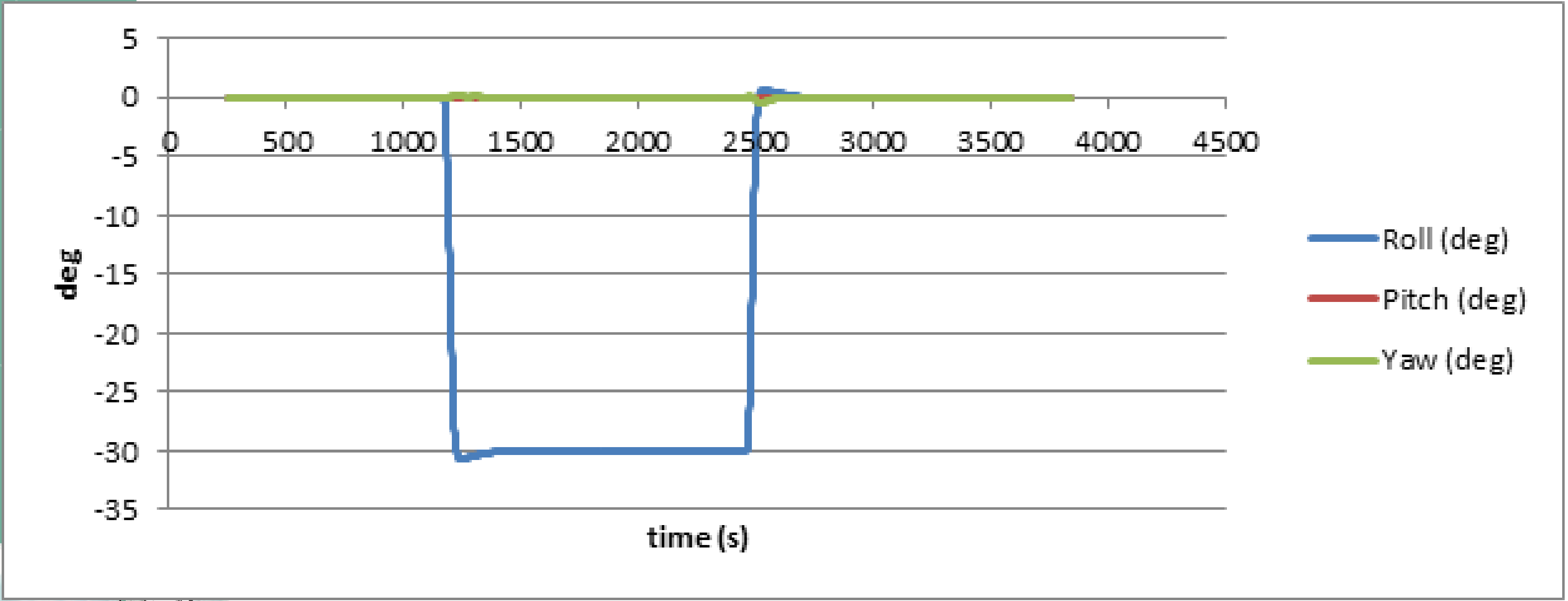
Performance

Sensitivity Range (Mag)	<3.8
Number of Stars Tracked	20
Accuracy (deg, 1σ)	0.01 (cross bore) 0.03 (roll)
Update Rate (Hz)	1
Max Tracking Rate (deg/s)	0.3
Max Acquisition Time (ms)	1000

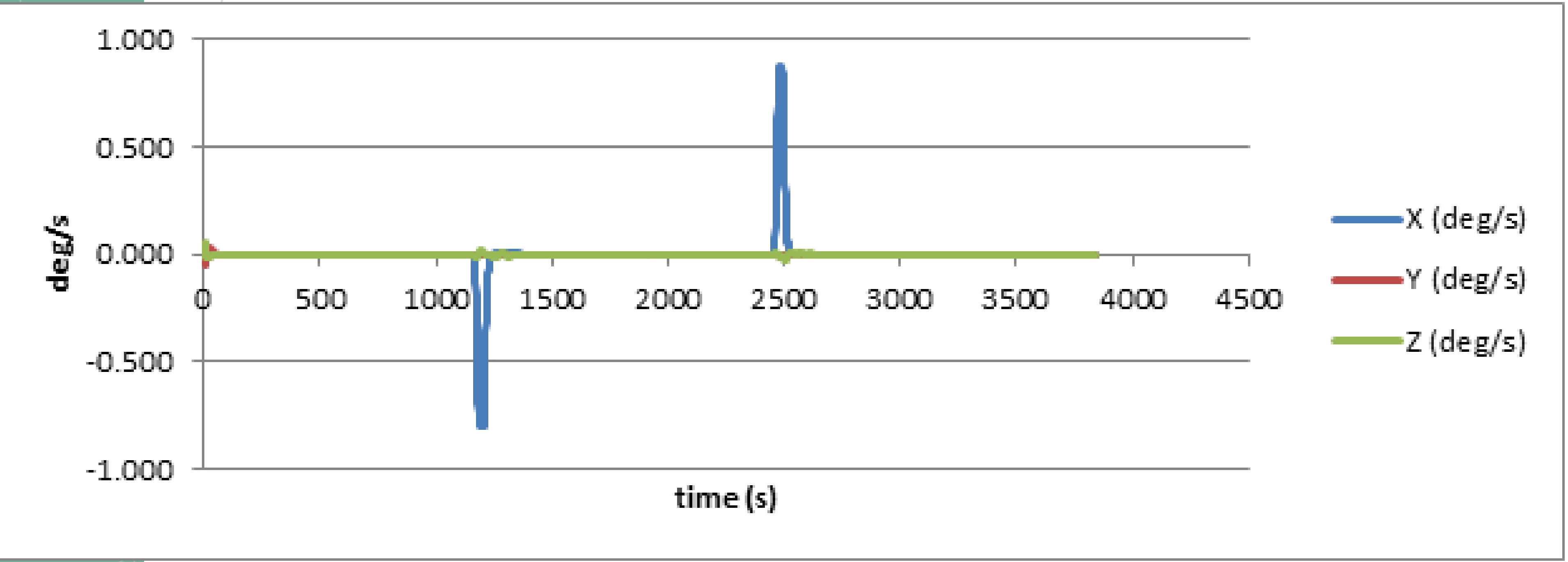
- CubeStar has been tested in a lab environment and under the night sky.
- Vacuum and thermal testing to be completed soon

Imaging ADCS Sim (I)

- SSO, 700 km
- ADCS+3 x Cubestar star cameras (no IMU)
- Also, the simulation assumes the reaction wheels can be controlled perfectly around 0 RPM.
- Ixx = 2.25 kg.m^2, Iyy = 2.25 kg.m^2, Izz = 0.12 kg.m^2
- RW: Wheel Max Torque = 0.002 Nm, Wheel Max Speed = 6000.0 RPM



Angular rates



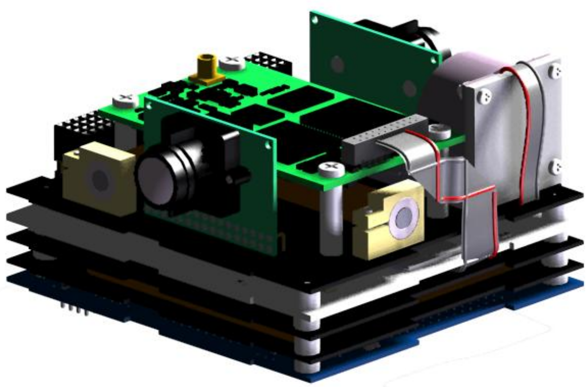
Imaging ADCS Sim (II)

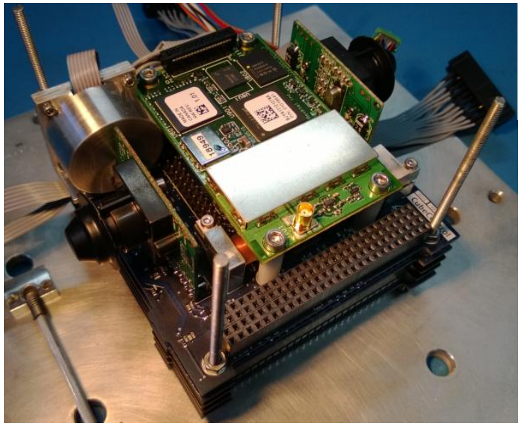
- At zero commanded RPY angles, the roll and pitch angles are bound by 0.005 deg. Yaw angles are a bit higher – bound by 0.03 deg.
- Angular rates for all 3 axes are well within 0.001 deg/s. Yaw angular rates are highest – between plus and minus 0.0005 deg/. The reason for larger yaw angles and rates is mainly because of the high cross products in the moment of inertia tensor, and smaller I_zz (compared to Ixx and Iyy).

- For a 30 deg roll command, once the attitude has settled, the roll angle remains within 0.05 deg of 30 deg. (pitch and yaw still bound as before). The angular rates in this time are also below 0.0005 deg/s

Commissioning on QB50 Precursors 1

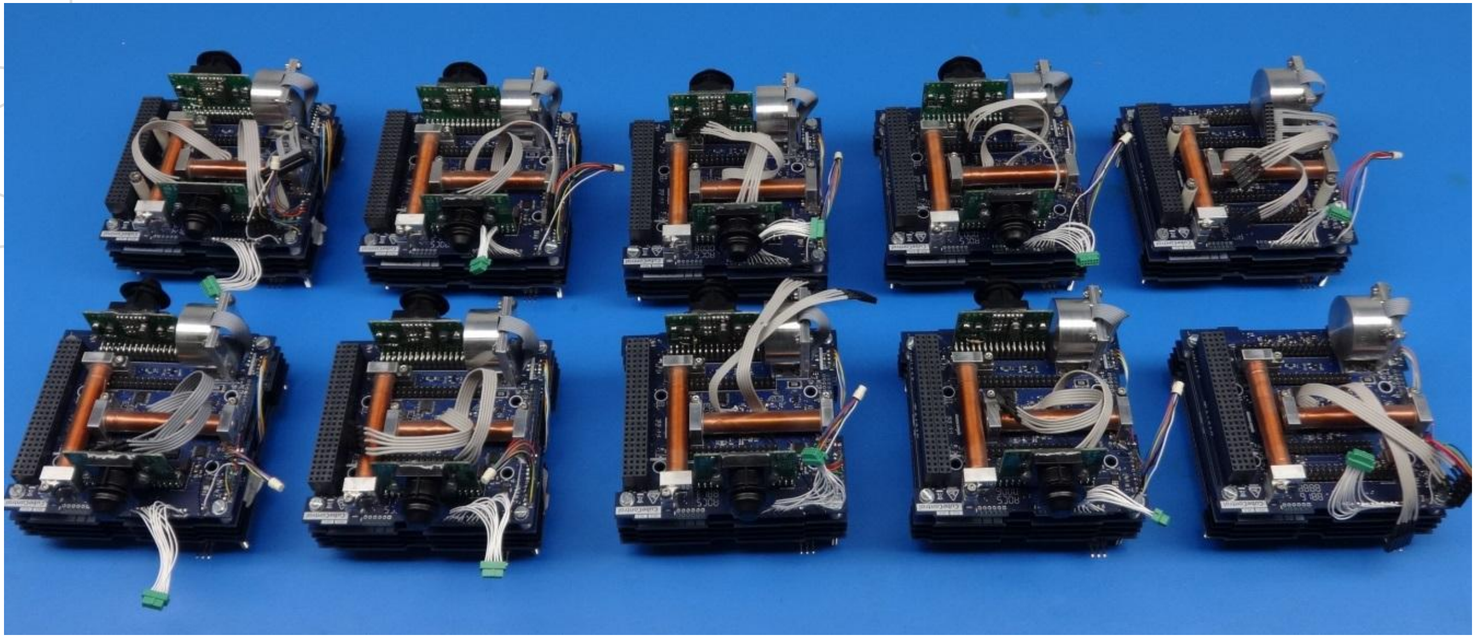
The ADCS bundle is currently on orbit as part of the two QB50 precursor satellites





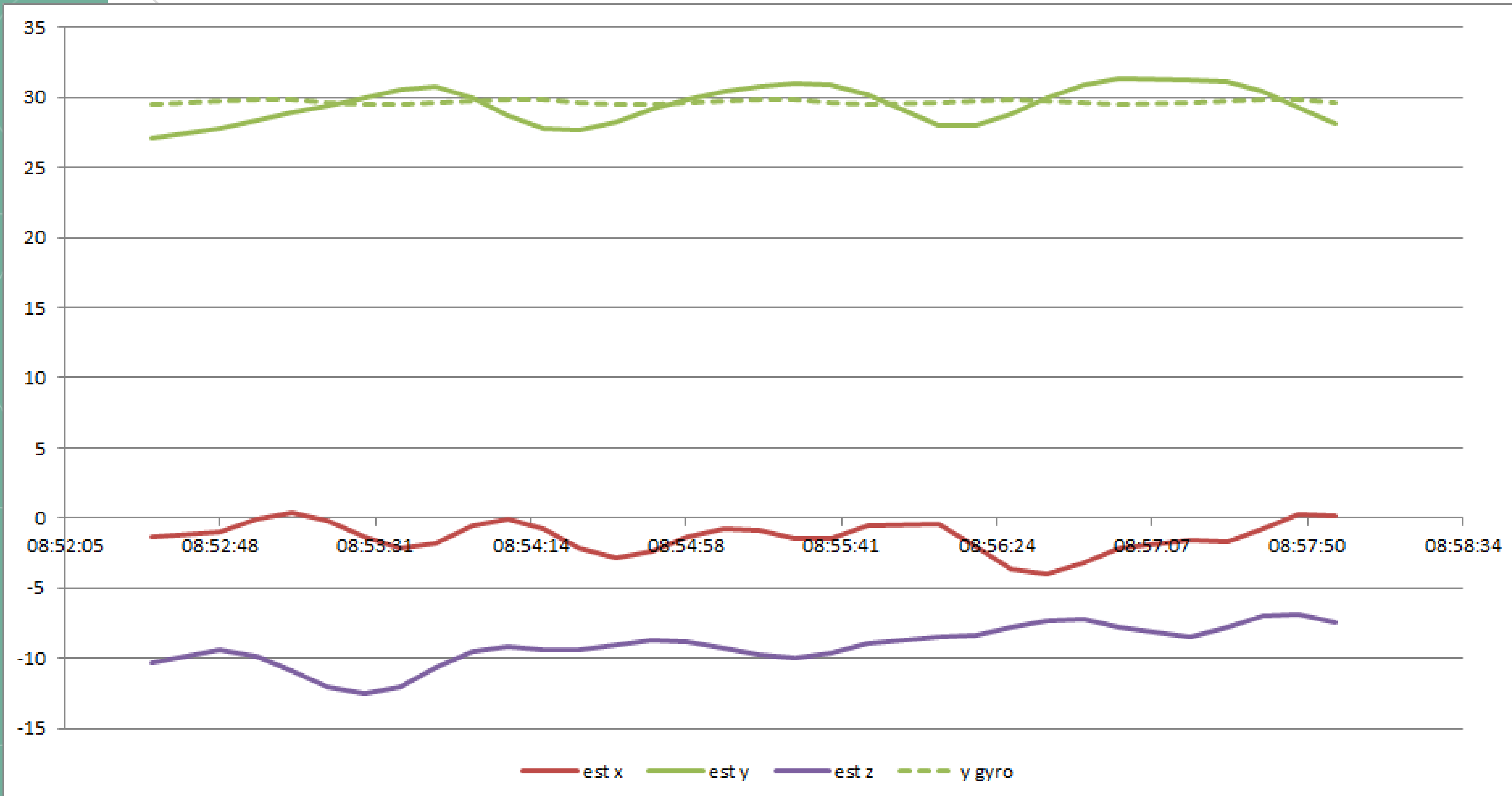
- CubeComputer has gone more than 24 hours without a reset
- Magnetometer and coarse sun sensors giving valid readings
- Initial ADCS performance tested

15 ADCS Systems Delivered!



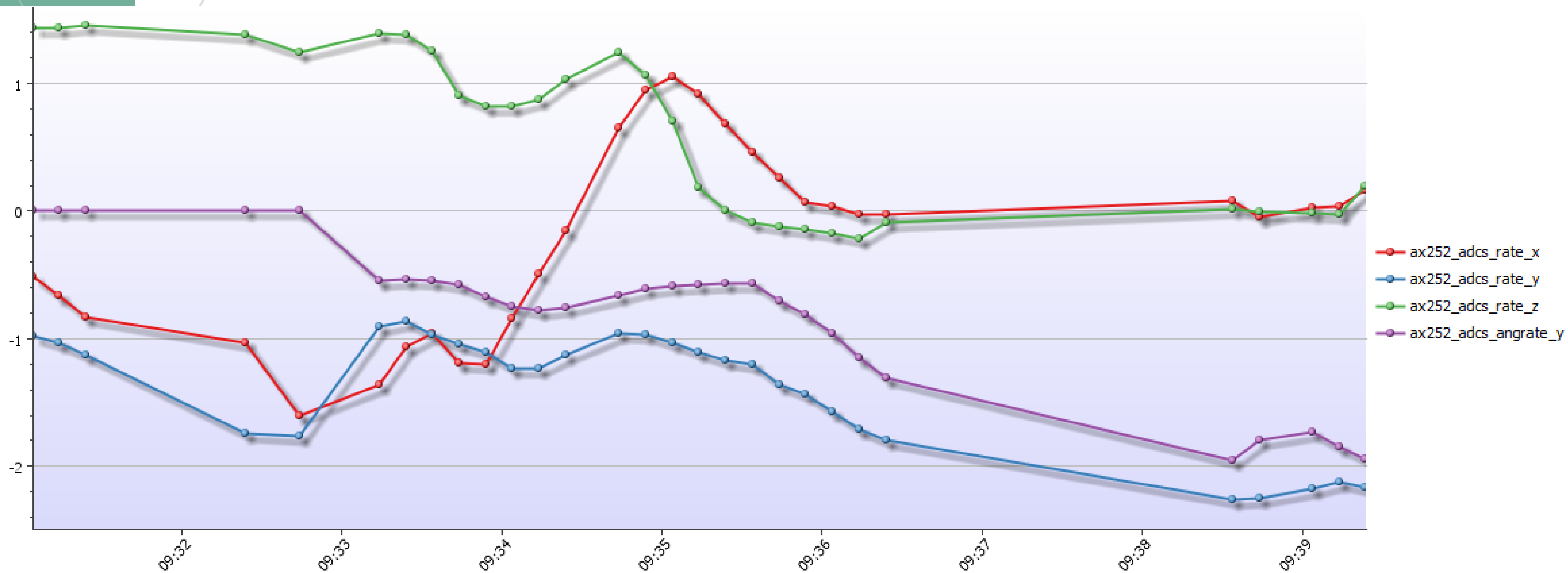
- 2 ADCS Systems launched on June 19 on a DENPR on 2 QB50 precursor cubesats

Commissioning on QB50 Precursors 2



Magnetic Rate Estimator works and matches gyro reading.
High initial rates >30 deg/s

Commissioning on QB50 Precursors 3



Successfully detumbled from high initial rates into -2 deg/s Y-Thomson spin

Commissioning on QB50 Precursors 4

Coming up:

- Commission CubeSense (sun + horizon sensor)
- Activate full-state estimator
- Test momentum wheel
- Enter 3-axis stabilised, nadir pointing attitude

ADCS Future work

- Asses RW jitter (Kistler table tests)
- Test new damping system on RW (Kistler table tests)
- Develop jitter disturbance model with Caltech:

1) To determine the type of resonance modes we have at spacecraft level (FEA Analysis)
2) To determine the type of resonance modes we have at camera level (FEA Analysis)
3) To determine the type of resonance modes they have at reaction wheel level
4) To know the predominant micro-vibration sources from the reaction wheel (Kistler test)