AAReST Spacecraft Update:

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

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Surrey Agenda

Tuesday (Sep 12): AM 384 Firestone; PM 232 Guggenheim

9:00 – 9:45	Surrey MirrorSat Structure & Bus Sub-Systems
	EPS/Batt./Solar Cells, ADCS/OBC S/W and Gnd. Stn.
9:45 – 10:30	Propulsion, Docking Port and Air Bearing Trials
10:30 – 10:45	*Break*
10:45 – 11:30	Docking Port & EM Modeling 2017 Work
11:30 – 12:00	LIDAR/Machine Vision RDV Sensors
12:00 – 1:00	*Lunch*
1:00 – 1:45	MirrorSat Payload Interface Computer
1:45 – 2:45	System Budgets, CONOPS & Video Link
2:45 – 5:00	Discussion

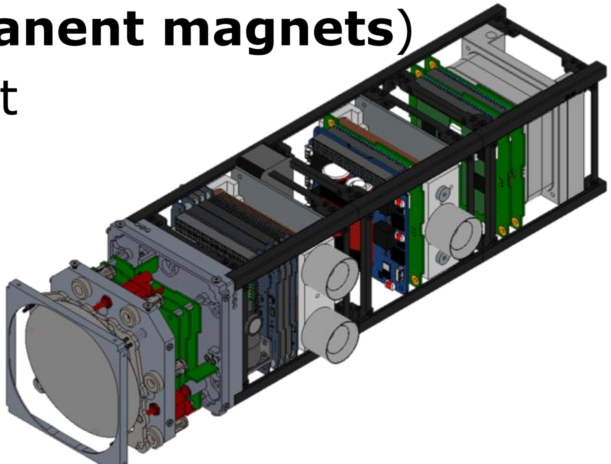
Surrey AAReST MirrorSat Structure & Bus Sub-Systems:

Structure, EPS, Battery, Solar Cells,

ADCS, OBC, S/W, SSC Ground Station

MirrorSat Spacecraft Bus

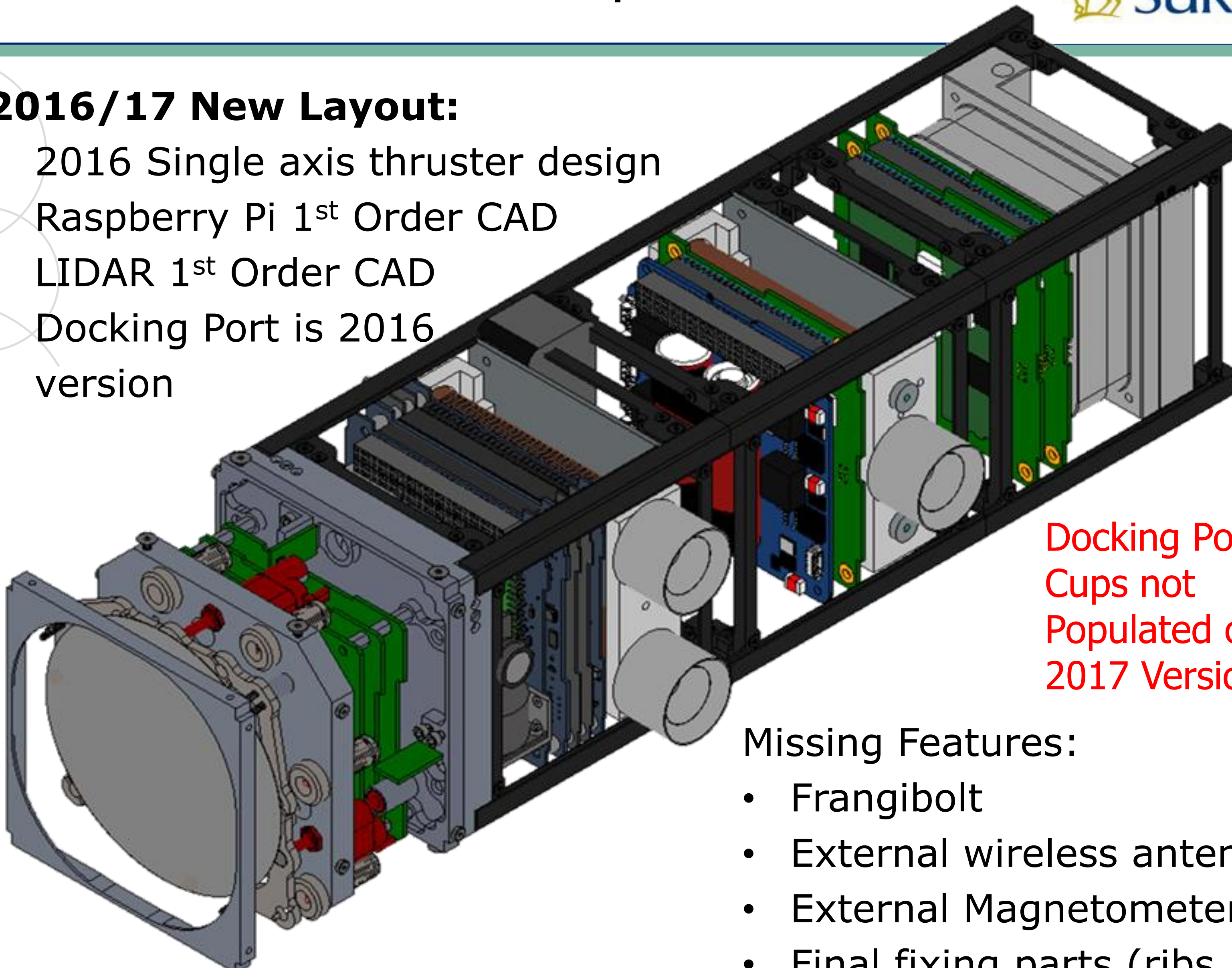
- **MirrorSat Requirements**
  - Must support the Deformable Mirror Payload (DMP) mechanically and electrically via a 5V 1A supply (2W continuous operational power) and TTC via a UART interface
  - Must be able to operate independently of other units
  - Must be able to communicate with the CoreSat out to 1km max. via Wi-Fi ISL
  - Must be able to **undock, rendezvous** and **re-dock** multiple times – **relative motion/capture/docking EM controlled**.
  - Must have **3-axis control** and **1 DOF propulsion** capability
  - Must provide low/zero power magnetic latch to hold in position on CoreSat in orbit (via **CoreSat permanent magnets**)
  - Must be able to safely enter the CoreSat Docking Port's acceptance cone:
    - ~50cm distance (mag. capture);
    - ±45° full cone angle; < 5 cm offset
    - <±10° relative RPY error;
    - < 1 cm/s closing velocity at 30cm;
    - < ±2° relative RPY error at first contact.



MirrorSat Spacecraft Bus

2016/17 New Layout:

- 2016 Single axis thruster design
- Raspberry Pi 1st Order CAD
- LIDAR 1st Order CAD
- Docking Port is 2016 version



Docking Port Cups not Populated on 2017 Version

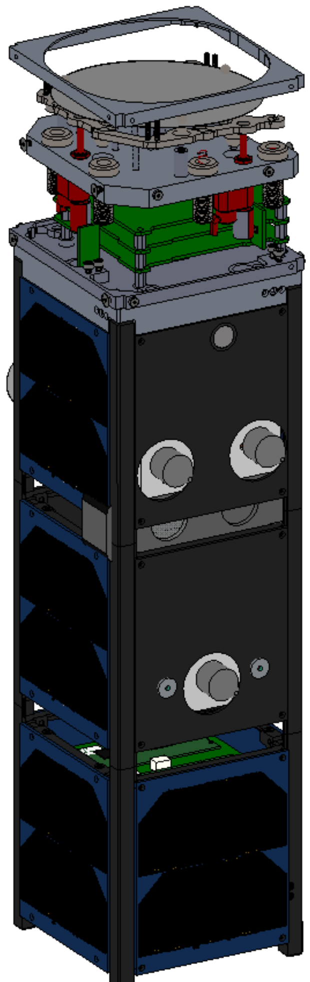
Missing Features:

- Frangibolt
- External wireless antenna
- External Magnetometer
- Final fixing parts (ribs, etc)

MirrorSat Spacecraft Bus

- **MirrorSat System New Layout 2017**

Note: CAD still being updated



CalTech Payload

ESL ADCS/OBC Bundle

Top EM Docking Port

Soft Kinetic LIDAR DS325

Frangibolt goes here

Gomspace EPS + 20 Wh Batt.

Power Switch Board (PSB)

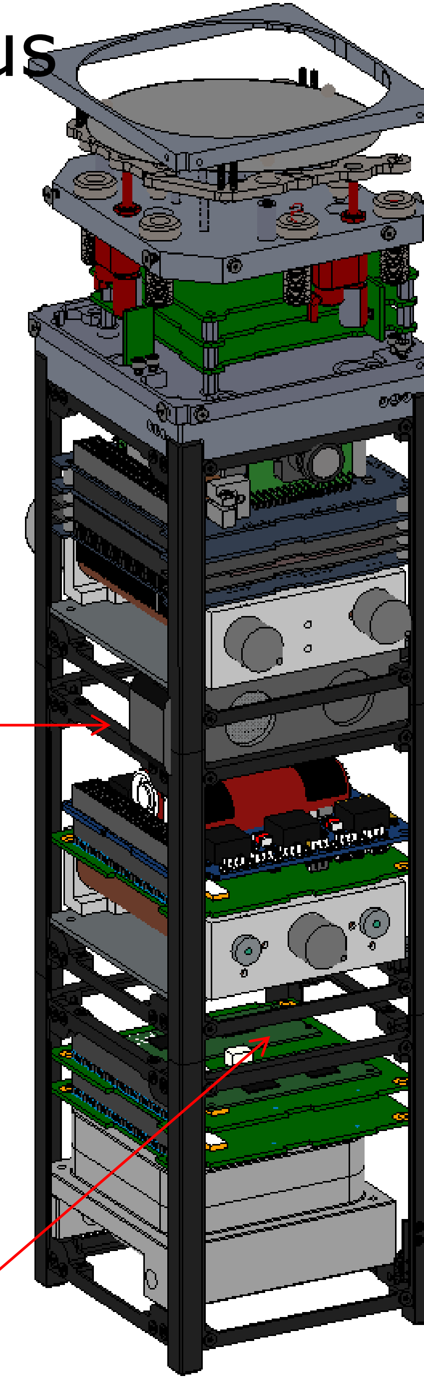
Bottom EM Docking Port

Payload Interface Computer (Dual redundant RPi)

Thruster Control Board

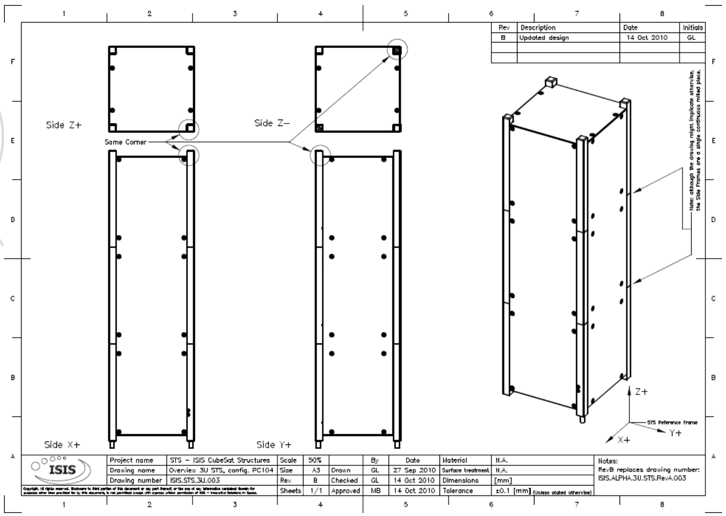
Z Axis Butane Thruster

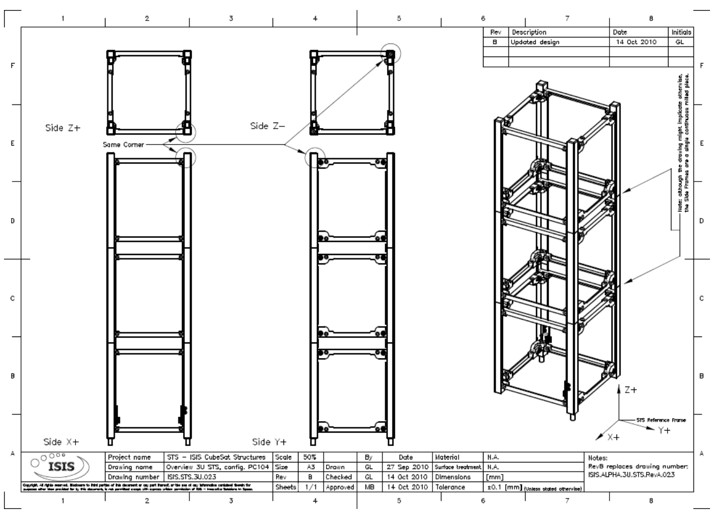
Lidar/Camera moves to here



MirrorSat Spacecraft Bus

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

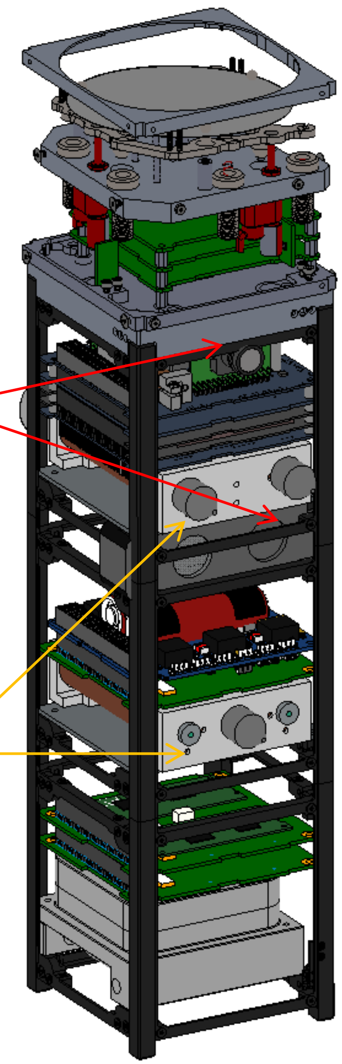




Note: CAD still being updated

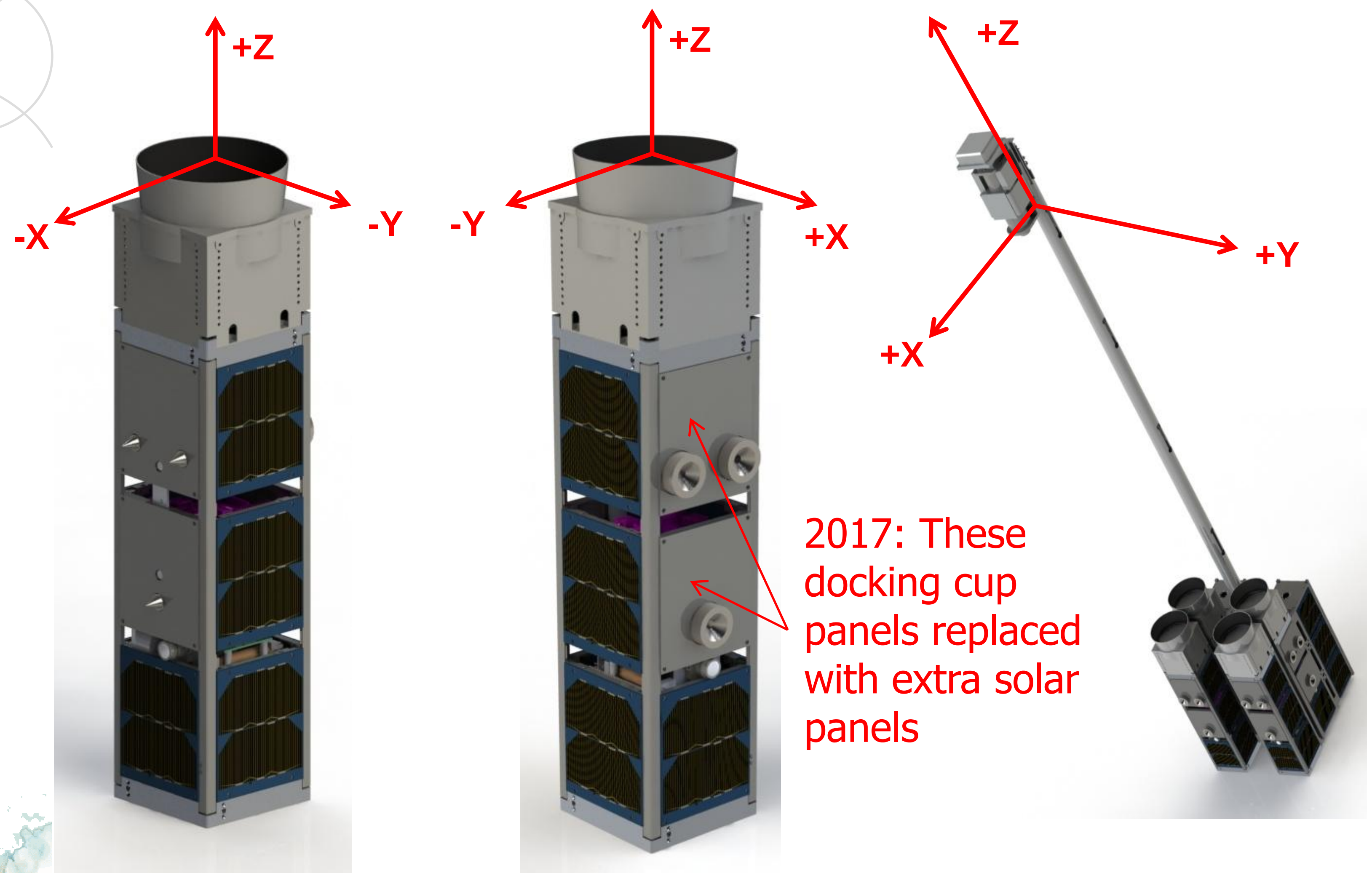
Ribs need modification so as not to block the LIDAR and cameras

Docking port location set by rib positions



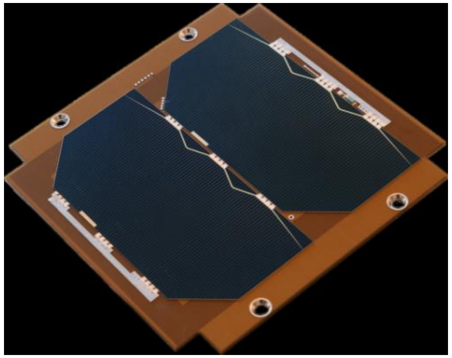
MirrorSat Spacecraft Bus

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



MirrorSat Spacecraft Bus

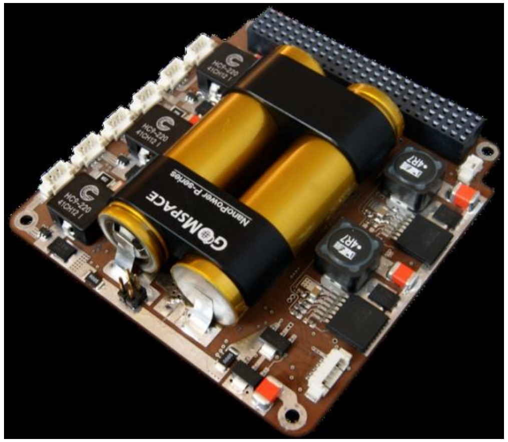
- **MirrorSat Solar Panels**
  - **COTS GOMSPACE NanoPower P110 Series**
  - Compatible with ISIS structure
  - AzurSpace 3G30A space qualified triple junction cells at ~30% efficiency with CMX 100 cover glass (100um); 26-29g per 1.1mm thick; blocking diode, Sun Sensor and Temperature Sensor included on each PCB.



  - **-X facet** (Docking Port side) has 1 PCB – generating 500mA at 4.7V (**2.3W**) max. per facet.
  - **+X and Y facets** have **three PCBs** connected in parallel – generating 1.5A at 4.7V (**6.9W**) max. per facet.
  - Orbit average power for the free-flying MirrorSat ~2.5W (depending on final orbit choice and attitude scenario).
  - When docked, -X and one of the Y facets will be shadowed – however, an additional 5V at 0.8-1A (**4-5W**) is available to the MirrorSat via the Docking Port connected to the **USB Charger port** of the MirrorSat EPS.
  - **Note: Solar Panels will be similar bespoke Surrey design**.

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 telemetry and telecommand.

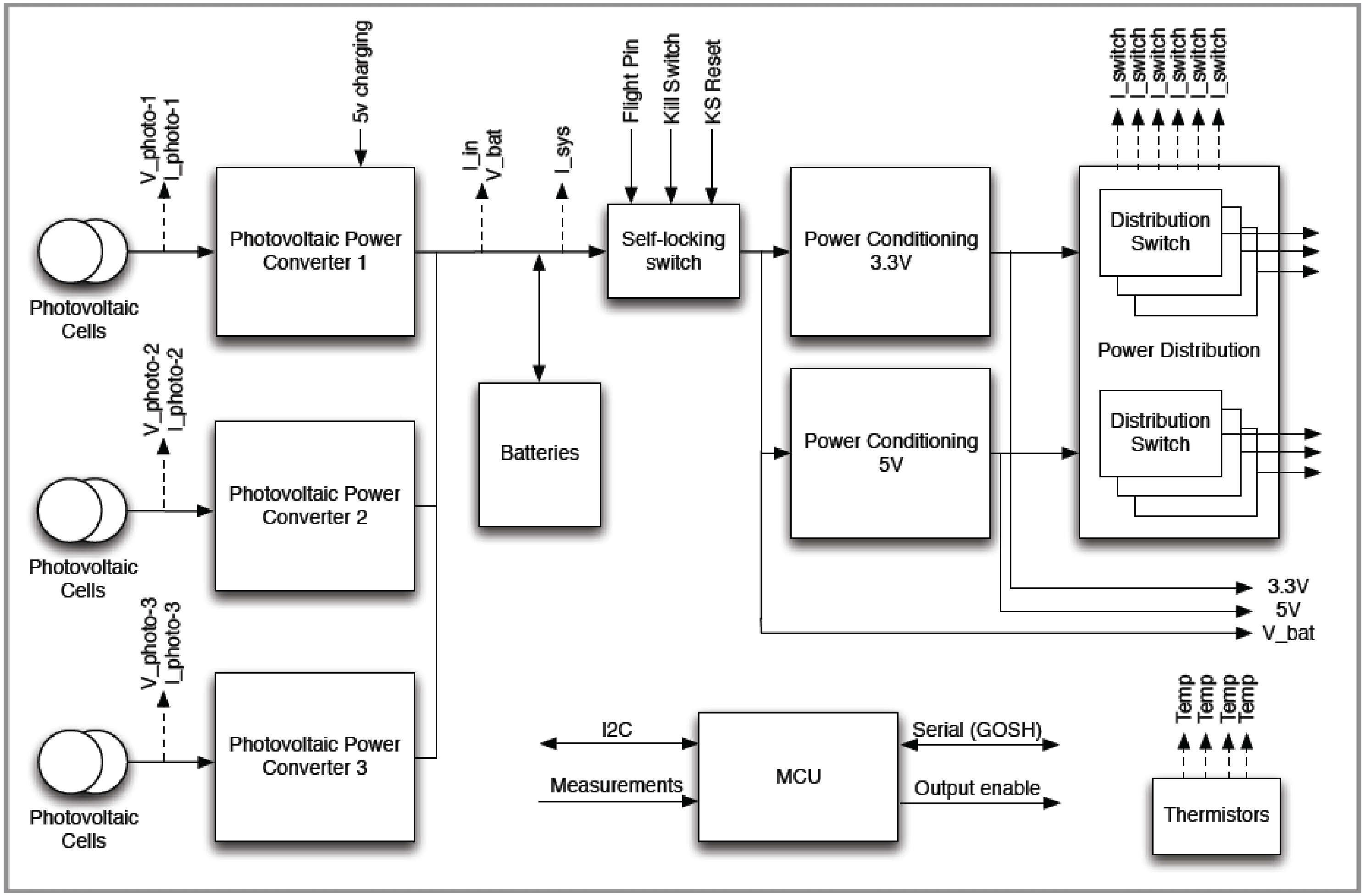


MirrorSat Spacecraft Bus

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

MirrorSat Spacecraft Bus

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



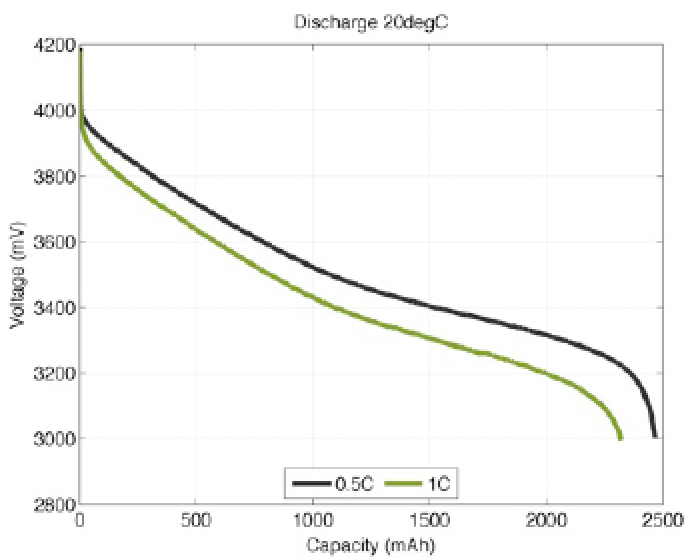
- **MirrorSat EPS**
  - **Housekeeping (I2C):**
    - Four temperatures
    - Current into and out of photovoltaic power converters
    - Photovoltaic input voltage for each input converter
    - Battery voltage
    - Total current into the output bus converters.
    - Current out of all power output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

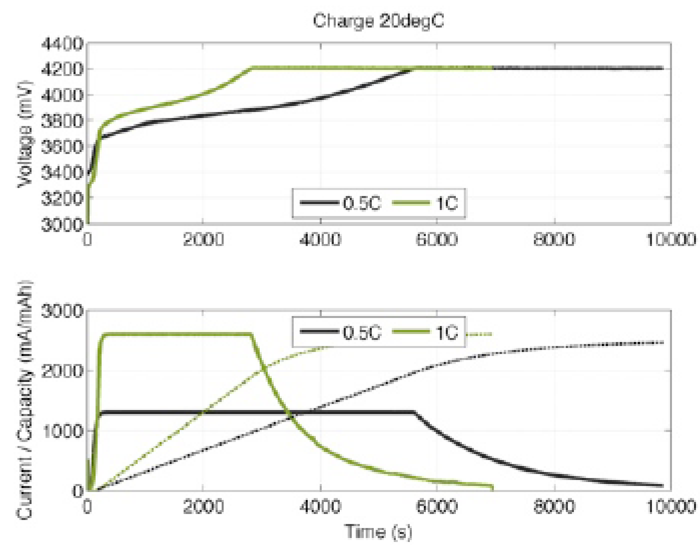
Parameter	Range (non-S)	Resolution (non-S)	Range (S)	Resolution (S)
Temperature	-40 to +125 deg C	1 deg C	-40 to +125 deg C	1 deg C
I_photo	0 to 3A	3mA	0 to 3A	3mA
I_in	0 to 6A	6mA	0 to 6A	6mA
I_sys	0 to 12A	12mA	0 to 12A	12mA
I_switch	0 to 2.4A	3mA	0 to 2.4A	3mA
V_photo	0 to 9.5V	10mV	0 to 19V	20mV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

MirrorSat Spacecraft Bus

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

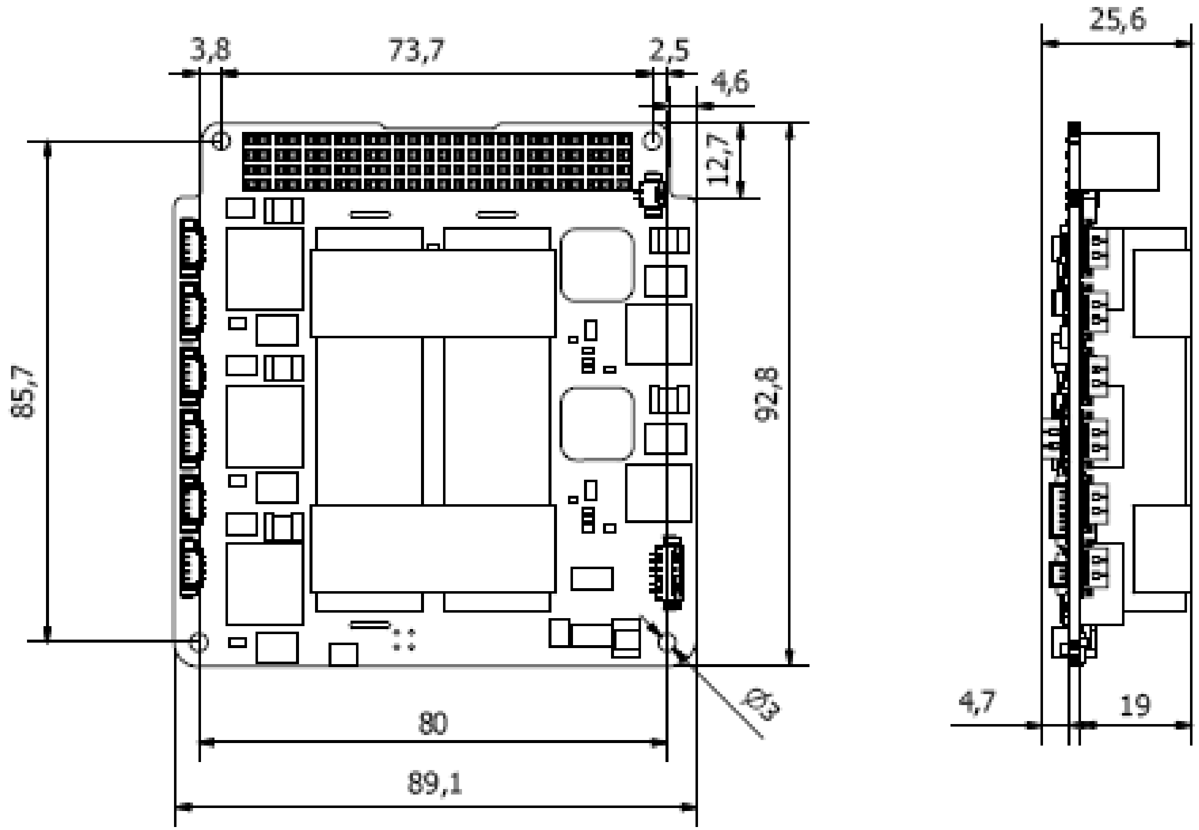
Parameter	Condition	Min	Typ	Max	Unit
Lithium-Ion Cell					
- Voltage		3.0	3.7	4.2	V
- Charge current			1000	2500	mA
- Discharge current			1000	3750	mA
- Charge temperature		-5		45	ºC
- Discharge temperature		-20		60	ºC
- Storage temperature	80% recovery after 1 year	-20		20	ºC
- Internal impedance		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





MirrorSat Spacecraft Bus

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

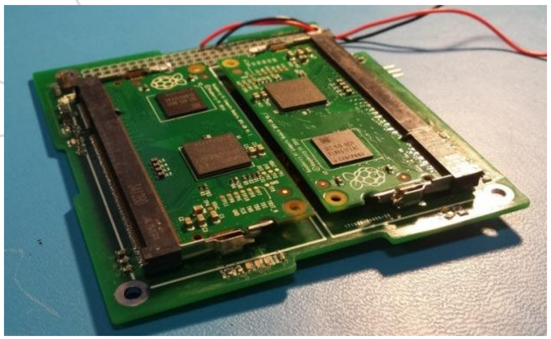


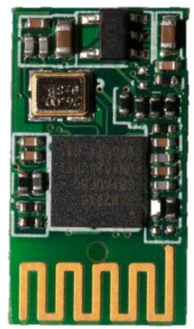
MirrorSat Spacecraft Bus

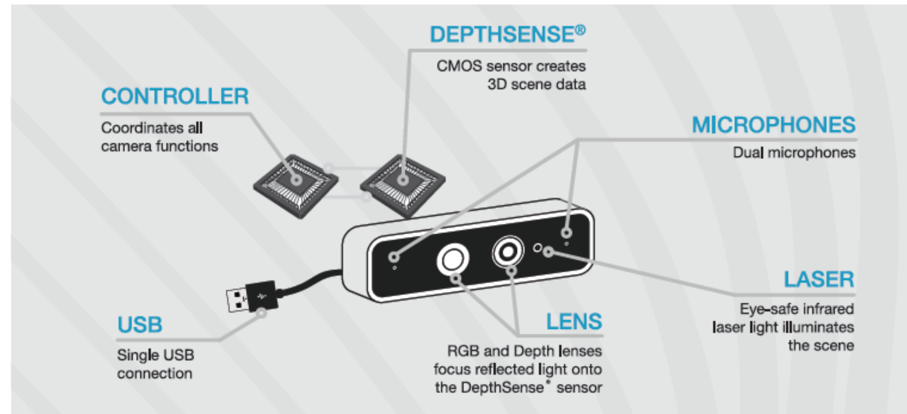
- **MirrorSat Power Budget (not updated)**
  - Systems connections/ power budget:
    - **EPS:** 125 mW on; 60 uA off (700 day min. discharge)
    - **ADCS:** (**CubeControl**; **CubeSense**; **CubeComputer**) – ADCS **3.3V sw.**; ADCS **5V sw.**; GPS **3.3V fixed**; GPS **5V fixed**; total consumption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

MirrorSat Spacecraft Bus

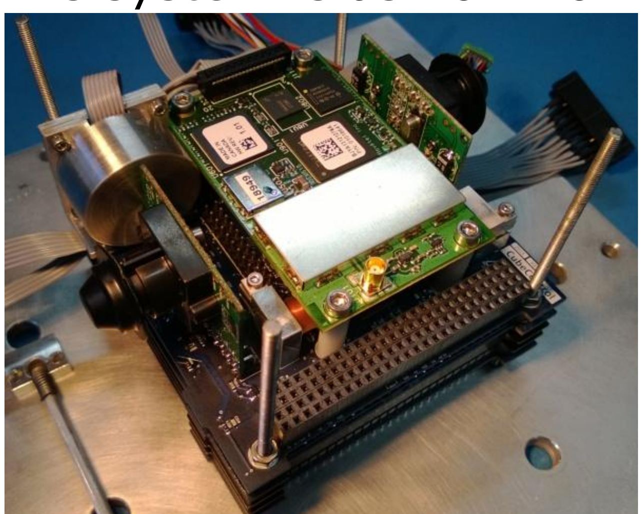
- **MirrorSat PICs: Payload Control/ISL Communications**
  - These systems and their current status will be presented by Dr Chris Bridges shortly.

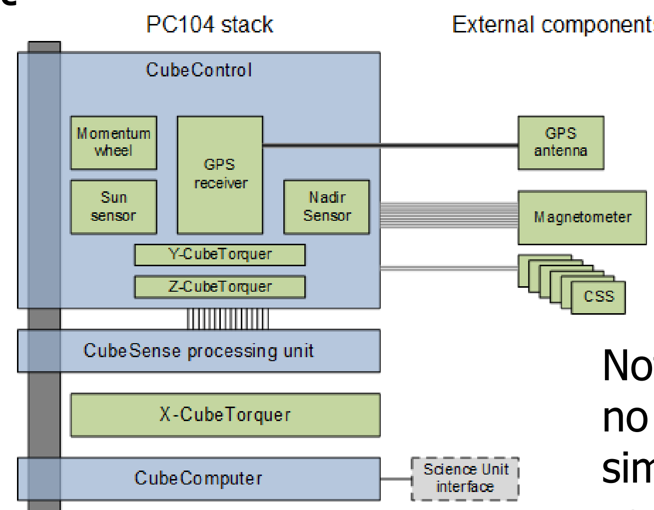






- **MirrorSat ADCS/OBC**
  - This system is as flown on QB50 with the latest software.

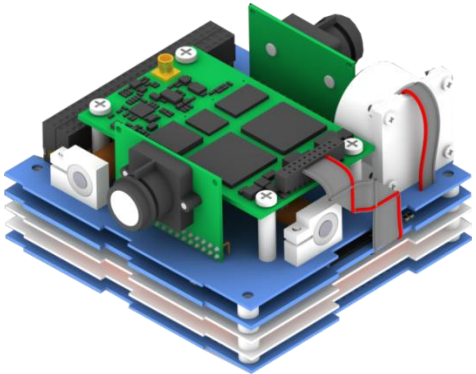




Note: Propose no GPS to simplify export control issues

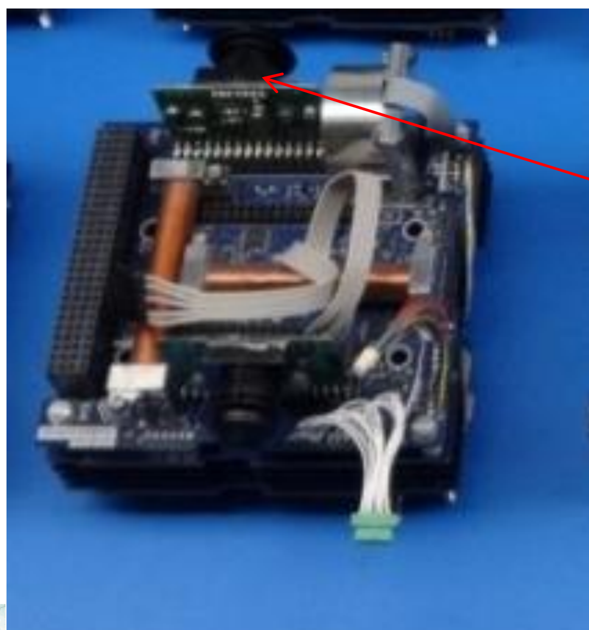
MirrorSat Spacecraft Bus

- **MirrorSat ADCS/ OBC**
  - Compact (450g) Integrated ADCS System developed for QB50 by Prof. Steyn (Stellenbosch - ESL) and Lourens Visagie (Surrey).
  - OBC functionality/ Real-Time Operating System (RTOS) developed by SSC. Comprises:
    - CMOS Camera Digital Sun Sensor (remote mount)
    - CMOS Camera Digital Earth Sensor (remote mount)
    - 6 Course Analogue Sun Sensors (must fly all 6)
    - 3-Axis Magnetoresistive Magnetometer
    - 3-Axis Magnetorquer (2 Rods + 1 Coil)
    - MEMS Gyro
    - Pitch-Axis Small Momentum Wheel
    - GPS Receiver (Novatel OEM615) interface (NOT POPULATED)
    - Updated EKF and B-dot control software built-in + RTOS/OBC S/W
    - SGP4 Orbit Propagator
    - 1 Hz control loop rate
    - **~2^{o} pointing stability (in sunlight)**

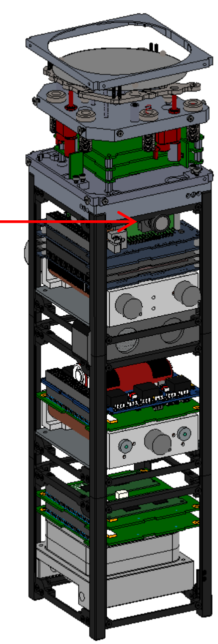


MirrorSat Spacecraft Bus

- **MirrorSat ADCS/ OBC**
  - The **nadir sensor** can also act as an optical camera, and so this is configured to lie on the –X facet, such that it “looks” at the CoreSat when the MirrorSat is docked.
  - Thus, upon separation, this sensor should capture images of the CoreSat for later downloading.
  - The momentum wheel axis is aligned with the Y-axis, and thus gives “**pitch” control** relative to the CoreSat and provides **stiffness in the roll and yaw** axes relative to the CoreSat.



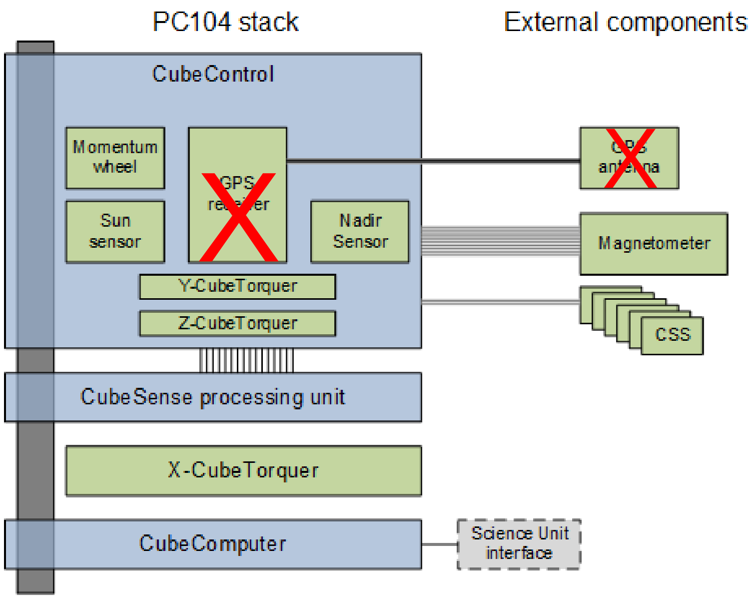
Nadir Sensor:
180º FoV
Monochrome
CMOS
Camera

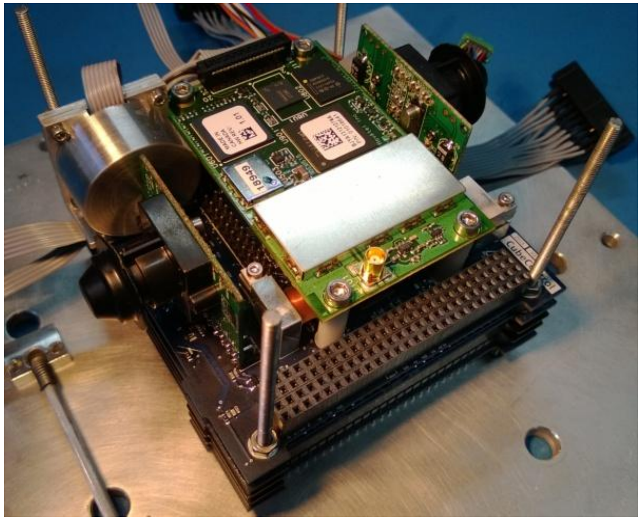


MirrorSat Spacecraft Bus

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

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





MirrorSat Spacecraft Bus

MirrorSat ADCS

- 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

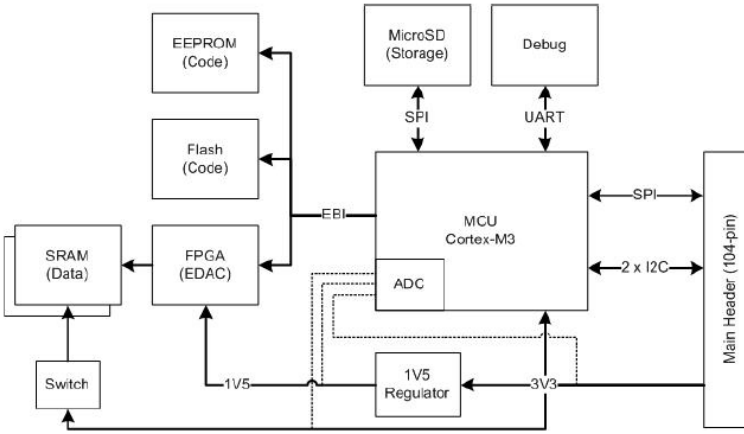
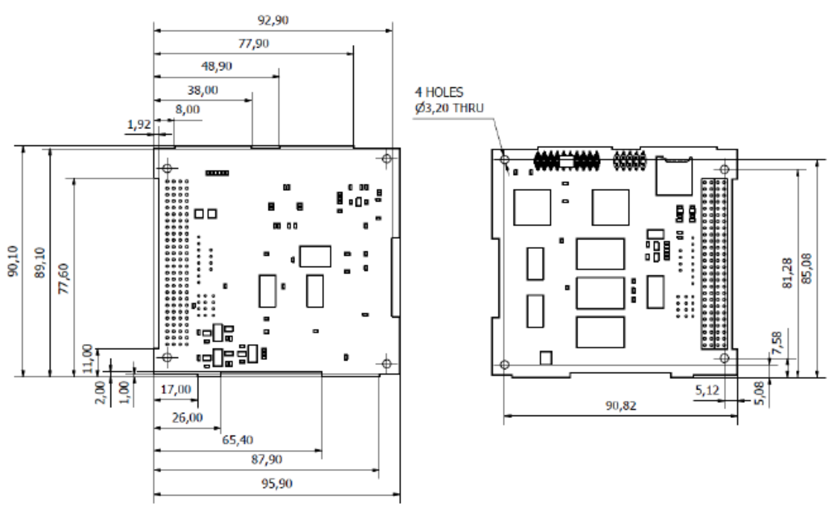


FIGURE 1 - CUBECOMPUTER BLOCK DIAGRAM



MirrorSat Spacecraft Bus

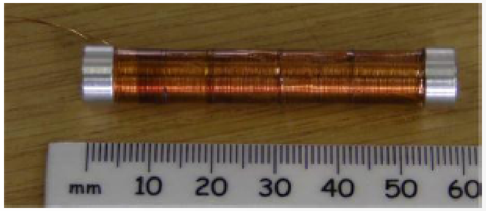
- **MirrorSat ADCS/ OBC**

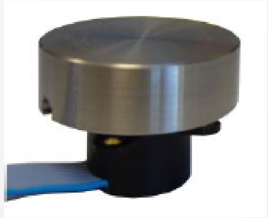
Sensors

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

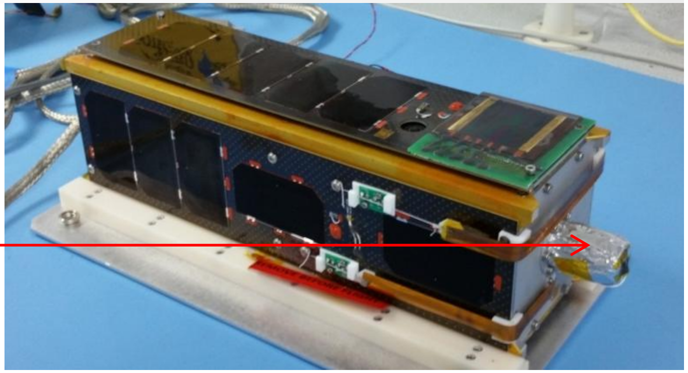




External Magnetometer: 16 x 17 x 6mm

- Mounted on –Z Facet as per AlSat-1N

MLI covered 3-Axis Magnetometer



MirrorSat Spacecraft Bus

- **MirrorSat ADCS/ OBC**
  - **ADCS Specifications:**

Specification	Value	Notes
Physical		
Mass	400g	Complete system including GPS receiver and deployable magnetometer boom
Dimensions		
PC104 stack	90 x 96 x 60 mm	
CSS	4 x 11 x 2 mm	
External magnetometer housing	16 x 17 x 6 mm	
Performance		
Attitude update rate	1 Hz	
Attitude measurement accuracy (>200 km)		
Pitch	< 0.5°	1σ
Roll and yaw	< 2.0°	1σ
Pointing accuracy (Y-momentum mode)		
> 300km altitude	< 0.5° [1]	1σ
> 200km altitude	< 2.5° [1]	1σ
Time to reach steady-state Y-Thomson motion from 10°/s initial tip-off rate (at 350km altitude)	< 0.5 days [1]	Maximum time from Monte-carlo simulation of 1000 test cases.

- **MirrorSat ADCS/ OBC**
  - **ADCS Specifications:**

Specification	Value	Notes
Magnetorquers		
Maximum magnetic dipole	0.2 Am^2	
On-time command resolution	0.2 ms	For a 1Hz control period
Momentum wheel		
Maximum momentum storage	1.7 mNms	
Maximum wheel speed	± 8000 rpm	
Maximum torque	0.35 mNm	
Wheel inertia	2.0 $kg.mm^2$	

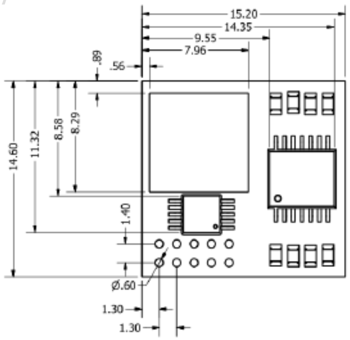
  - **Status:**
  - The QB50 ADCS hardware flown with success.
  - Surrey use the ADCS Computer as the primary OBC.

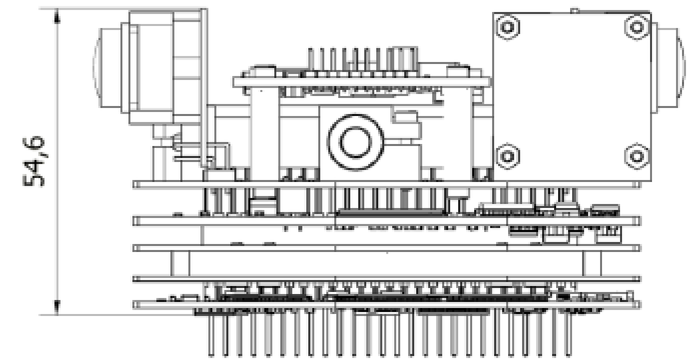
MirrorSat Spacecraft Bus

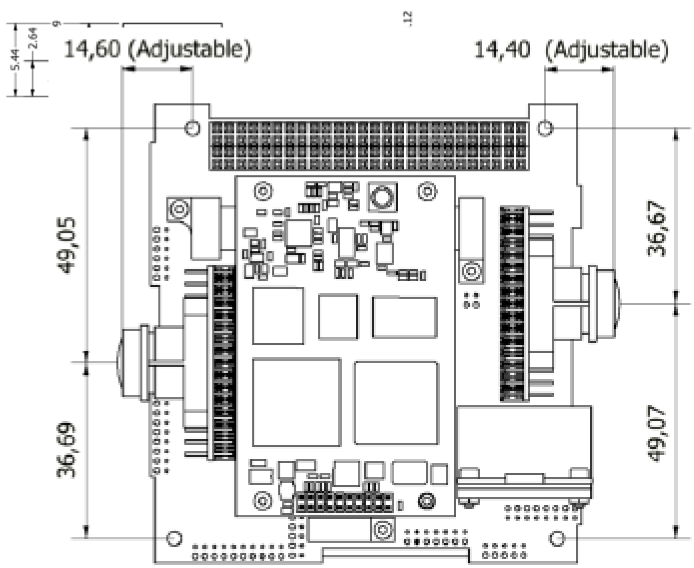
SURREY SPACE CENTRE

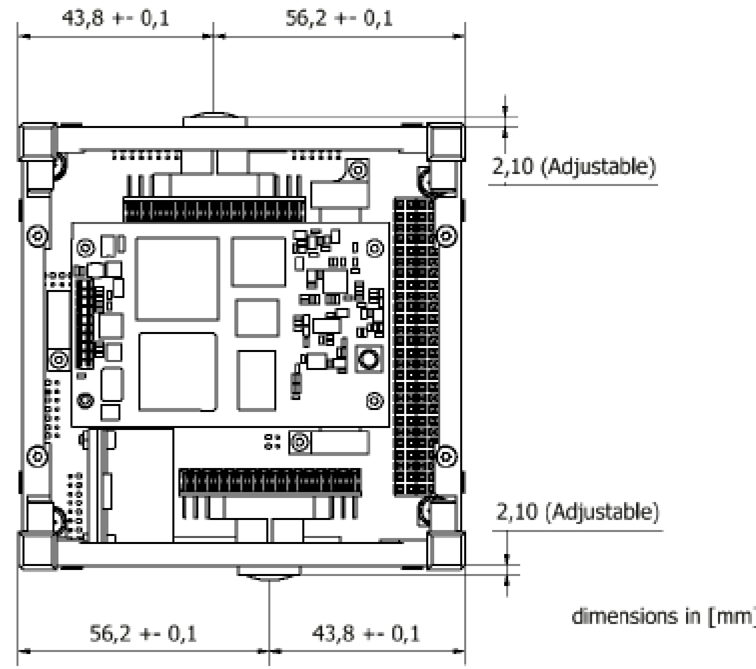
UNIVERSITY OF SURREY

- **MirrorSat ADCS/ OBC**
  - **Dimensions:** (460g mass)









- **MirrorSat ADCS/ OBC**
  - **ADCS PC104 Header Pin Allocation:**

H2	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51
H1	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51

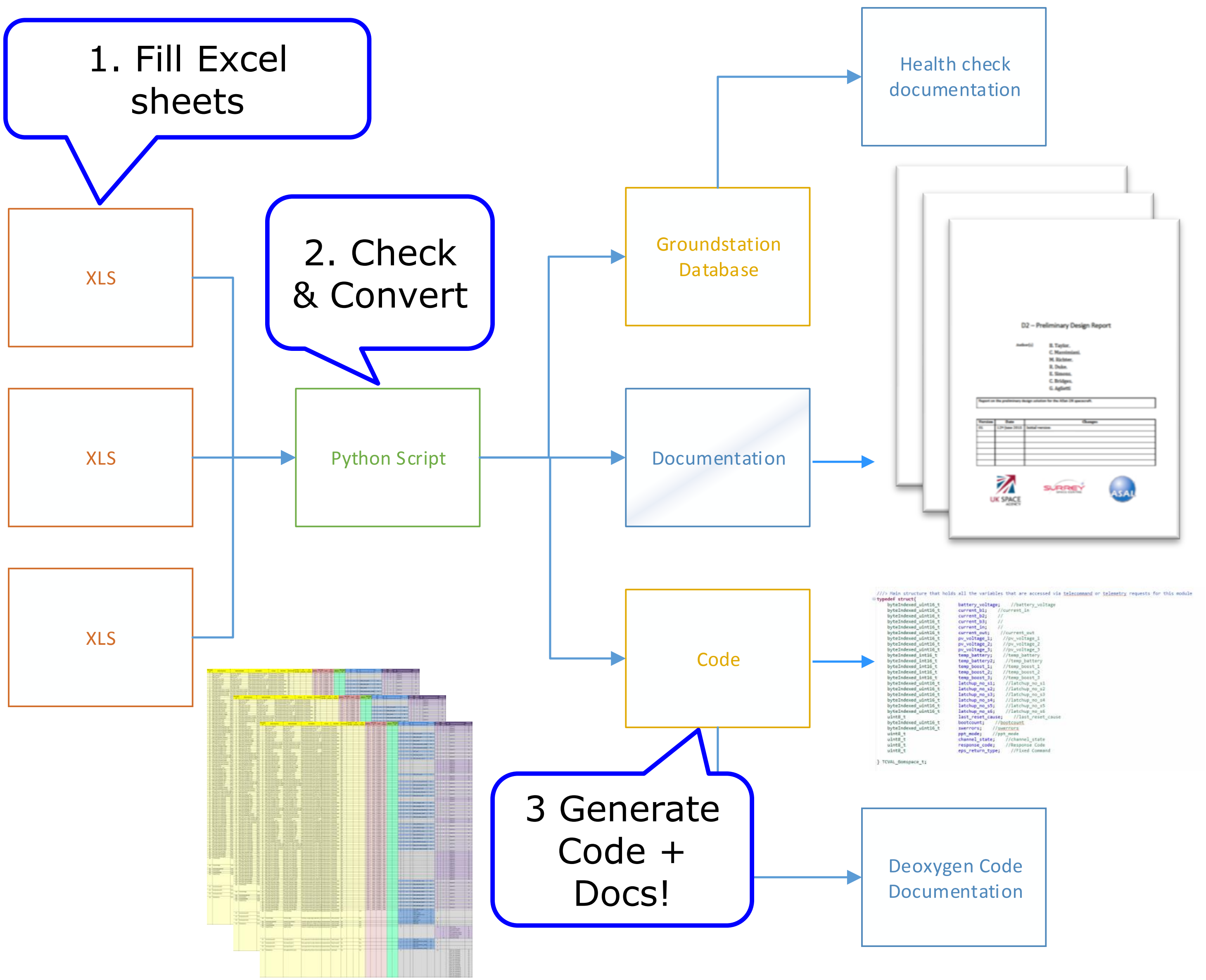
PC104 Interface pins				
	H1	41	SYS I2C_SDA	System I2C Data
	H1	43	SYS_I2C_SCL	System I2C Clock
	H1	47	ADCS +5V	+5V ADCS supply
	H1	48	ADCS +3.3V	+3.3V ADCS supply
	H1	50	GPS +3.3V	GPS 3.3V supply
	H2	27/28	+3V3	connect to 3V3 (either switched on with H1-48 or always on)
	H2	29	GND	Ground connection
	H2	30	GND	Ground connection
	H2	32	GND	Ground connection
	H2	45	V Bat	Battery bus
	H2	46	V Bat	Battery bus

PC104 Reserved pins				
	H1	21	ADCS I2C_SCL	ADCS I2C Clock (used internally)
	H1	23	ADCS I2C_SDA	ADCS I2C Data (used internally)
	H2	20	CubeSense Enable	Enable line to control CubeControl power switch (used internally)

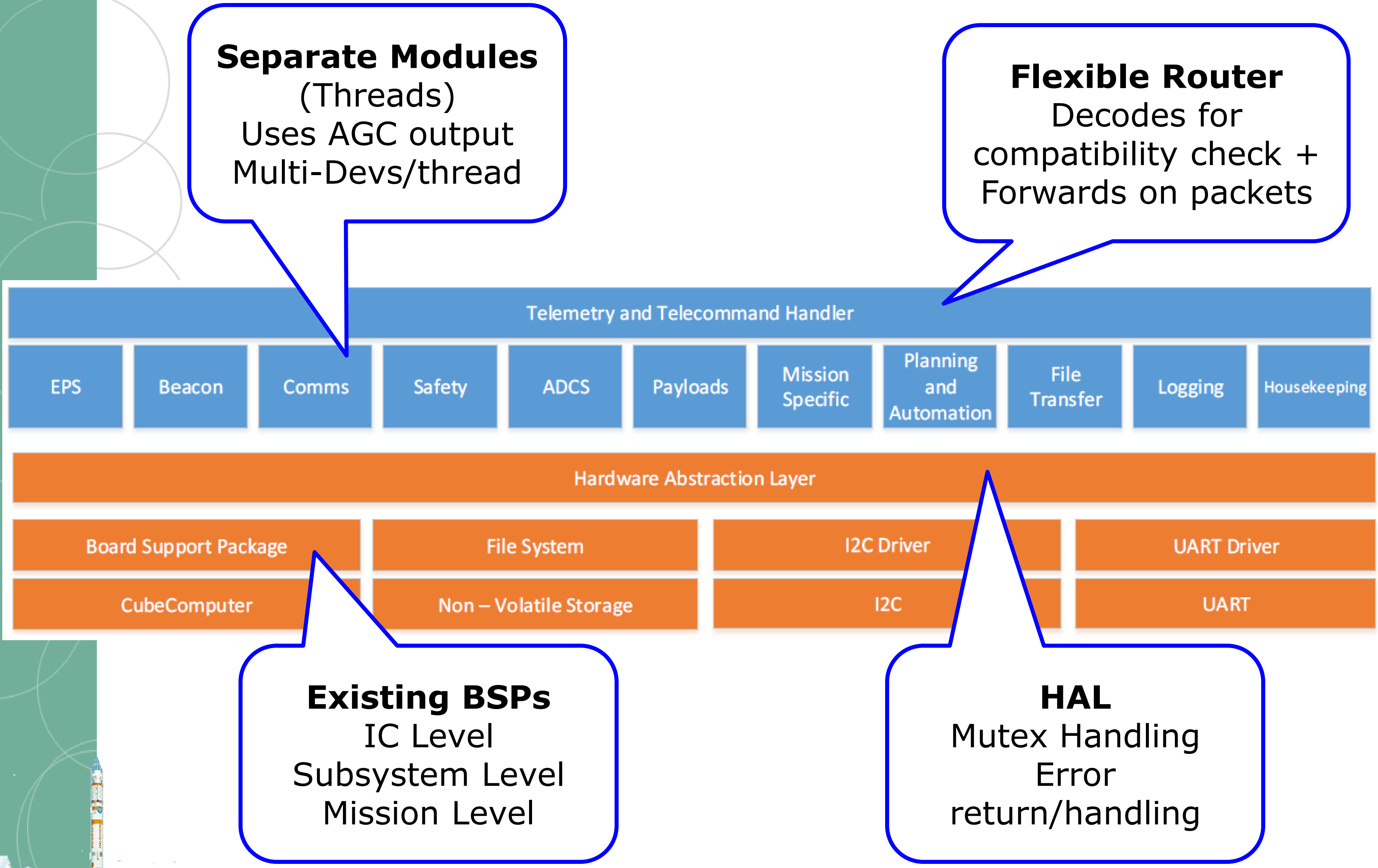
MirrorSat Spacecraft Bus

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

MirrorSat Spacecraft Bus

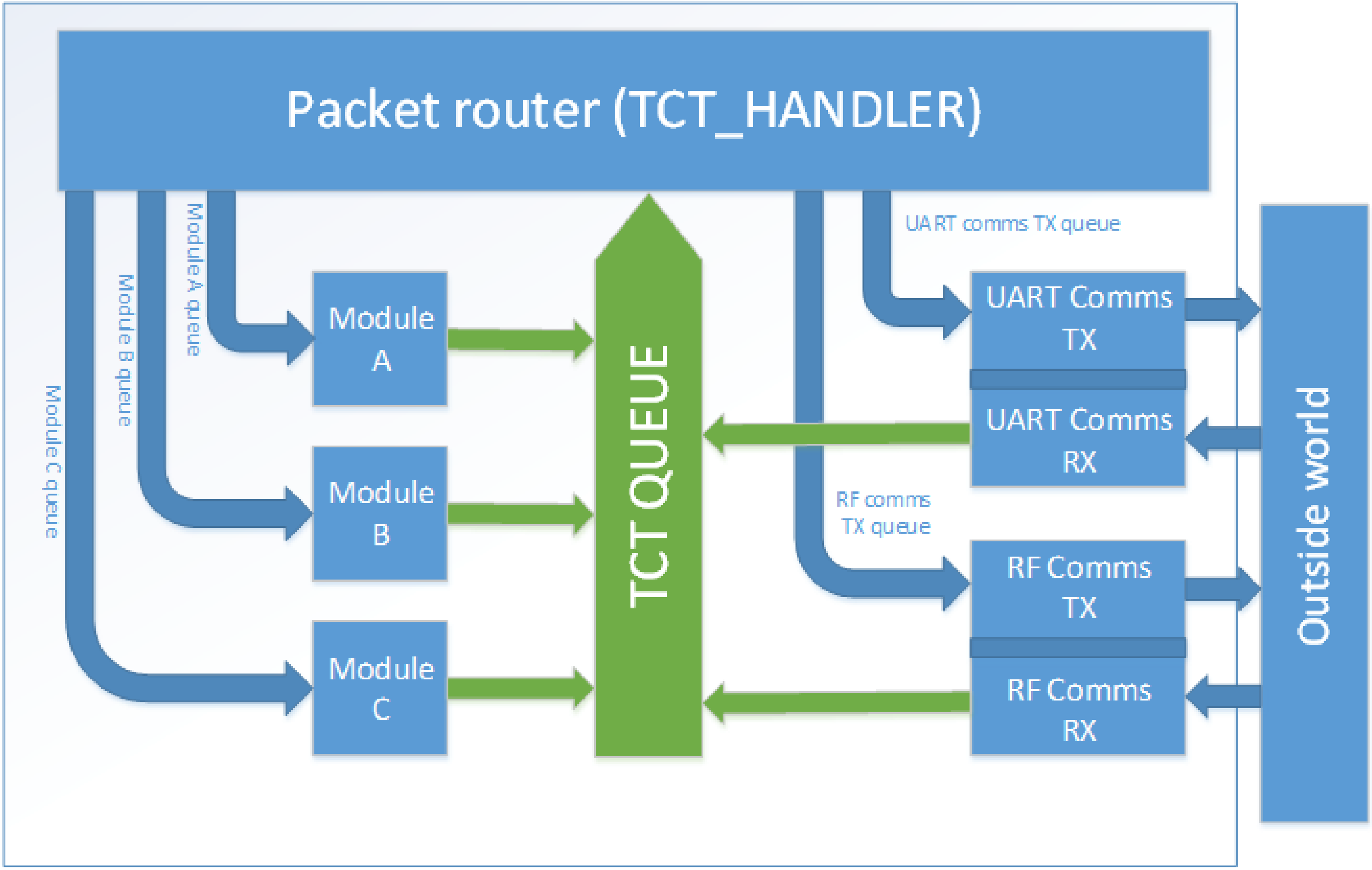


MirrorSat Spacecraft Bus

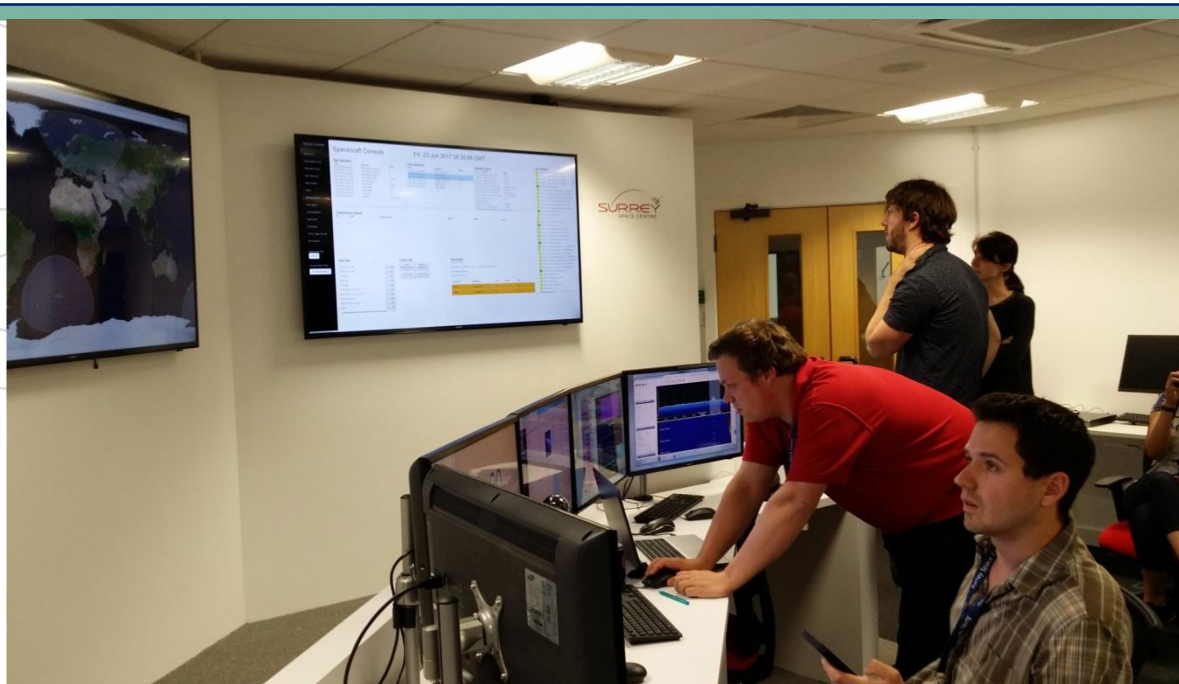


MirrorSat Spacecraft Bus

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



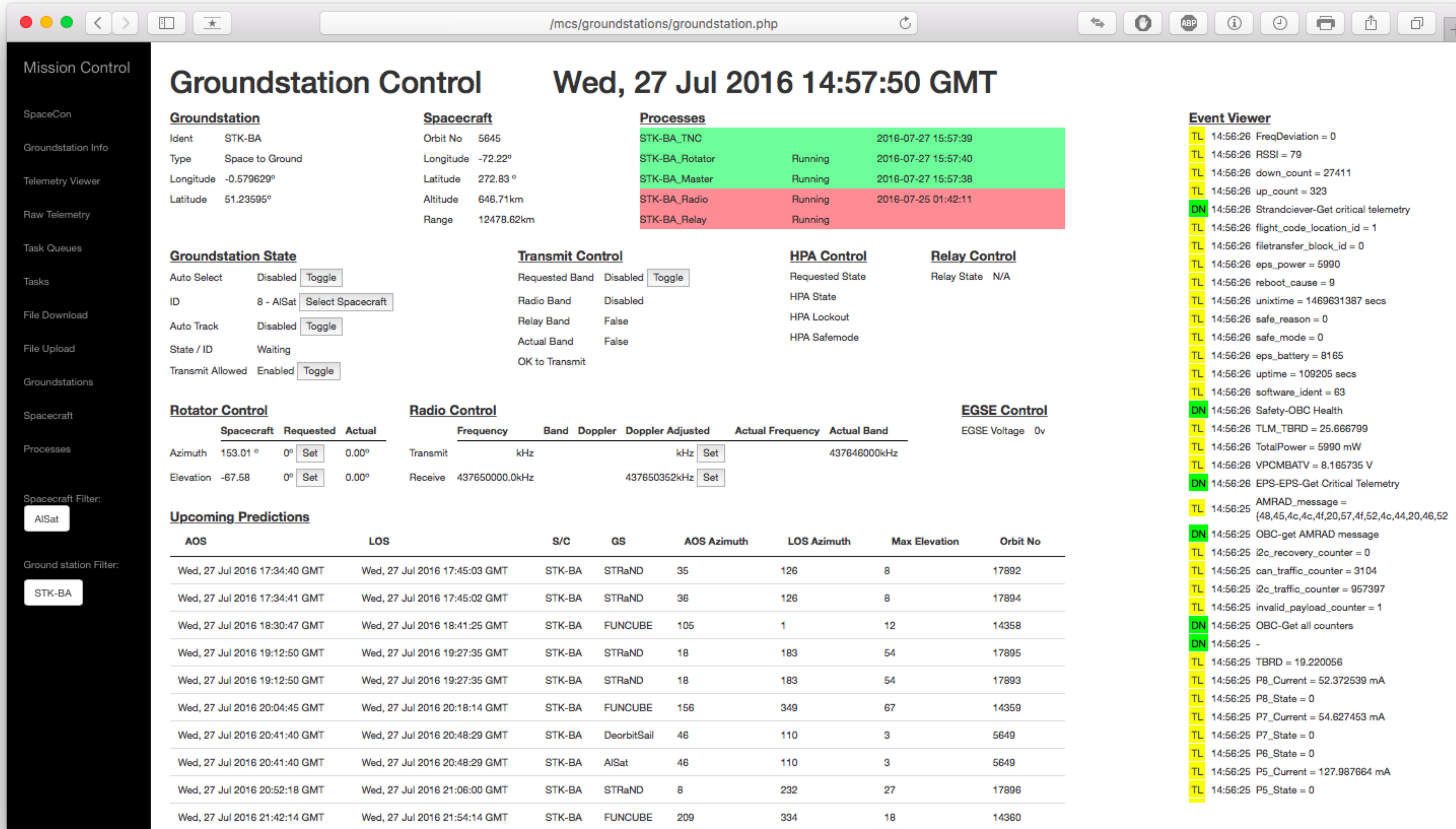
Surrey Ground Station



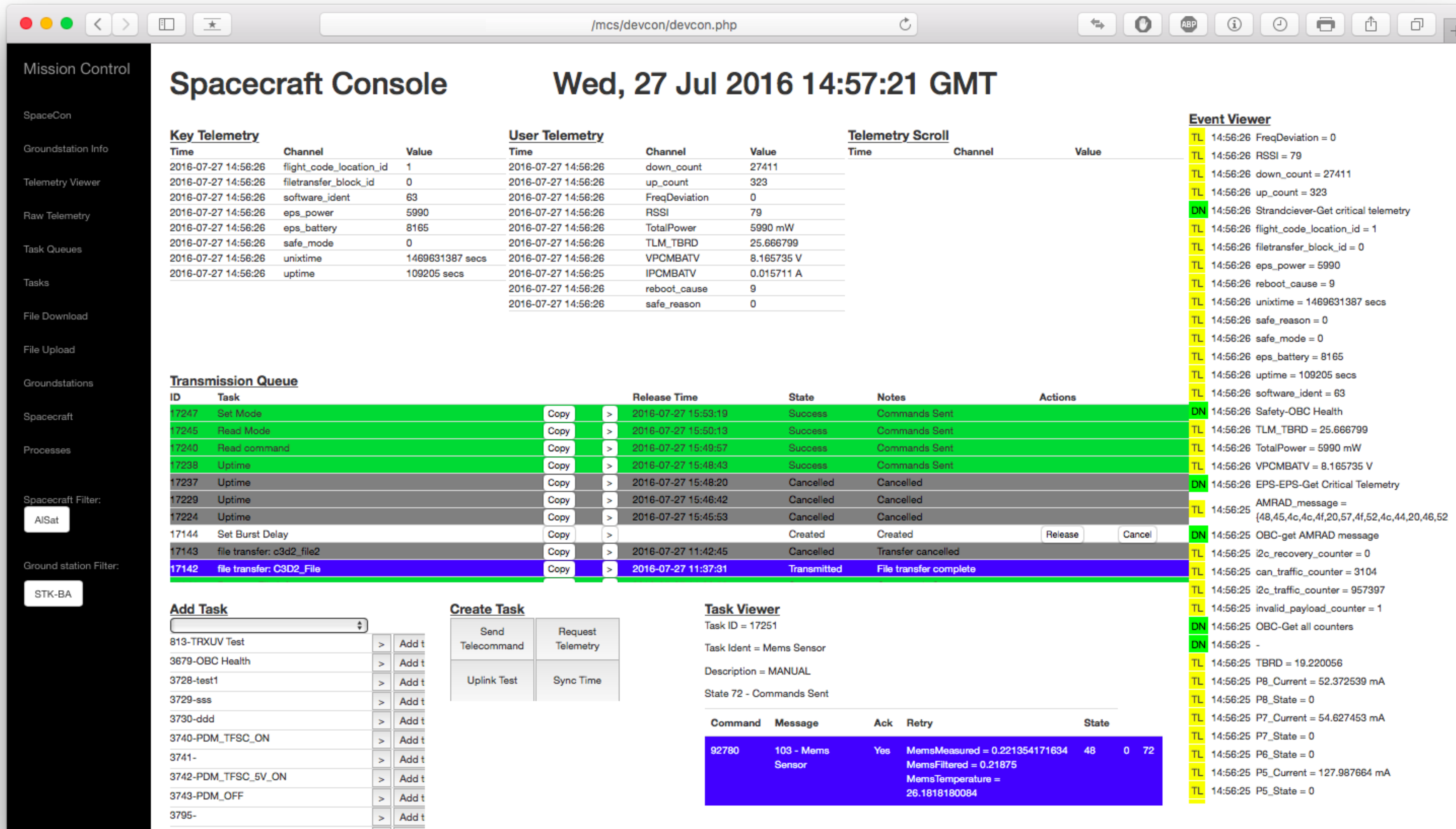
Upgraded SSC Ground-Station is in daily use for SSC Mission Operations.

23 dBi Gain Antennas

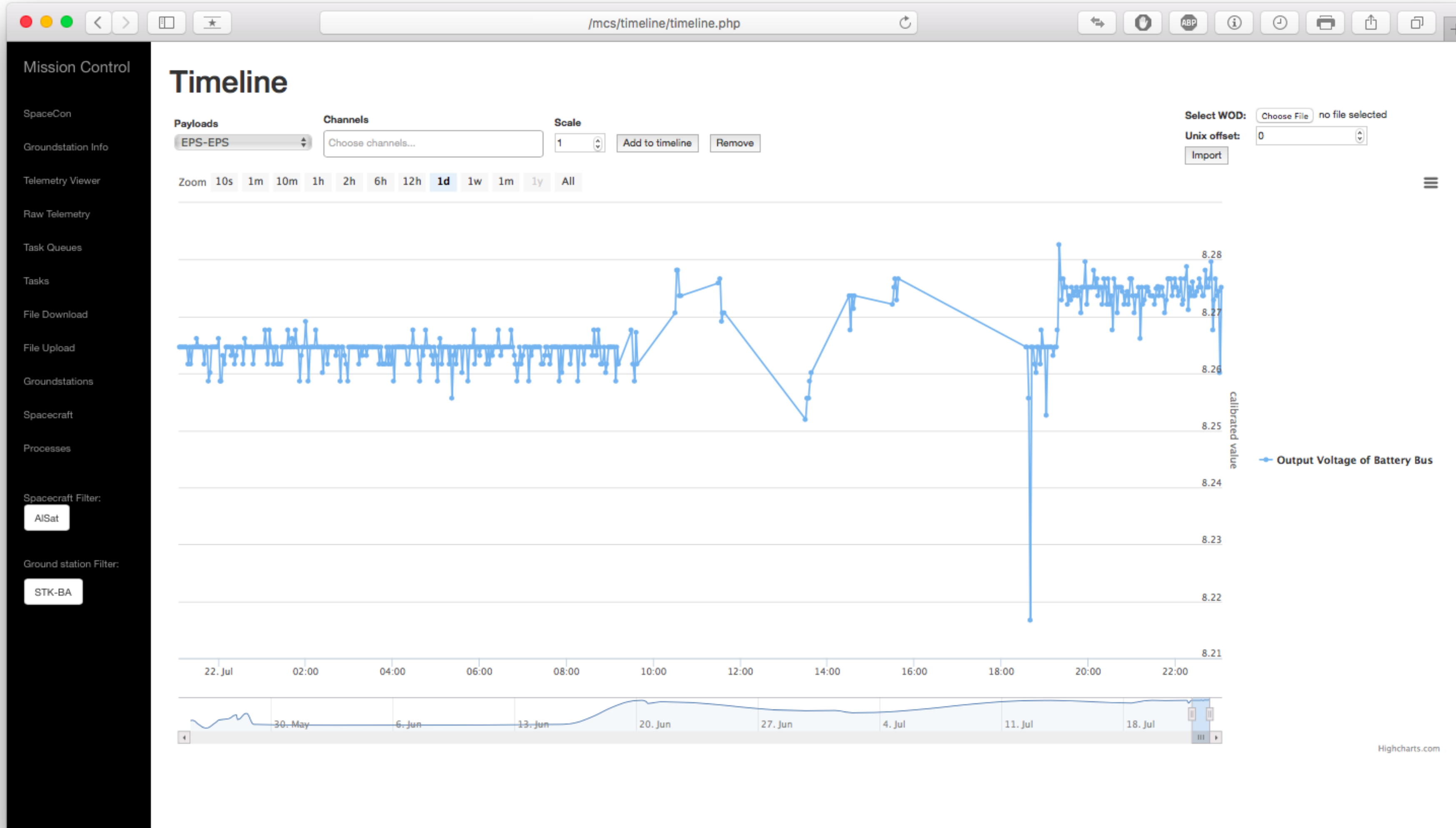
Surrey Ground Software



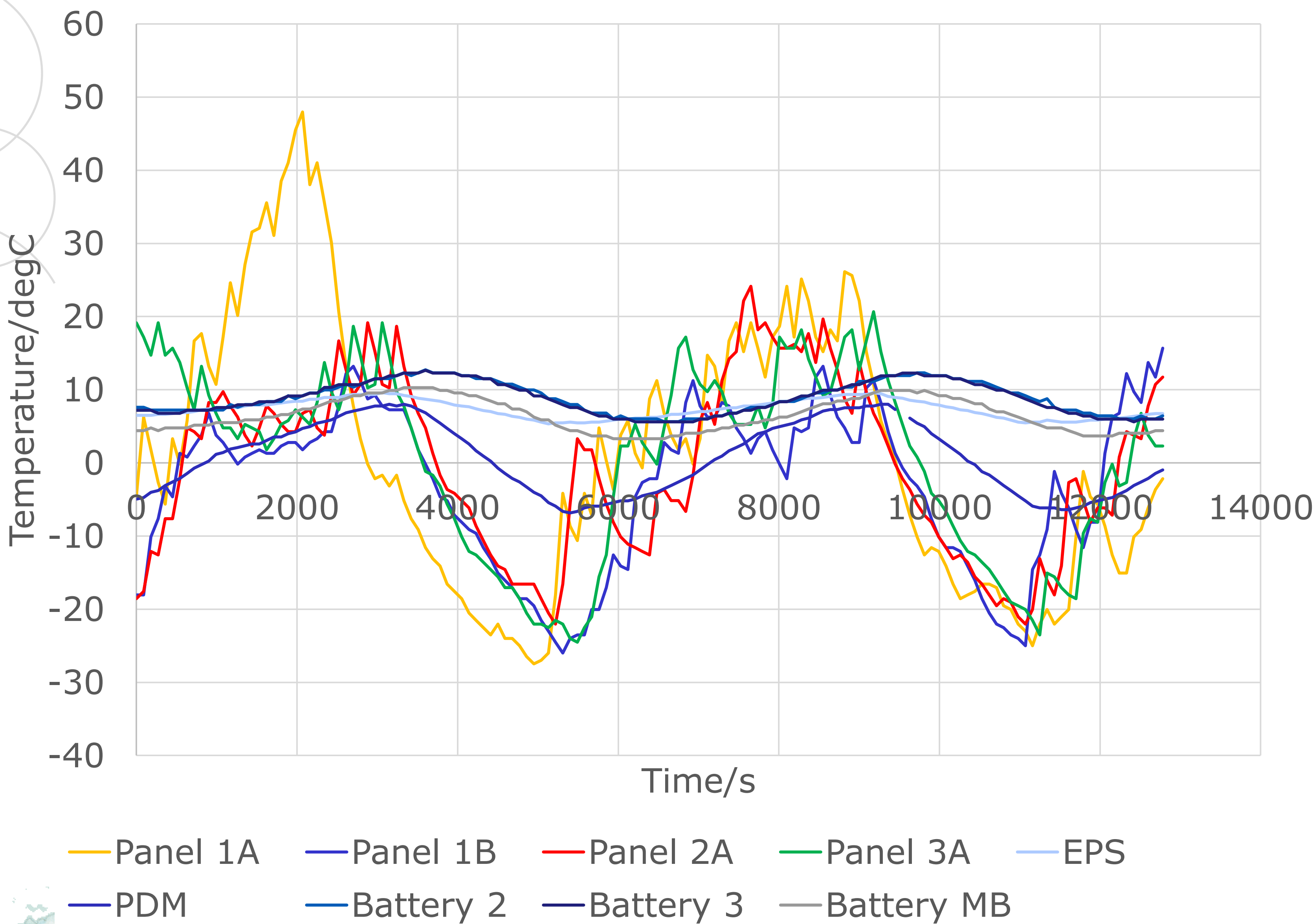
Surrey Ground Software



Surrey Ground Software

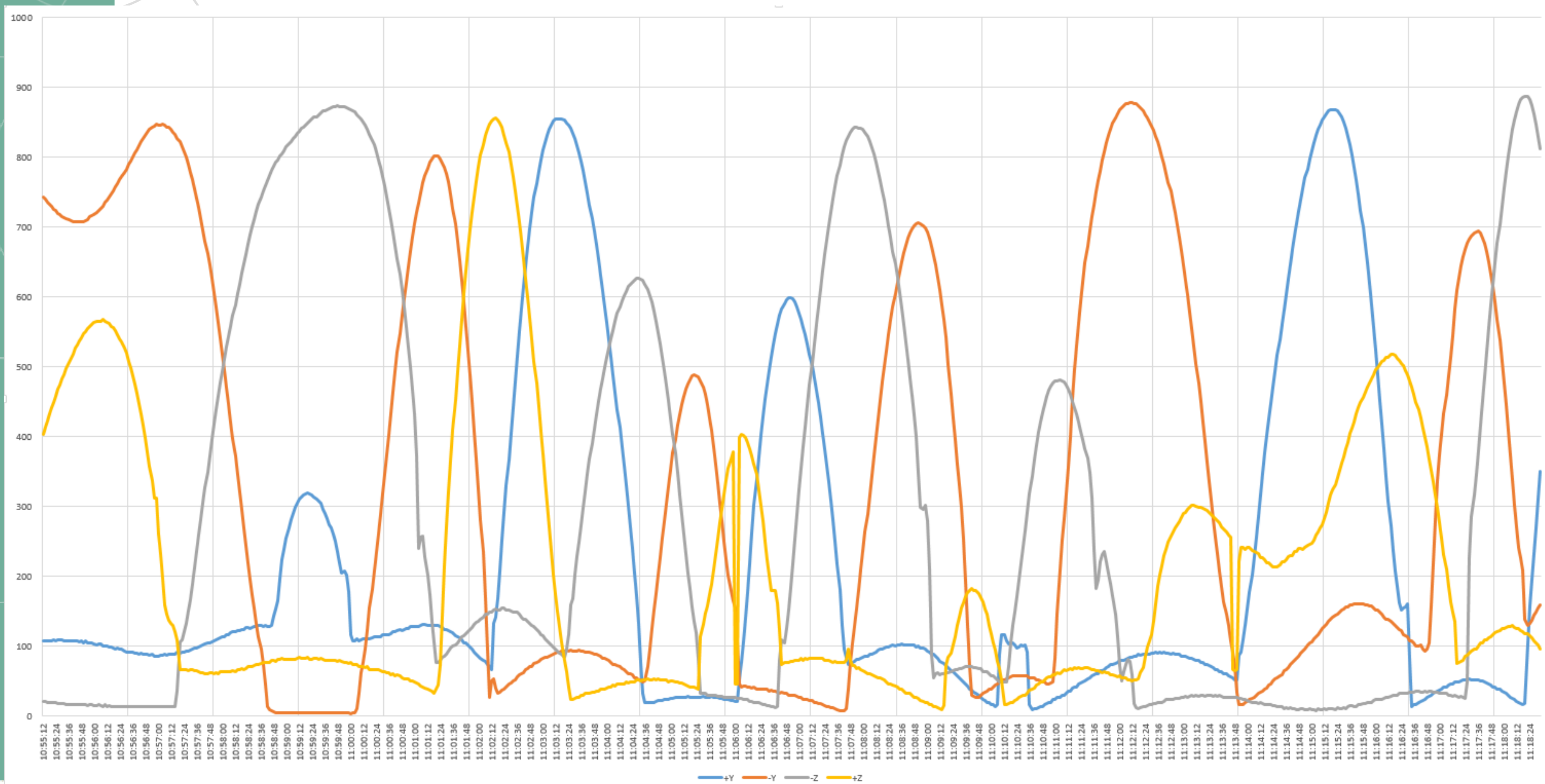


On-orbit Stability



On-orbit Stability

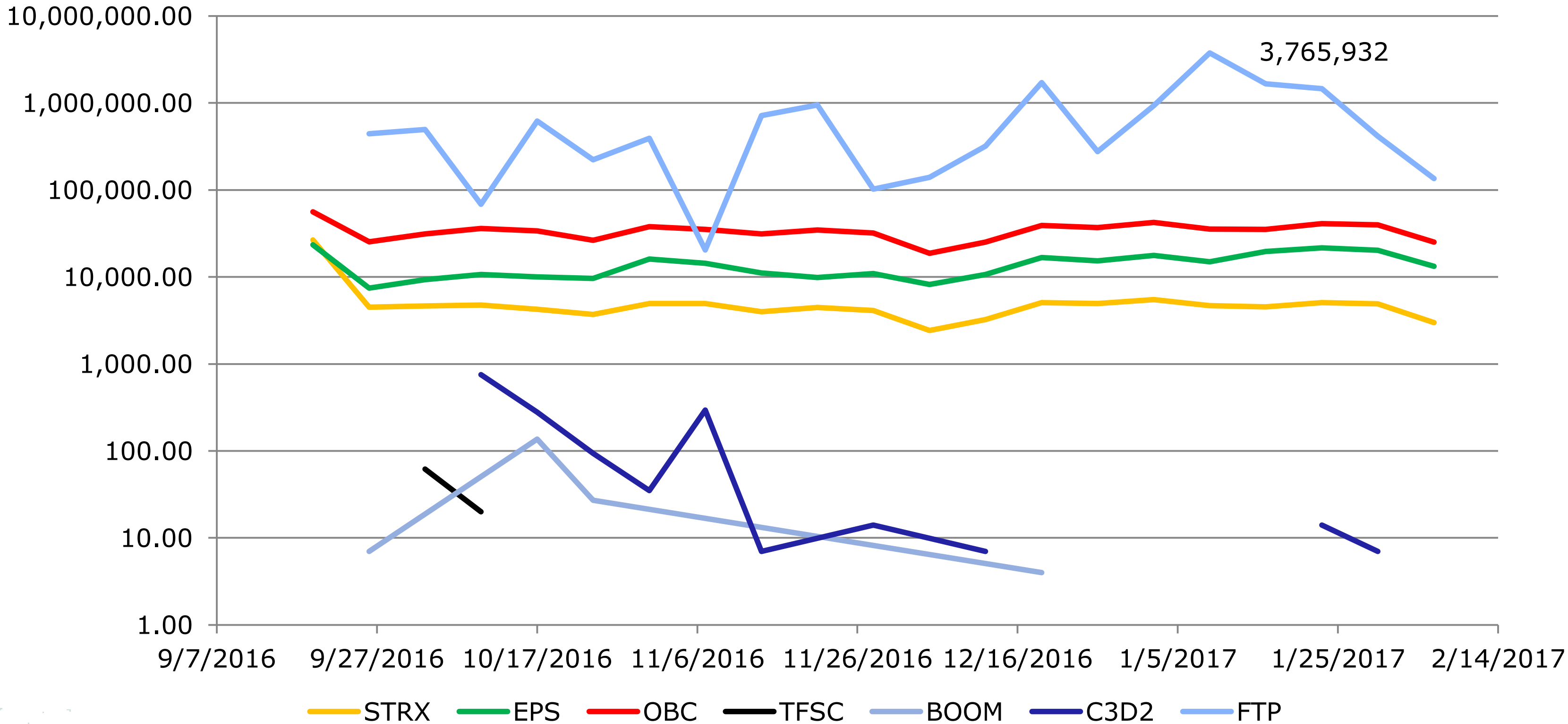
Flight Day: 39
Date: 4th November 2016 10:52:10
Interval: 2s, Duration: 30 minutes, File: W33-34



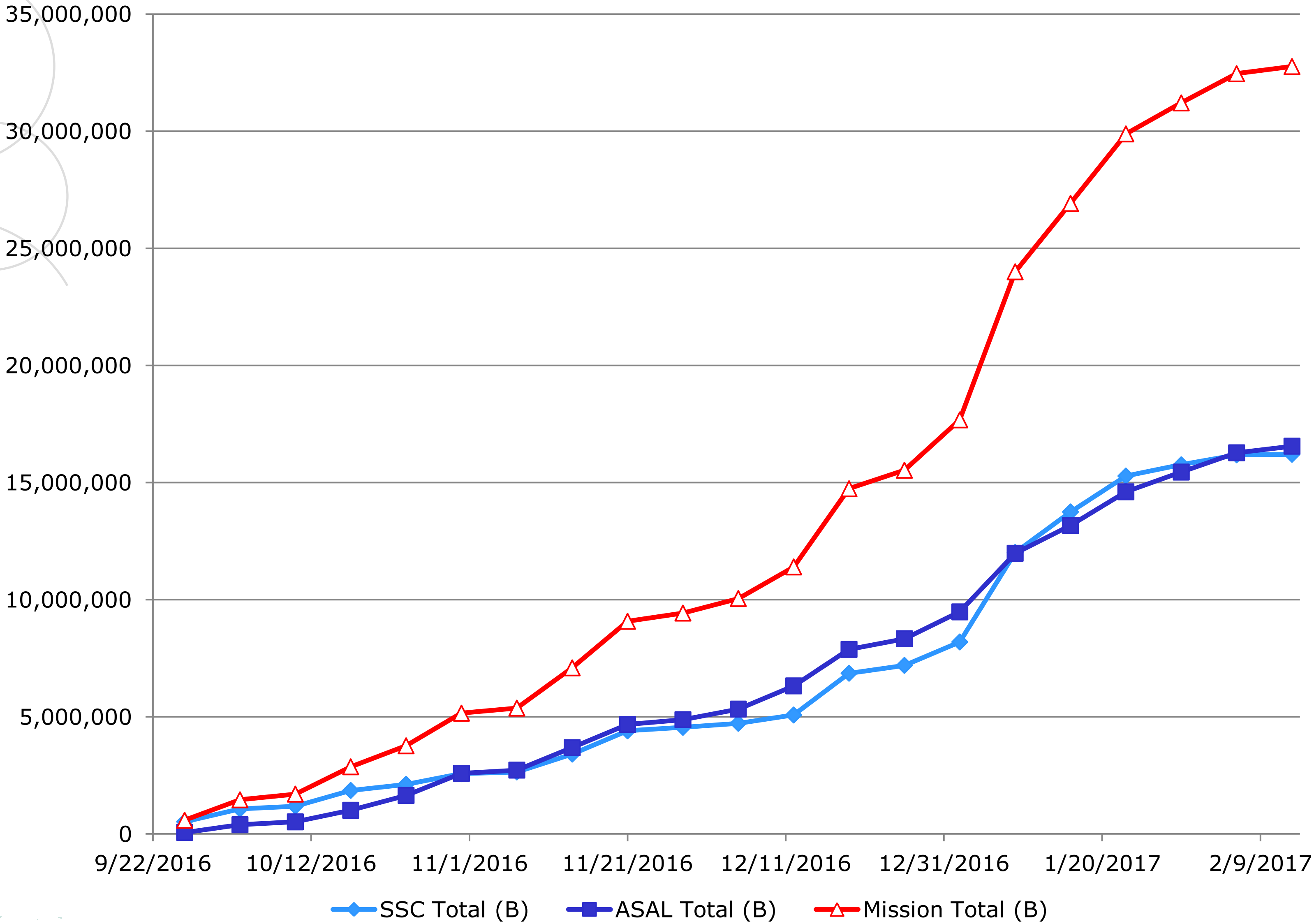
Communications Metrics

Throughput from SSC Groundstation:

- File Operations for large files (WODs, images, etc)
- Regular Health of Transceiver, Power & OBC
- Simple TM/TC > Configuration Settings



Communications Metrics



SURREY SPACE CENTRE

MirrorSat Spacecraft Bus

UNIVERSITY OF SURREY

- **MirrorSat Bus Sub-Systems Status:**

Structure: ISIS Structure Procured.

EPS/Battery: Old GOMSPACE P31u available – new one to be procured (fresh battery).

ADCS/OBC: Ex-SSC CubeSat development example available.

Solar Cells: Some Triple Junction Cells spare from previous missions are available – 6+6+6+2 = 20 cells needed. May need to purchase some.

Solar Panels: Bespoke Panels to be fabricated at SSC.

ADCS/OBC Software: Basic operating System written: File Handling, I2C communications, TT&C functionality. Bespoke AAReST specific code to be developed.

Questions?

Surrey AAReST MirrorSat Propulsion Unit

Valves, Tubing, Connectors and Filters

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

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

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

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

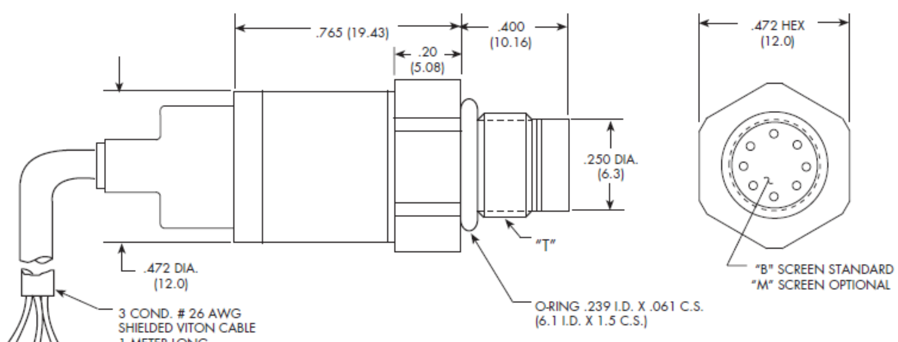
- 1/16th inch stainless steel swagelok tubing rated to 560 bar

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

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

Pressure Transducer

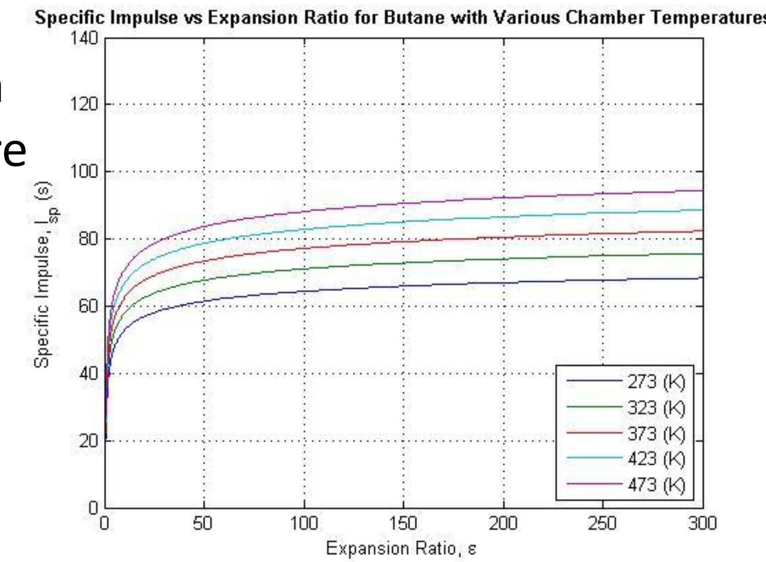
- Kulite ETM-634-312M pressure transducer used for monitoring plenum pressure and feedback input to valve
- Smallest high performance amplified transducer worldwide
- Operating temperature range of -55° C to 185° C
- Pressure range 0 – 15 Bar absolute with burst pressure of 45 bar
- Rated excitation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

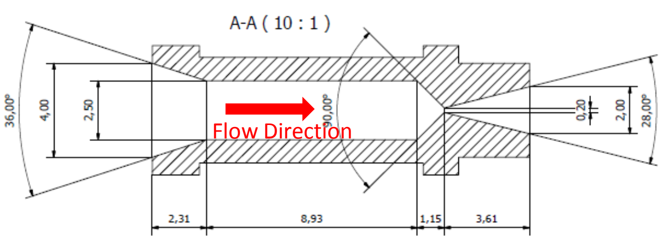


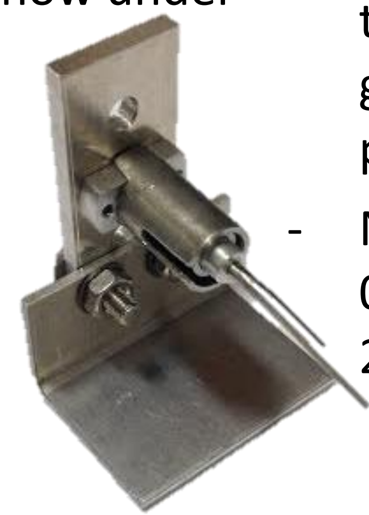
- Output impedance of 200 Ohms (Typ.)
- Analogue voltage output
- Full scale reading of 4.5V ± 1%
- Mass of 15g
- Stainless steel diaphragm

MirrorSat Propulsion

- **MirrorSat Prop. Tests 2015**
  - Heating tests performed in vacuum on a test piece yielded a thruster temperature of 140 °C with 1 watt input power
  - Expelled gas temperature initially assumed to be in the region of 100 °C leading a chosen nozzle expansion ratio (A_e/A_t) of 100 to provide a specific impulse of 80 seconds while still maintaining a small nozzle size
  - Fully representative system now under construction for testing.







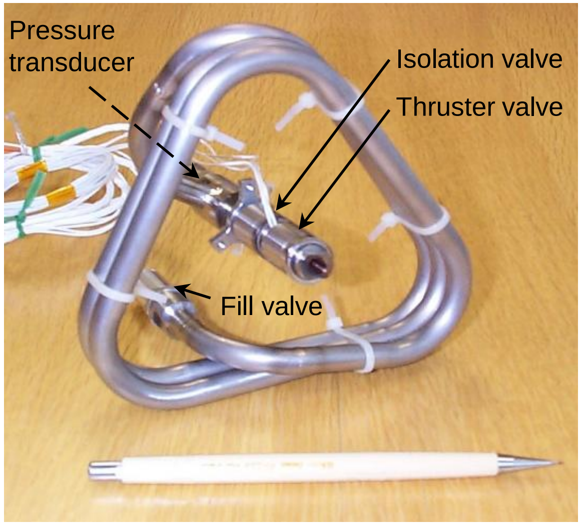
- Isentropic flow relations used to predict optimum throat geometry for nominal plenum pressure of 0.5 bar
- Nozzle throat diameter of 0.2mm and exit diameter of 2mm

MirrorSat Propulsion

- **MirrorSat Propulsion Capability**
  - 5 – 10 mN thrust range at ~ 80 s Isp.
  - Propulsion system provides ~5-10 m/s ΔV
  - Minimum valve opening time = 2 ms (500 Hz); Minimum Impulse bit = 10-20 μNs.
  - System mass estimated at 860 grams (wet); ~65g butane – slightly cut down from previous 2015 design.
  - Resistojets have a high degree of reliability, low system complexity and can be operated as a cold gas system in the event of heater failure.

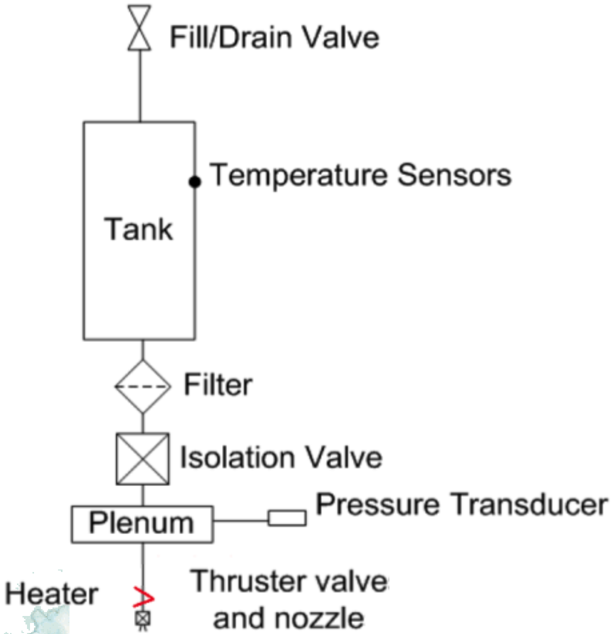
SNAP-1 System for Comparison

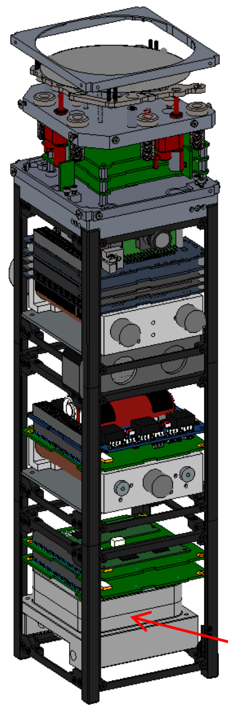
Propellant	**32.6 g butane**
Total impulse	**22.3 Ns**
Thrust range	**25 to 100 mN**
Module mass	**455 grams**
ΔV imparted	**2.1m/s (actual)**



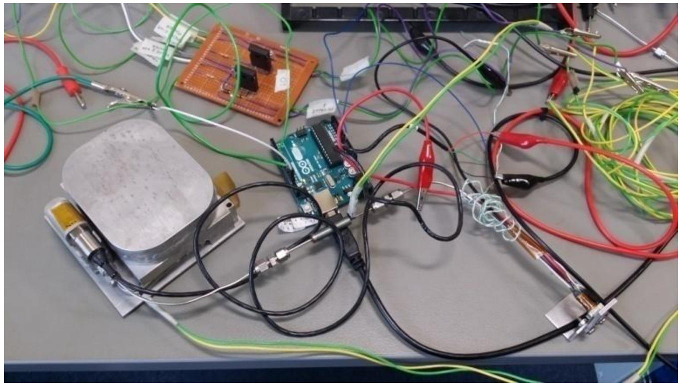
MirrorSat Propulsion

- **MirrorSat Propulsion System – Updated 2017**
  - Propulsion unit consists now of 1 x 1W micro-resistojet thruster to provide 1 DOF **single-axis thruster** (-Z axis)
  - Resistojet design simplified as a separate non-critical technology demonstration payload
  - Liquefied Butane propellant stored at 2 bar and expelled in gaseous phase at 0.5 to 1 bar via pressure controlled plenum.
  - Butane has good density, specific impulse and no toxic or carcinogenic qualities





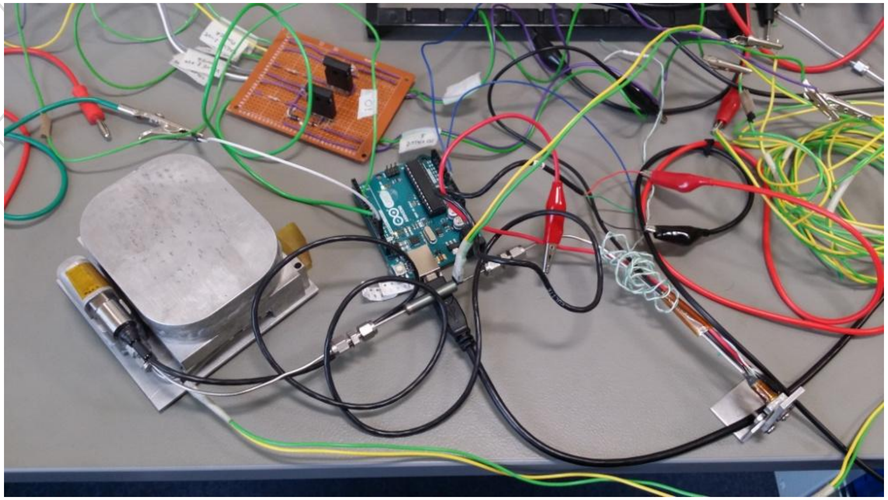
Propulsion Unit (Single Axis)

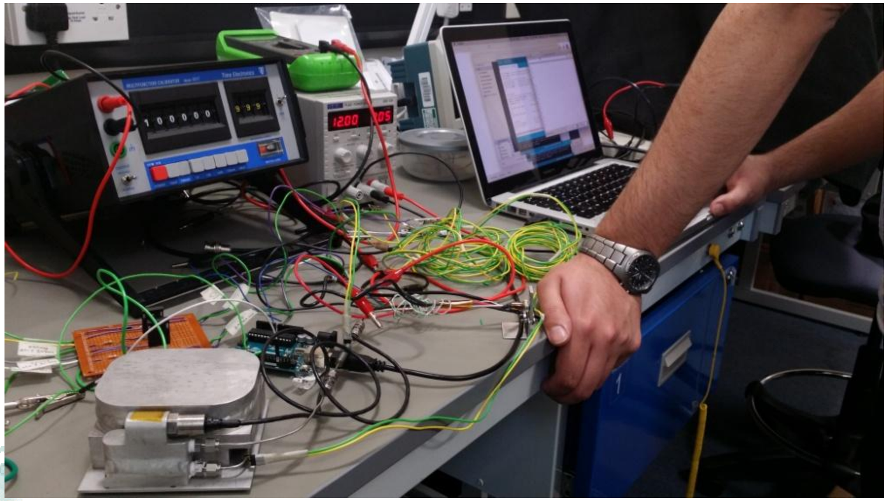


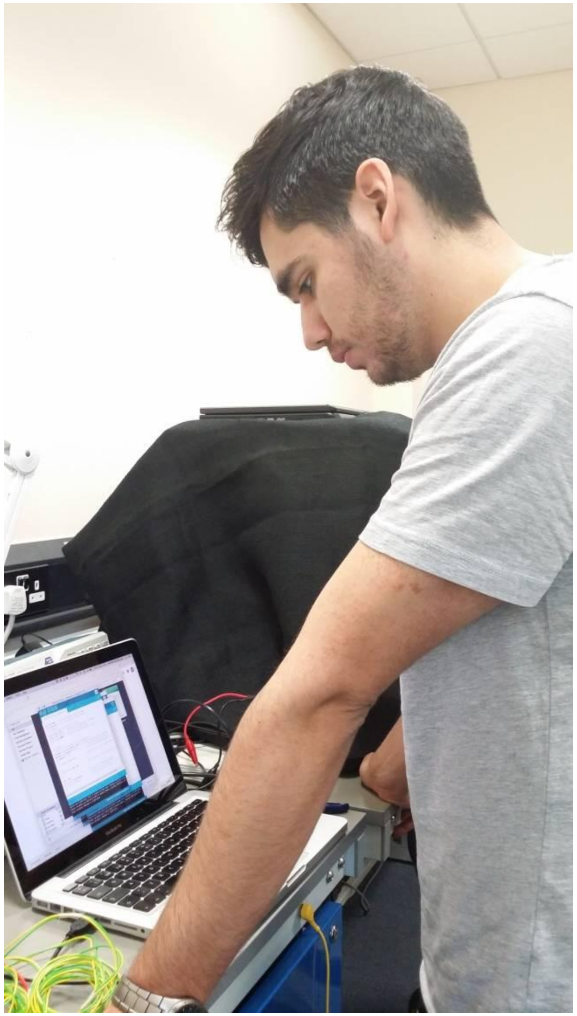
Components under test in air (2015/16 version)

MirrorSat Propulsion

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

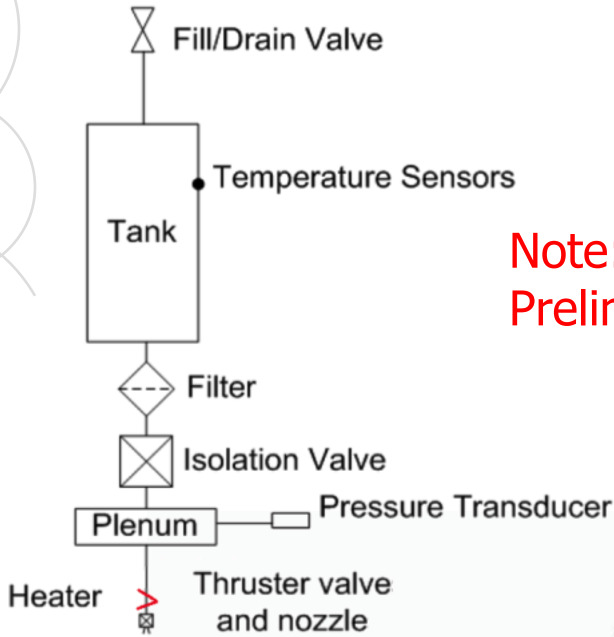




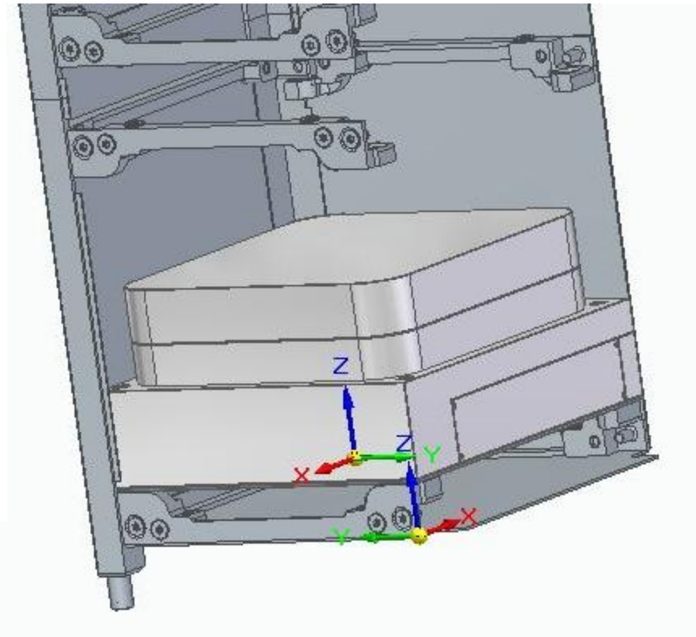


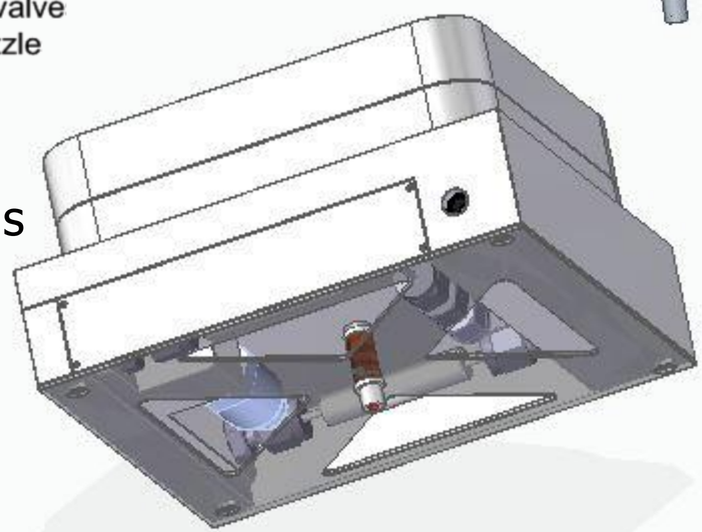
MirrorSat Propulsion

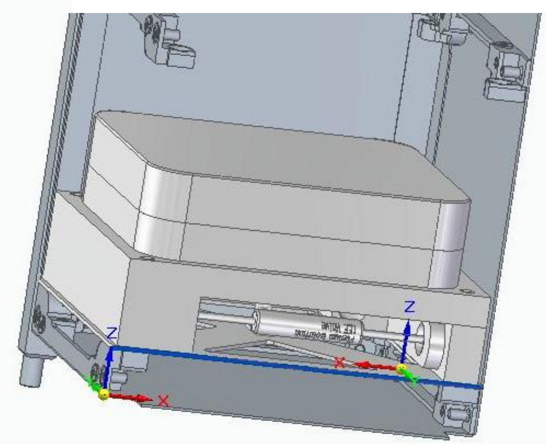
- **MirrorSat Propulsion System – Updated 2017**



Note:
Preliminary CAD







Nikolas Karefyllidis
(H/W design)

Dylan Fisher
(Electronics)

MirrorSat Propulsion

- **MirrorSat Propulsion System – Nikolas Karefyllidis**

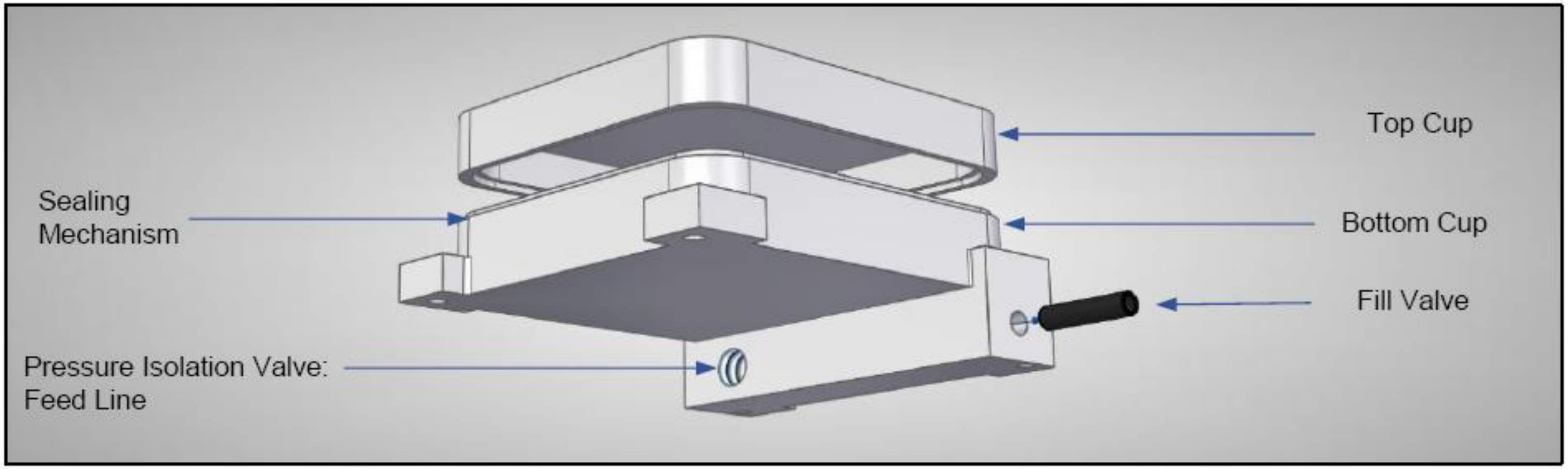


Figure 5.2:1 Propellant Tank: Exploded view

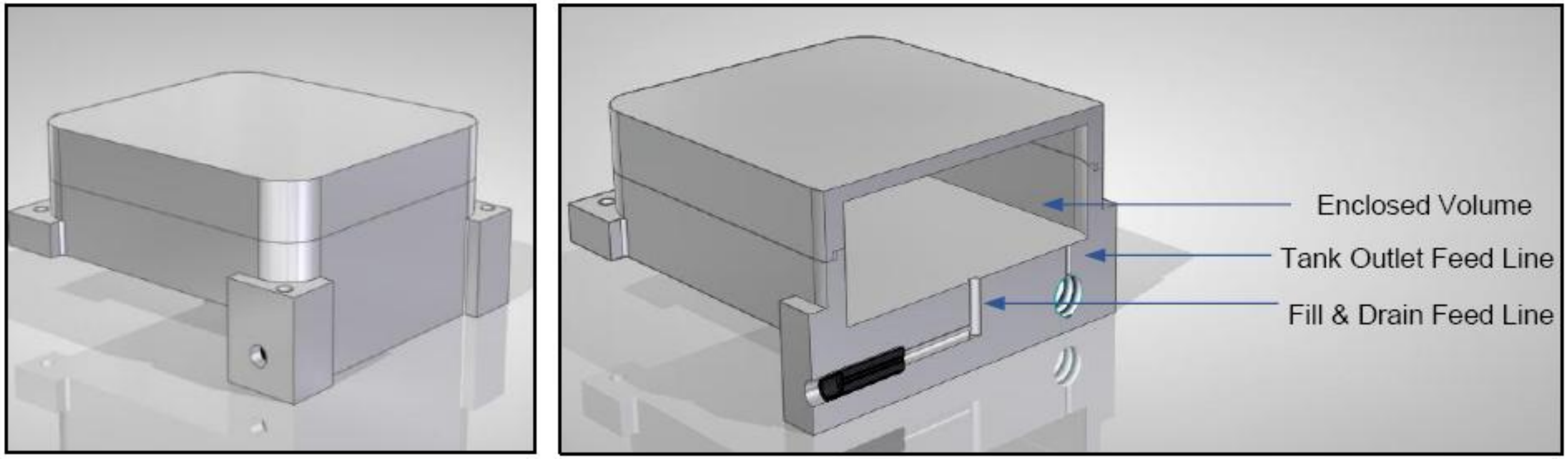


Figure 5.2:2 Propellant Tank: Angled Side and Sectional View

MirrorSat Propulsion

- **MirrorSat Propulsion System – Nikolas Karefyllidis**

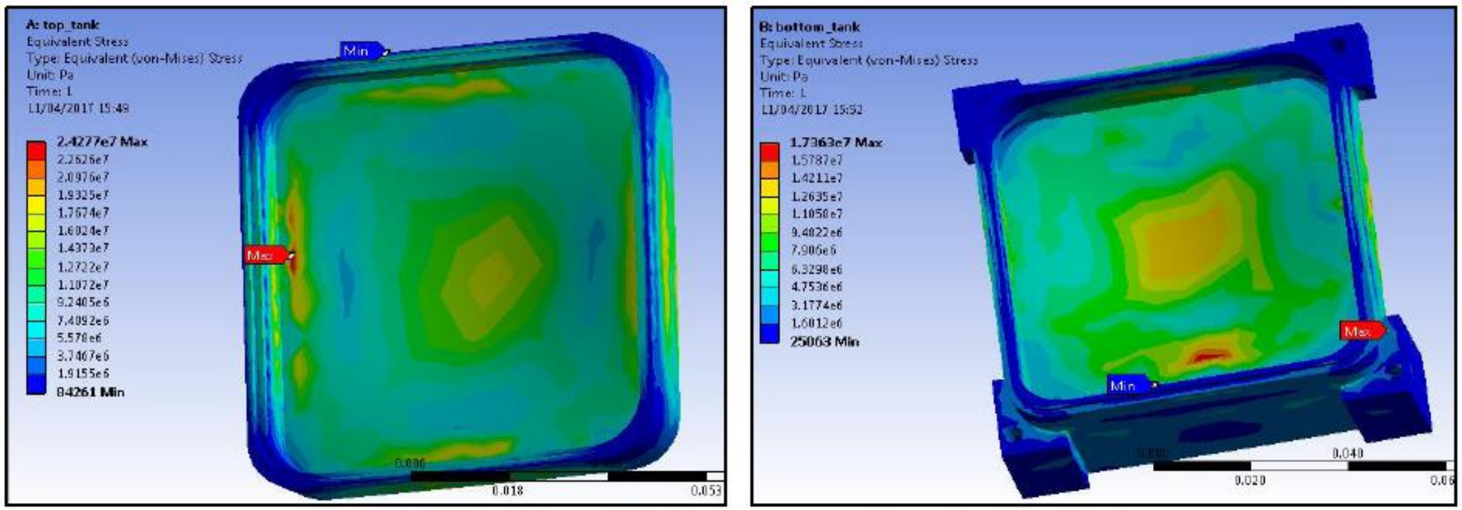


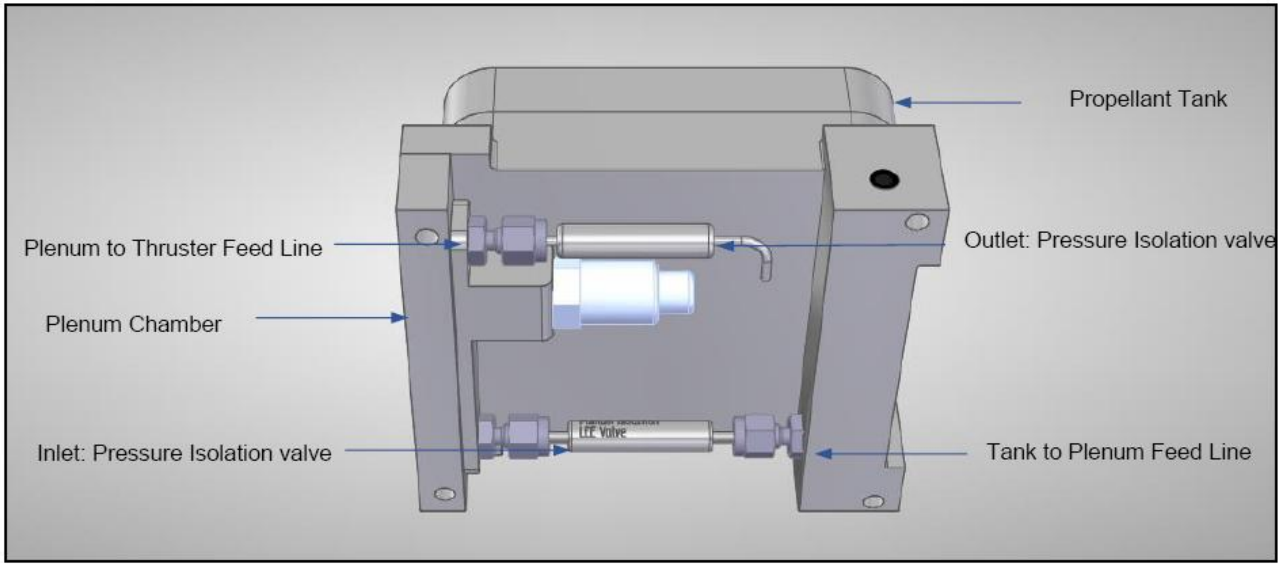
Figure 5.2:3 Tank System FEA: Stress concentration points Identification

CAPABILITIES	METRIC
Enclosed Volume	140 m
Dry Mass	243 g
Liquid Mass	85 g
Max. Deformation	0.056 mm
Max. Von-Mises Stress	24.27 MPa
Max. Equivalent Elastic Strain	0.03 %
Max. Shear Stress	63.08 MPa
Safety Factor	> 15

MirrorSat Propulsion

- **MirrorSat Propulsion System – Nikolas Karefyllidis**

Figure 5.2:4 Propellant Tank: Fabrication and Mesh System Installation (Without Welding)



Anti-Slosh Baffle and liquid containment mesh

Figure 5.3:2 Propellant Tank and Plenum Chamber Assembly

- **MirrorSat Propulsion System – Nikolas Karefyllidis**

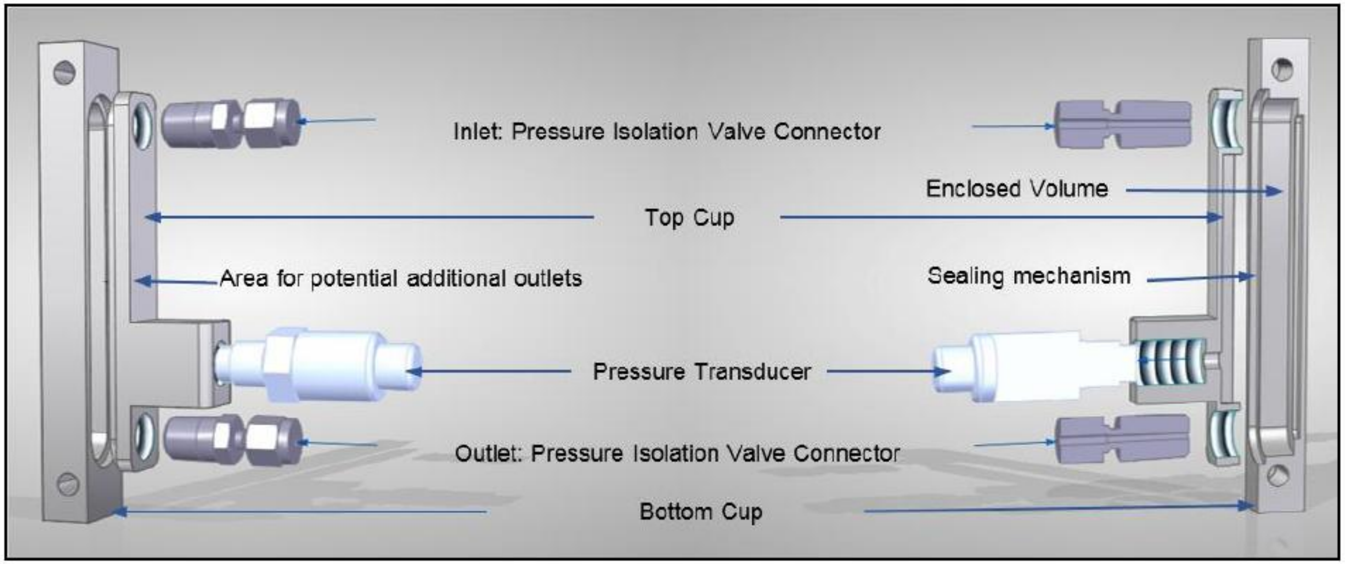
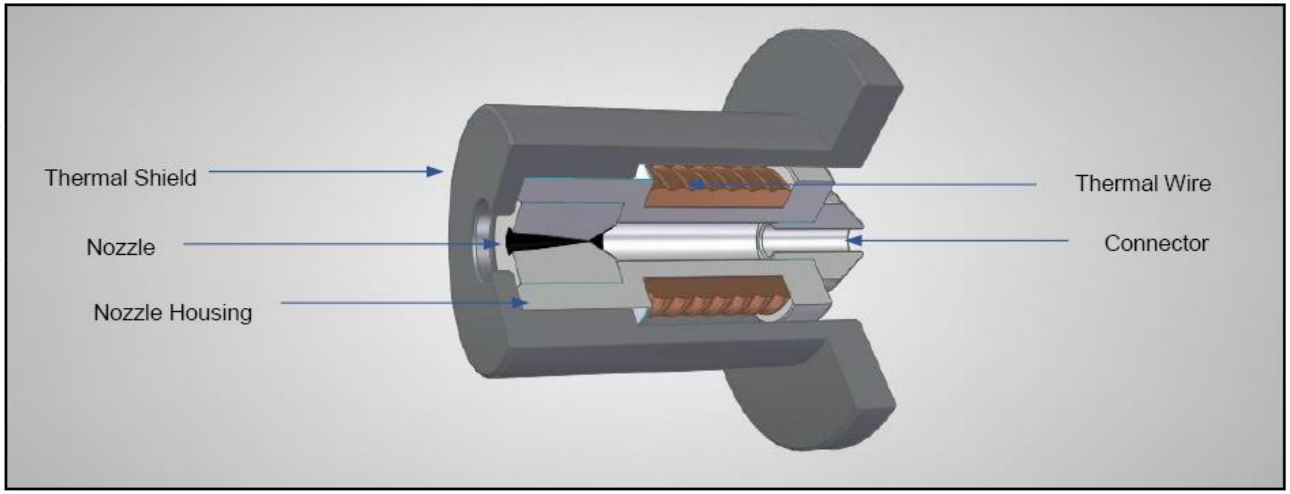


Figure 5.3:1 Plenum Chamber: Exploded and Exploded Sectional Side View

CAPABILITIES	METRIC
Enclosed Volume	5 ml
Dry Mass	29 g
Max. Deformation	0.28 mm
Max. Von-Mises Stress	2.07 MPa
Max. Equivalent Elastic Strain	0.03 %
Max. Shear Stress	0.23 MPa
Safety Factor	>15

MirrorSat Propulsion

- **MirrorSat Propulsion System – Nikolas Karefyllidis**



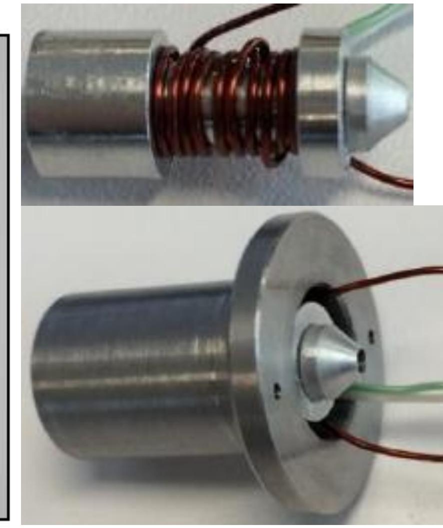
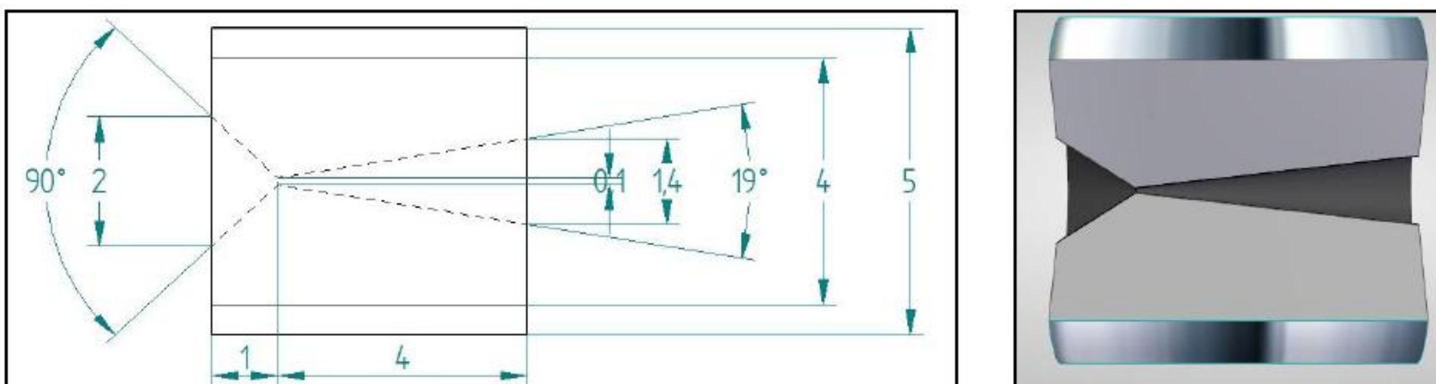


Figure 5.4:1 Resistojet Schematic

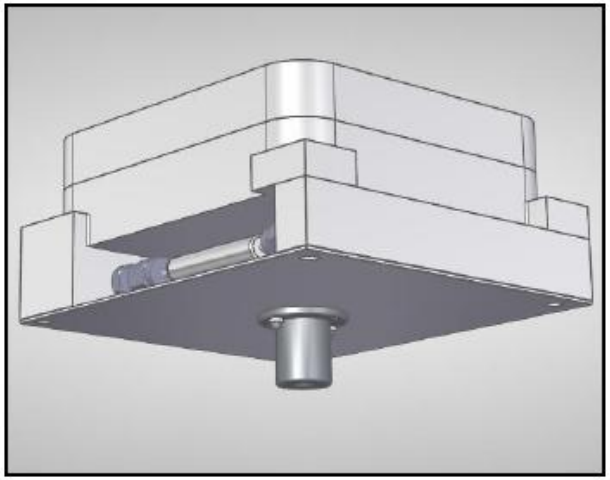


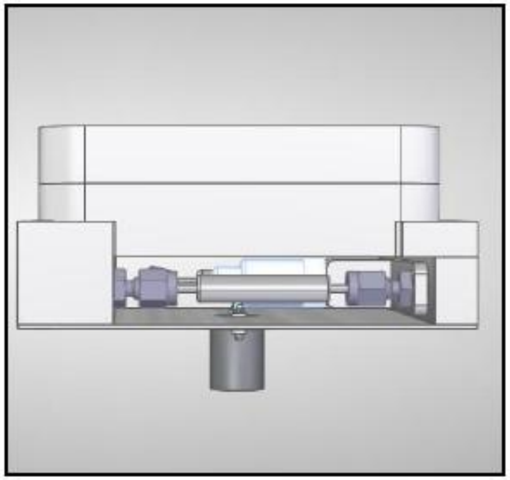
0.1mm Throat
2mm Exit
=200:1 Expansion

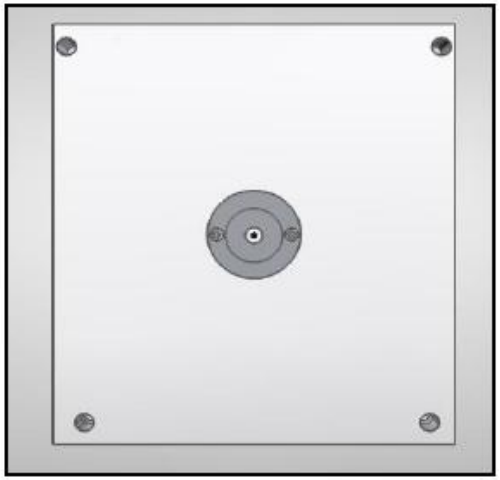
Figure 5.4.1:3 Nozzle Schematic and cross sectional side view

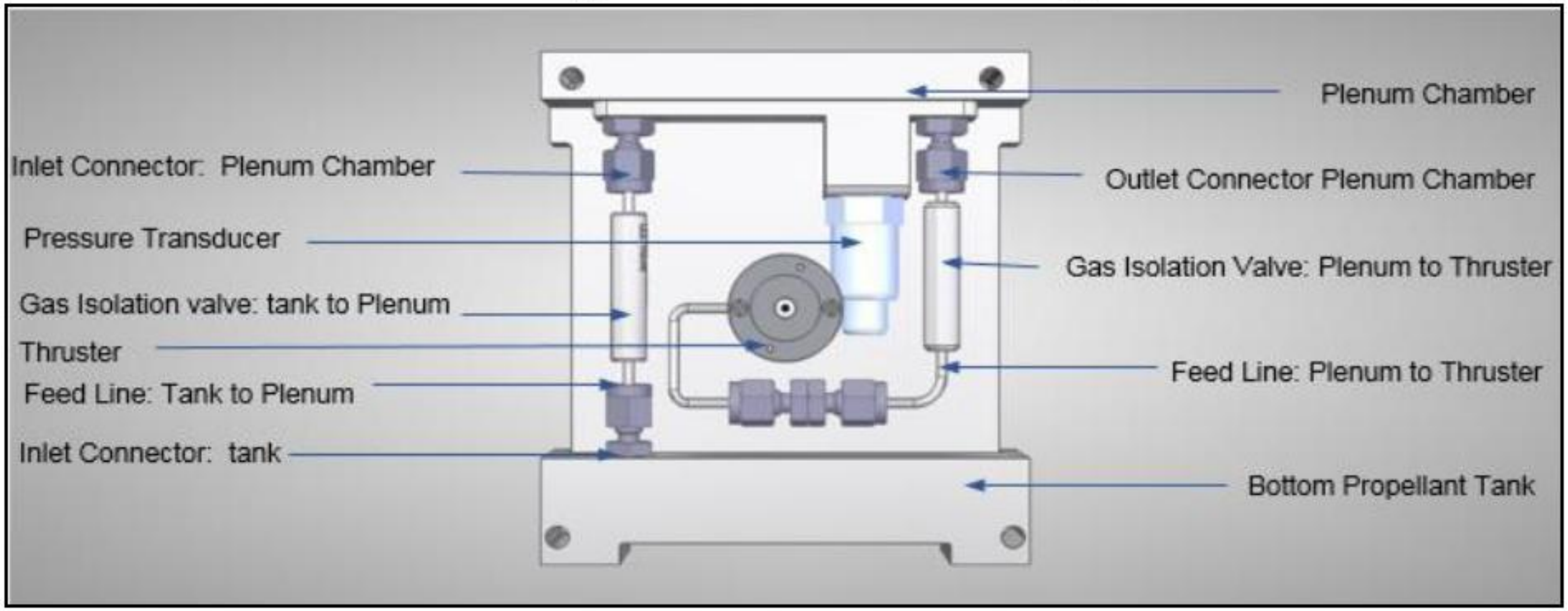
MirrorSat Propulsion

- **MirrorSat Propulsion System – Nikolas Karefyllidis**



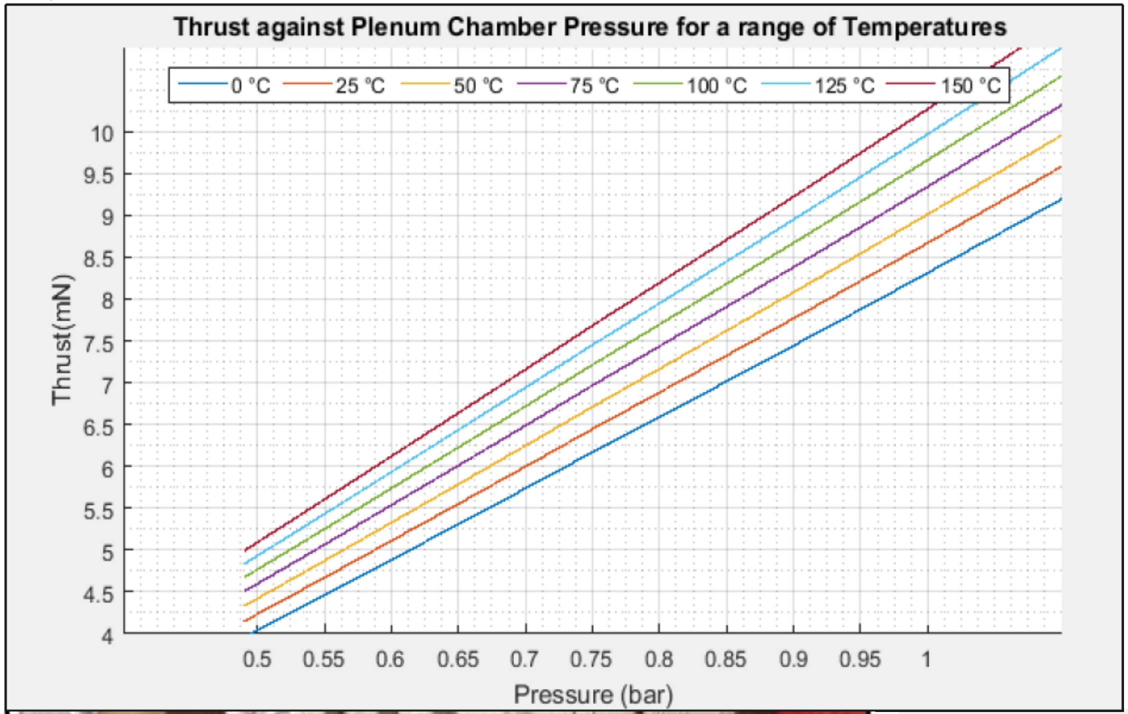


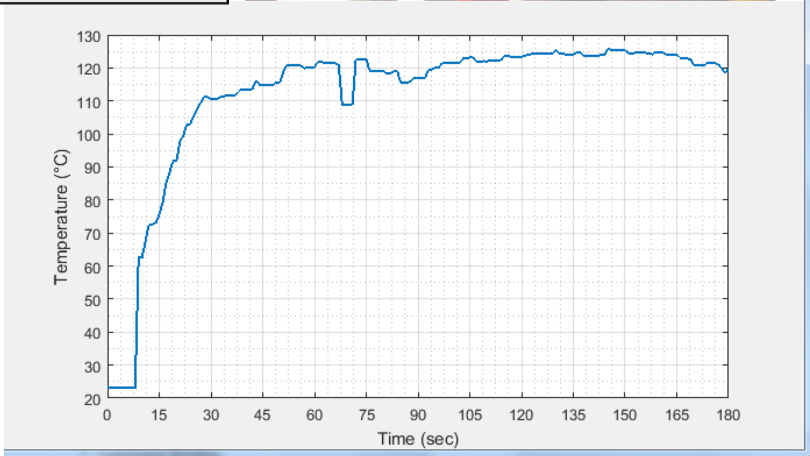




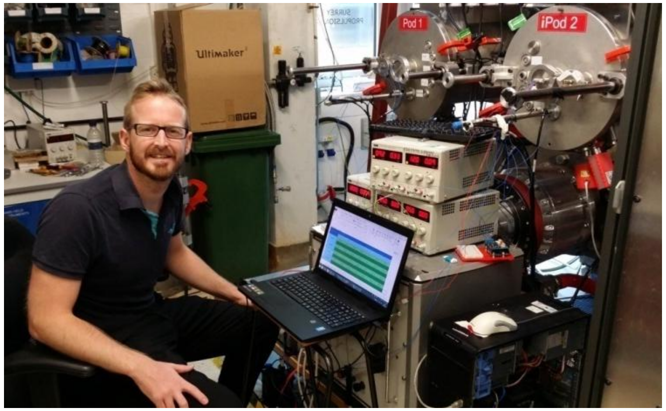
MirrorSat Propulsion

- **MirrorSat Propulsion System – Nikolas Karefyllidis**





- **MirrorSat Propulsion Update 2017**
  - All system components built and tested – Propulsion tank, plenum chamber, (single) thruster/heater and valves – 2015 , 2016, 2017.
  - Two-part aluminium propellant tank welded successfully.
  - Butane filling very straight-forward from standard COTS cartridges.
  - Multiple cycle operation demonstrated in the Daedalus vacuum chamber. Valve operation at <5V – low power in latched mode.
  - Gas temperature slightly lower than in initial tests – but thrust is good (3 and 10 mN dependent on plenum pressure)
  - Testing was from 0 - 3 Watts in 0.5 W steps at 3 plenum pressures (0.5 bar, 1 bar and 1.5 bar) – 8 measurements at each point – 168 in total.
  -



MirrorSat Propulsion

- **MirrorSat Propulsion System – Dylan Fisher**
  - **Electronic Driver Circuits - TBD**
  - **New Thruster Measurements in Vacuum – TBD**
  - **New Pressure Transducer Proposed**
  - **Proto-Flight Model to be Constructed**

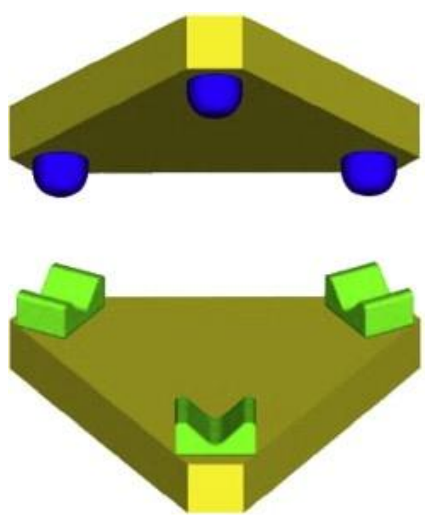
Kulite ETM-634-312M	Model	MS5837-30BA
12±4VDC	Excitation voltage	1.5-3.6VDC
-55/175	Temperature	-20/85° C
25mA	Excitation current	(stand-by)0.1-0.6μA
±0.015 bar	Pressure Resolution	±0.005 bar
15g	Mass	1.8g

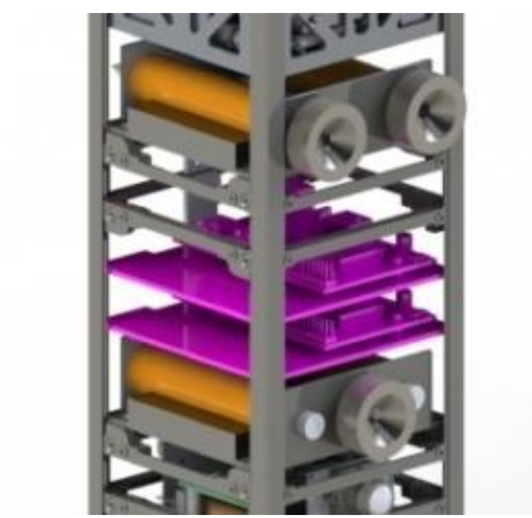
Questions?

Surrey AAReST
Docking Port
Development &
Air Bearing Trials

RDV/Docking Port

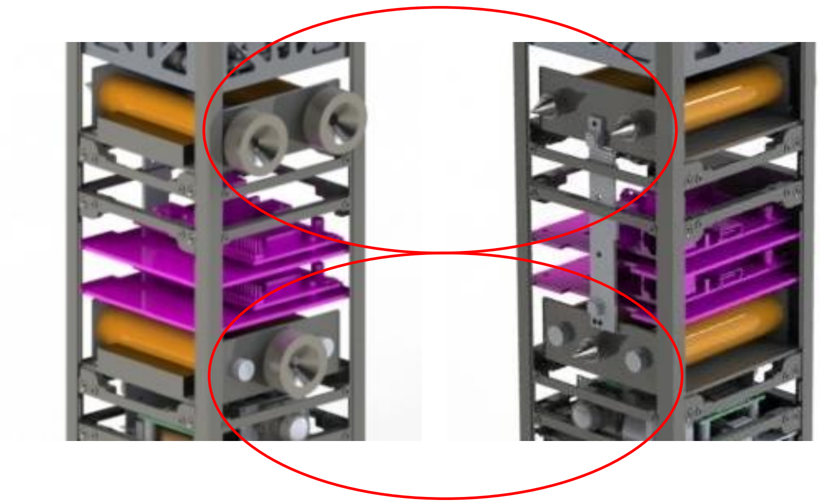
- **EM Docking System Concept**
  - SSC Electro-Magnetic Kelvin Clamp Docking System (EMKCDS)
  - Comprises four PWM controlled, H-bridge-driven, dual polarity electro-magnets, each of over 800 A-turns
  - These are coupled to three “probe and drogue” (60^{o} cone and 45^{o} cup) type mechanical docking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

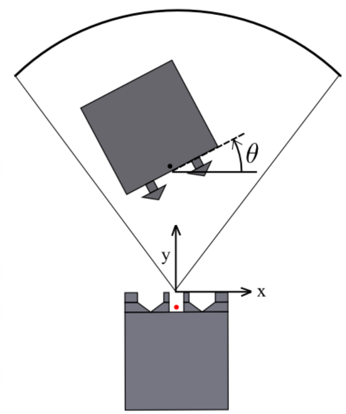


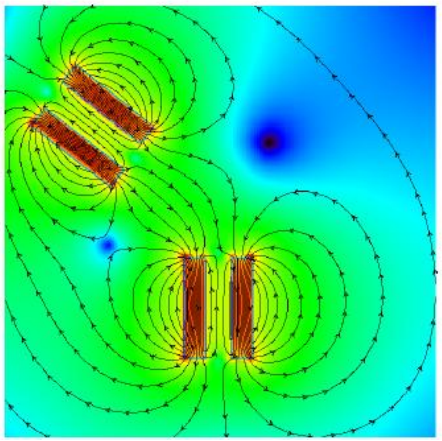


RDV/Docking Port

- Designed for proximal operation within ~30-50cm separation distance.
- The objective is to keep the **MirrorSat** and **CoreSat** in close proximity, such that the docking ports on the two spacecraft face one another during **magnetic separation** and **magnetic capture and latching.**





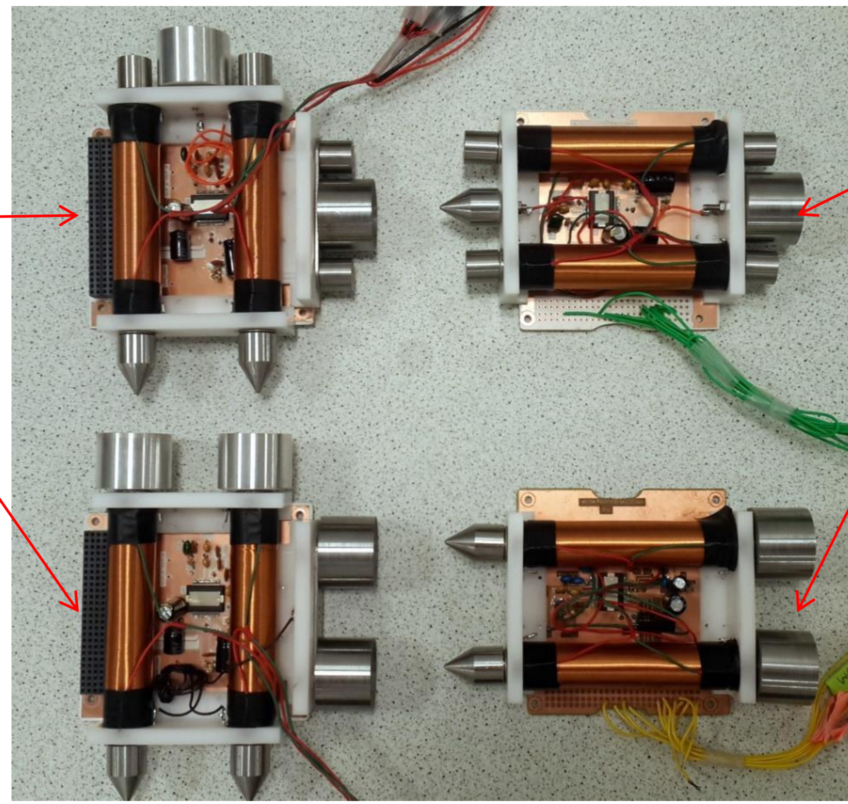


- An accompanying **RDV Sensor** suite supports these proximal operations by generating relative pose, range, pose-rate and range-rate information.

RDV/Docking Port

- **2015 EM Docking System Prototype**
  - Prototype Docking Port hardware designed and built:

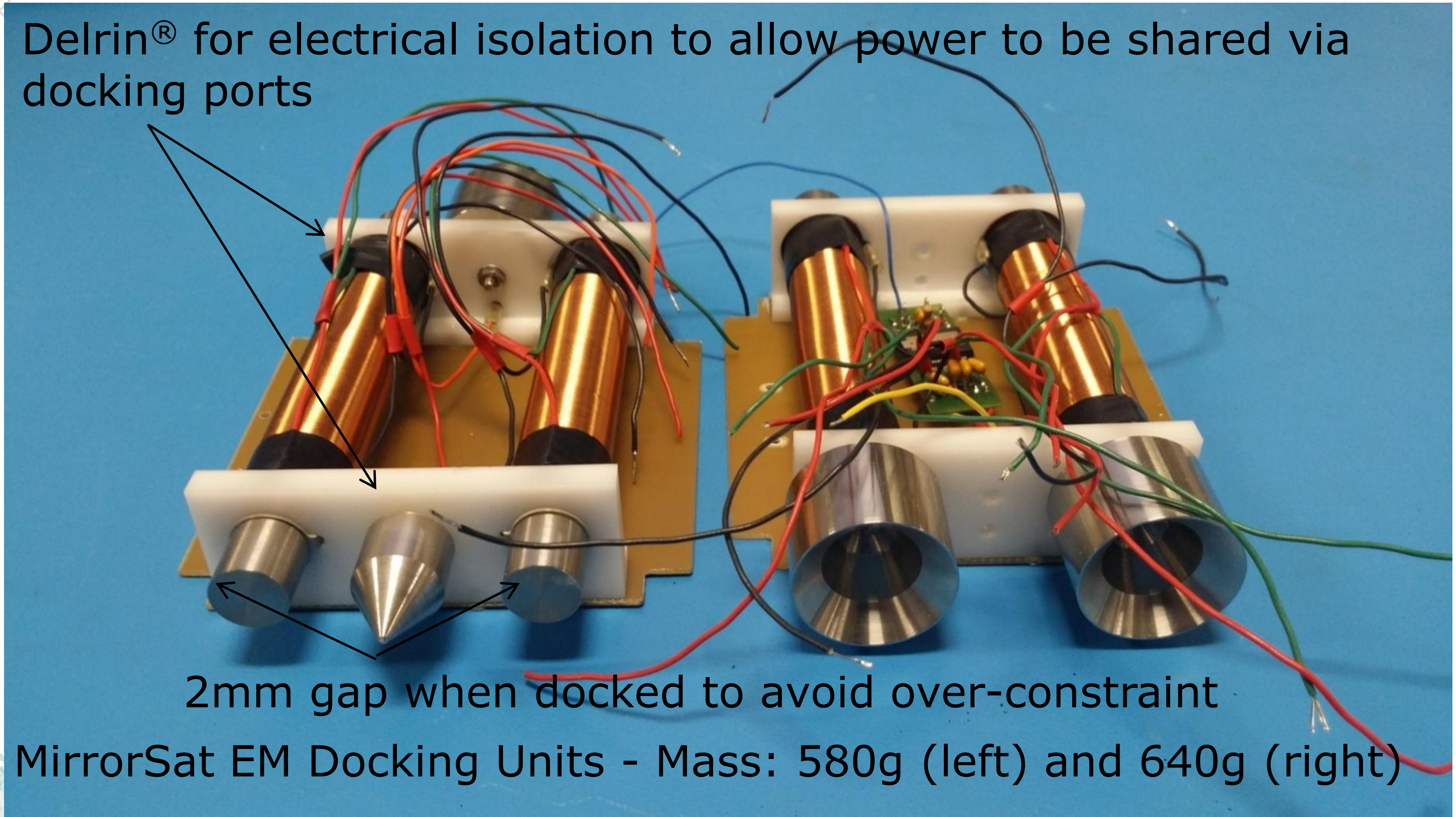
CoreSat Units
(Note 8.7mm Offset between X and Y facets)



MirrorSat Units

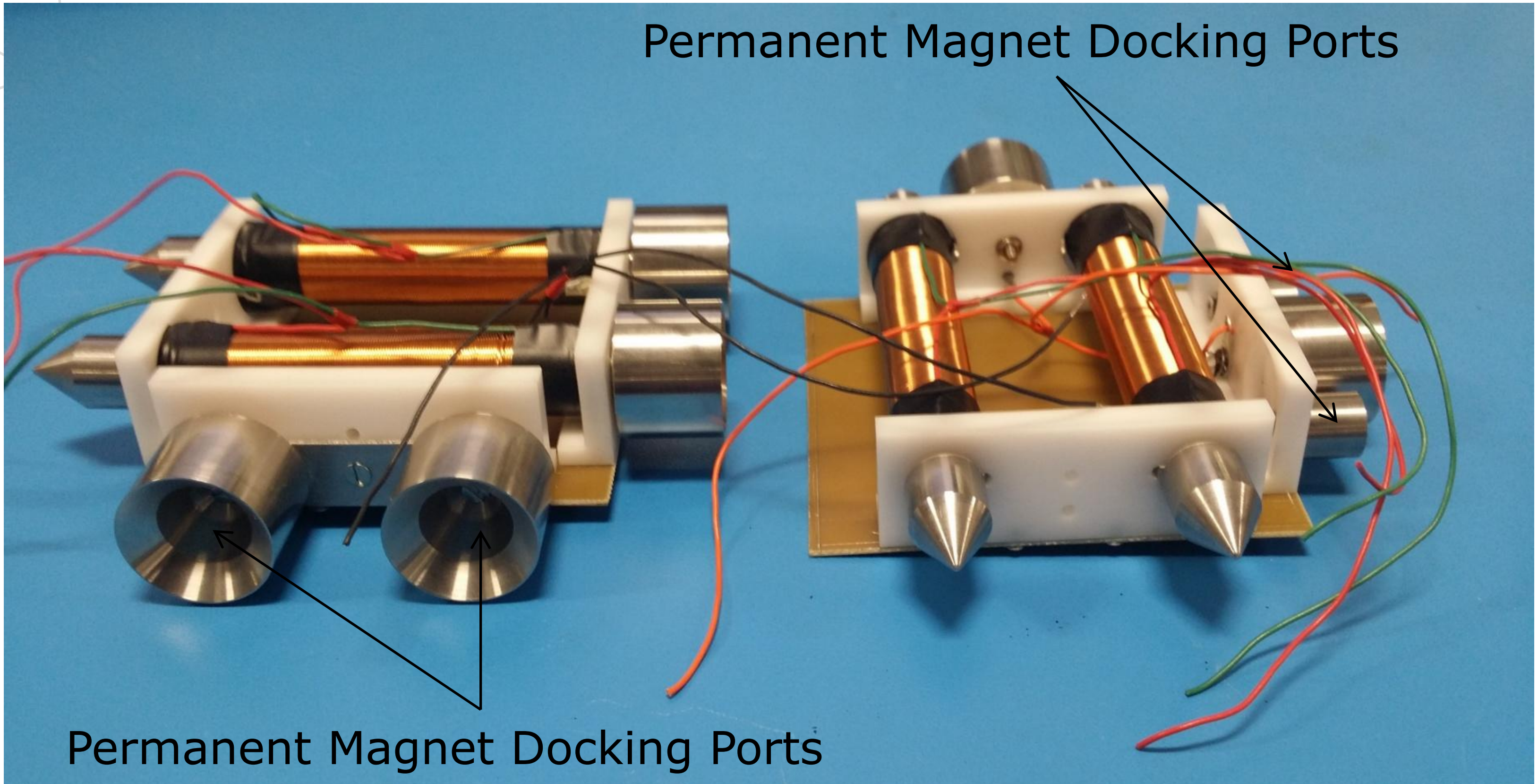
RDV/Docking Port

- **2015 EM Docking System Prototype**
  - Note 2017 Units have reduced flux extenders to avoid premature contact. Delrin end-caps may be added.
  - The docking cups are removed from the MirrorSat Units to free up space for extra solar panels.



RDV/Docking Port

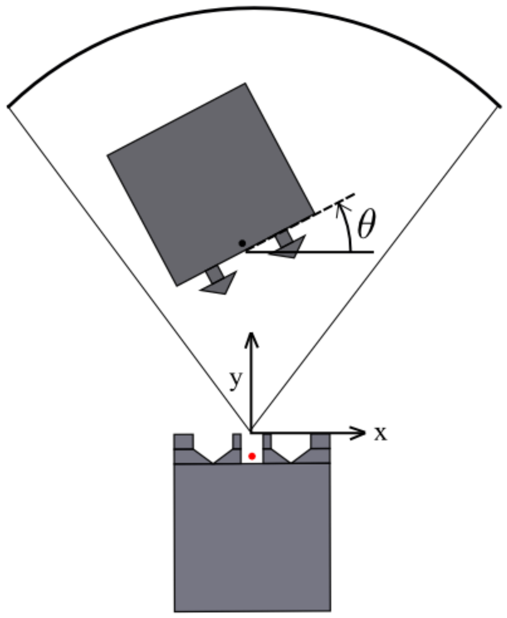
- **2015 EM Docking System Prototype**
  - Note: CoreSat Electro-Magnets are on ±Y Sides (Wide Mode) to aid capture, as their forces are longer range c.f. Permanent magnets.



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

RDV/Docking Port

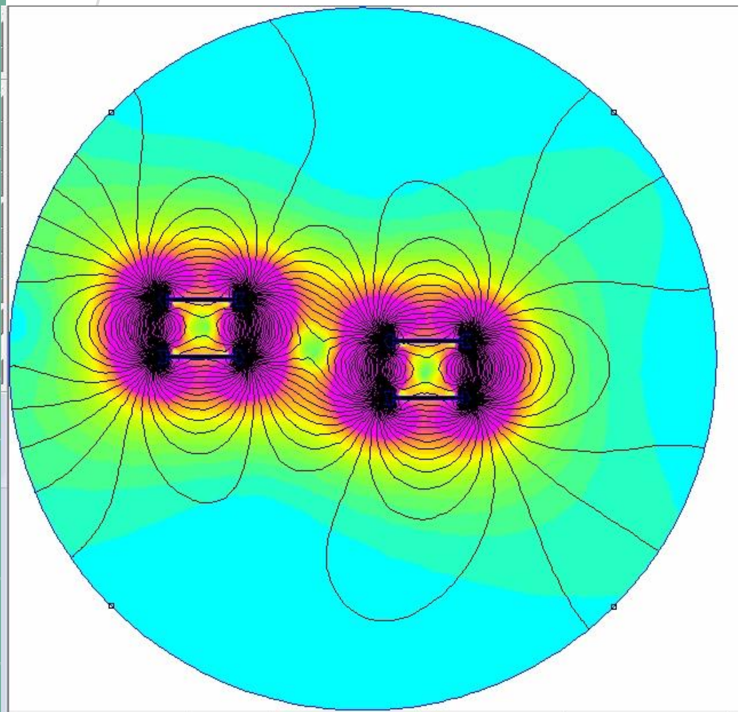
- **EM Docking System Testing**
  - CalTech and SSC initial Air-Bearing Table experiments show:
    - Capture distance is between 20-30cm for two pairs
    - Automatic self-alignment works, but choice of polarities is important to avoid miss-alignment/false-capture.
    - Attractive force is highly non-linear!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

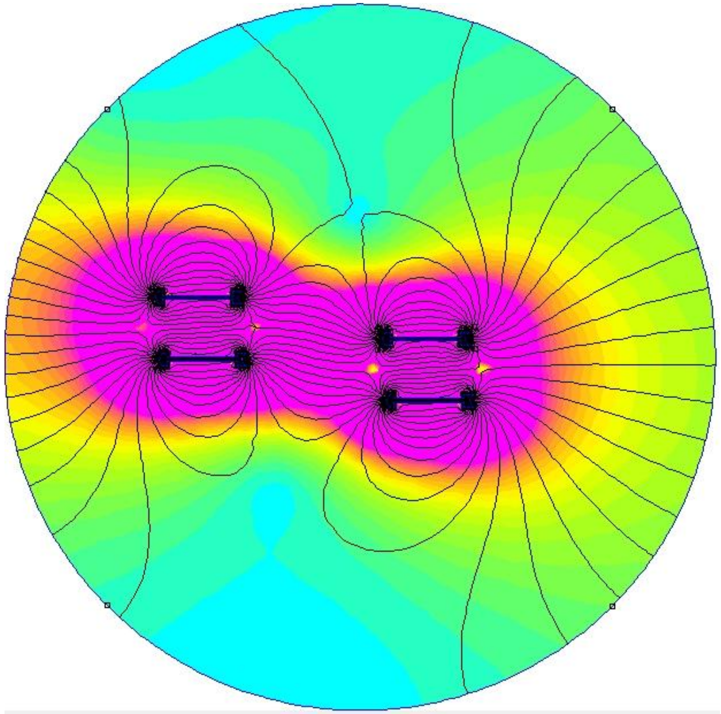


*Radius from centre of one face to centre of 'docking plane'; **Half angle

RDV/Docking Port

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



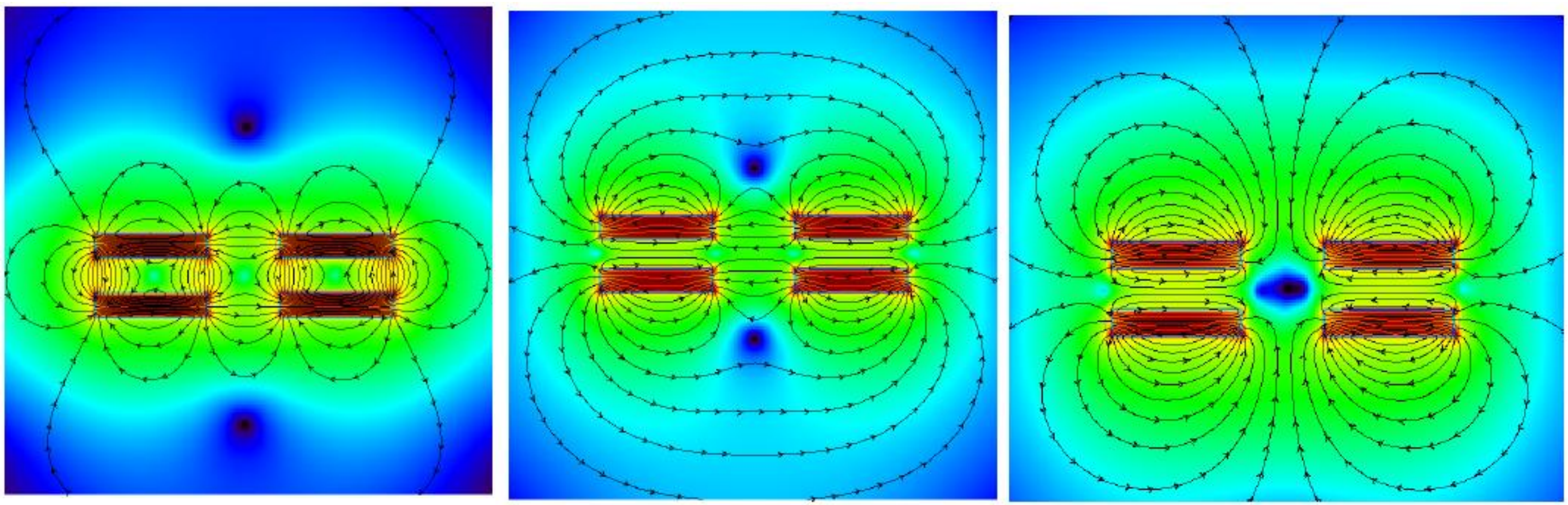


- Force is highly non-linear if the electro-magnets are simply energised.
- PWM control is used to vary the current to compensate for the distance effect.
- Useful force beyond 30cm separation.

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

RDV/Docking Port

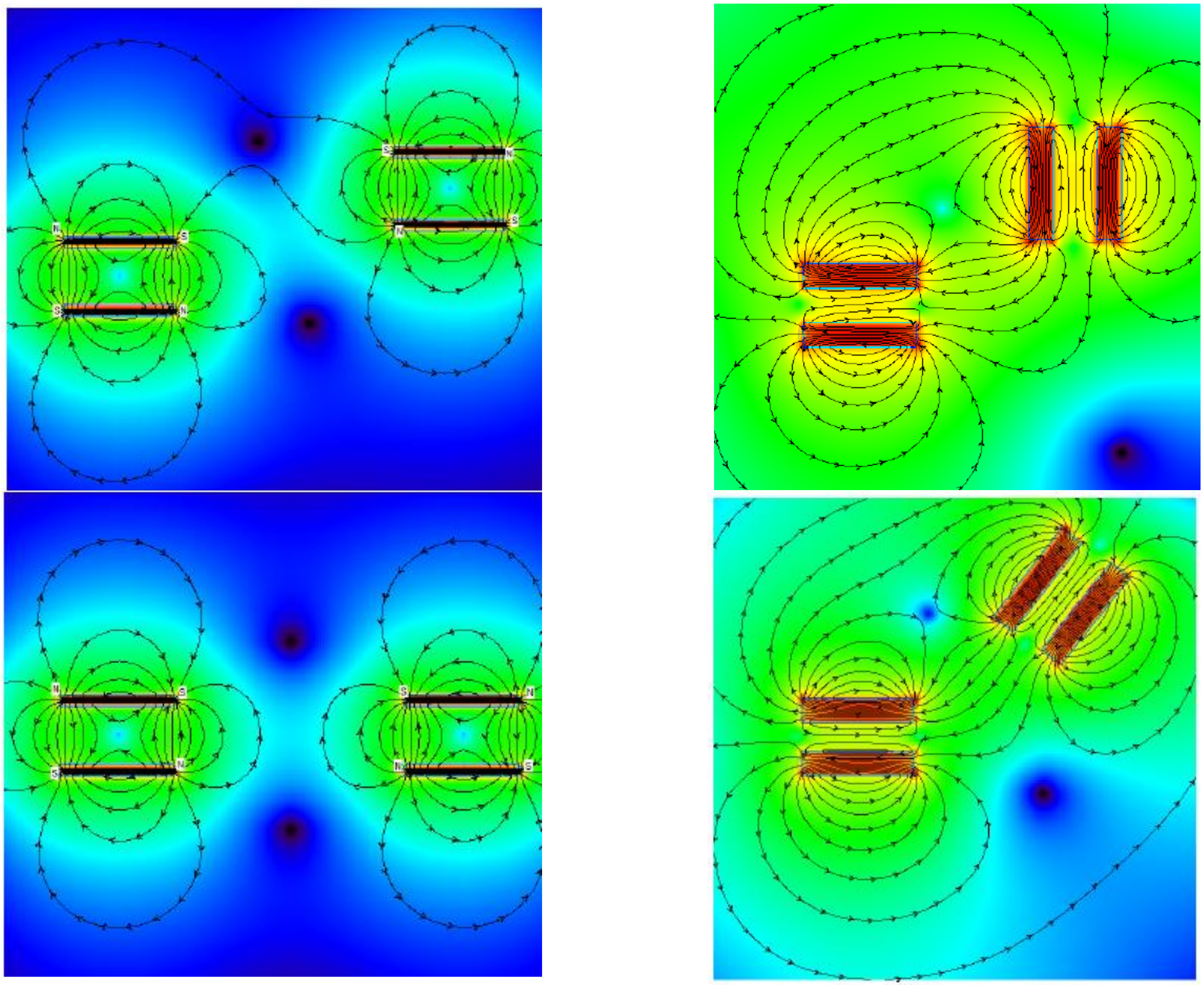
- **EM Docking System Tests 2015**
- (MSc Project:)
  - A simple 2D simulation was set up using the Vizimag software to help visualise the characteristics of the solenoids placed at various distances, polarity configurations and angular offsets.



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

RDV/Docking

- **EM Docking System Tests 2015**

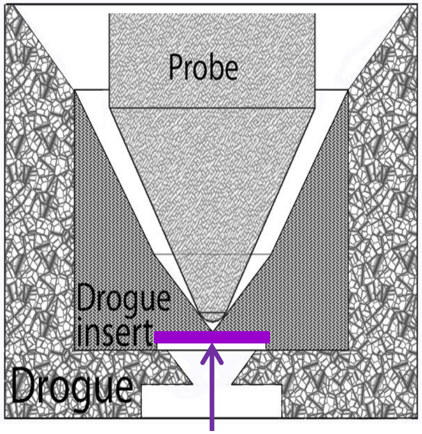


RDV/Docking

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

RDV/Docking Port

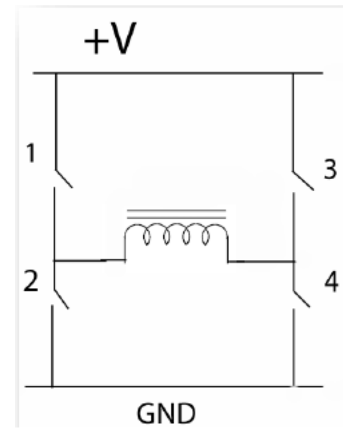
- **EM Docking System Tests 2015**
  - A new two-part drogue was been developed, which aids manufacture and assembly.
  - A built in neodymium permanent magnet (6mm dia., 1mm thick) provides the **latching action** to hold the spacecraft together when the electro-magnets are turned off.
  - We found the drogue must be non-ferrous, otherwise the probe "feels" no pull-in force. We used aluminium. 303 stainless steel should also work if we need to withstand greater pre-load.
  - The Kelvin-Clamp V-grooves would be spark etched for flight.
  - The probe, solenoid core and magnetic field extenders are all now pure iron (not Supra50 alloy).
  - 2017 version needs no separate latching magnet.

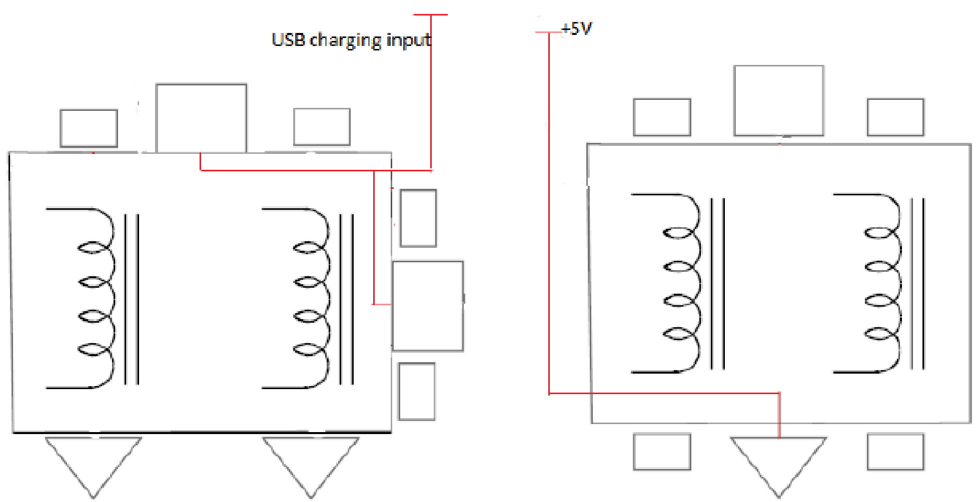


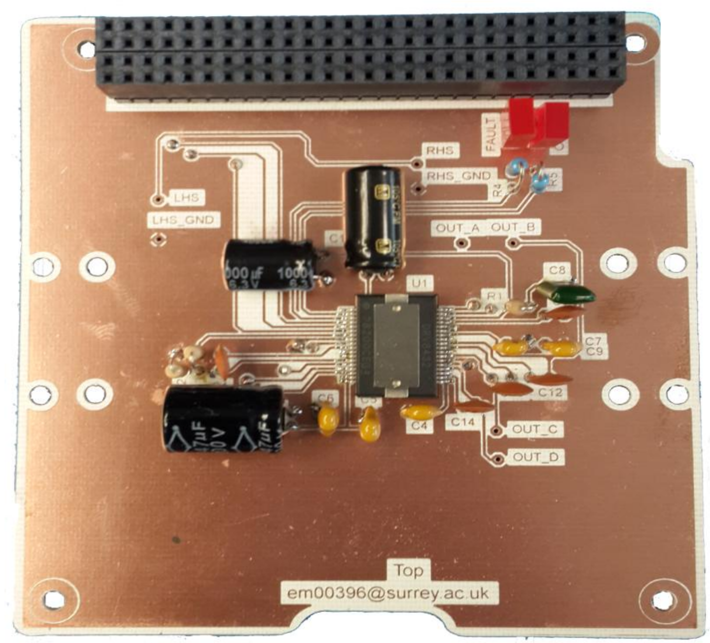
Latching Permanent Magnet

RDV/Docking Port

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



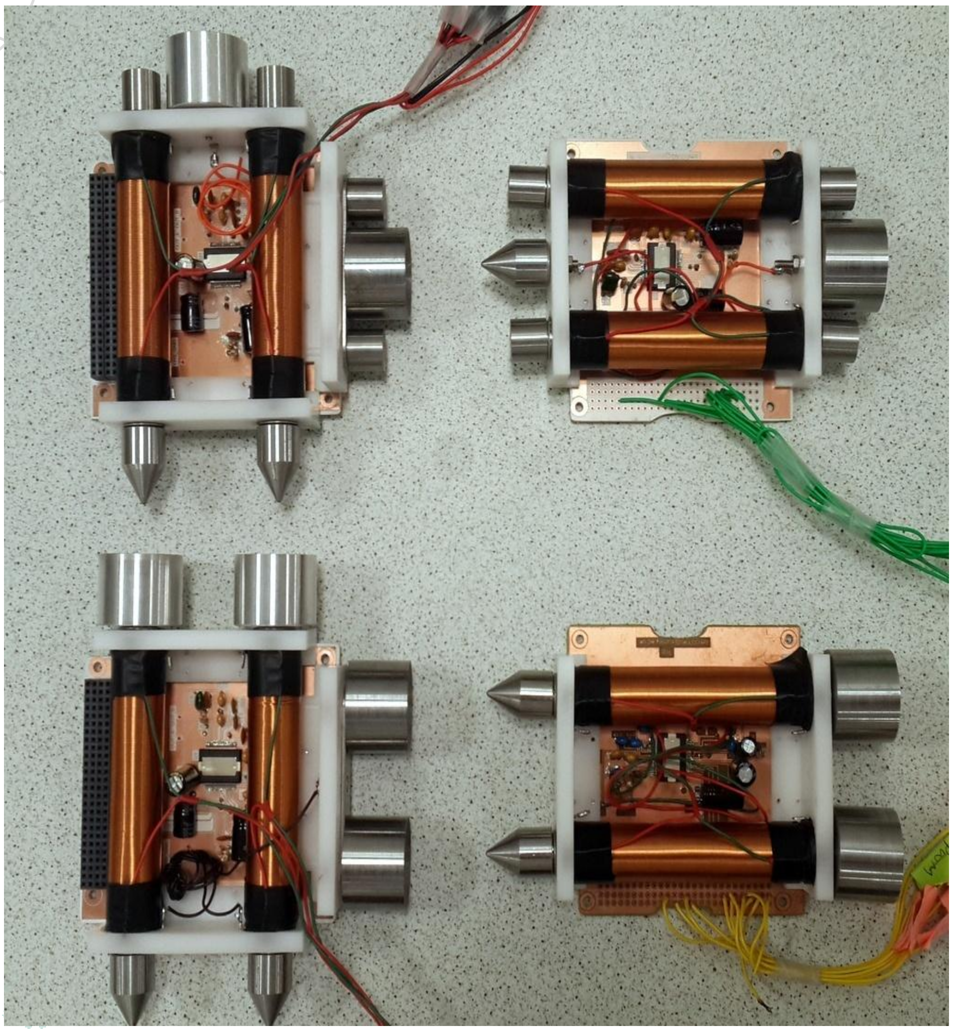


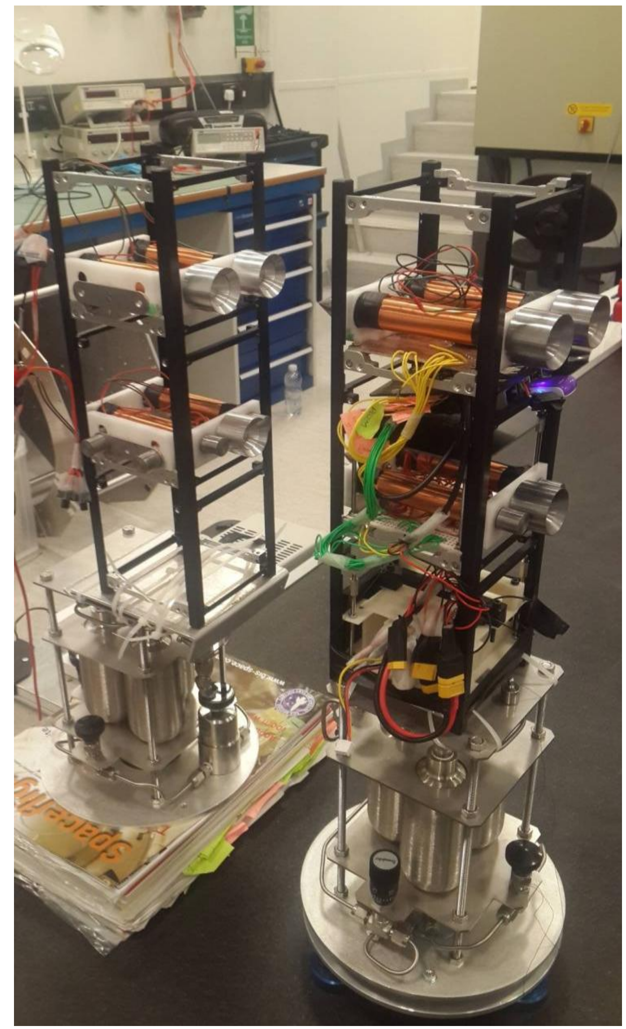


2017 – Design for 2-way power transfer?

RDV/Docking Port

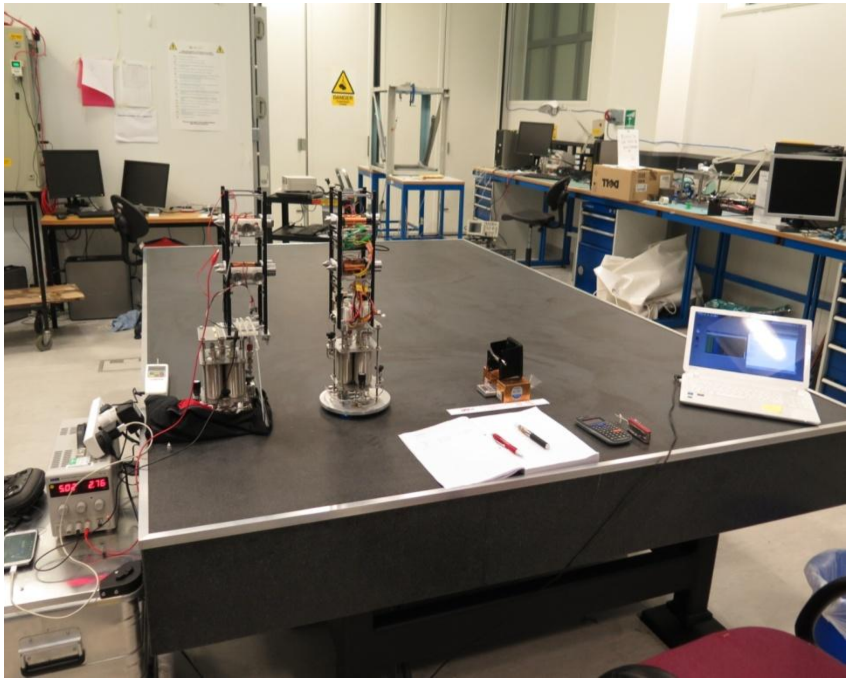
- **EM Docking System Tests 2015**
  - Re-designed Docking Ports and 2D Air Bearing Test Rig





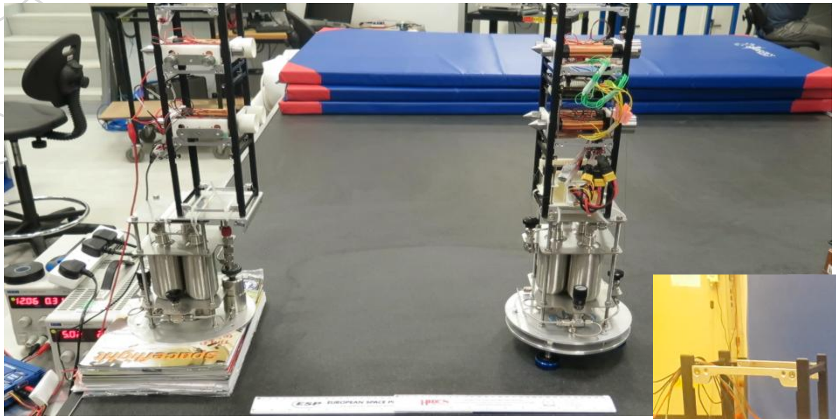
RDV/Docking Port

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

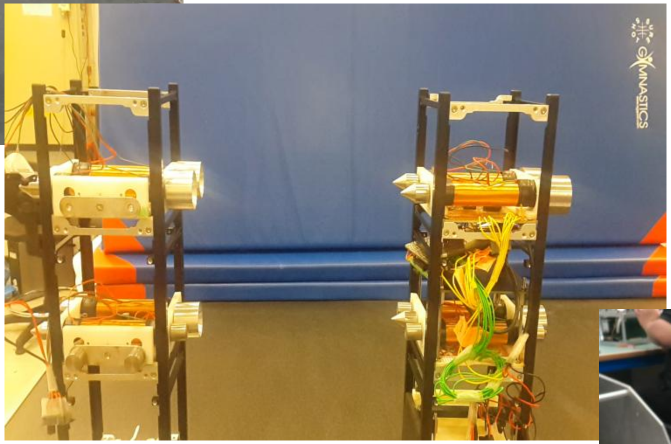


RDV/Docking Port

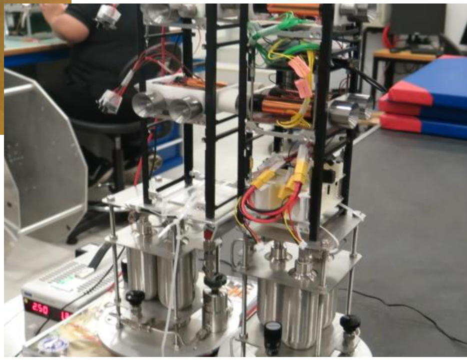
- **EM Docking System Tests 2015**
  - Videos: 50cm Docking; 20cm Docking; Repel and Hold at Distance



Docking from 50cm



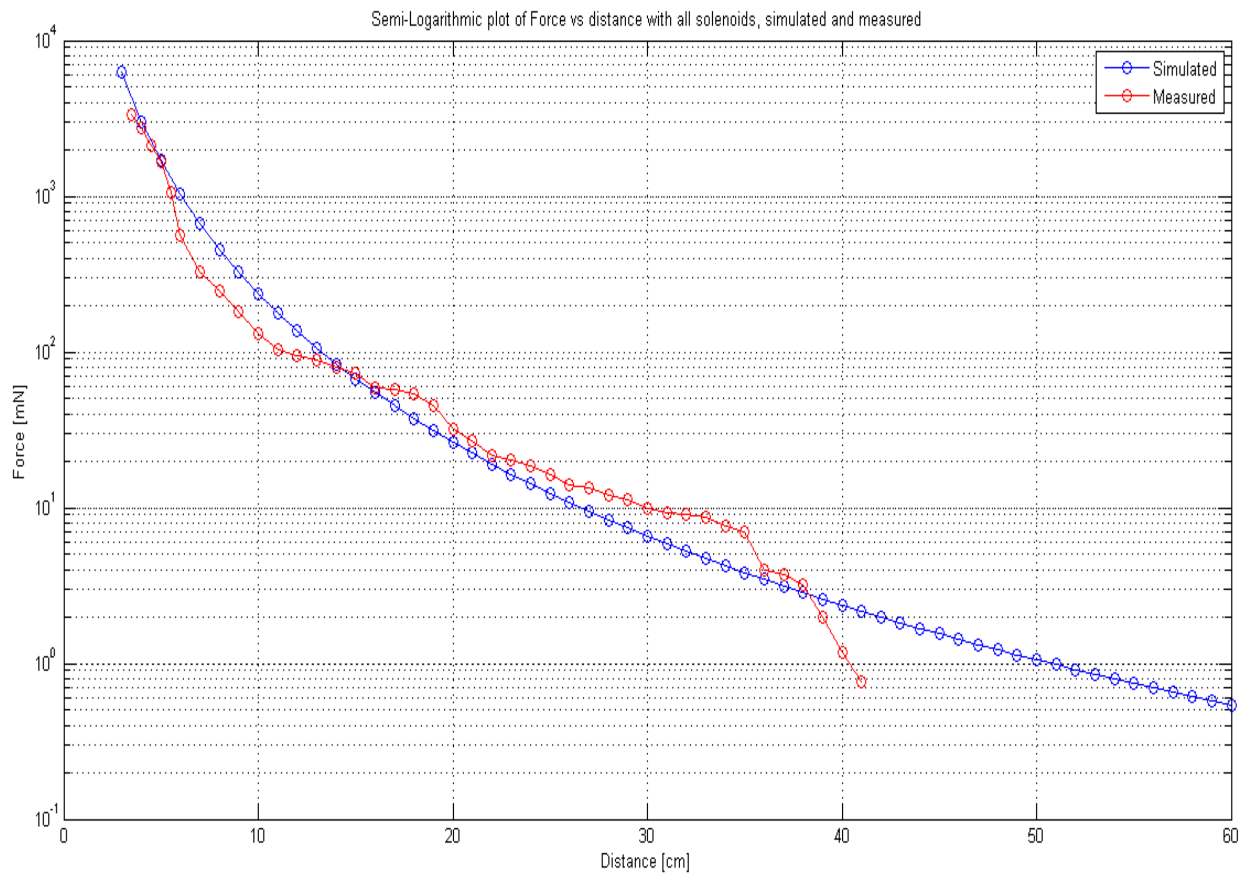
Docking from 20cm



Repel and Hold

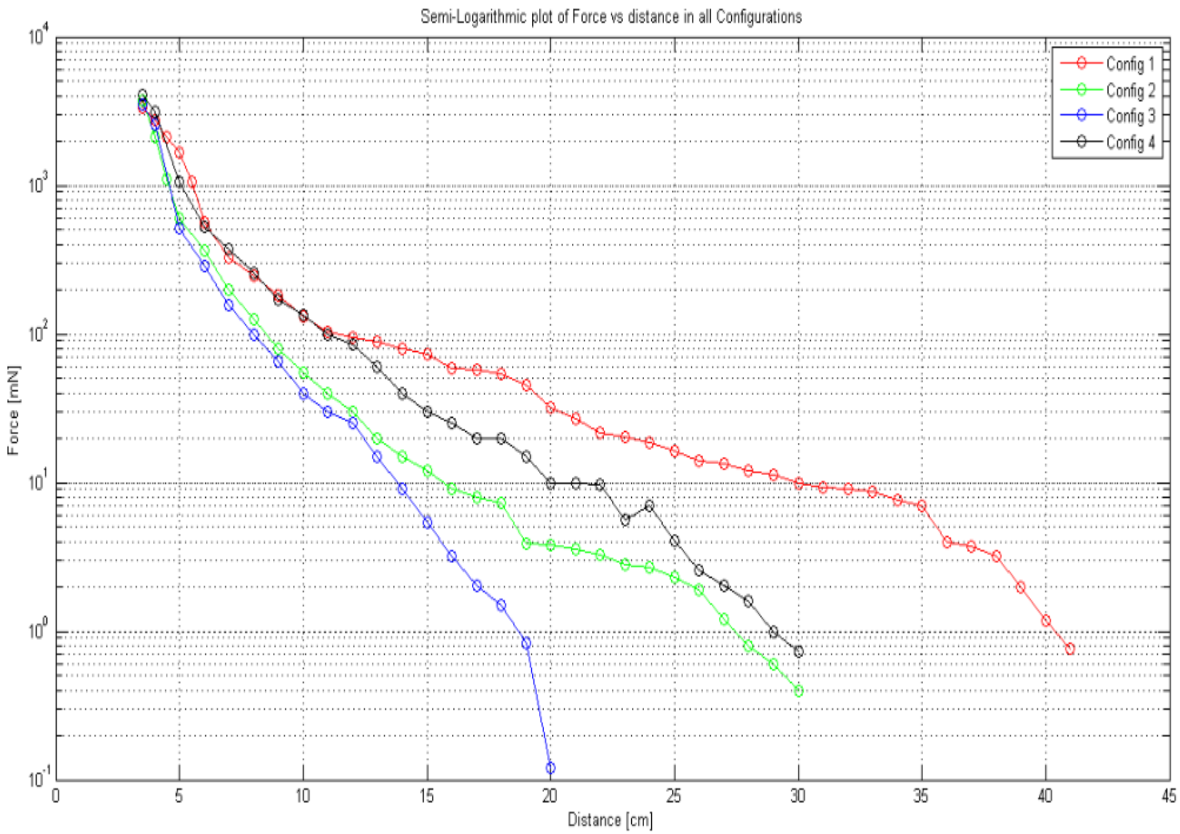
RDV/Docking Port

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



RDV/Docking

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



RDV/Docking

- **EM Docking System Development Summary**
- Summary (2015/16 MSc work): Enda McKenna and Patrick Maletz:
  - Re-designed docking cone or 'drogue' to ease manufacture.
  - Designed and verified the performance of an H-bridge driver.
  - Implemented PWM control using Raspberry Pi over Wi-Fi.
  - Demonstrated docking and undocking on Air Bearing Table.
  - Measured attraction and separation forces, acceptance angles and average tolerances
  - Verified performance of latching magnets (note: needed Electro-Magnets on **both sides** to overcome these latching forces.
- Remaining Work for 2017:
  - Add Kelvin Clamp grooves and re-design ports and flux extenders to include permanent magnets (for CoreSat and latching)
  - Link Docking System control to Docking Sensor system and develop dynamic control strategy.
  - Verify performance on 2D air bearing (3DoF) and develop "2½ D" test rig (2 translations, 2 rotations).
  - Complete 6 DoF simulator and address geomagnetic field torque and magnetic field extender contact issues.

Questions?

Surrey AAReST Docking Port & Electro-Magnetic Modelling 2017

RDV/Docking Port

- **EM Docking Update 2017 – Peter Mazurenko Taylor**

Project Objectives:

- Construct magnetic and electromagnetic mathematical models that can be used as a foundation for informed PMDS design;
- Produce a series of designs fulfilling the PMDS design requirements;
- Select a final design and produce fully formed CAD models Fabrication of PMDS;
- Produce all components associated with the PMDS;
- Facilitate V-groove manufacture, likely through spark erosion;
- Measure torques for the PMDS interacting with Earth's magnetic field for different permanent magnet configurations;
- Measure PMDS-EMDS docking forces;
- Produce CAD models of all docking system components;
- Update electronics so they are compatible I2C serial bus and the orbit environment;
- Refine the docking system power sharing design.

RDV/Docking Port

- **FEMM Modelling**
  - Modelling of Neodymium Disc Magnet matched theory.
  - Modelling of EMDS shows a modal flux density along the solenoids pole face of 0.097 T and a maximum flux density of 0.46 T – well below the saturation density of the iron (1.6-2 T) and far above that of an equivalent coil without an iron core (0.0074 T) => complexity!

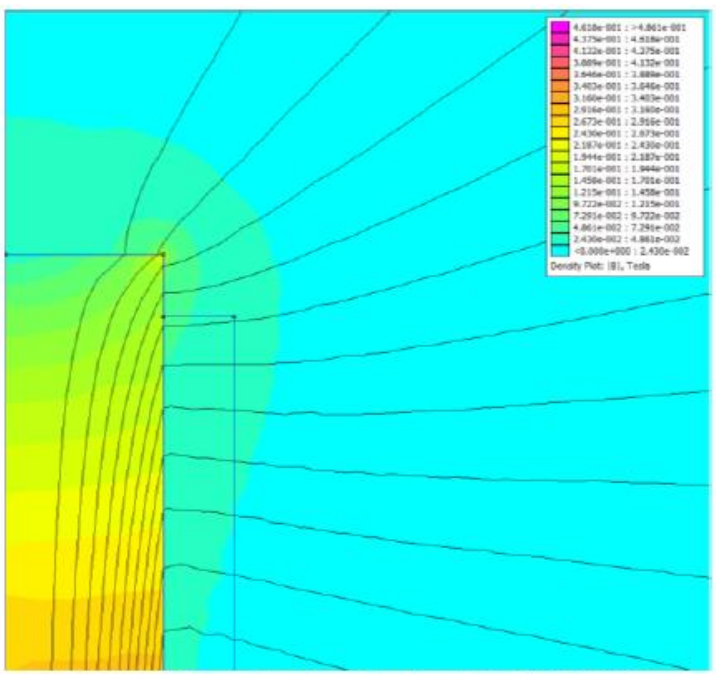


Figure 12 Flux density plot for ARReST EMDS solenoid FEMM simulation

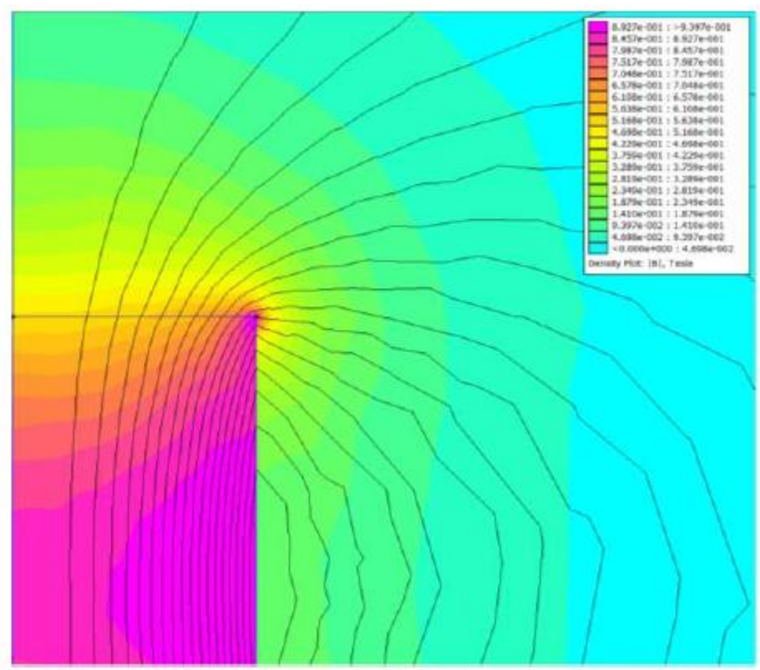


Figure 13 Flux density plot for 5mm by 12mm N35 neodymium disc magnet FEMM simulation

- **FEMM Modelling**
  - Investigated 3 methods: Weighted Stress Tensor Volume Integral (**WSTVI**); Maxwell Stress Tensor Line Integral (**MSTLI**) – difficult to use correctly; and **Coenergy**:
  - MSTLI (blue) gave best fit – but results varied – still underestimates force.

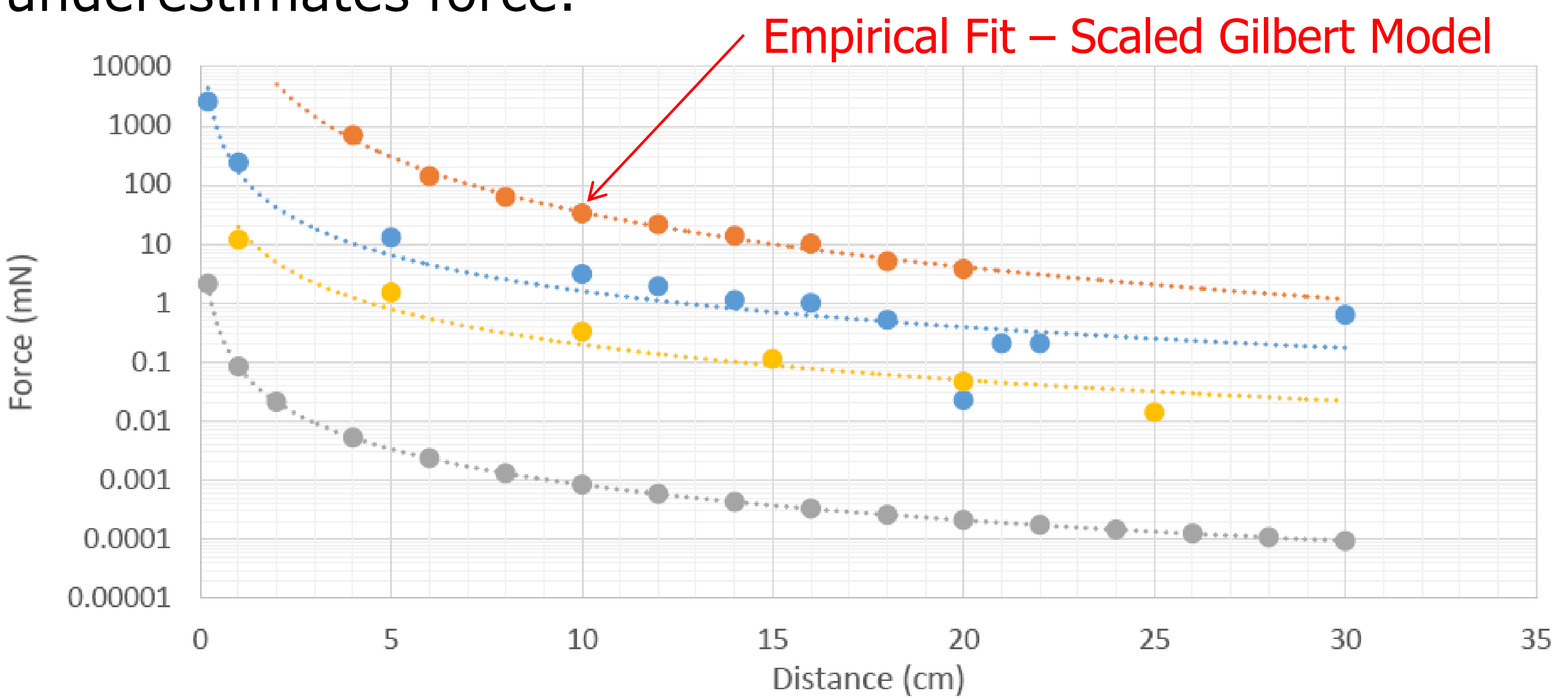


Figure 14 Semi-log force against distance plot for different modelling approaches. Gilbert model (Grey), adjusted empirical data set (orange), FEMM using coenergy theory (yellow), FEMM using Maxwell Stress Tensor Line Integral theory (blue)

RDV/Docking Port

- **Force Modelling**
  - Abandoned FEMM – went for Scaled Gilbert Model
  - The empirical found pole strength for the solenoids was 133.6 Am^2. Gilbert Theory says 0.0968 Am^2.

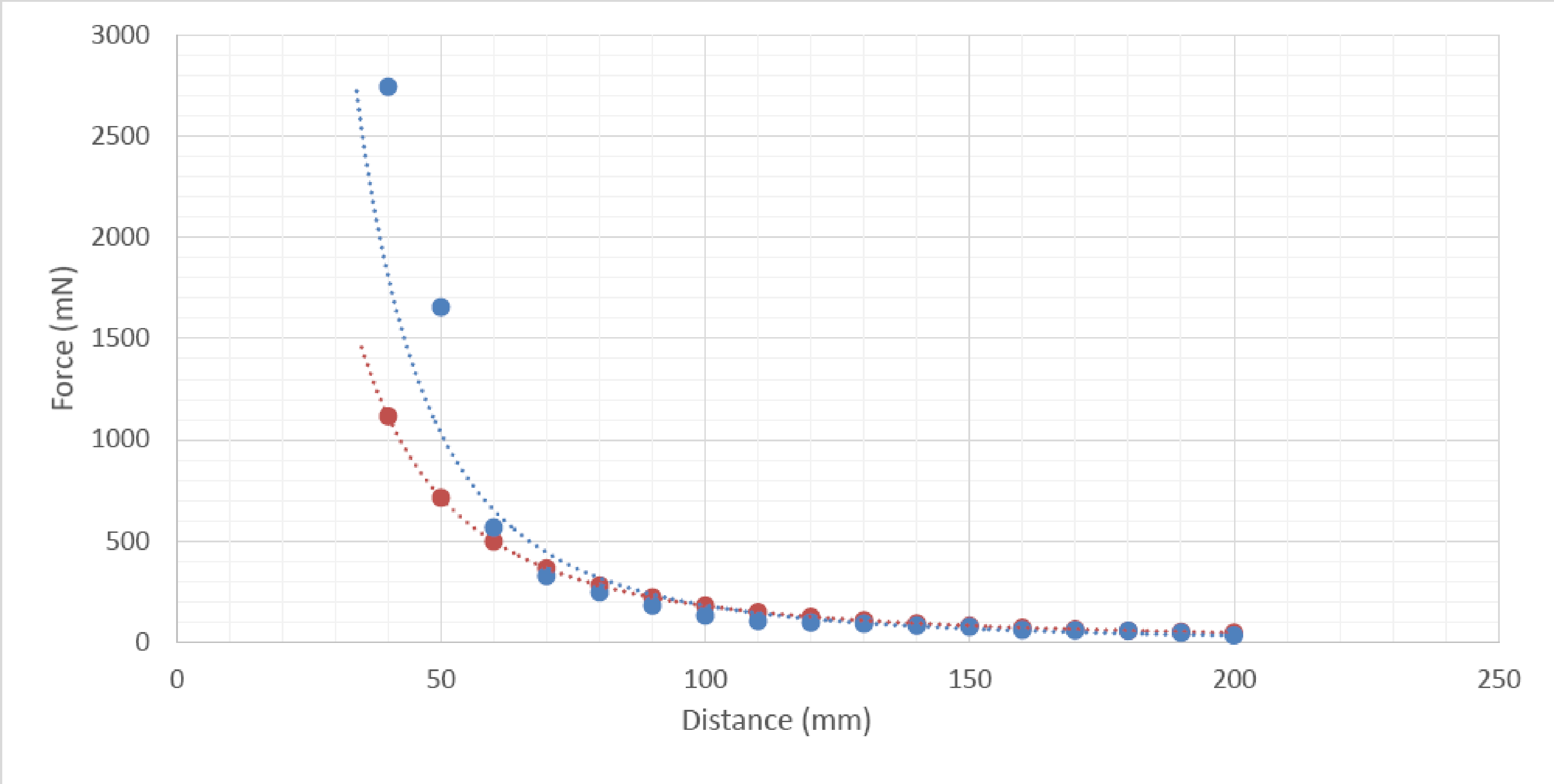
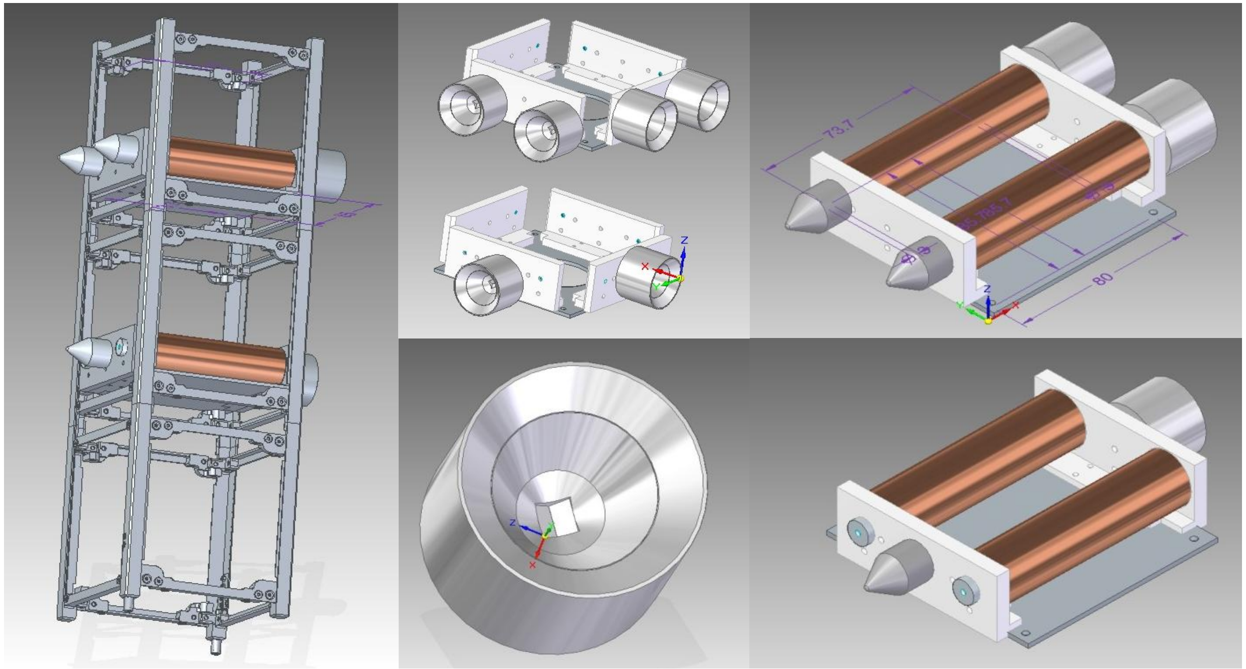


Figure 15 Force against distance (taken at pole faces) for two axially aligned solenoids. Adjusted pole strength Gilbert model (red), Empirical data (McKenna, 2015) (blue)

RDV/Docking Port

- **CoreSat Permanent Magnet Docking System (PMDS)**
  - One key change to the design for 2017 was to make the Docking Ports on the CoreSat **all permanent magnets** (rather than a mixture of permanent and EM as before).
  - This requires care choice of polarity, so as to minimise the magnetic moment but maximise the RDV pull-in.
  - Neodymium disc magnet stacks were proposed:



RDV/Docking Port

- **Force Modelling**
  - Plotting the repulsive force between two solenoids vs. the attractive force of a 12mm by 5mm radius N35 neodymium disc magnet and an iron cylinder, shows why we cannot undock using one EM vs. PM/iron – the PM/iron attractive force is too strong at close range.

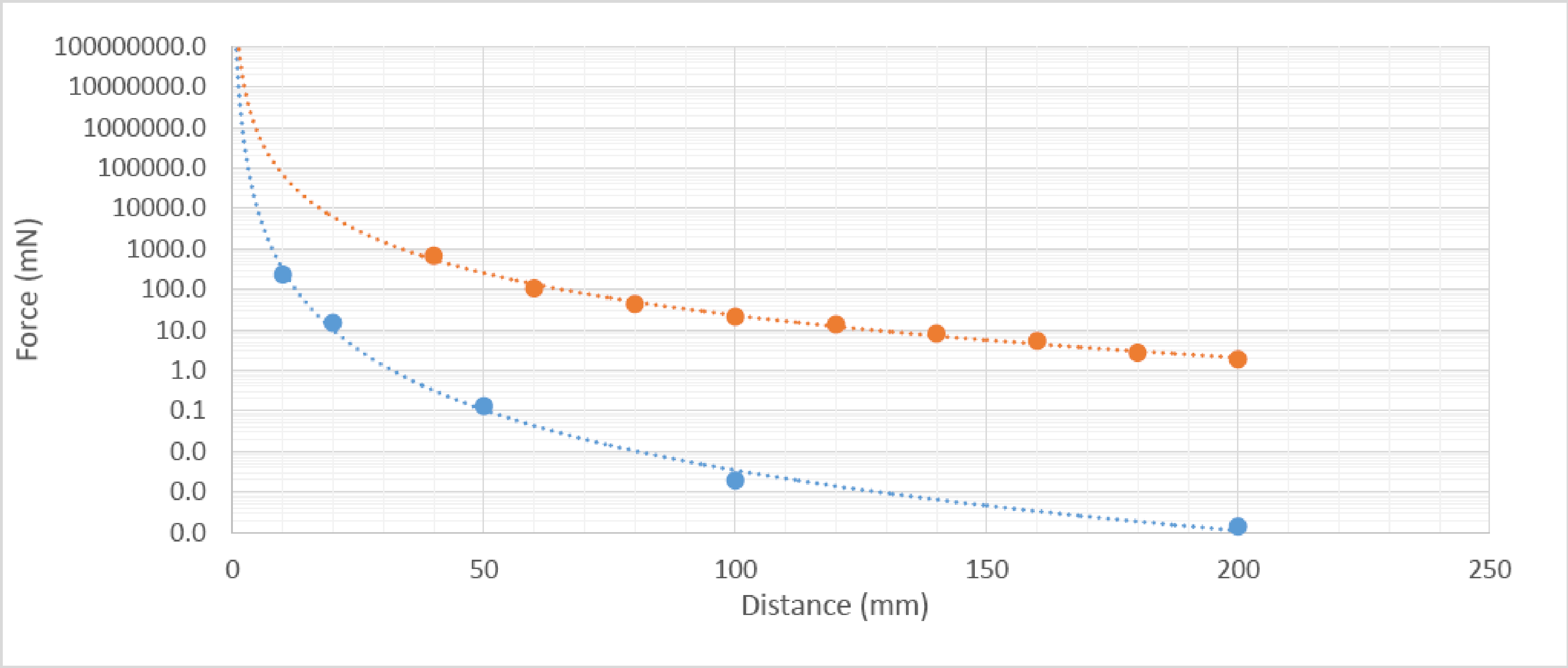


Figure 16 Repulsive force for a solenoid pair (orange) against the attractive force between a permanent magnet and iron cylinder (blue)

RDV/Docking Port

- **Force Modelling**
  - Derived EMDS-EMDS and EMDS-PMDS forces using a scaled Gilbert Model.
  - PMDS-EMDS model exhibits a consistently smaller force-distance profile. This model shows a 49% smaller force at each distance for the PMDS-EMDS system relative to the EMDS-EMDS system.

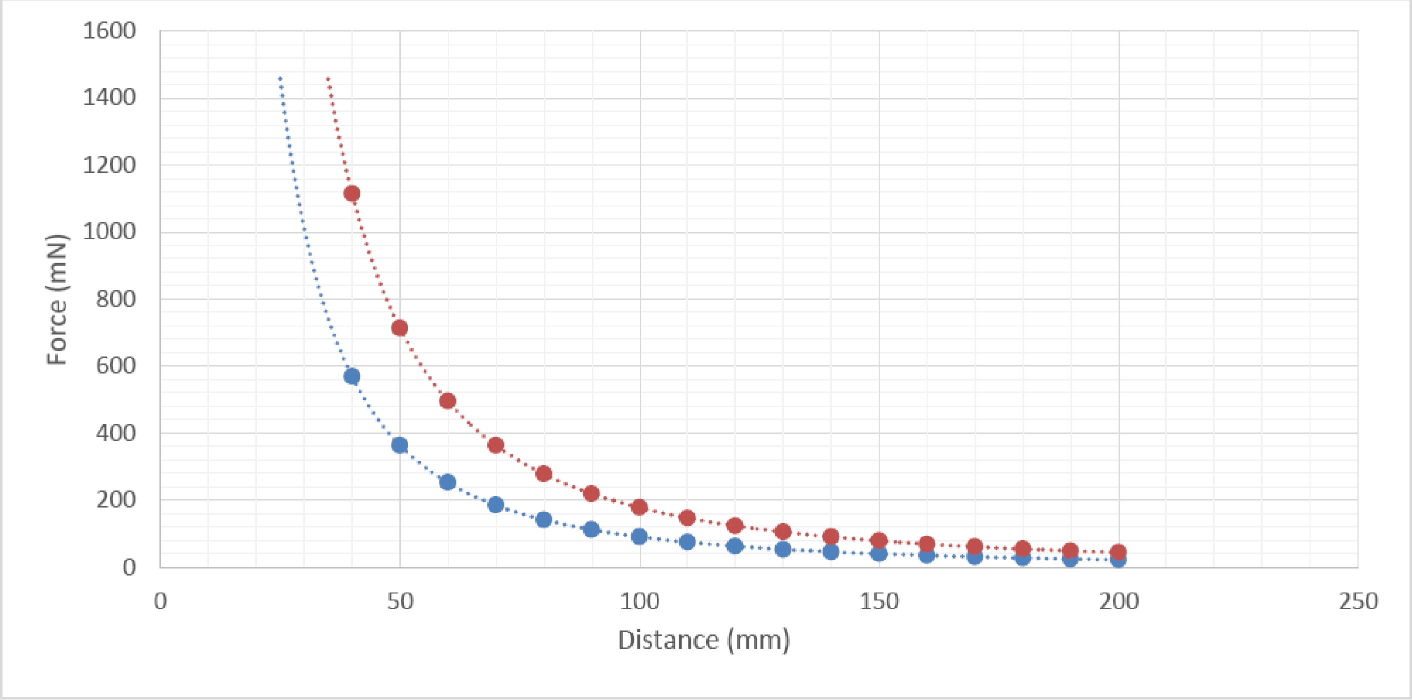
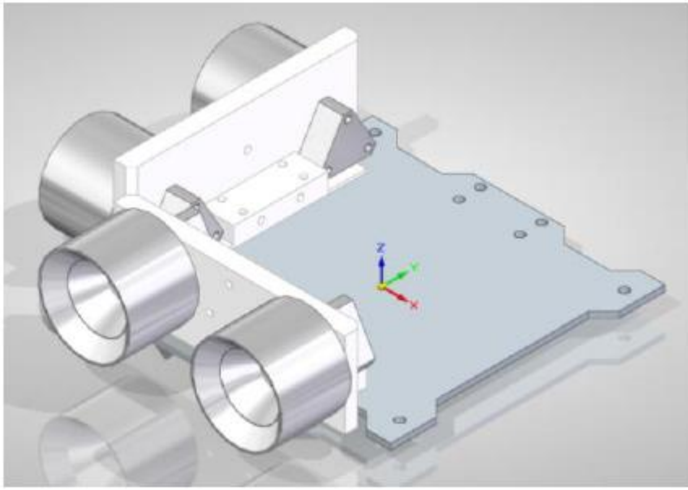
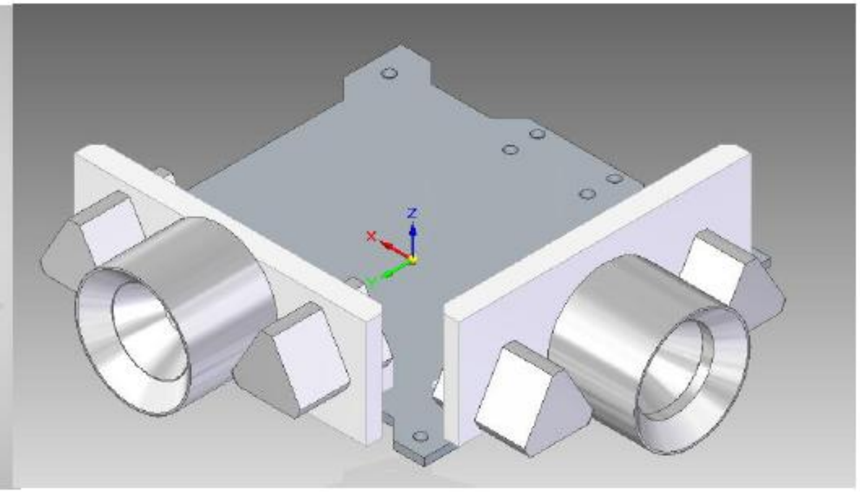


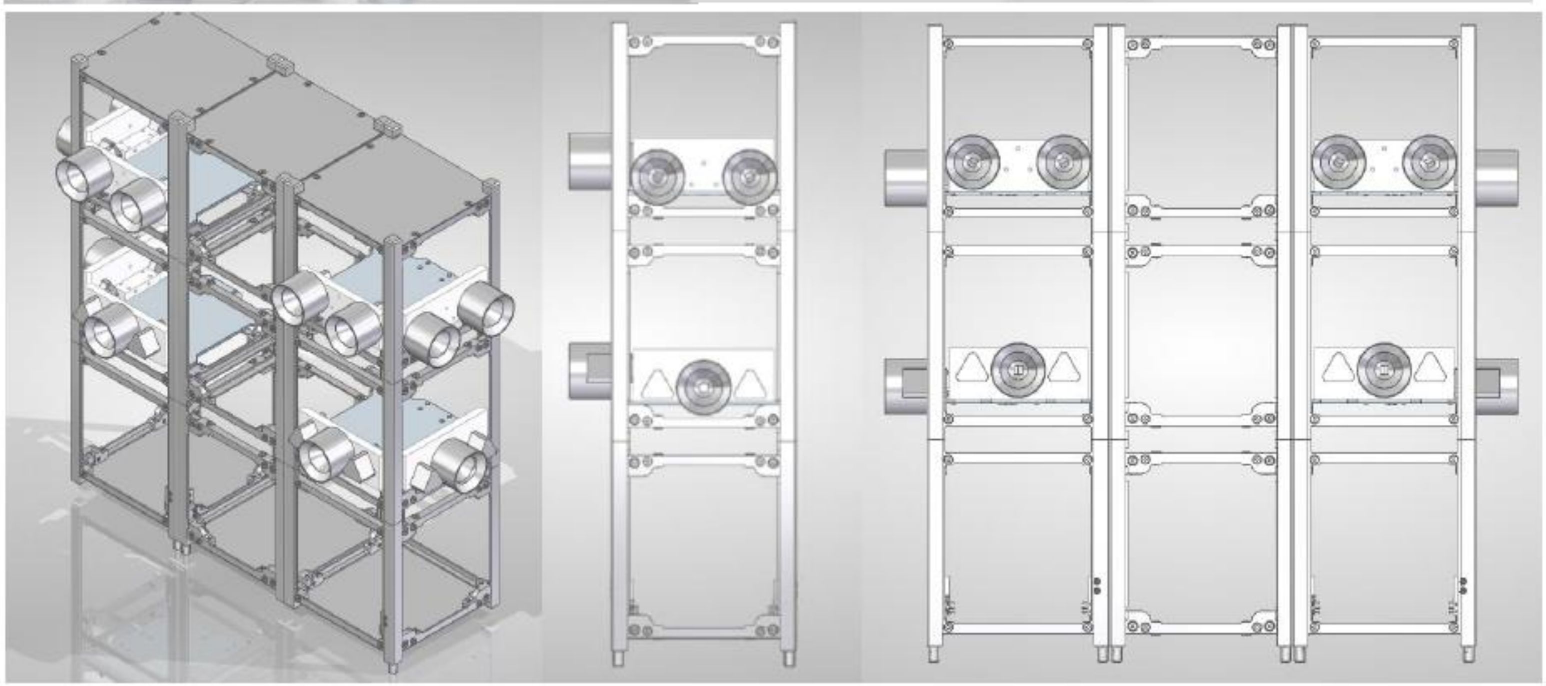
Figure 17 Force against distance plot for Gilbert model approximation of PMDS-EMDS magnet-solenoid pair (blue) and EMDS-EMDS solenoid pair (red)

RDV/Docking Port

- **PMDS (Only) Design for CoreSat**

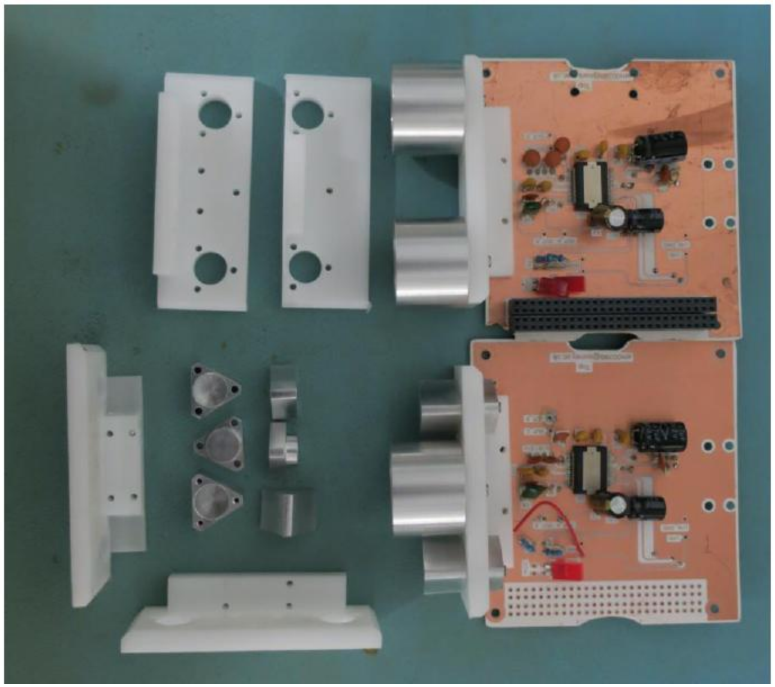


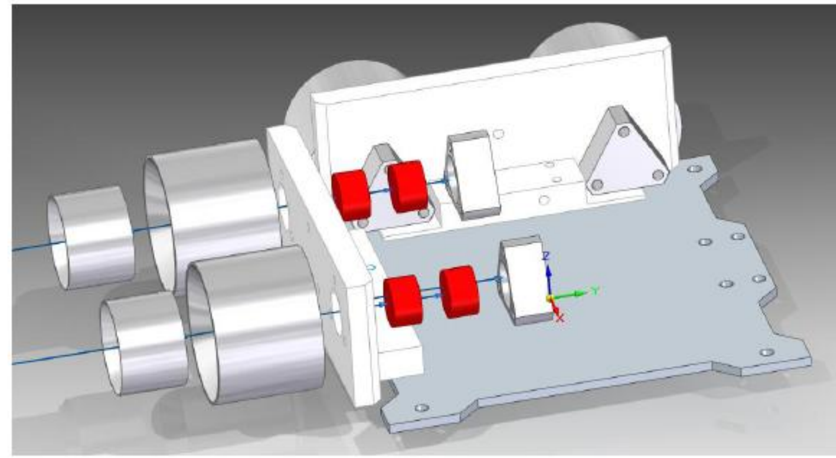


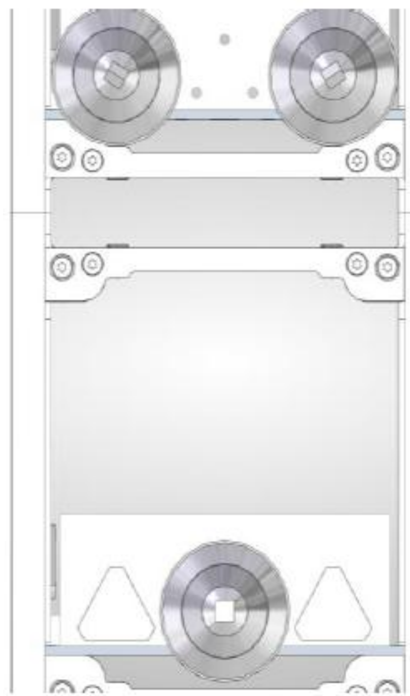


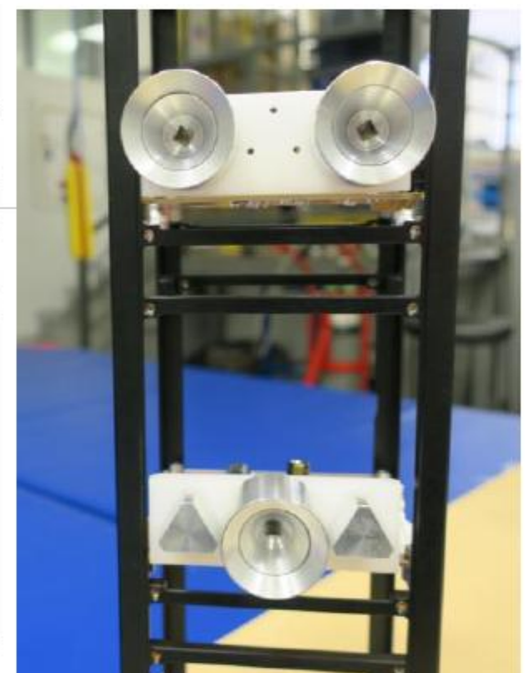
RDV/Docking Port

- **PMDS (Only) Design for CoreSat**









Note: Aluminium V-Grooves showed signs of polishing after many contacts – suggests moving to harder (non-magnetic) material: 303 Stainless Steel.

RDV/Docking Port

- **Flux Extender**
  - Pure Iron Fux Extender spacing increased from 2mm to 4.12 and 6.5mm to reduce risk of premature contact and "locking".

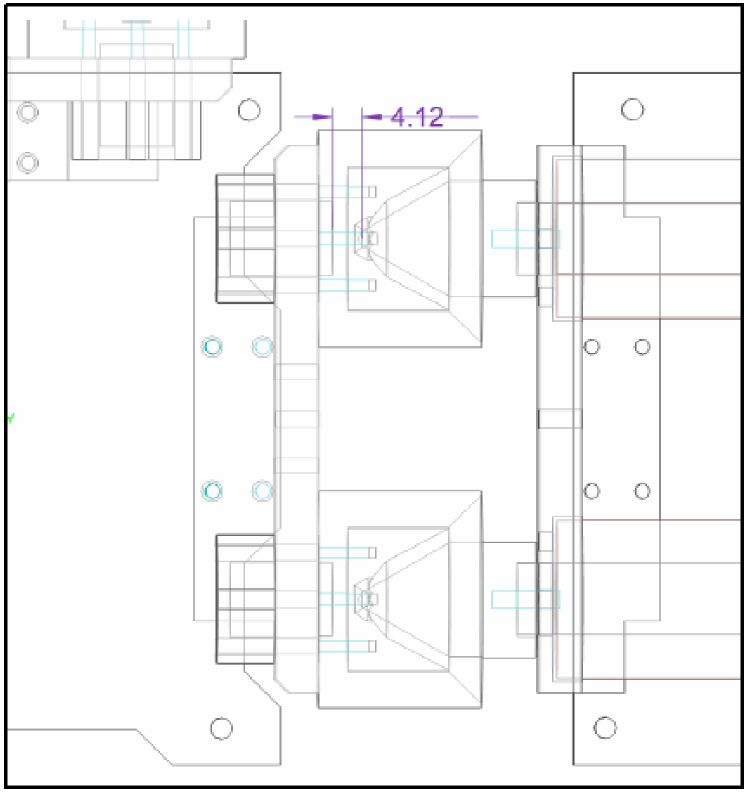


Figure 32 EMDS-PMDS double probe docked position (dimensions in mm)

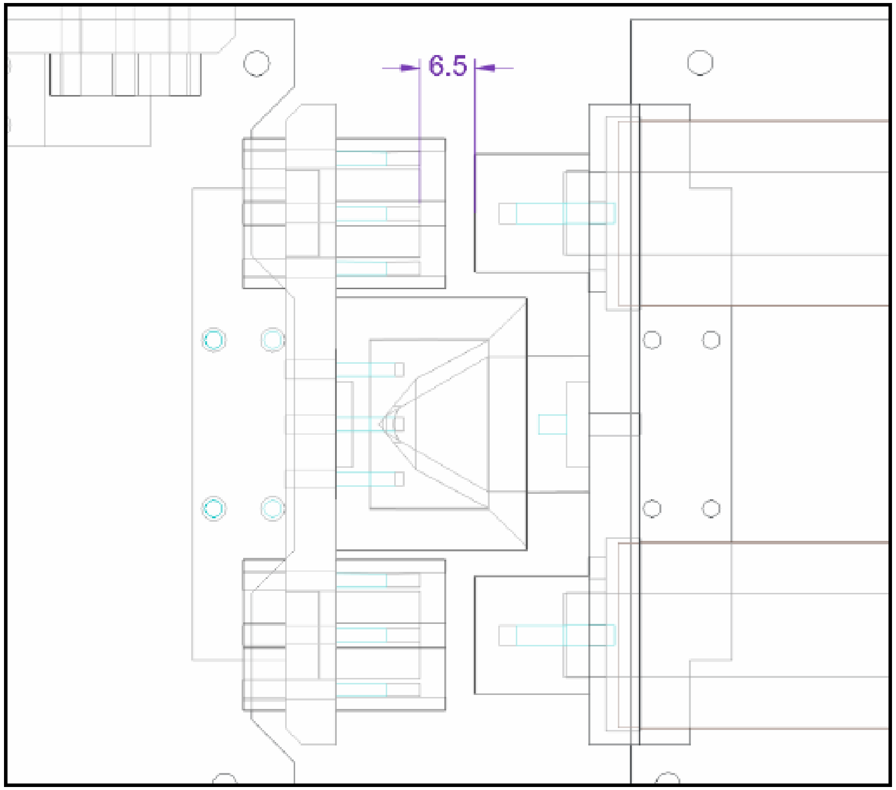
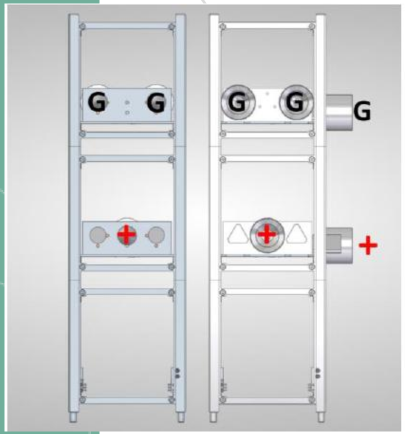


Figure 33 EMDS PMDS single probe docked position (dimensions in mm)

RDV/Docking Port

- **Docking Port 5V, 1A Power Sharing** – Uses TPS2061 switches rated at 1 A for 2.7 to 5.5 V with 1.5 A current limiting short circuit (thermal) protection. Developed and Tested.



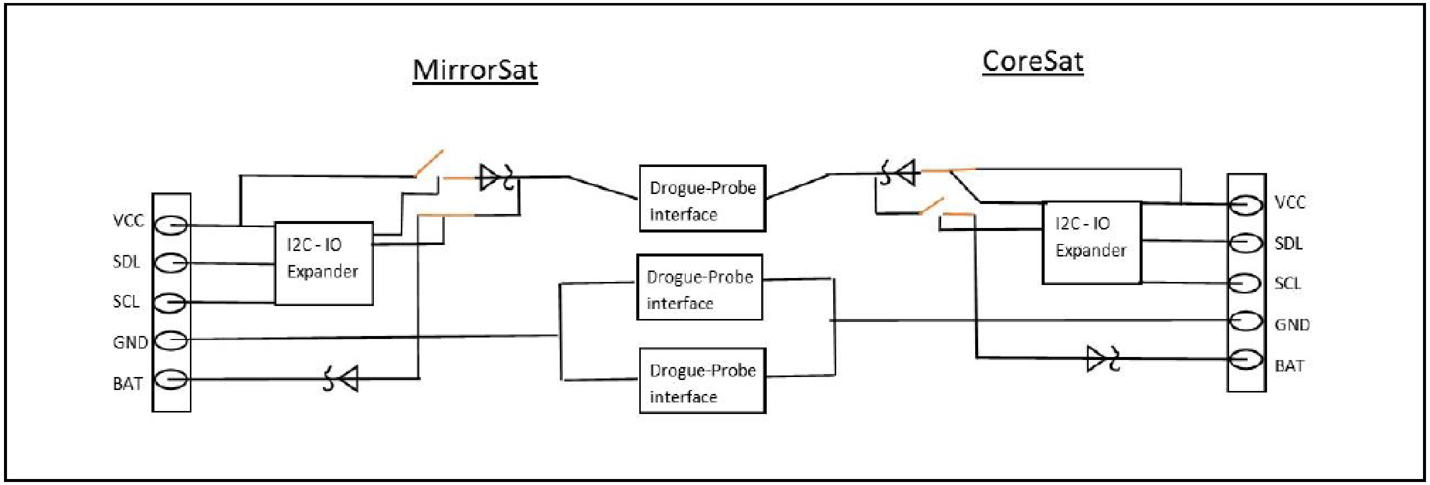


Figure 37 Power sharing circuit layout diagram (Switches shown in orange). CoreSat charging MirrorSat

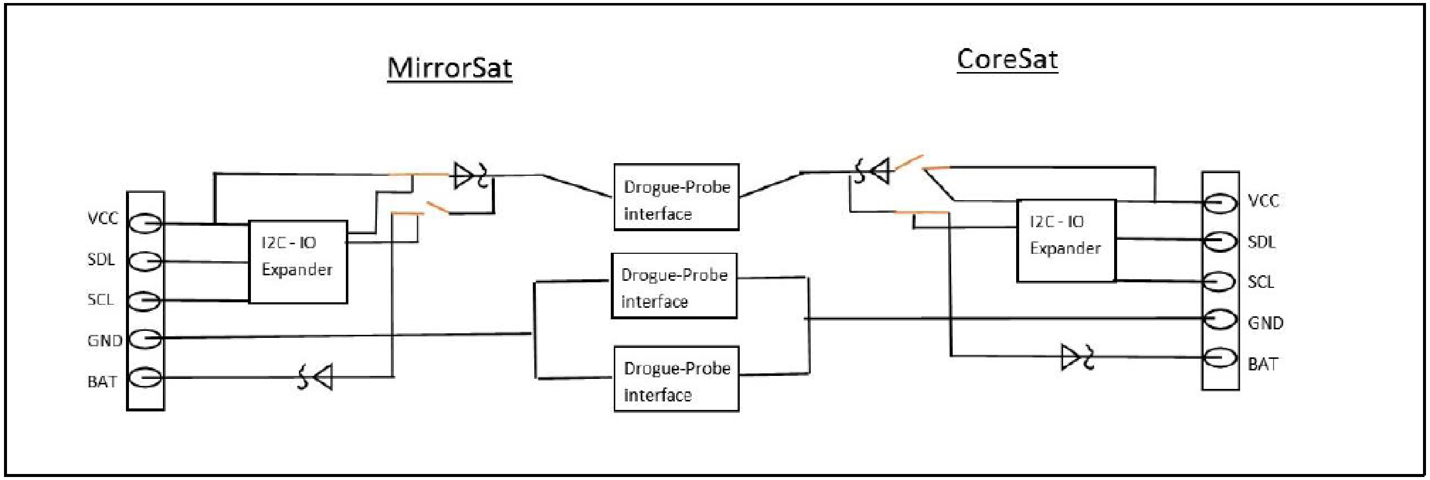
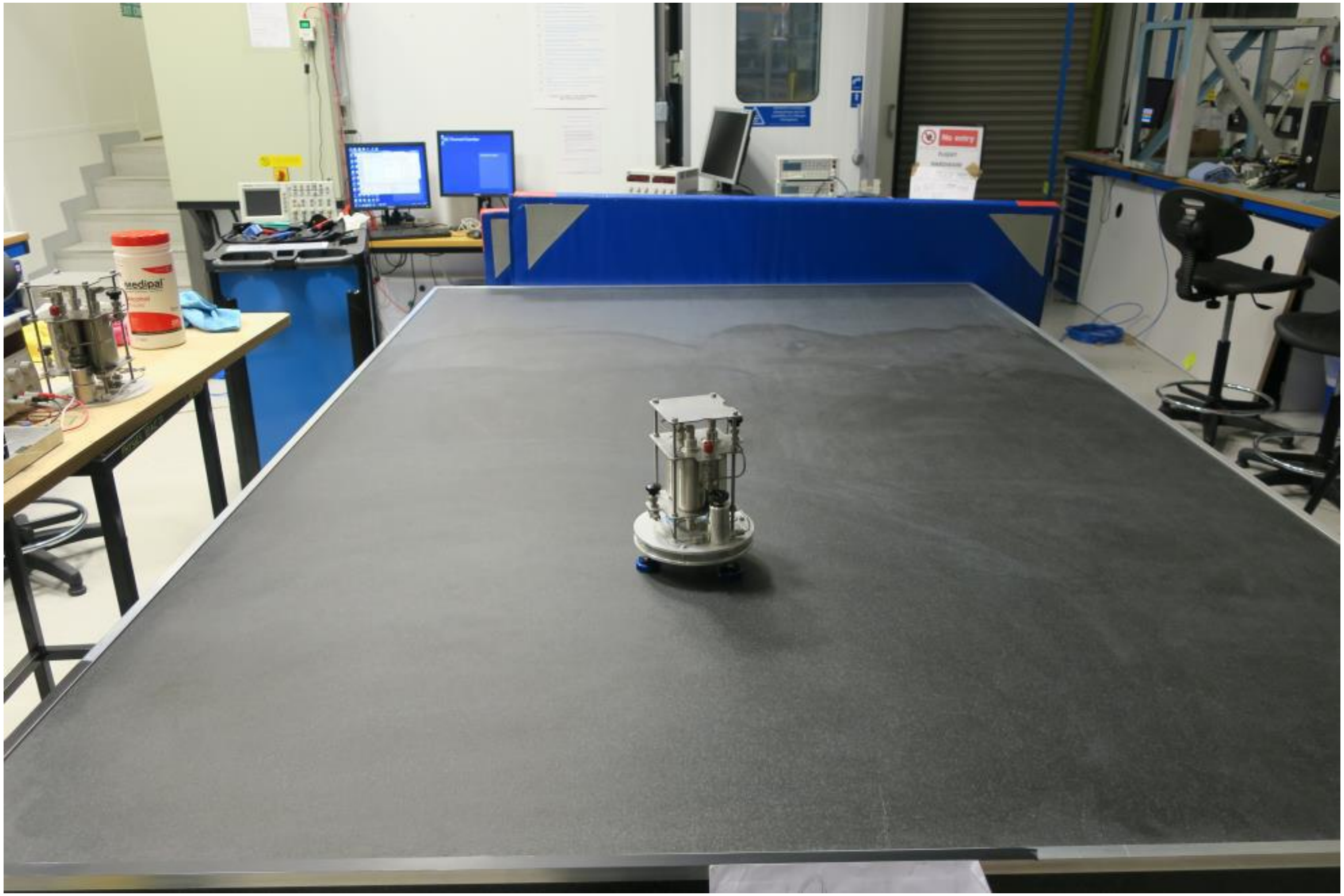


Figure 38 Power sharing circuit layout diagram (switches shown in orange). MirrorSat charging CoreSat

RDV/Docking Port

- **Air Bearing Table Tests**
  - SSC 3DoF 2D Air Bearing Table



RDV/Docking Port

- **Air Bearing Table Tests**
  - PM Magnetic Torque Tests (using Geomagnetic field)
  - Done by measuring time to rotate through an angle.
  - Different configurations used, 0.15 to 1.25 mNm torques measured (difficult due to small disturbances)
  - ESL ADCS standard MW has 1.7 mNm torque.

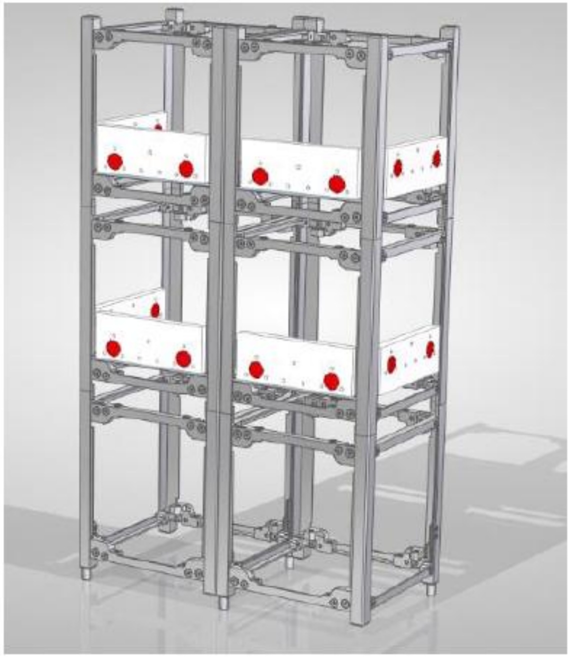


Figure 41 CAD model of CoreSat magnetic torque testing rig (magnets shown in red)

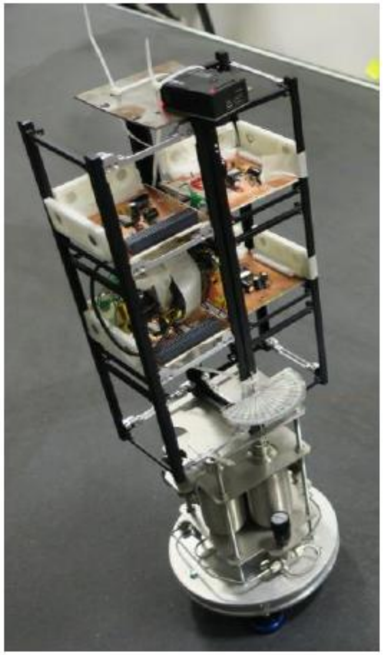
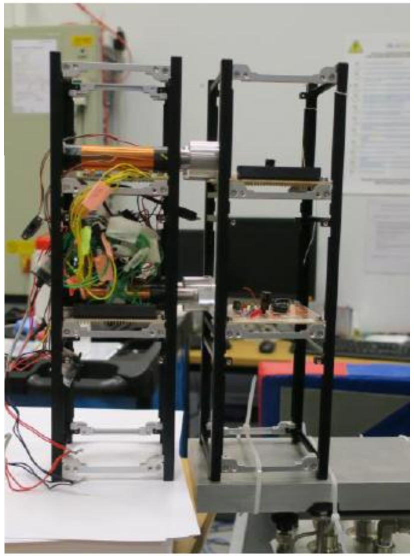


Figure 42 CoreSat magnetic torque testing rig

RDV/Docking Port

- **Air Bearing Table Tests**
  - Undocking Tests – With Iron Flux Extenders:

Nylon Spacer Thickness (mm)	Magnet Thickness (mm)	Powerpack Output Current (A)				Equivalent PWM (%)
		1	2	3	Mean	
7.05	5.00	0.97	0.91	0.91	0.93	35.77
6.25	6.00	1.35	1.29	1.39	1.34	51.67
4.75	7.00	1.78	1.89	1.78	1.82	69.87
3.95	8.00	2.35	2.42	2.49	2.42	93.08
3.15	9.04	2.80	2.83	2.55	2.73	104.87



  - Using Polymer "flux Extenders":

Magnet Thickness (mm)	Powerpack Output Current (A)				Equivalent PWM (%)
	1	2	3	Mean	
12.00	0.48	0.46	0.48	0.47	18.21

  - Conclusion: Remove iron flux extenders on PMDS.

RDV/Docking Port

- **Air Bearing Table Tests**
  - Configuration Tests show magnets do interact

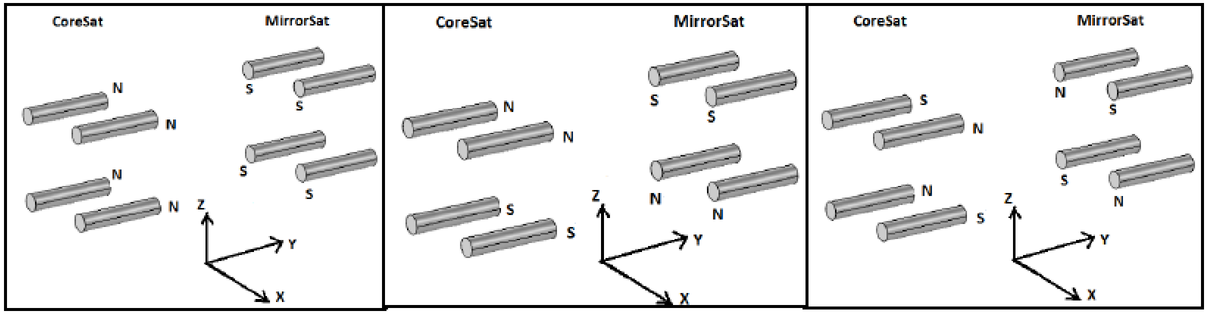


Figure 52 Magnet polarity configurations (McKenna, 2015). From left to right: Configuration 1, Configuration 2, Configuration 3)

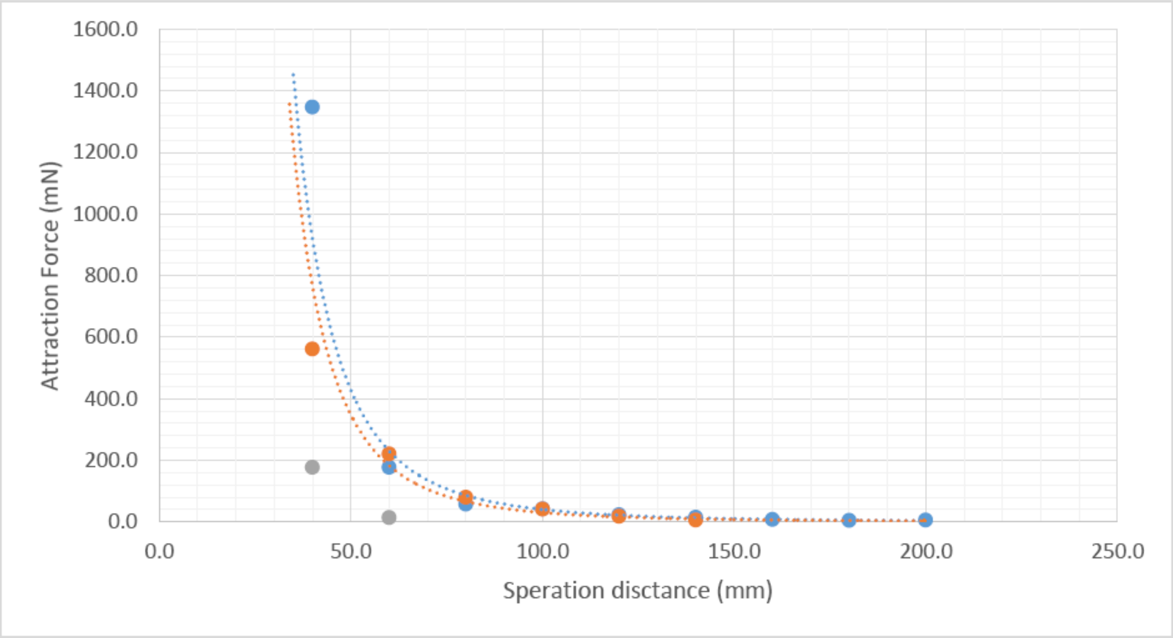
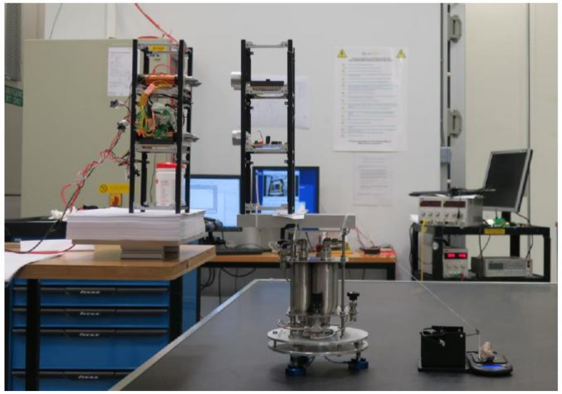


Figure 53 Force against distance for EMDS-PMDS docking using weight offset method. 7 mm N35 magnets, configuration 1 in blue, configuration 2 in orange and configuration 3 in grey

RDV/Docking Port

- **Air Bearing Table Tests**
  - Latching Force was found to be ~**1N**
  - Attraction forces vs. range were ~50% smaller than for the EMDS – as predicted, giving a maximum range of **20-25cm**.



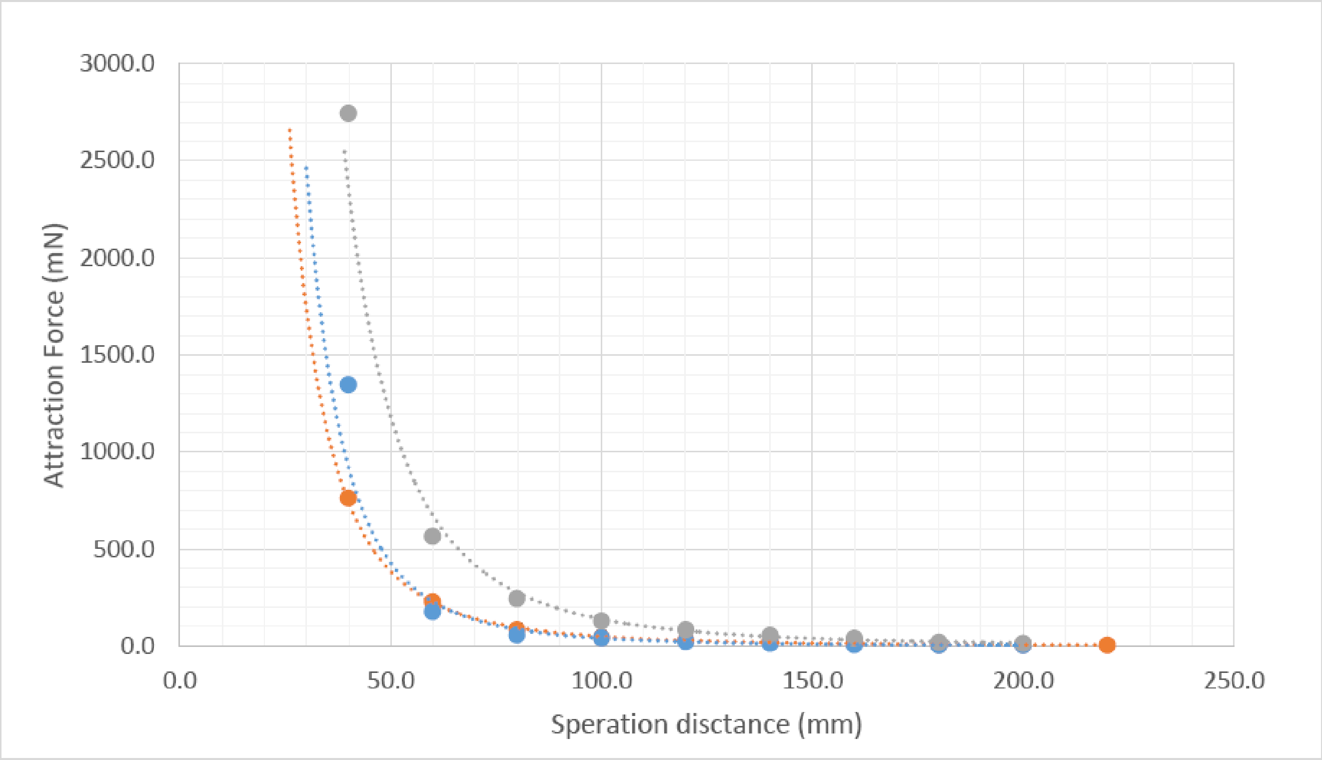
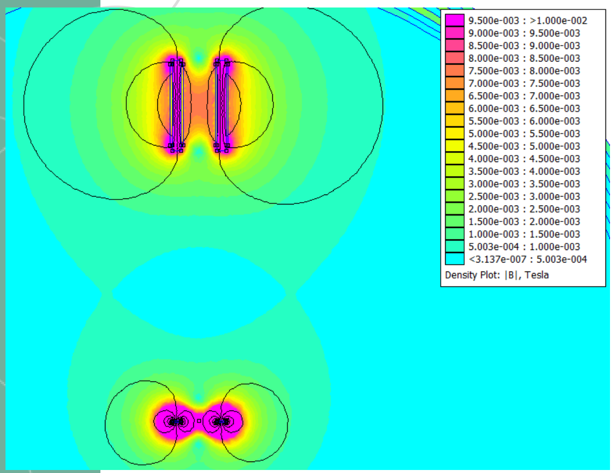
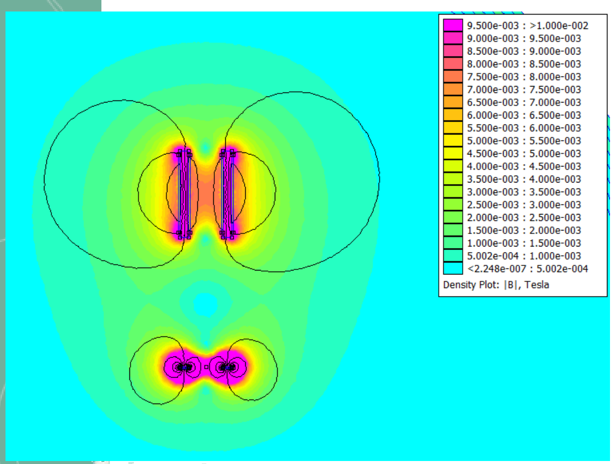


Figure 54 Force against distance for various docking systems. EMDS-EMDS (grey) (McKenna, 2015), EMDS-PMDS 7 mm (blue), EMDS-PMDS 12 mm removal of iron probes and flux extenders (orange)

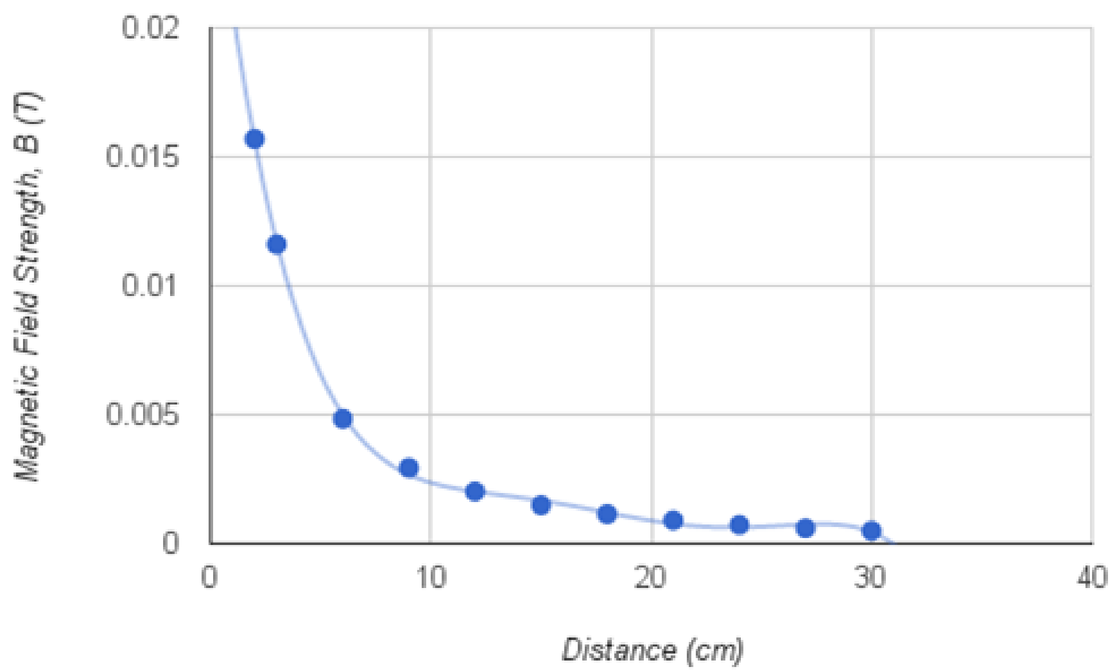
RDV/Docking

- **Chris' FEMM in Jan 2017:**
  - 15 & 30 cm depths investigated



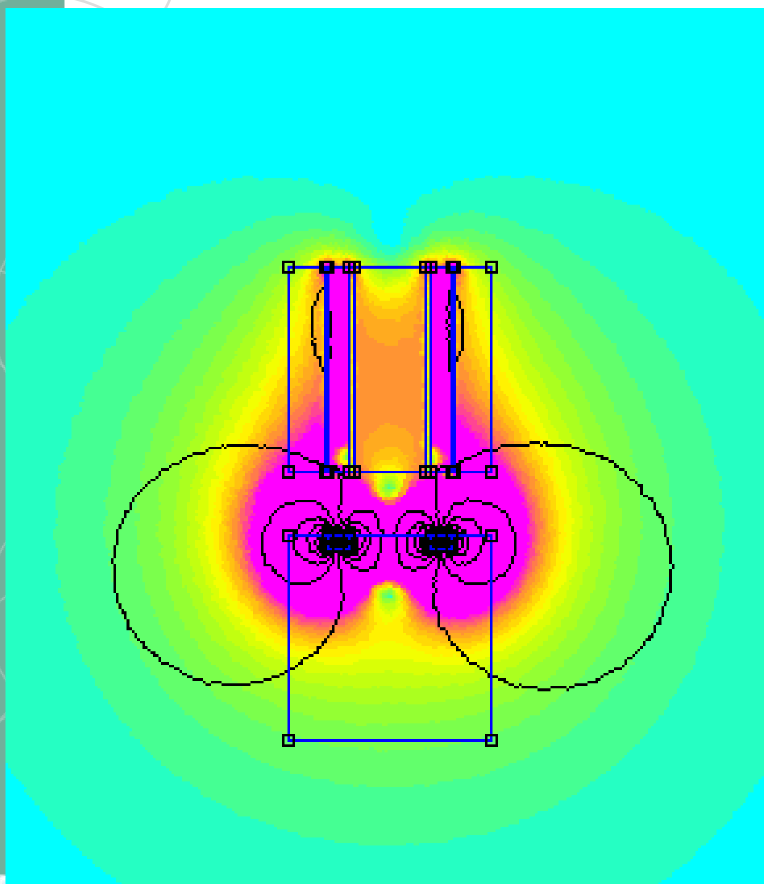


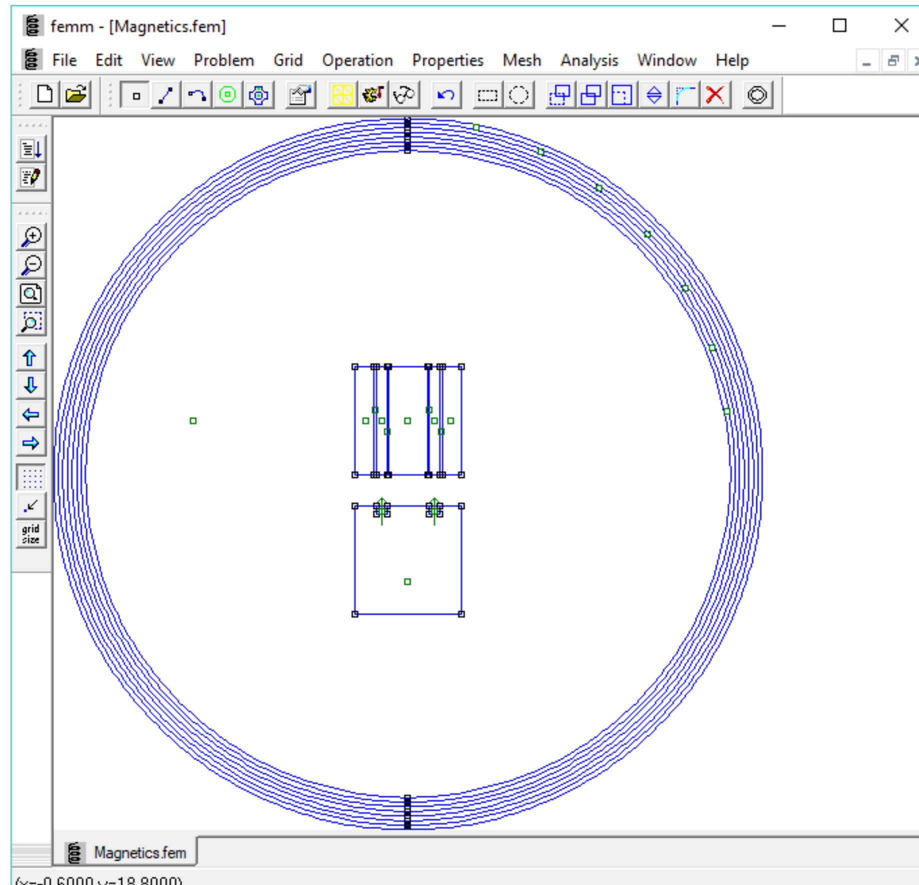
- Magnetic field strength of permanent magnets done
- BUT, with have Earth's B field, solar panels, power lines, actuators, etc (!)



RDV/Docking

- 2D model: MirrorSat (solenoids) & CoreSat (passive magnets)
- Simulate the magnetic field from 3cm (docked) to 1m
- Returns force & torque information
- Use 'hidden' LUA script for propagation





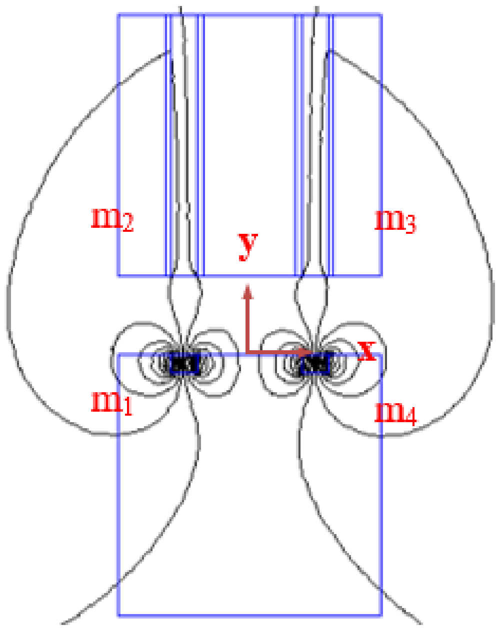
RDV/Docking

Equations:

- Magnetic field: $\boldsymbol{B}(\boldsymbol{m},\boldsymbol{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\boldsymbol{m}\cdot\boldsymbol{r}}{r^5}\boldsymbol{r} - \frac{\boldsymbol{m}}{r^3}\right)$
- Force:

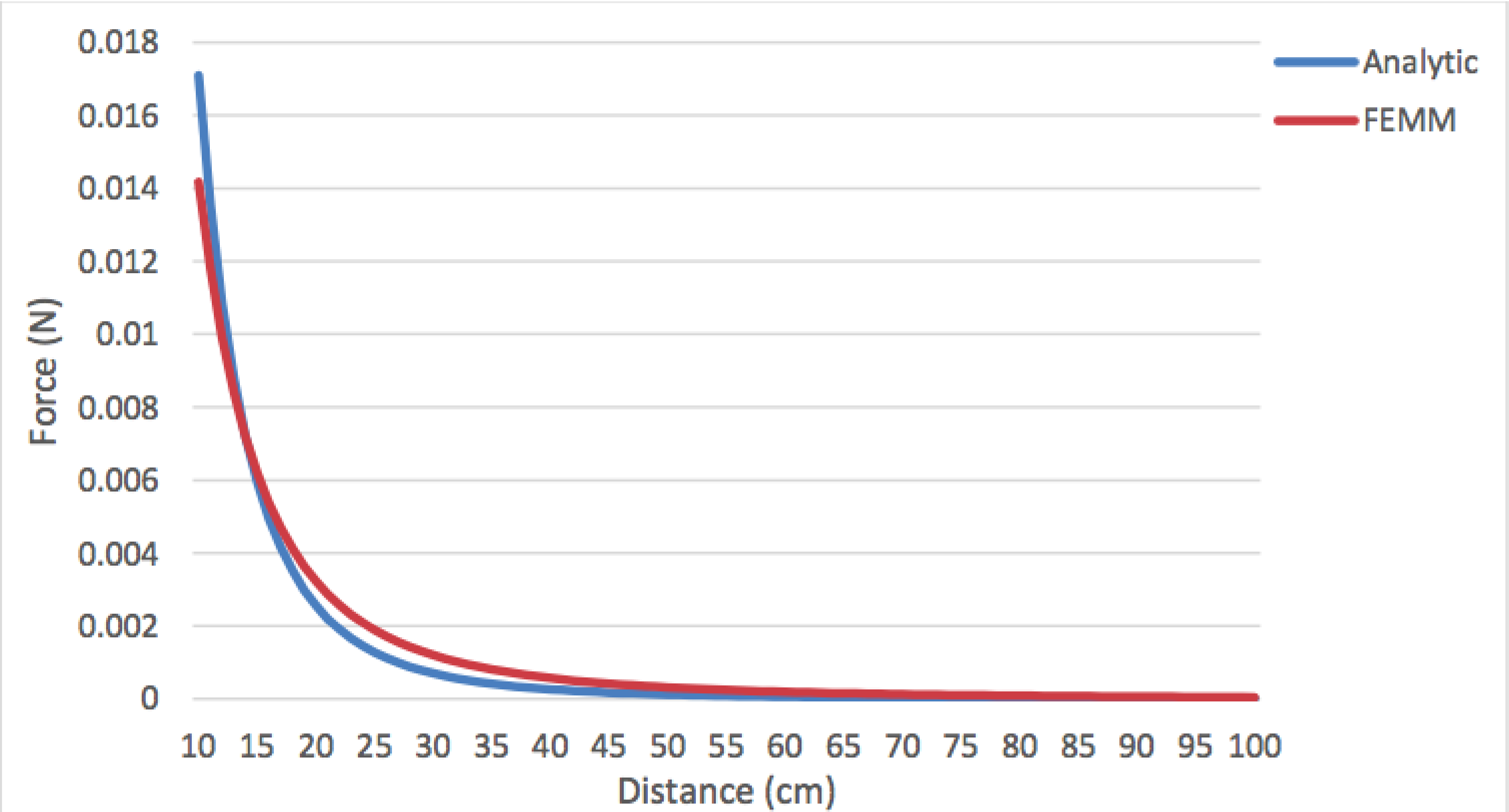
$$\boldsymbol{F}_{12} = \frac{3\mu_0}{4\pi r_{12}{}^5}\left((\boldsymbol{m}_1\cdot\boldsymbol{r}_{12})\boldsymbol{m}_2 + (\boldsymbol{m}_2\cdot\boldsymbol{r}_{12})\boldsymbol{m}_1 + (\boldsymbol{m}_1\cdot\boldsymbol{m}_2)\boldsymbol{r}_{12} - \frac{5(\boldsymbol{m}_1\cdot\boldsymbol{r}_{12})(\boldsymbol{m}_2\cdot\boldsymbol{r}_{12})}{r_{12}{}^2}\boldsymbol{r}_{12}\right)$$

- Torque: $\boldsymbol{T} = \boldsymbol{m}\ x\ \boldsymbol{B}$
- Magnetic Dipole Moment: $m = \frac{1}{\mu_o}B_r V$
  - $m_s = \frac{1}{\mu_o}B_r V + NIA$



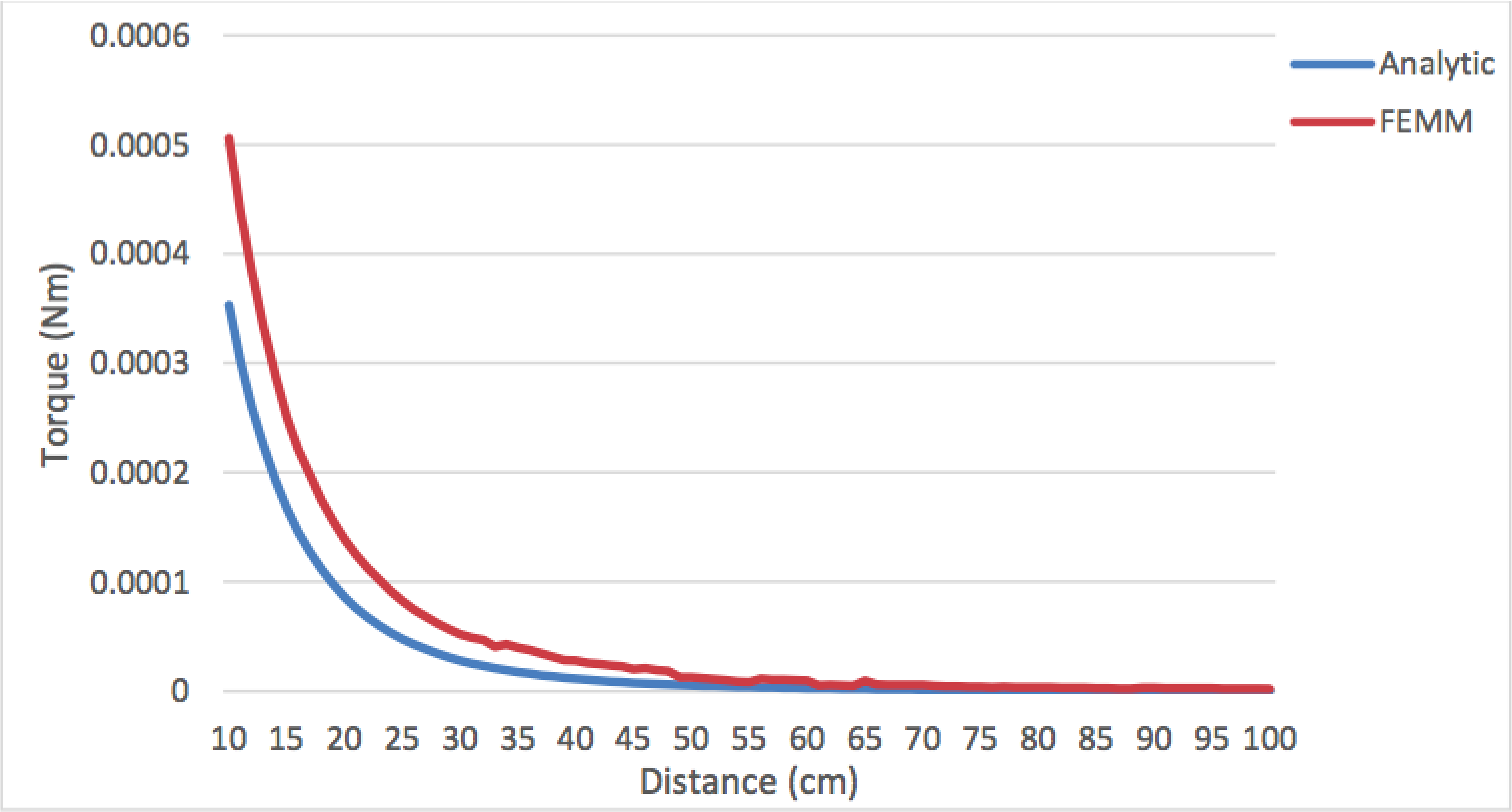
Compare analytical solution to FEMM

RDV/Docking



$$F = \sum_{i=1,3,4} F(m_i, m_2, r_{i2}) + \sum_{i=1,2,4} F(m_i, m_3, r_{i3}).$$

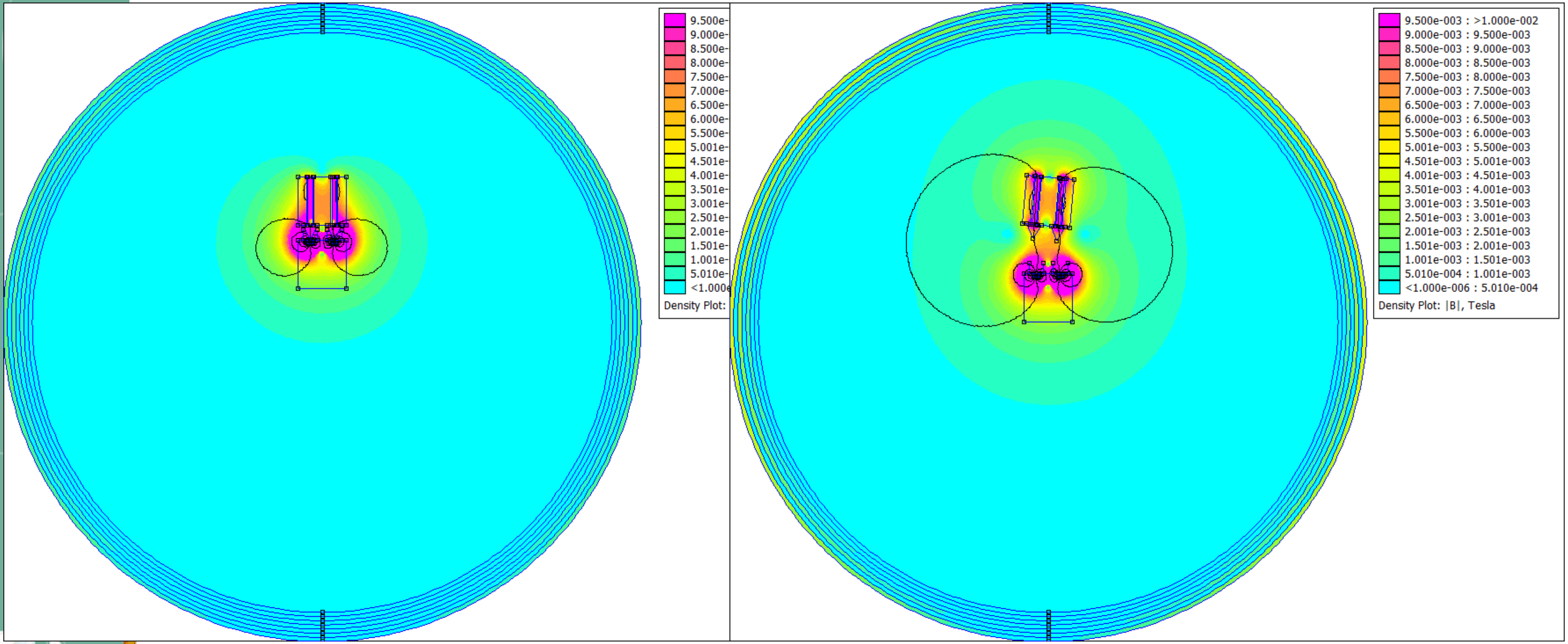
RDV/Docking



$$T = m_2 \, x \sum_{i=1,4} B(m_i, r_{i2}) + m_3 \, x \sum_{i=1,4} B(m_i, r_{i3})$$

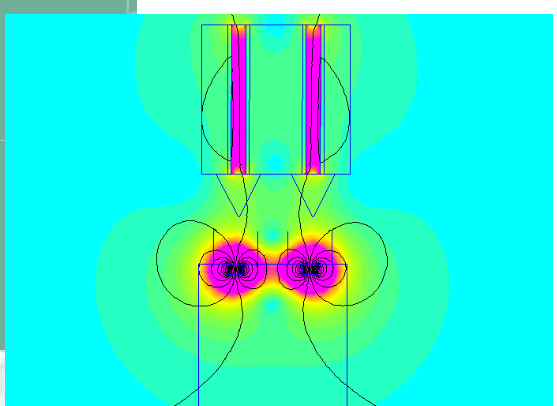
RDV/Docking

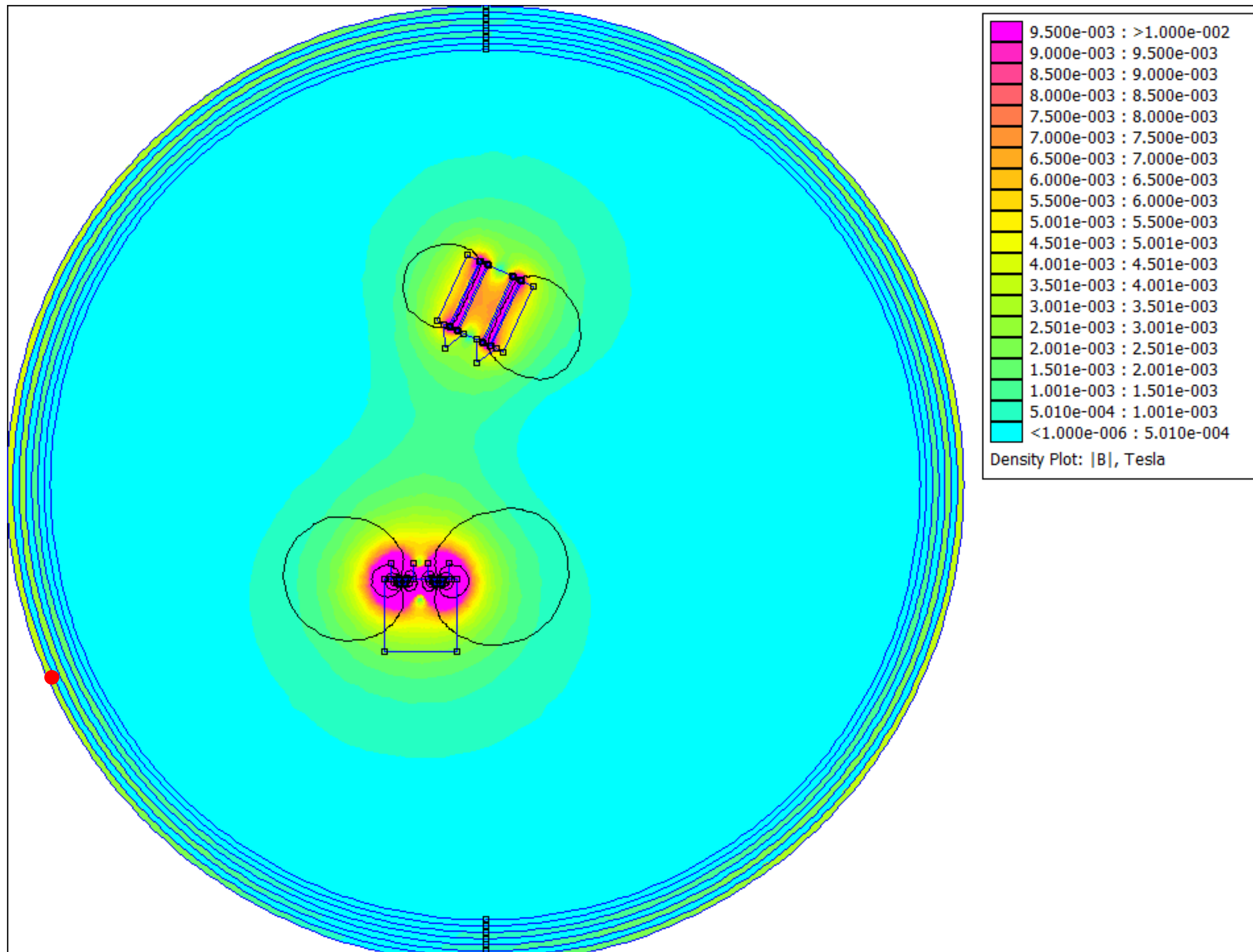
- Simple propagation of undock/dock manoeuvre
  - 26 cm maximum vertical distance, ‘holds’ for 12 seconds.
- Torque added at docking (5^0 rotation at 10 cm)



RDV/Docking

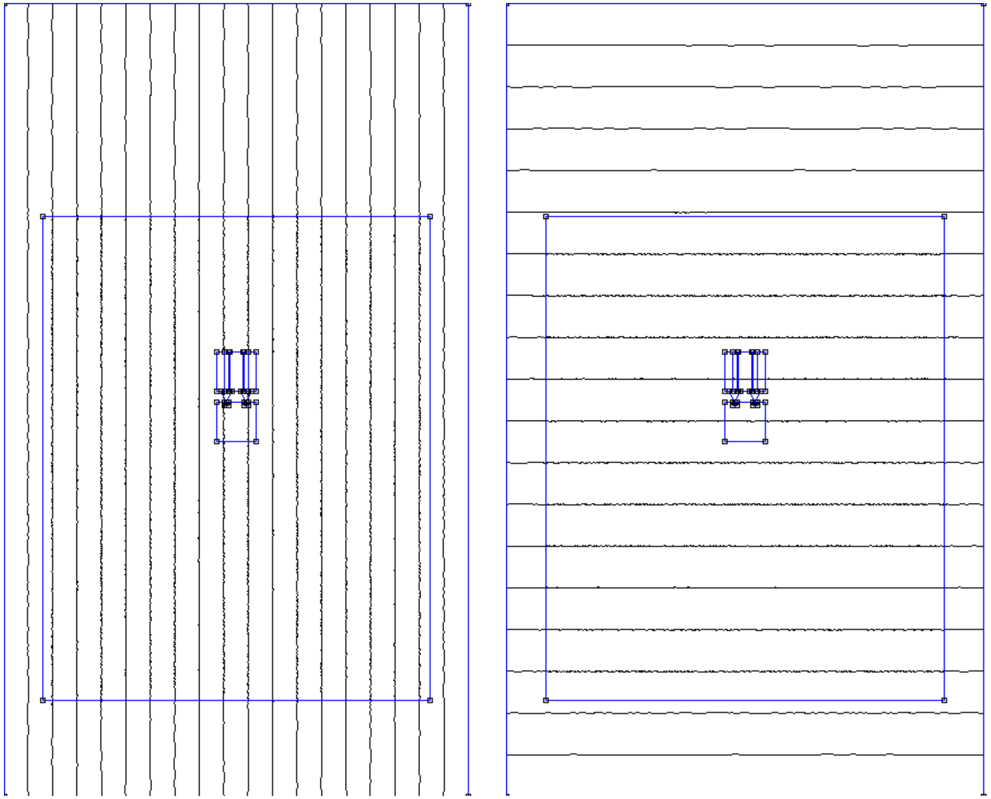
- Automatic capture are where active control is not needed
  - 45^0 cone from docking plane
- Maximum parameters
  - 30cm: 50^0
  - 15cm: 34^0
  - 5cm: 16^0





RDV/Docking

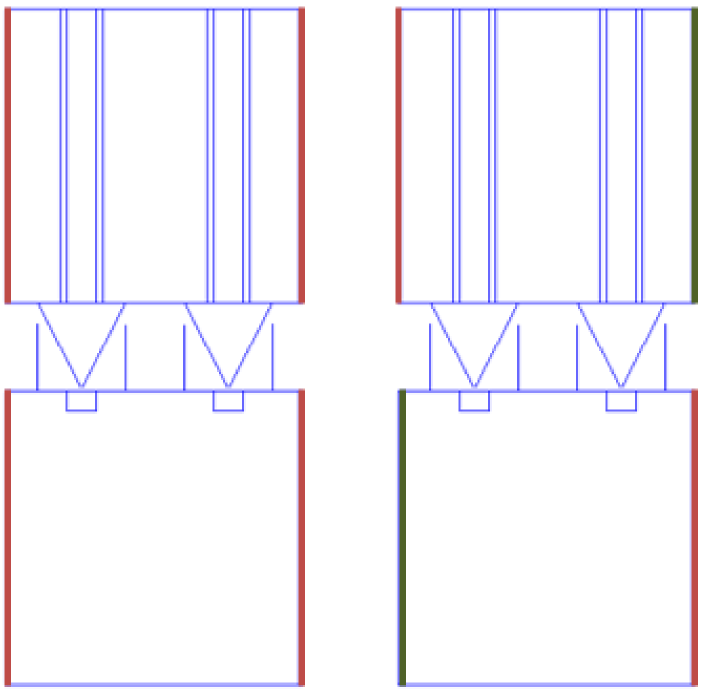
- Earth's magnetic field added using boundary properties
  - Worst-case: Magnetic Poles (South Pole total field 49,714.9nT)
  - Best-case: Magnetic Equator (17.862.3nT total field)
- Open boundary vs truncated boundary
  - Force and torque values within 5%



- Need to consider orientation of spacecraft
- Vertical field has worse effect
- One direction can be modeled at a time

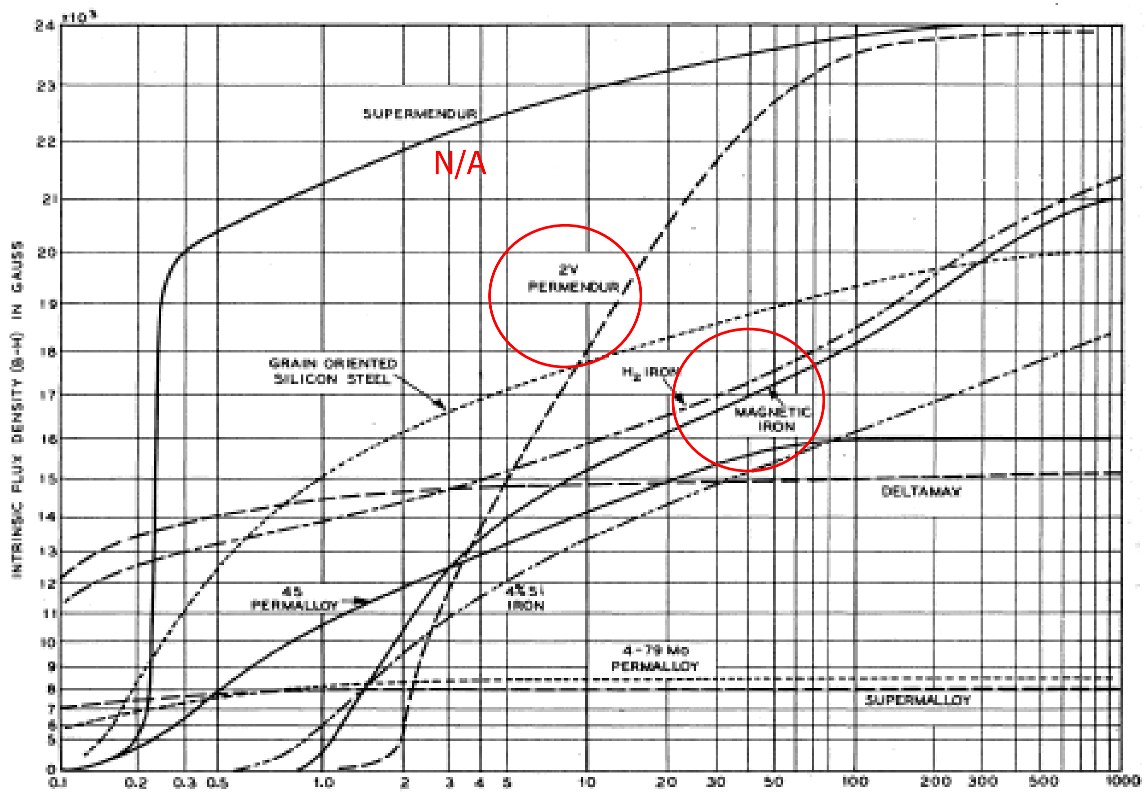
RDV/Docking

- Solar Arrays create electric fields which can interact with magnetic fields
  - Solar cell current is 0.5 Amps
- Solar cells use Kovar (magnetic) interconnects – limited amount
- Only electric field considered
- Cells modeled as coils with 0.5A current each
  - Two configurations considered
  - Opposing currents have much smaller effect
- Mitigation:
  - Always perform reconfiguration during eclipse
  - Minimize electric field by orientation of panels



RDV/Docking Port

- **Conclusions Future Work**
  - PMDS shown to be viable for the CoreSat – if we can accept ~20cm operational range.
  - Could revert to PMDS/EMDS – with EMDS on the capture (wide) side and PMDS on the undocking (narrow) side.
  - Investigate substitution of PERMENDUR for pure iron to increase range.
  - Continue FEMM propagator sims w/ disturbances.
  - Build & Test PFM.

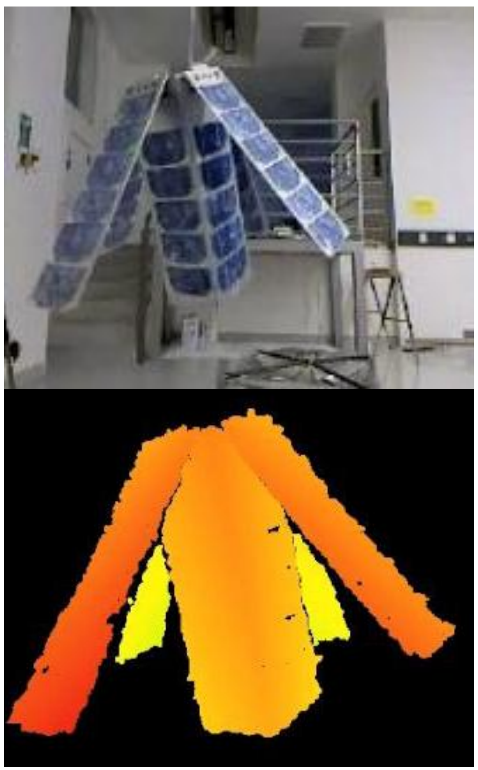


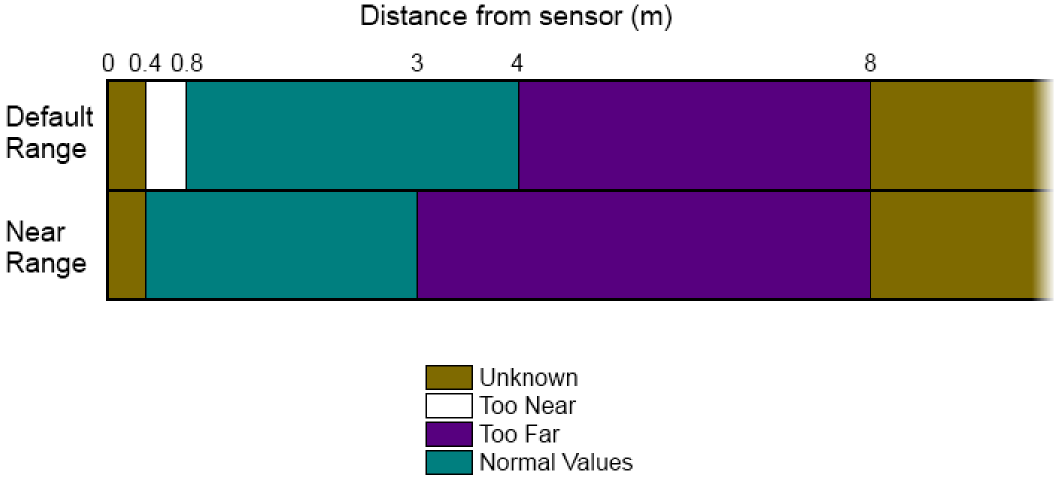
Questions?

Surrey AAReST RDV Sensors (1): COTS NIR Lidar

COTS Lidar Sensor

- **Investigated Microsoft Kinect®**
  - We calibrated the Kinect® and assessed its accuracy at providing pose and range estimates.
  - Accuracy was good (<3mm lateral error, <2cm depth error) from within the EM docking system's acquisition distance (30cm) out to 8-10m.

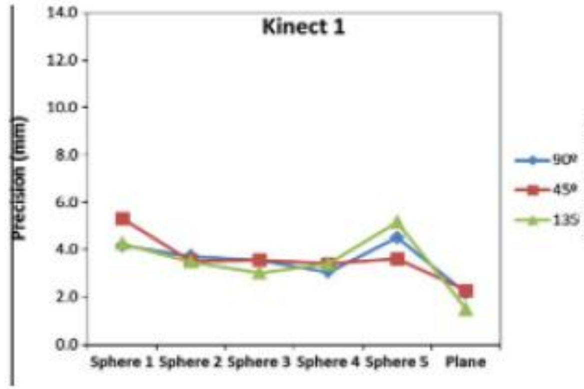


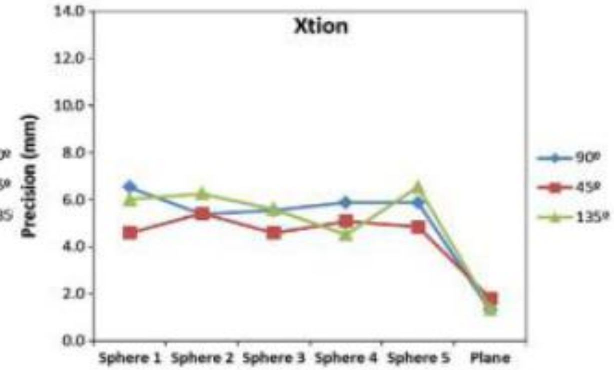


Kinect® Depth View from a 3U CubeSat Model with Solar Panels in the SSC Space System Development Laboratory

COTS Lidar Sensor

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





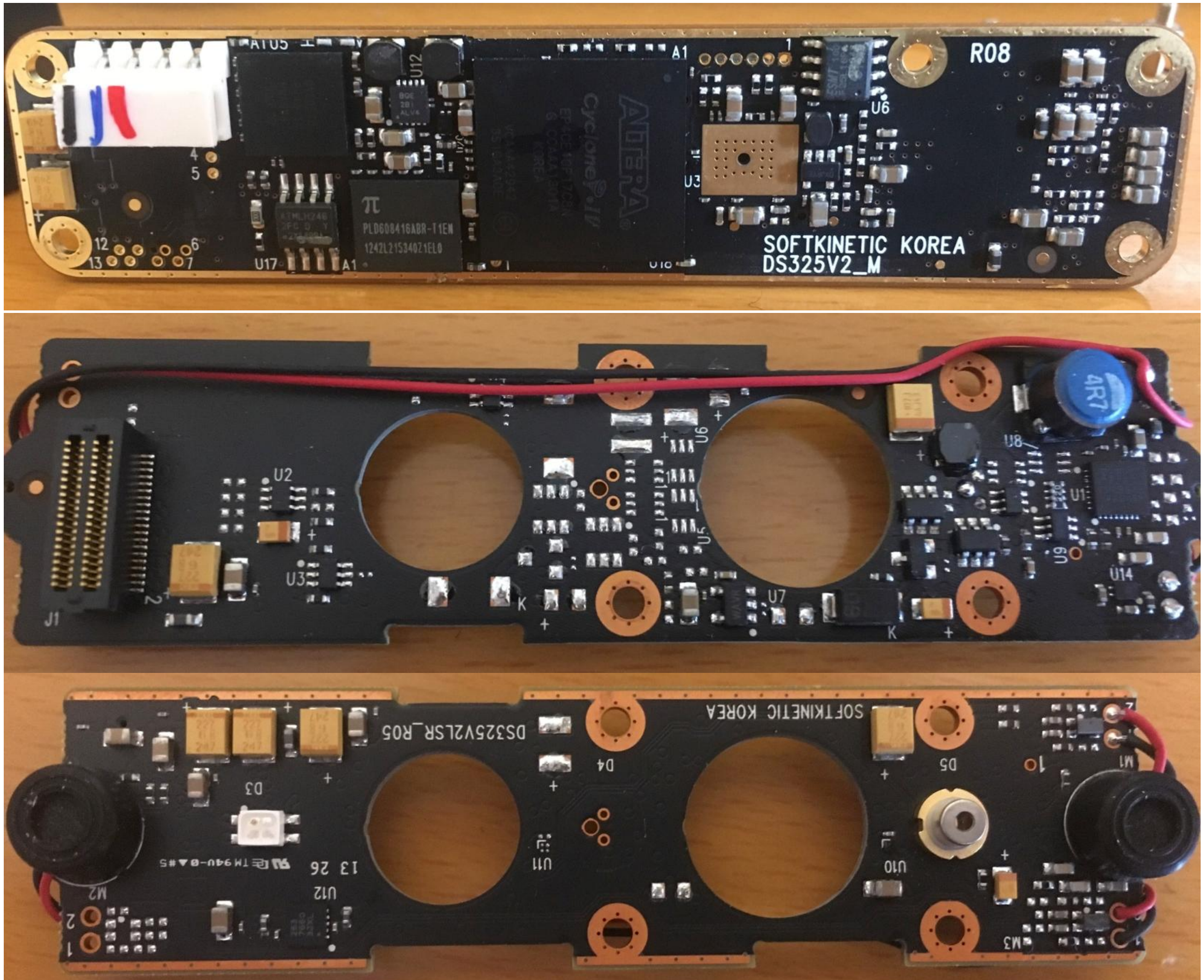
Power Consumption	Distance of Use	Field of View	Sensor	Depth Image Size
<2.5W	0.8-3.5m	58/45/70 Degrees H/V/D	RGB & Depth	VGA (640x480): 30fps QVGA(320x240): 60fps
Resolution	**OS Support**	**Programming Language**	**Dimensions**	**Software**
SXGA (1280*1024)	Win 32/64:XP, Vista, 7, 8 Linux Ubuntu 10.10:X86,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

COTS Lidar Sensor

Preferred sensor – now back in production (2017)

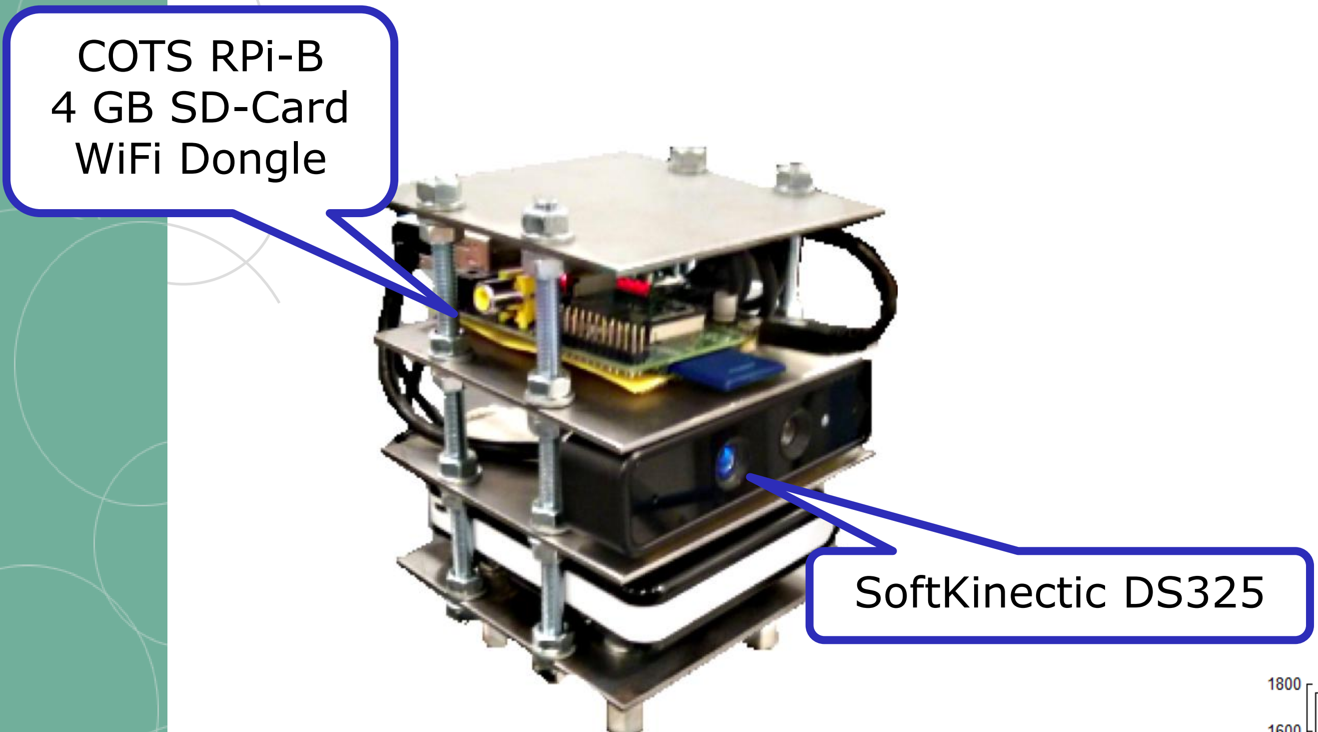
Softkinetic DS325
FoV: 87° x 58°
Range: 0.15 – 1m
QVGA: 320 x 240
USB 2.0 powered

COTS Lidar Sensor



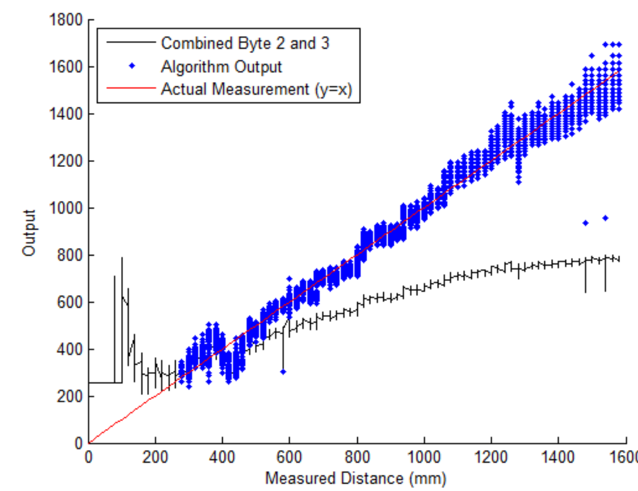
COTS Lidar Sensor

- **Initial Tests**



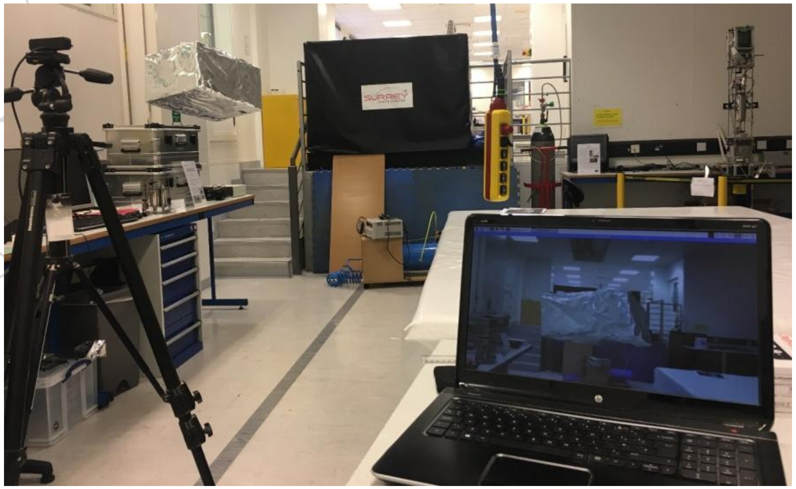
- OpenNI2DS325 driver used initially but tests showed it to be inaccurate.

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

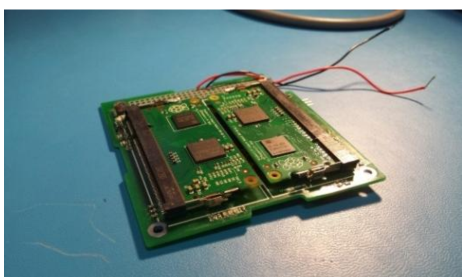


COTS Lidar Sensor

- **Recent Results**

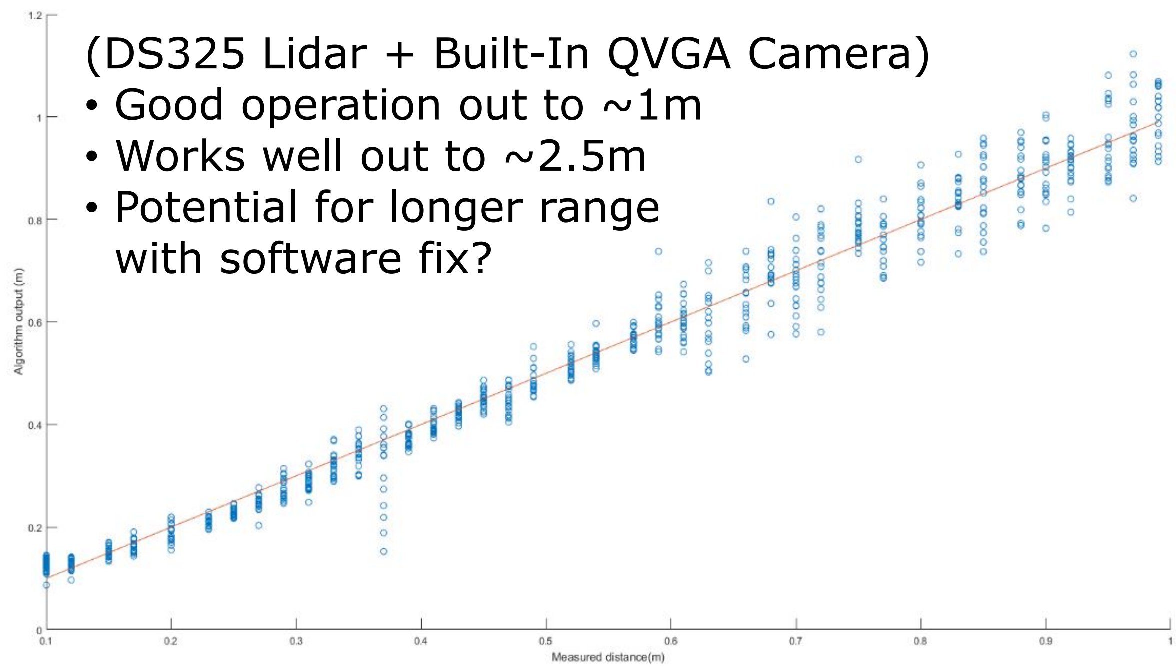


- The ARReST CoreSat (target) model is elevated using a crane and the distance between the crane and the LIDAR is measured using LIDAR and tape measures.
- The Raspberry Pi (R-Pi) acts as a WiFi hotspot and a laptop is used to control the R-PI using Virtual Network Computing (VNC) software.



Dual R-Pi Module

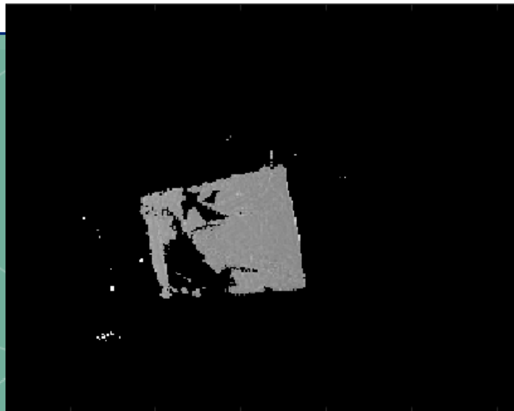
WiFi "Dongle" with Built-In Antenna

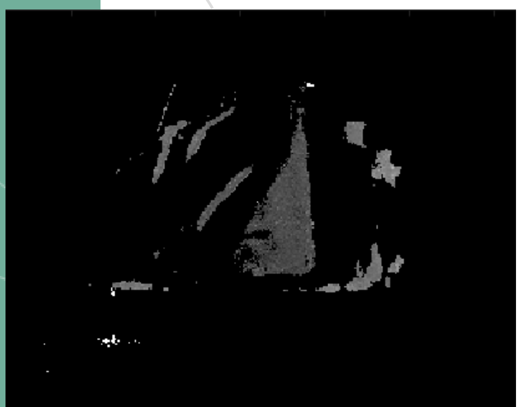


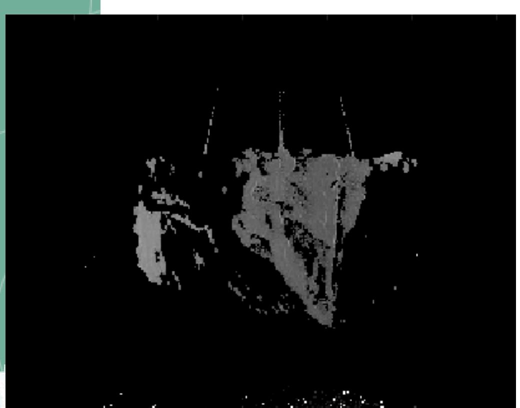
(DS325 Lidar + Built-In QVGA Camera)

- Good operation out to ~1m
- Works well out to ~2.5m
- Potential for longer range with software fix?

COTS Lidar Sensor



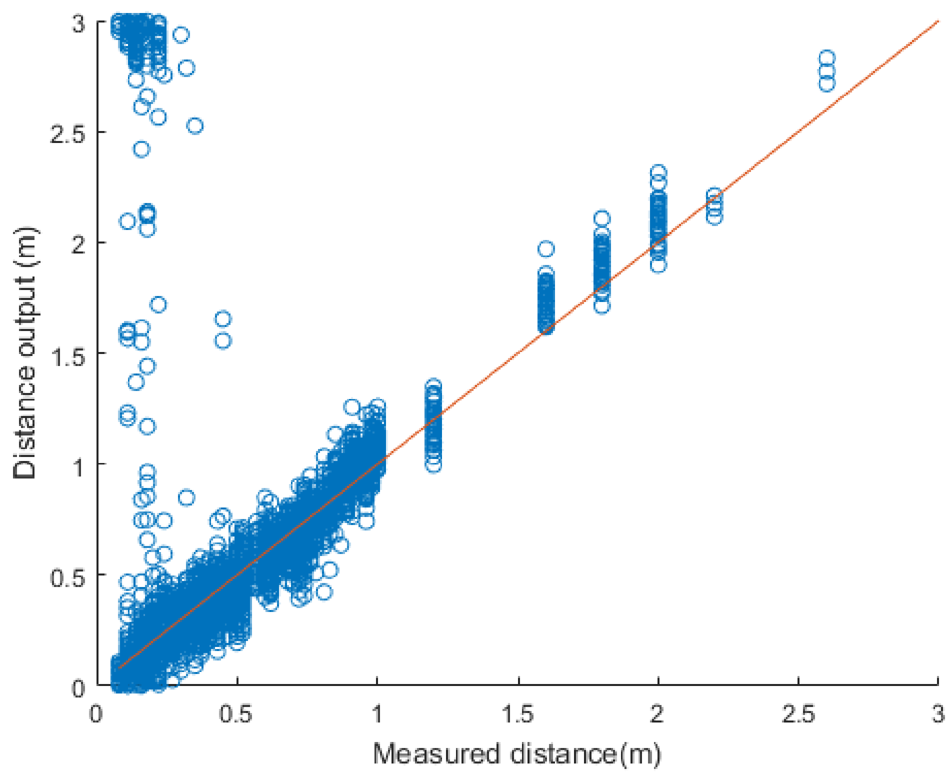




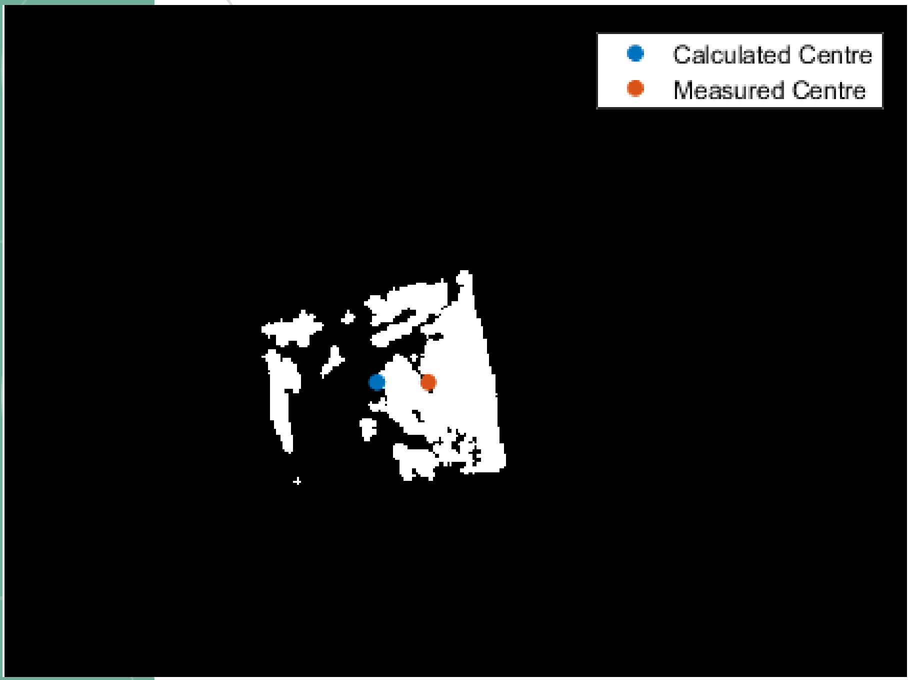
ARReST CoreSat (target) model ‘foiled’ us due to non-uniform surface characteristics. See images on left.

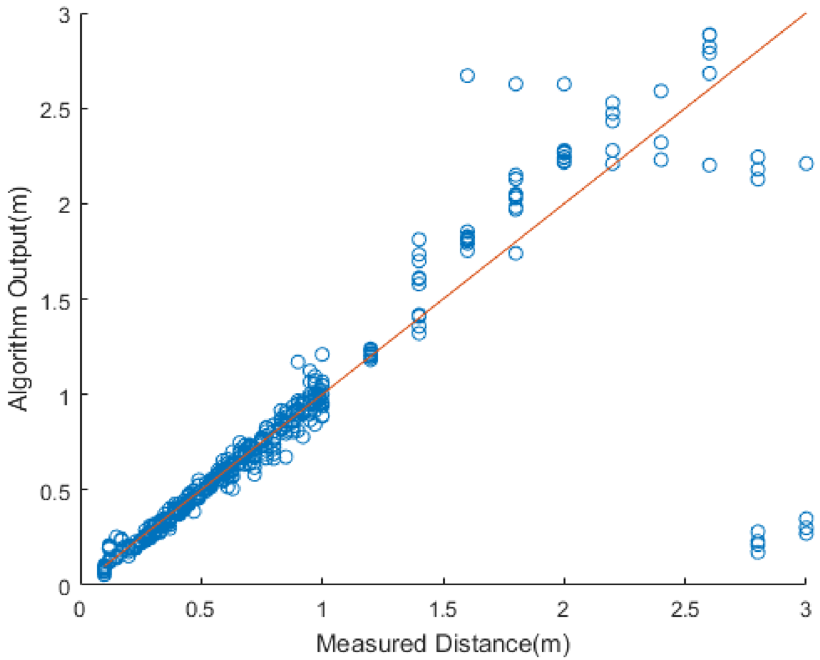
Key results:

- Saving to Screen = 20 fps, Optimised = 43 fps
- Tested out to 3m with consistent 5% error (15 cm)



COTS Lidar Sensor





- Centroid measurement highly sensitive to surface and pose conditions.
- If another object appears in the binary mask, the centre value of the target will be incorrect.
- Small true values can be filtered out by using an 'erosion' filtering process to create a final binary mask for forward evaluation.

SURREY SPACE CENTRE

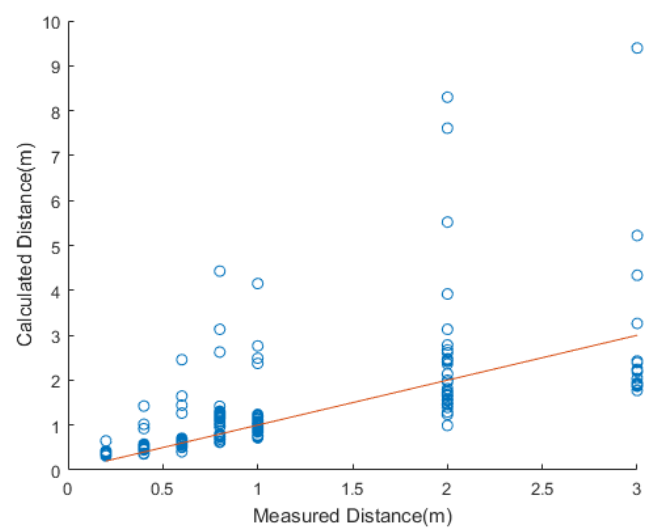
COTS Lidar Sensor

UNIVERSITY OF SURREY

We generate differing datatypes to analyse throughput vs accuracy:

- 'Full' or 'Decimated' images
- Post processed with bitmasks or connected components

Had issues with background artefacts (hence green target).



Final optical solution starts to deviate at longer ranges, requires filtering & further algorithm development.

Questions?

Surrey AAReST RDV

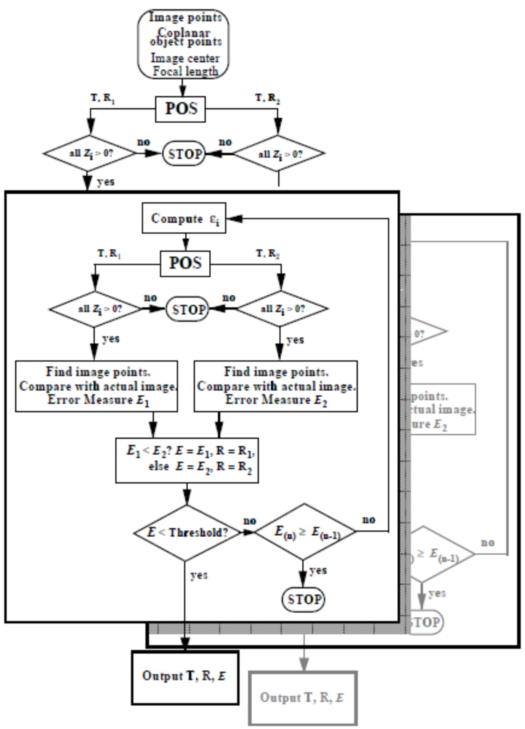
Sensors:

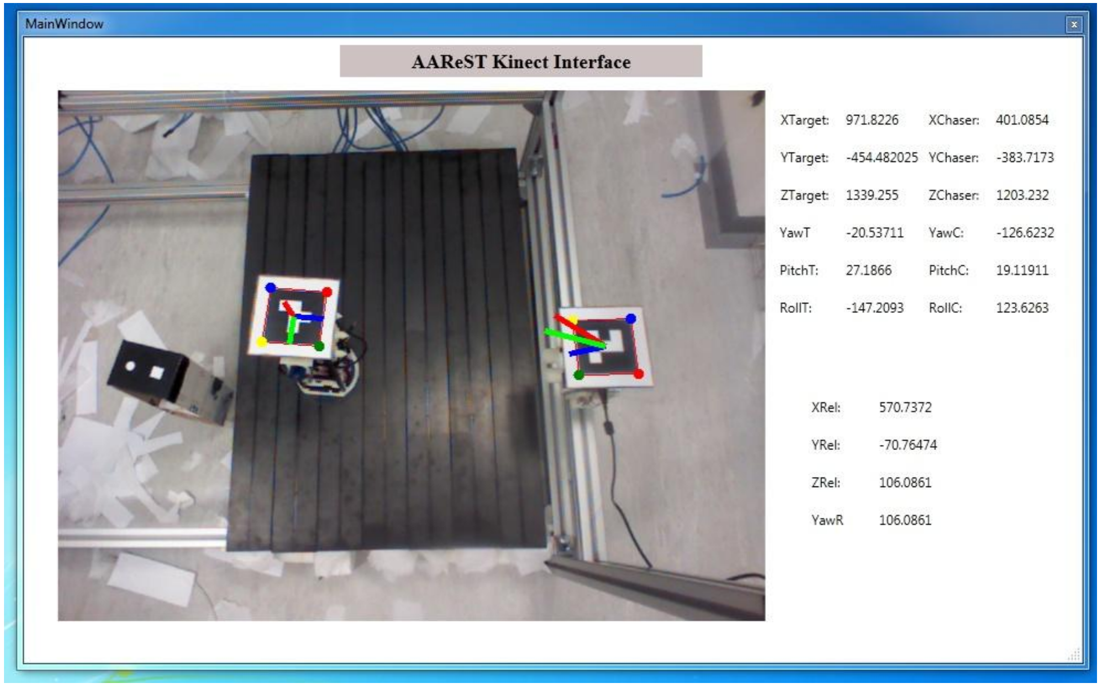
Machine Vision Camera

Glyphs & LEDs

MVS Camera Sensor

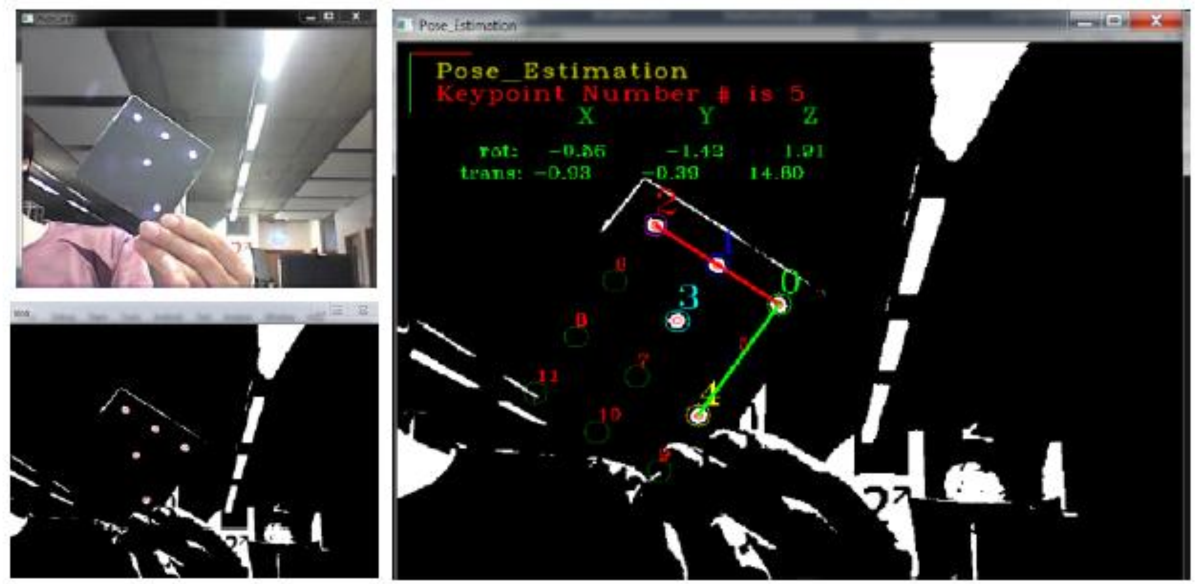
- Glyphs/LEDs:   
- Using glyphs to determine relative pose and range is well understood.
- SSC has had previous experience of using such targets as optical proximity operations targets for AAReST .





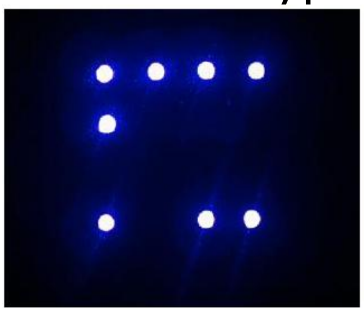
MVS Camera Sensor

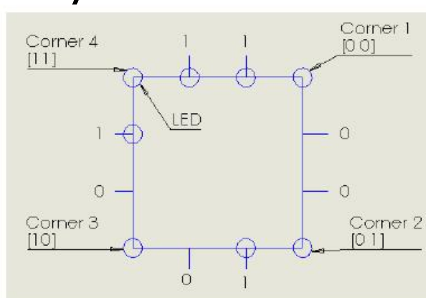
- In order to operate in low-light/dark conditions, the glyphs will be supplemented by light emitting diodes (LEDs). Two options will be investigated:
- Using LEDs as illuminating sources for the “white” squares of the glyphs.
- Using a glyph-like pattern of near-IR (850nm wavelength) LEDs to provide an optical target visible in “day” or “night” conditions.



RDV/Docking

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

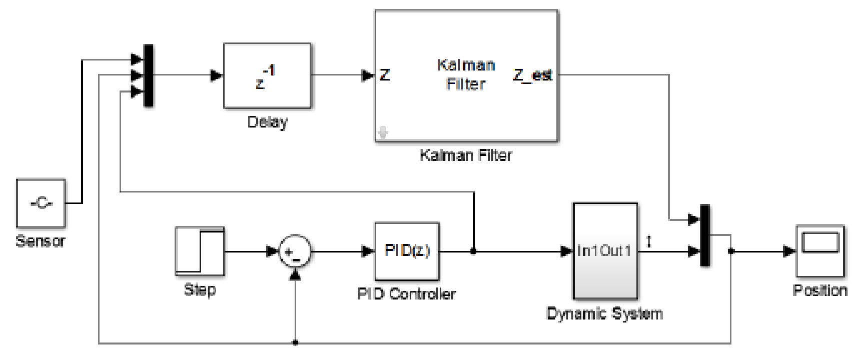


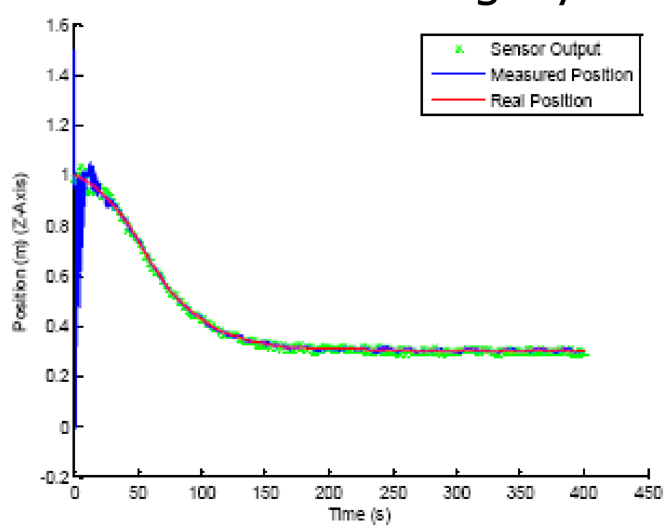


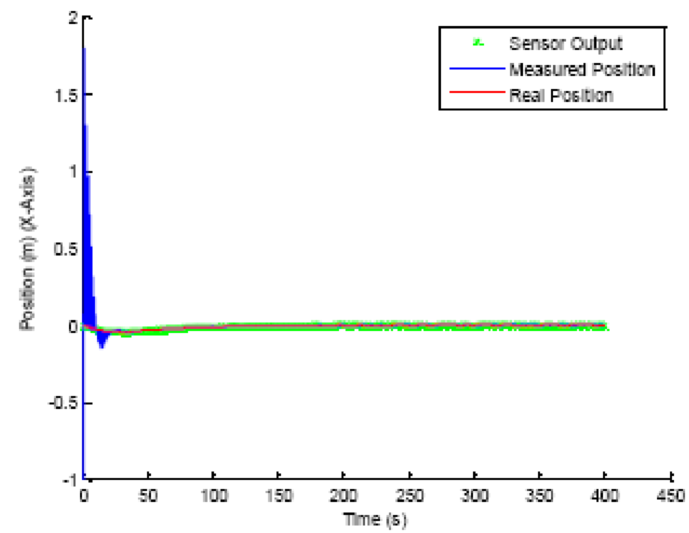
Axis	Range Interval (m)	Root Mean Square Error(mm)	Maximum Error (mm)	Standard Deviation (mm)	Confidence (%)
Z Axis	0-0.30	3.106	1.949	4.166	100
	0.30-0.80	5.787	11.265	3.687	100
	0.80-1.15	20.958	39.843	13.250	100
X Axis	0-0.30	1.9	0.2794	0.684	83
	0.30-0.80	1.7	2.851	0.585	91
	0.80-1.15	0.95	1.466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

RDV/Docking

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







Light Conditions

- **Solar Blind Breadboarding Investigation**
  - Basic principle: make use of the fact that the camera is actually most sensitive to NIR radiation.
  - Use 850nm wavelength, 10nm pass-band optical filter with or without 850nm NIR LED illumination.

- Solar blind

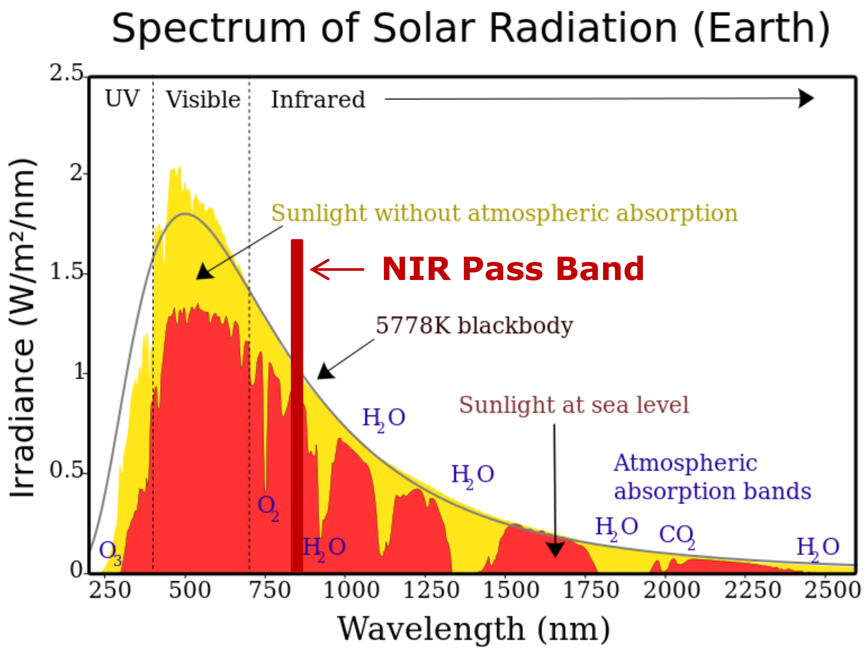
  Considerable sunlight mixed in with the detected signal.

  Signal to noise ratio issues.

- Spectrum of solar radiation

  Much attenuated in the infrared band.

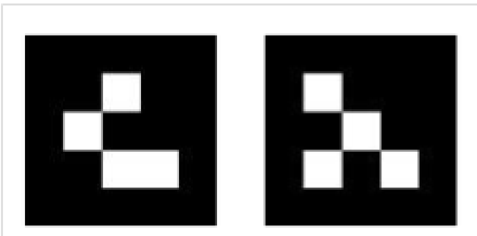
  Use NIR pass band filter on the camera and ultra-bright NIR LEDs for the active illuminated target.



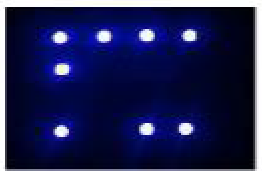
http://en.wikipedia.org/wiki/Sunlight

Design Scenarios

- Two possible solutions investigated
- Non-Active illumination: relying on distinct contrast 'Black and white glyphs' for a RGB (NIR-block) camera



- Active LED Illumination: low-cost lighting with high intensity NIR-LEDs ideally with a pass-band NIR optical filter



- Algorithm:
- Pattern recognition by basic image processing: edge detection, blob detection, pattern matching
- Pose estimation done by POSIT

Glyph Patterns

- Design of 3 by 3 glyphs:

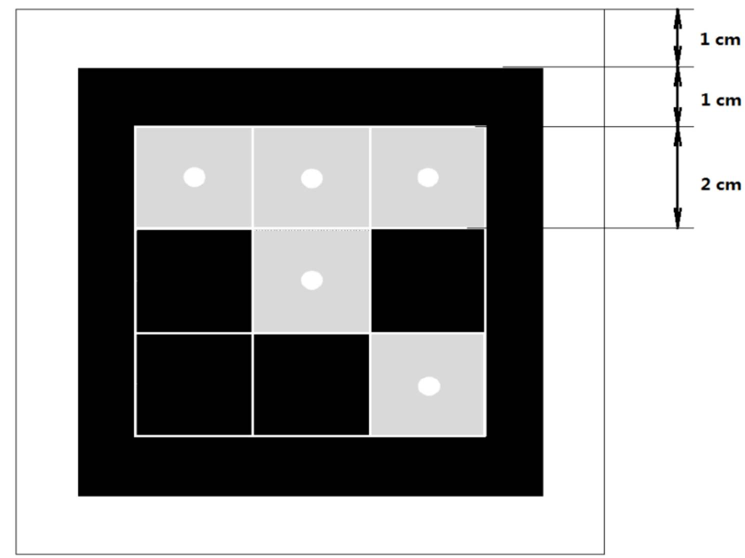
  10cm x 10cm (replaces one solar panel)

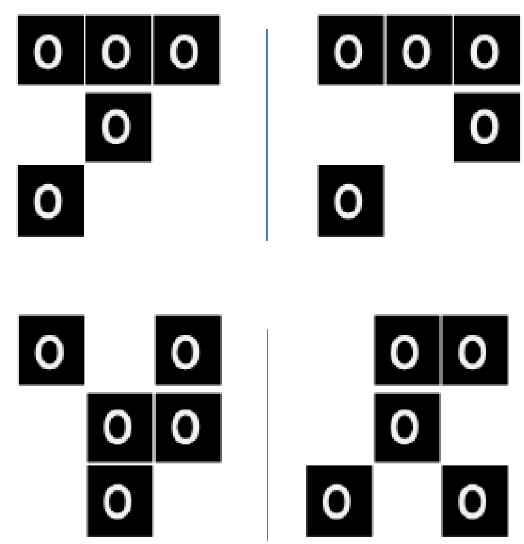
- Two boundaries are essential:

  Black boundary to outline the glyphs.

  White boundary to distinguish the pattern area.

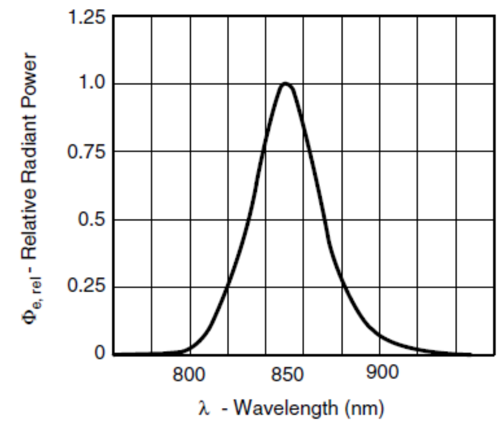
- Different (unique) patterns may be used to identify different faces or different target spacecraft.





LEDs

- NIR-LED Selection: Vishay TSHG6400

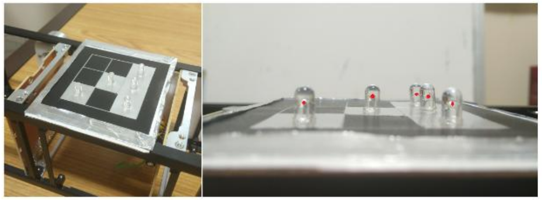


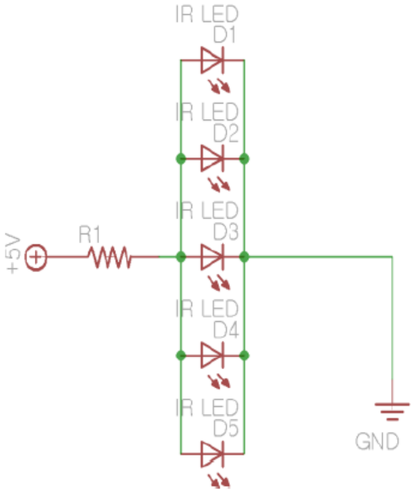
- Central wavelength: 850nm

  High intensity compared to sunlight: 2.3W max each (1A, 2.3V) 700mW/Sr

  Experiments done at 150mW each (100mA, 1.5V) = 70 mW/Sr

  5 LEDS (< 1W)





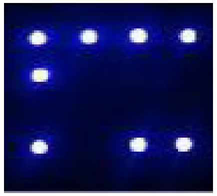
BASIC CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)

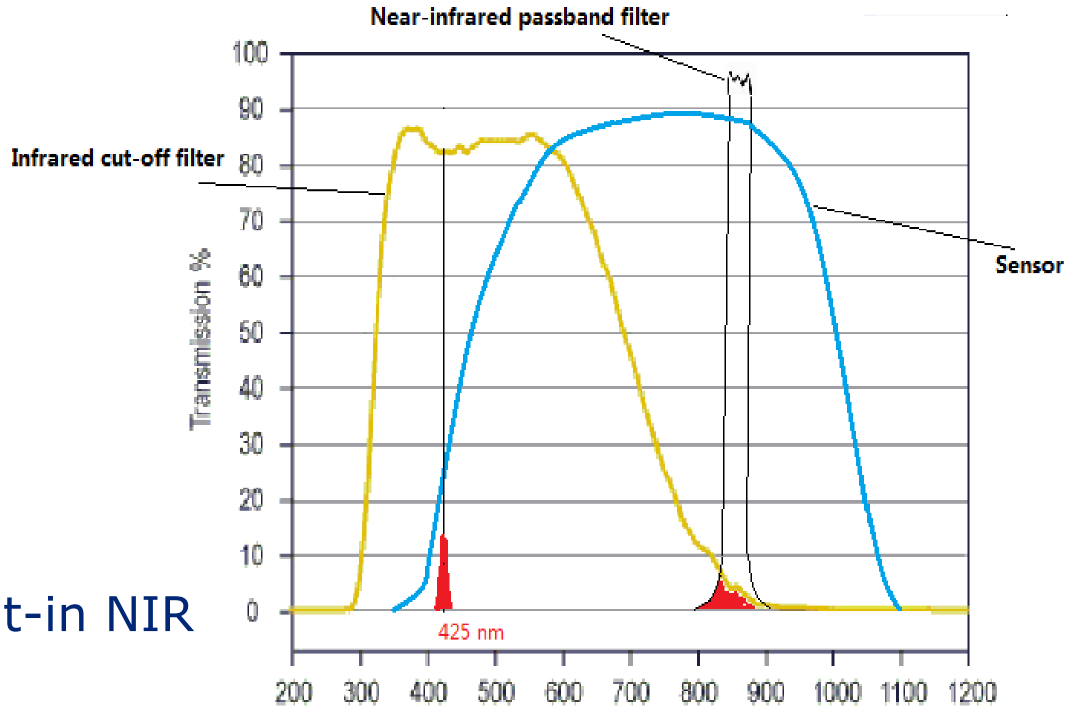
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Forward voltage	I_F = 100 mA, t_p = 20 ms	V_F		1.5	1.8	V
	I_F = 1 A, t_p = 100 μs	V_F		2.3		V
Temperature coefficient of V_F	I_F = 1 mA	TK_{VF}		- 1.8		mV/K
Reverse current	V_R = 5 V	I_R			10	μA
Junction capacitance	V_R = 0 V, f = 1 MHz, E = 0	C_j		125		pF
Radiant intensity	I_F = 100 mA, t_p = 20 ms	I_e	45	70	135	mW/sr
	I_F = 1 A, t_p = 100 μs	I_e		700		mW/sr
Radiant power	I_F = 100 mA, t_p = 20 ms	ϕ_e		50		mW
Temperature coefficient of ϕ_e	I_F = 100 mA	$TK\phi_e$		- 0.35		%/K
Angle of half intensity		φ		± 22		deg
Peak wavelength	I_F = 100 mA	λ_p		850		nm
Spectral bandwidth	I_F = 100 mA	Δλ		40		nm
Temperature coefficient of λ_p	I_F = 100 mA	$TK\lambda_p$		0.25		nm/K
Rise time	I_F = 100 mA	t_r		20		ns
Fall time	I_F = 100 mA	t_f		13		ns
Cut-off frequency	I_{DC} = 70 mA, I_{AC} = 30 mA pp	f_c		18		MHz
Virtual source diameter		d		3.7		mm

Camera and Optical Filter

- Camera: HP Webcam HD720p (1280 by 720 pixels)
- Additional filter: Edmund Optical Filter

  Central wavelength
  850 nm
  FWHM(Full Width-Half Max)
  10 nm
  pass wavelength
  λ / (2^n)   (blue/violet leakage)





- Camera itself has a built-in NIR cut-off filter
- Result: RGB webcam used is <u>very insensitive</u> to NIR –
- We expect much longer range detection with bespoke NIR monochome camera.

Software Design

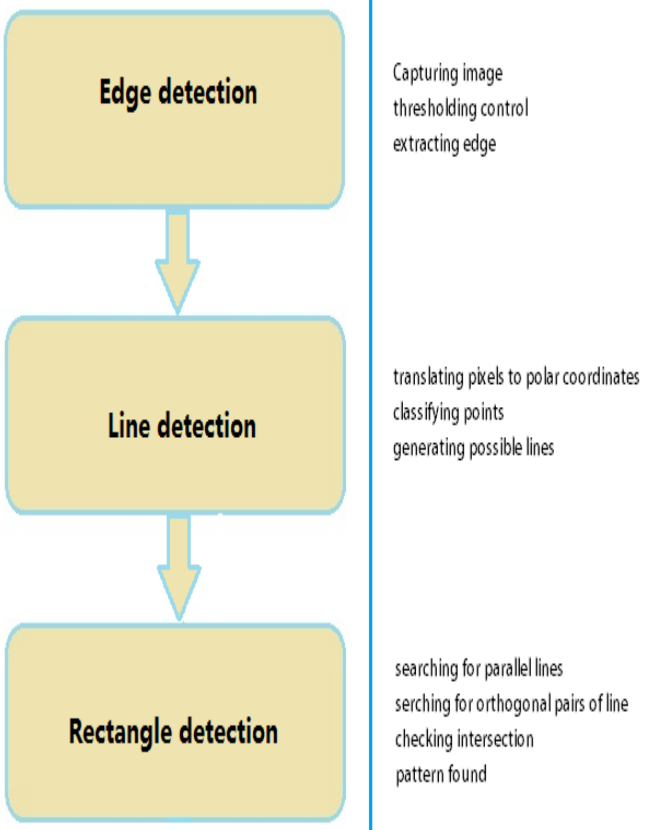
- **Image Processing**
  - Good Robust Algorithms are available, however, for this work, the student developed bespoke software in MATLAB.
  - We are sure that more robust, higher performance algorithms can be implemented using a more traditional approach.

- Traditional pattern recognition method

  Edge detection
  Line detection
  Shape detection

- Parallelogram features considered

  Two groups of parallel lines
  Lines with intersections near the end



Software Design

- **Image Processing**
  - Range and Roll angle was detected using this non-traditional approach.
  - A more sophisticated POSIT algorithm is needed to get relative azimuth and pitch angle.

- Different from traditional method

- Parallelogram features considered

  Loop curve

  Axial symmetry shape check

  Four maxima and minima distance to the shape centre

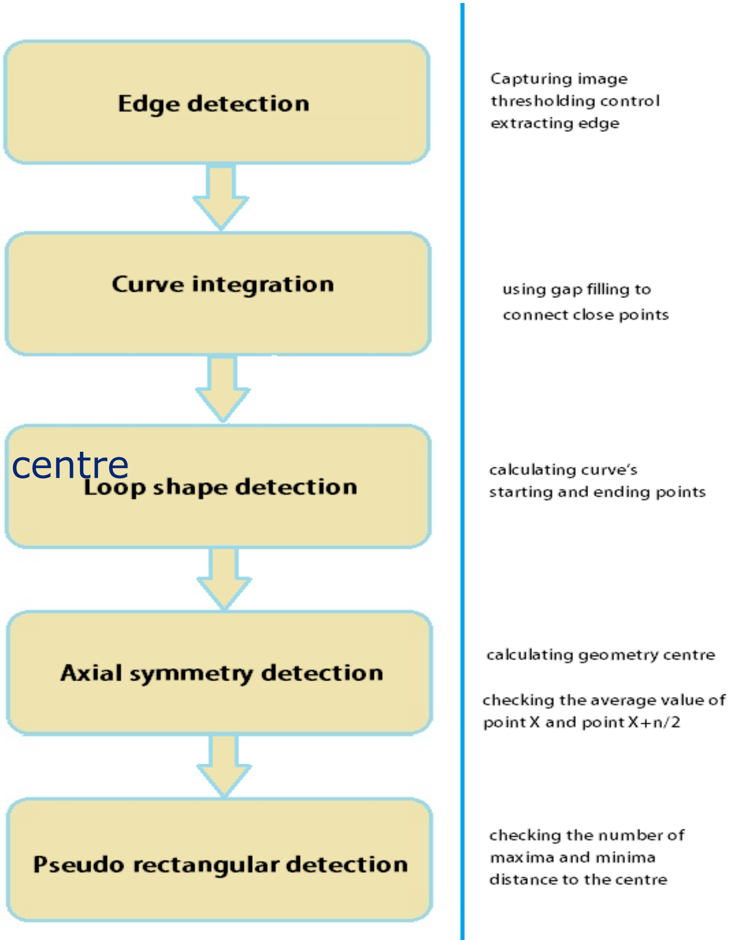
- Comments

  Pseudo shape detection method

  Not robust enough

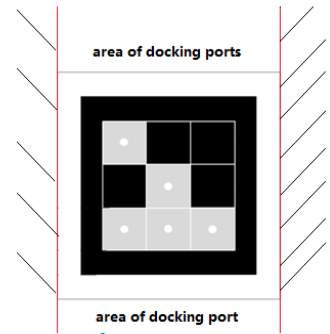
  Only effective for the particular task

  A risk of non-detection



Software Design

- **Image Processing**
  - For LED detection, a different image pre-processing method is used.
  - It can cope with the Sun in the field of view.



- Grey level translation

  Stretch to enhance contrast

- Detect pixels with maxima values among neighbourhood

- Integrate contiguous detected pixels as spots

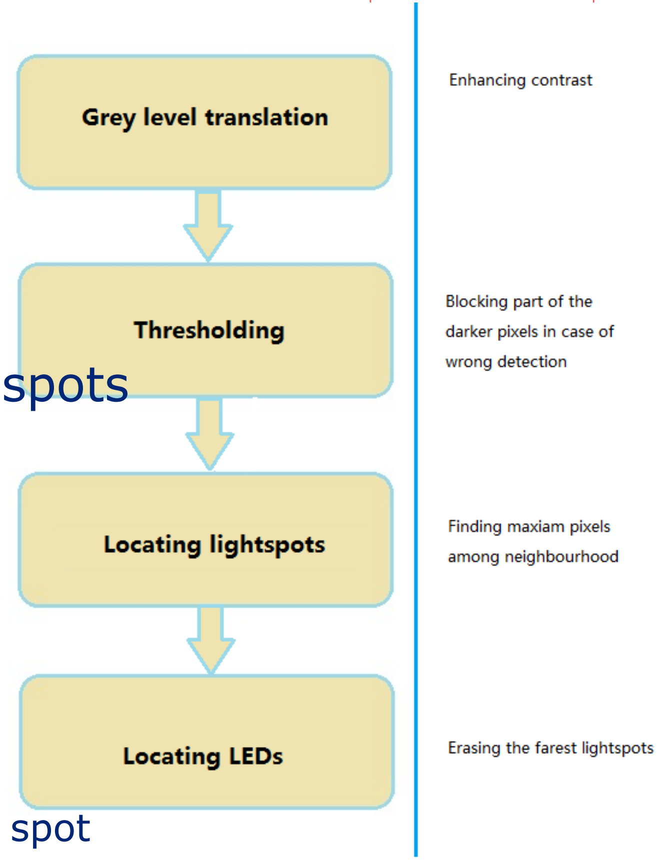
- Distinction between LEDs and the sun

  Checking total distance to all other lightspots

- Comments

  Not robust enough

  Probably recognize the Sun/LEDs as more than one spot



Experimental Results

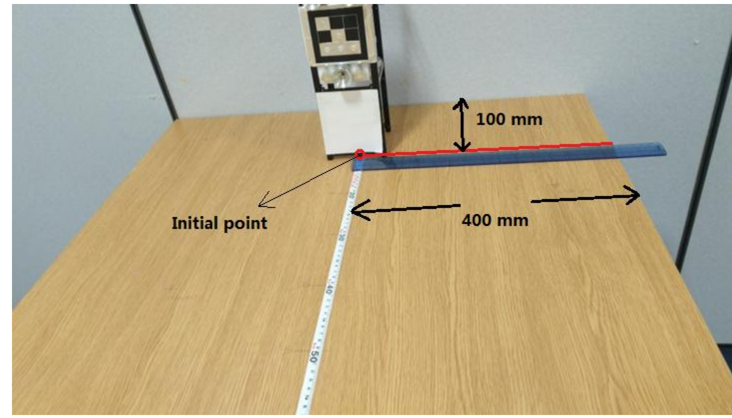
• Results – Passive Glyph – RGB Camera

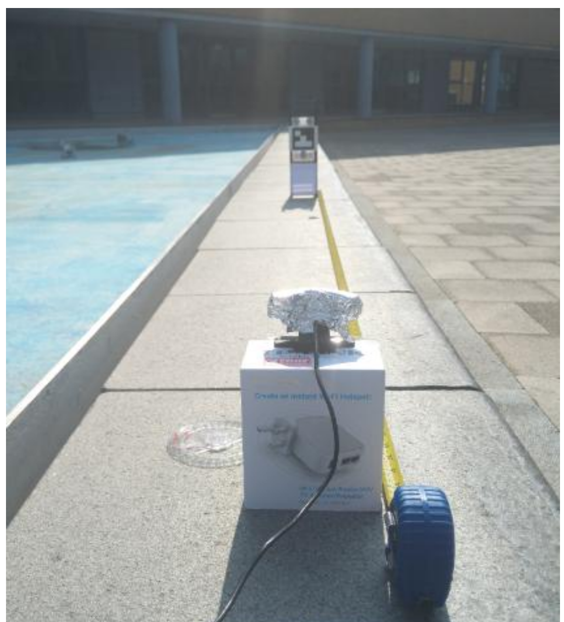
- Working conditions:

  Indoors (normal room lights);

  Outdoors with the Sun outside the camera's FoV;

  Outdoors with the Sun in the FoV – the camera is "blinded" – no detection can be made.





Experimental Results

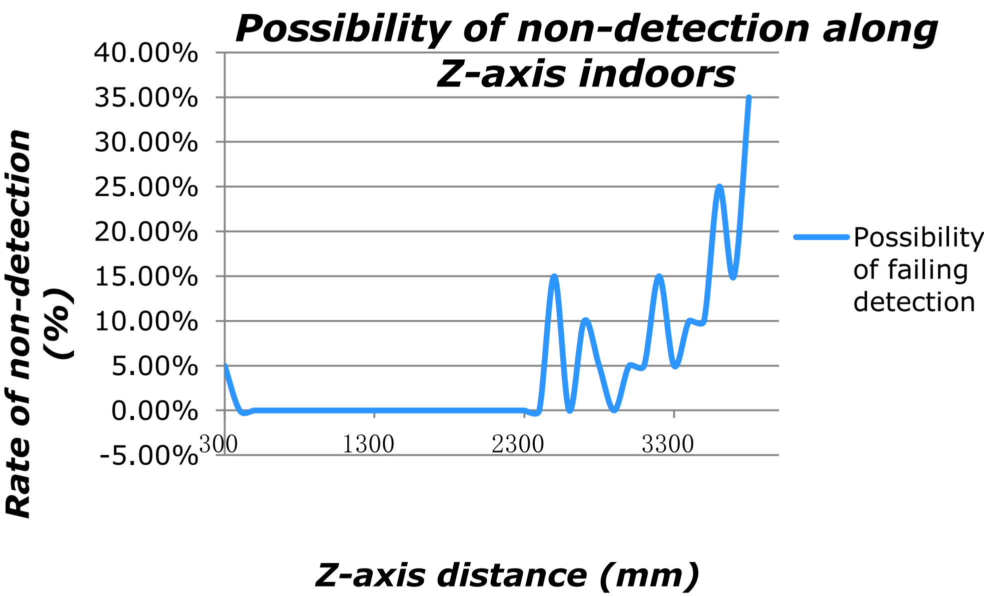
• Results – Passive Glyph – RGB Camera

- Capability:

  from 300mm to 3800mm in lab

  from 500mm to 1600mm outdoors

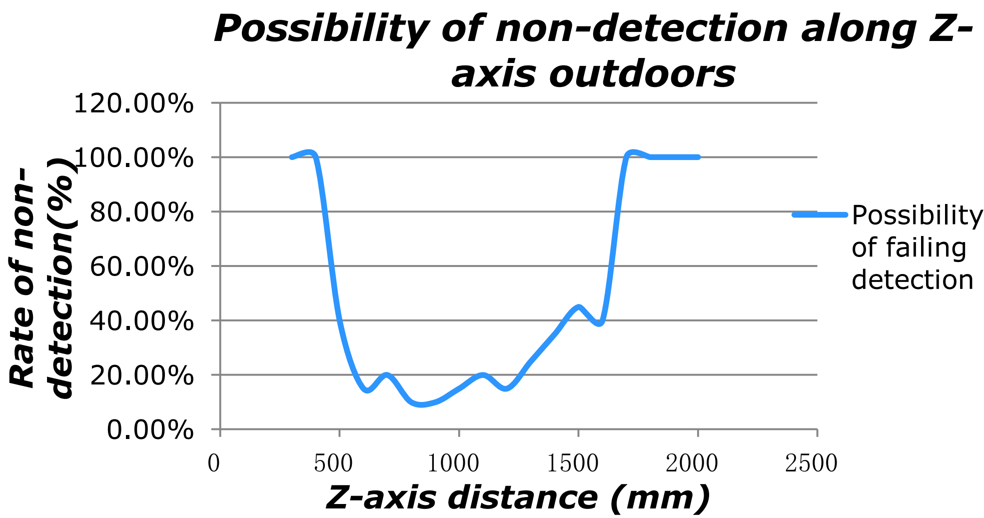
  Note: the algorithms used are not very robust and much higher performance should be possible.



Conclusions:

Should be OK for close operations, but not robust against sunlight in distant operations.

Unable to work with Sun in FoV as it is blinded – however this is **without NIR filtering.**



Experimental Results

- **Results – Passive Glyph – RGB Camera**

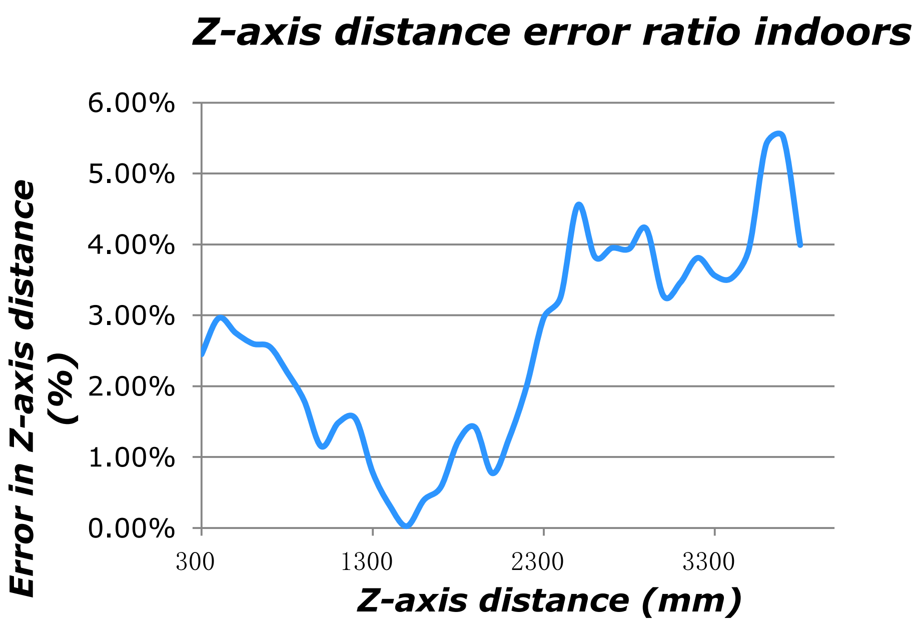
  - Depth estimation:

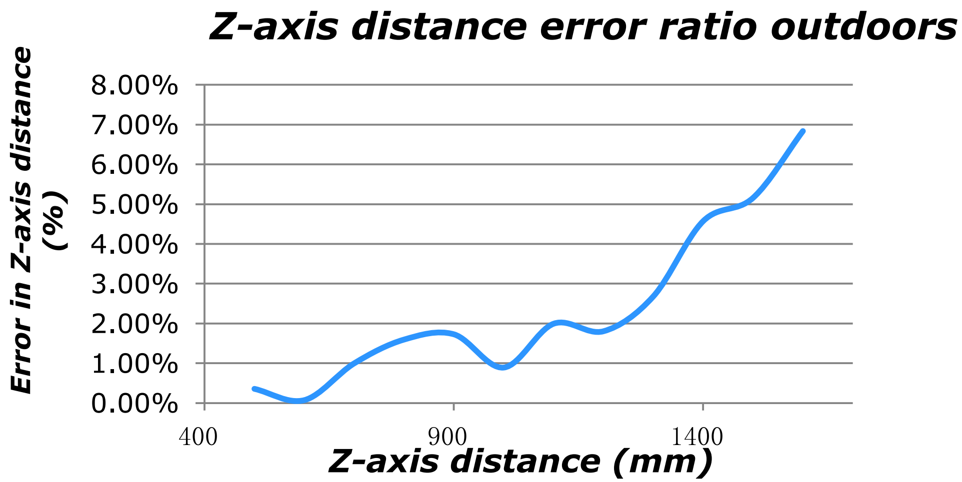
    6% error in accuracy indoors

    7% error in accuracy outdoors

Conclusions:

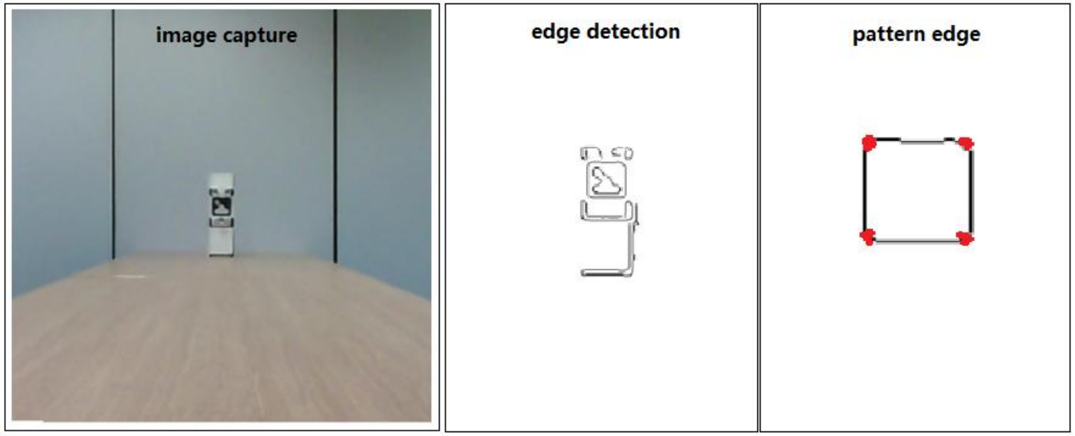
Although the algorithm used is not very robust – it is pretty accurate and gives distance error % similar to the LIDAR.

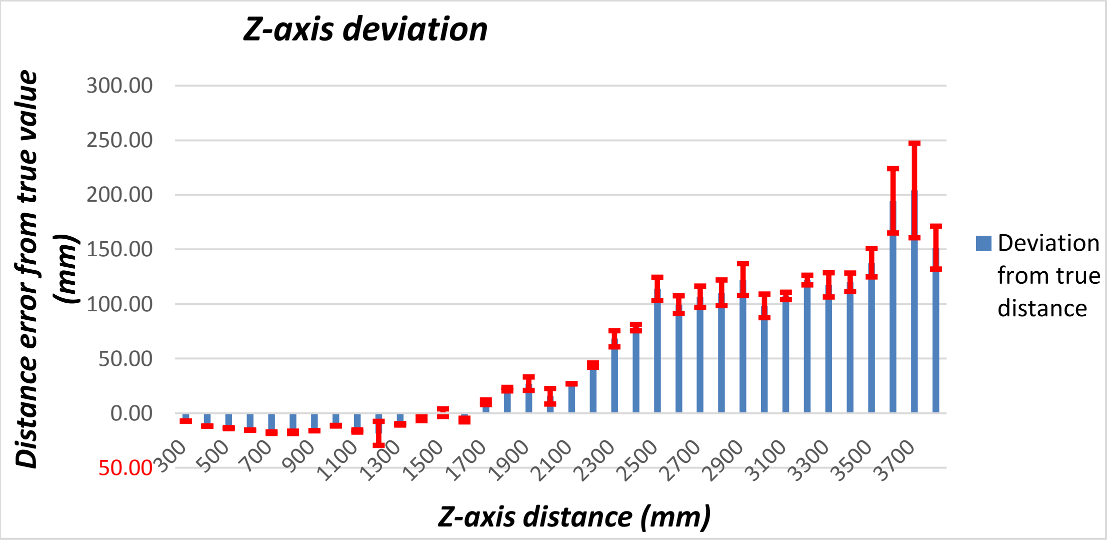




Experimental Results

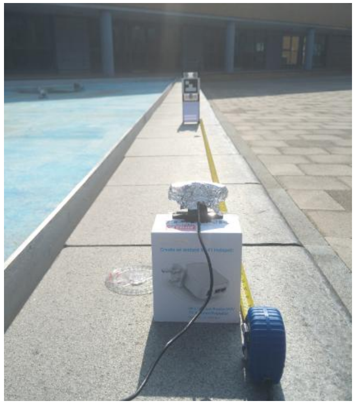
- **Results – Passive Glyph – RGB Camera - Indoors**

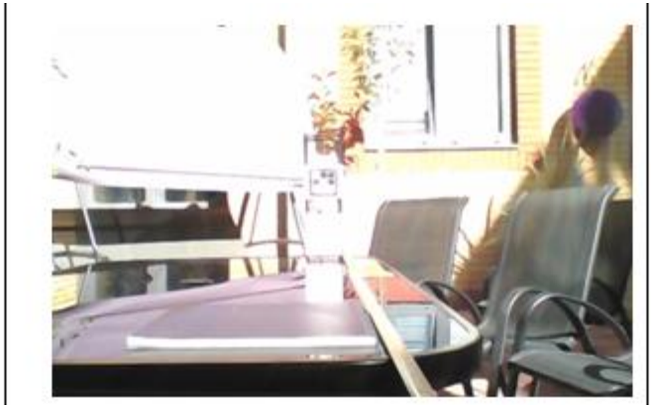


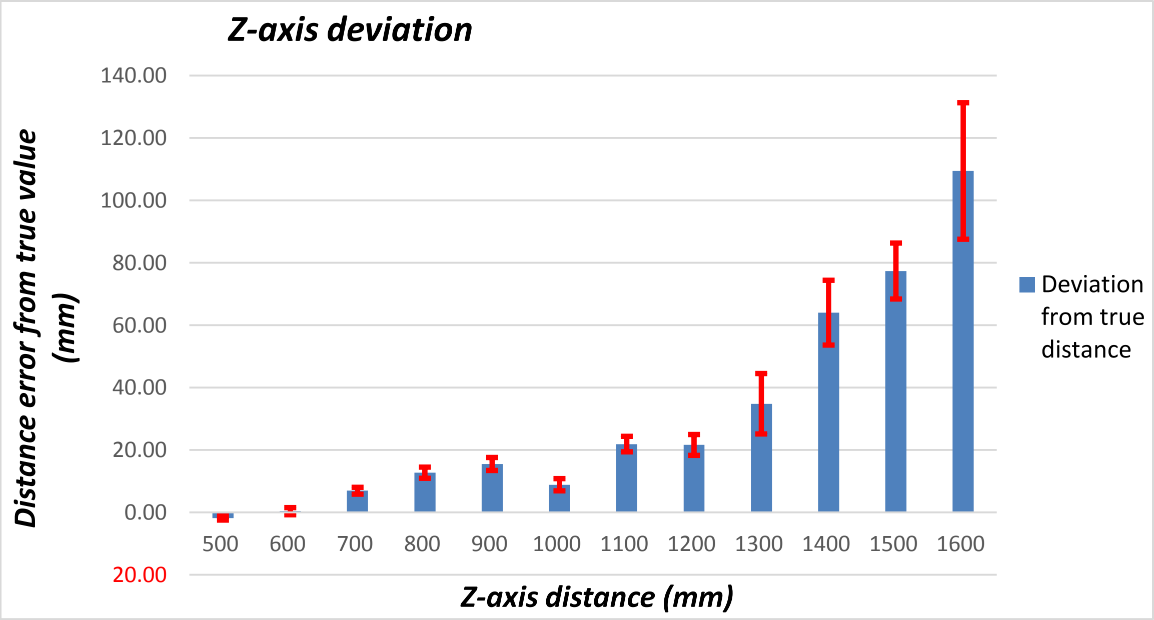


Experimental Results

- **Results – Passive Glyph – RGB Camera - Outdoors**





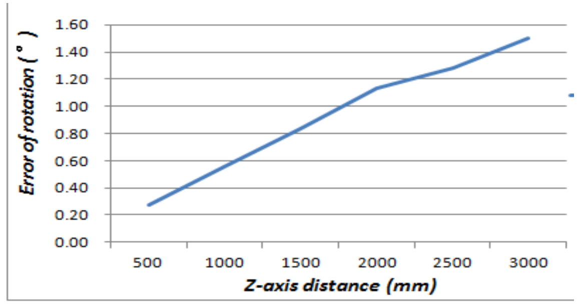


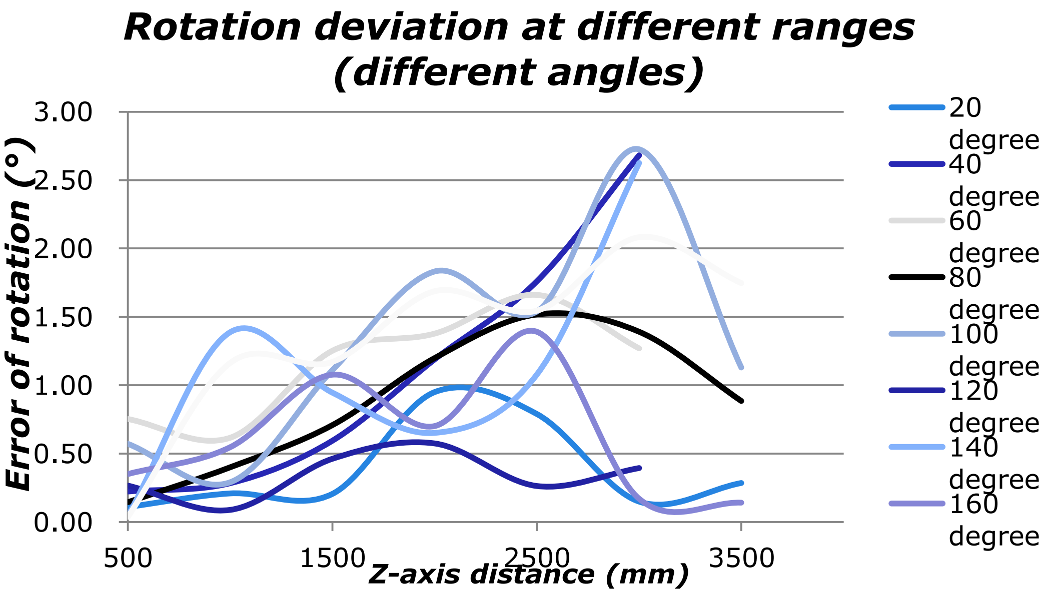
Experimental Results

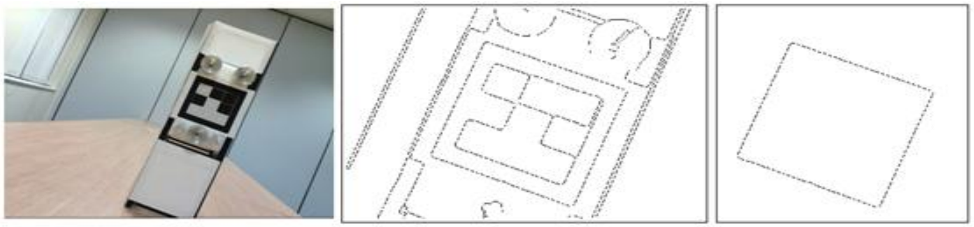
- **Results – Passive Glyph – RGB Camera**
  - Rotation (relative Roll) estimation:

    1.5 degree error in lab

    2.5 degree error outdoors
  - Conclusions: Within experimental error using the protractor at close range. Small increase in angular error with increasing range.







Experimental Results

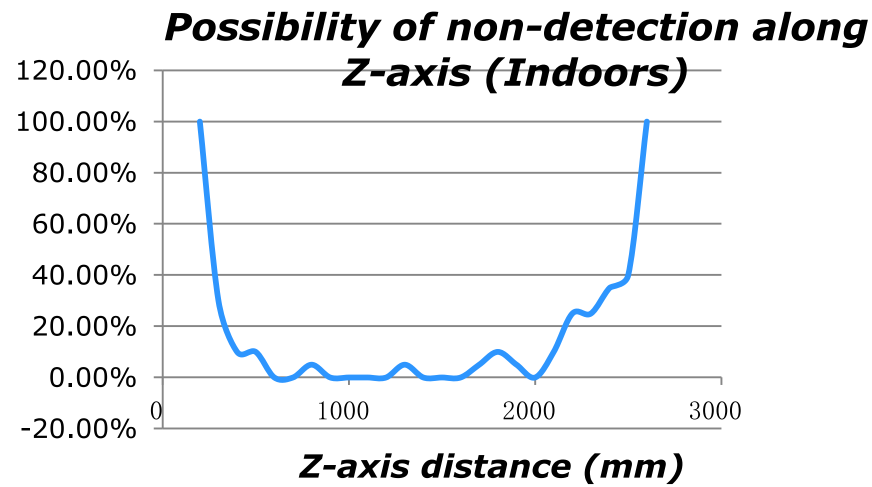
- **Results – Active LEDs – RGB+NIR Filter Camera**

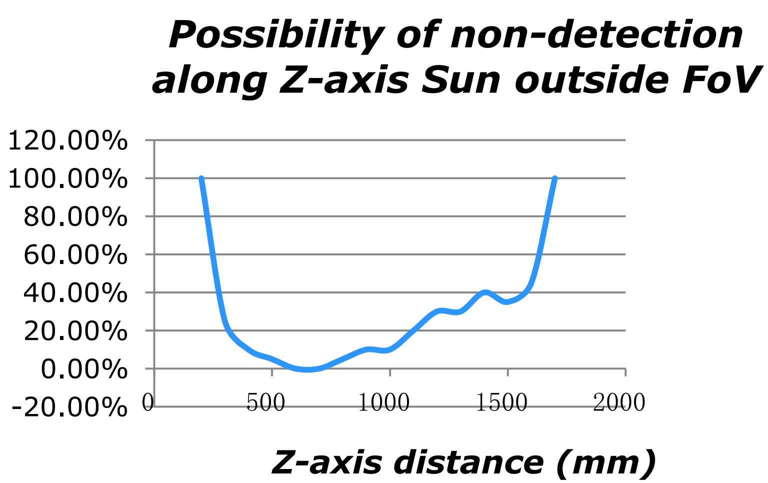
  - Range Capability:

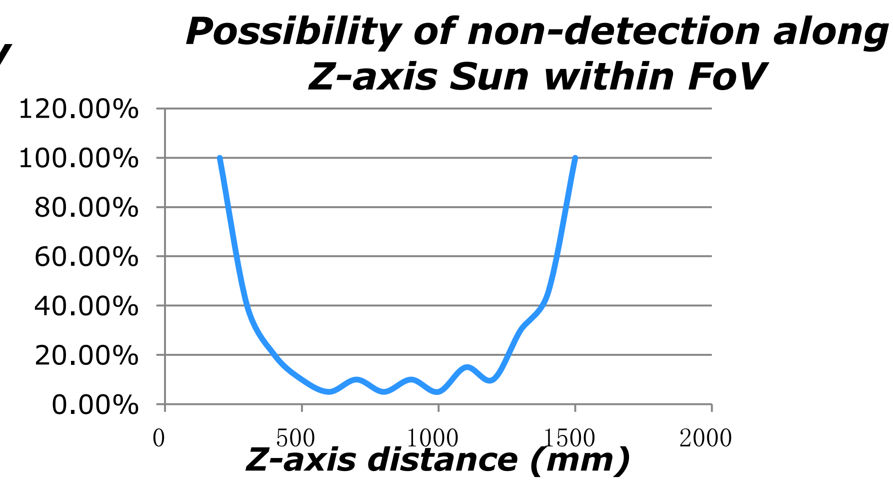
    from 300mm to 2500mm in lab

    from 500mm to 1600mm outdoors

    Insensitive to Sun in FoV







Experimental Results

- **Results – Active LEDs – RGB+NIR Filter Camera**

- Depth estimation:

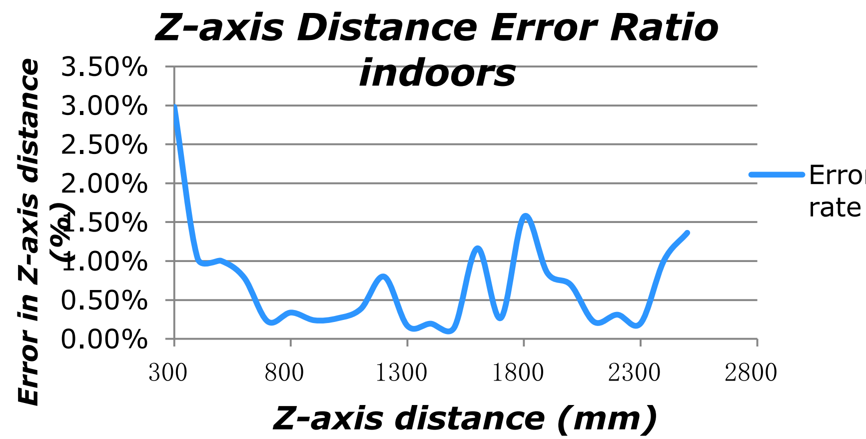
  1.6% error in accuracy indoors

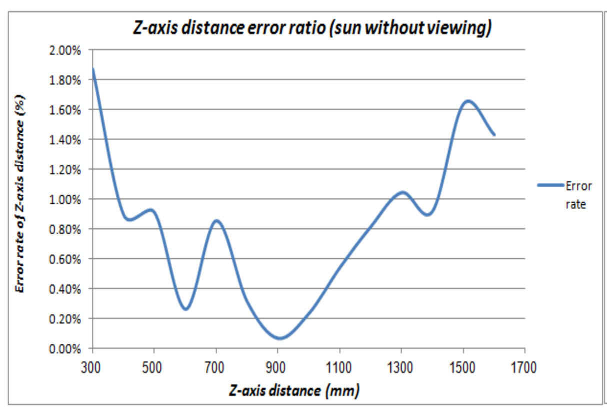
  2% error in accuracy outdoors

- Outdoors:

  error rate almost unchanged

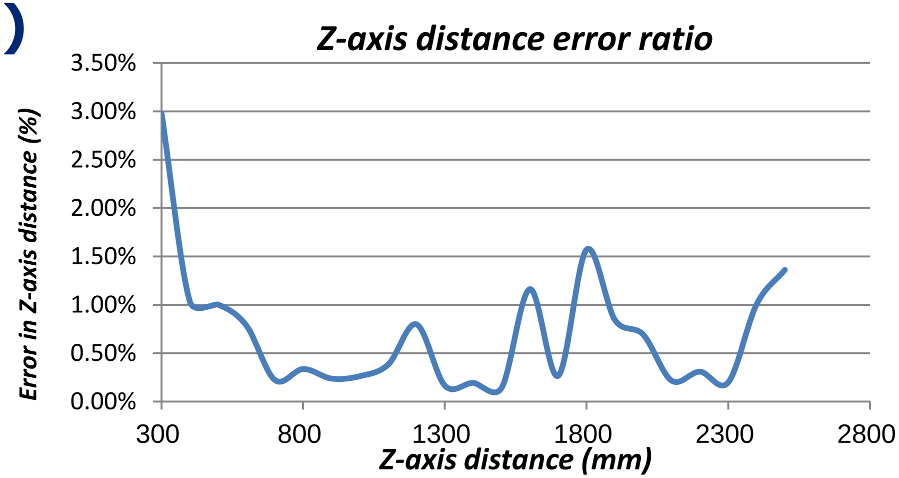
  stable in depth calculation no matter what light condition is

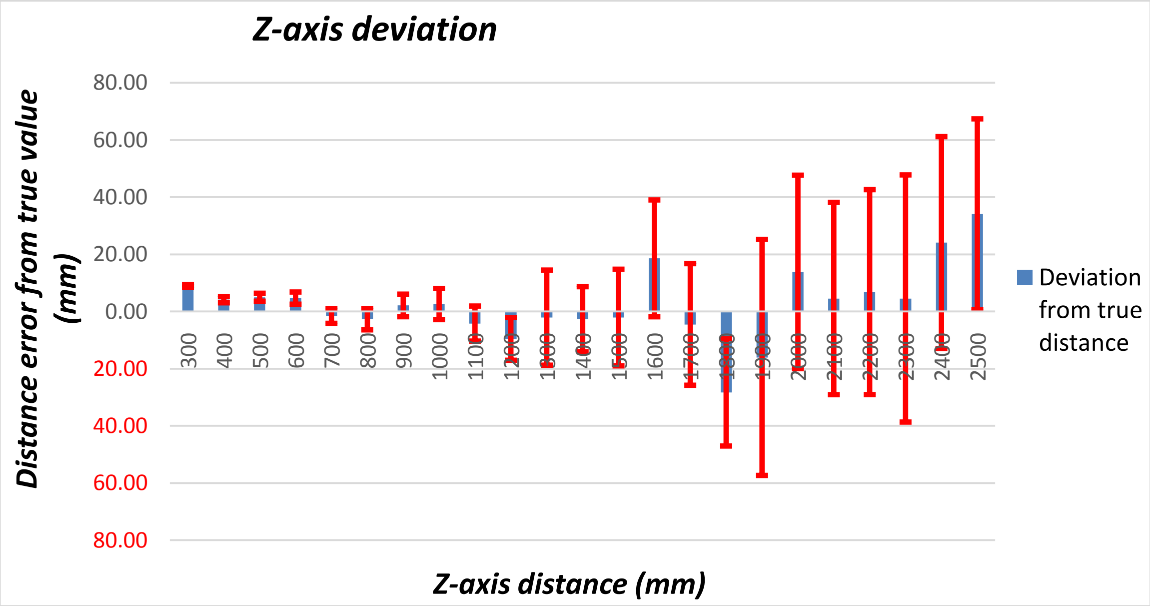




Experimental Results

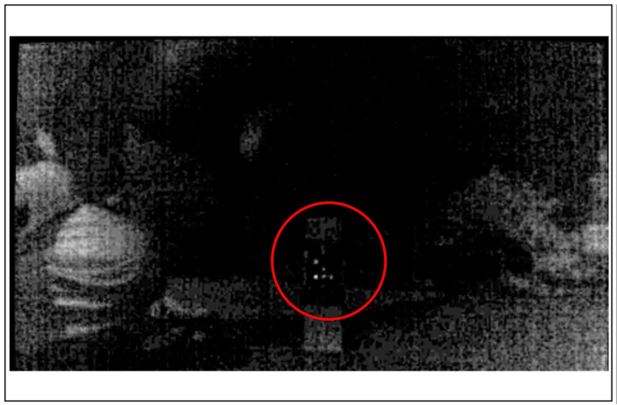
- **Results – Active LEDs – RGB+NIR Filter Camera (Indoors)**

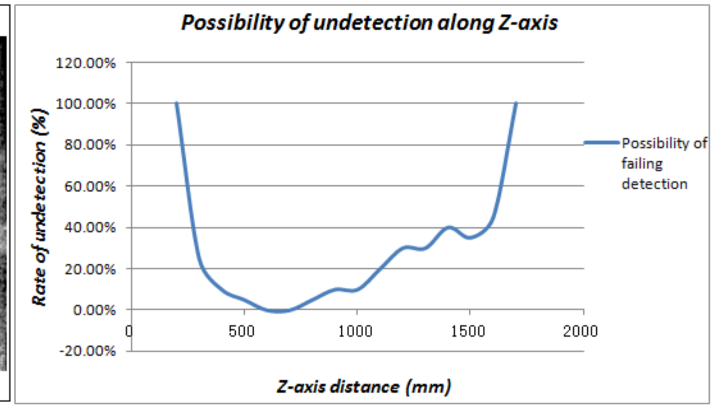


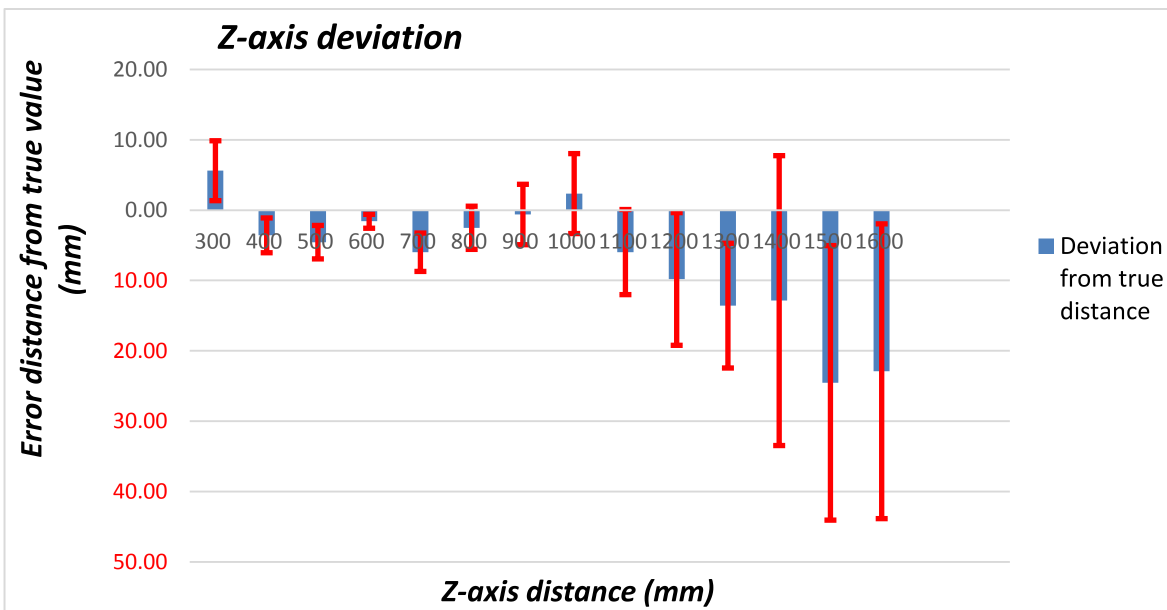


Experimental Results

- **Results – Active LEDs – RGB+NIR Filter Camera (Outdoors – Sun Outside FoV)**

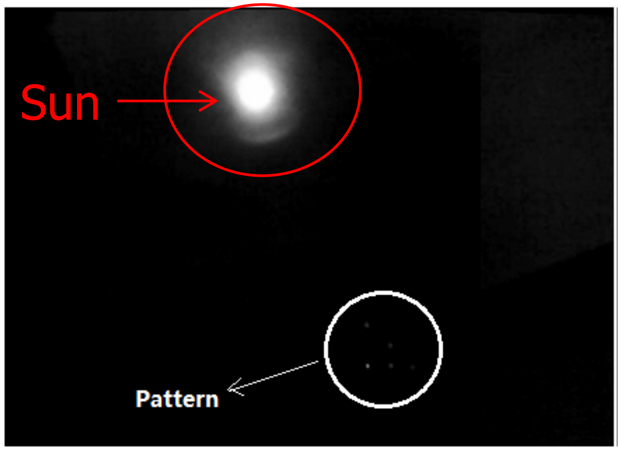


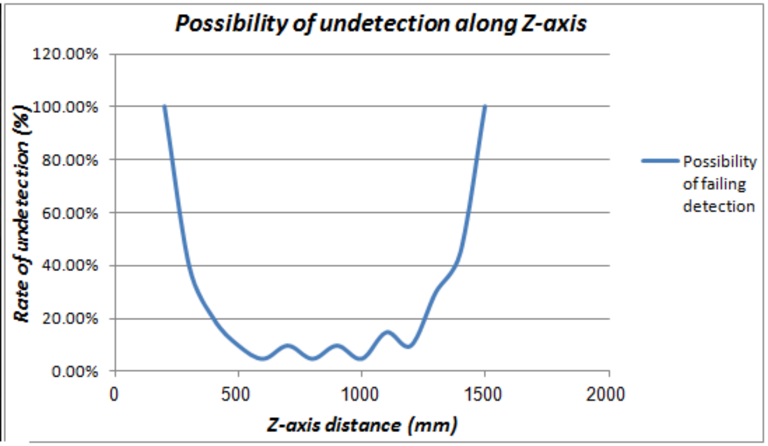


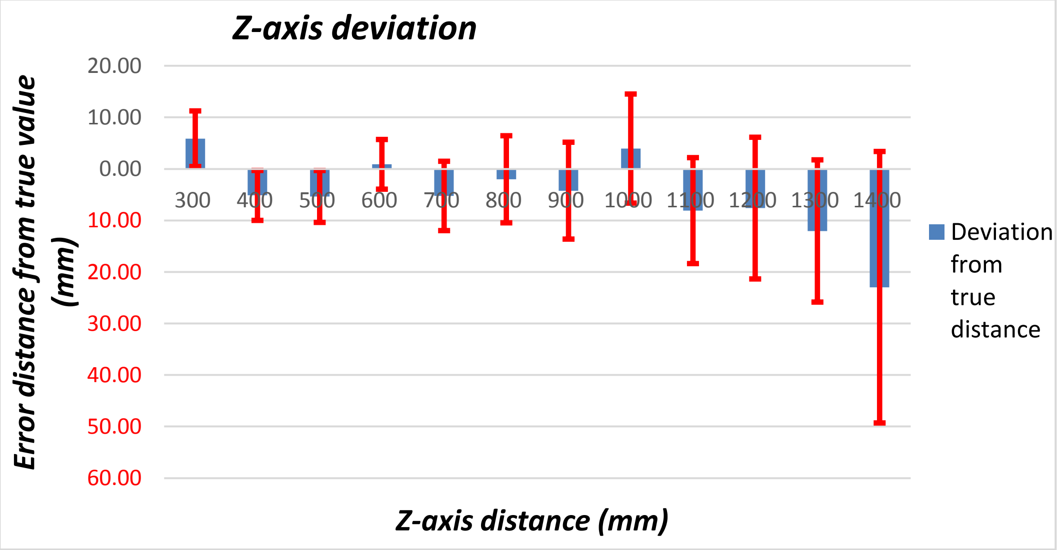


Experimental Results

- **Results – Active LEDs – RGB+NIR Filter Camera (Outdoors – Sun Inside FoV)**







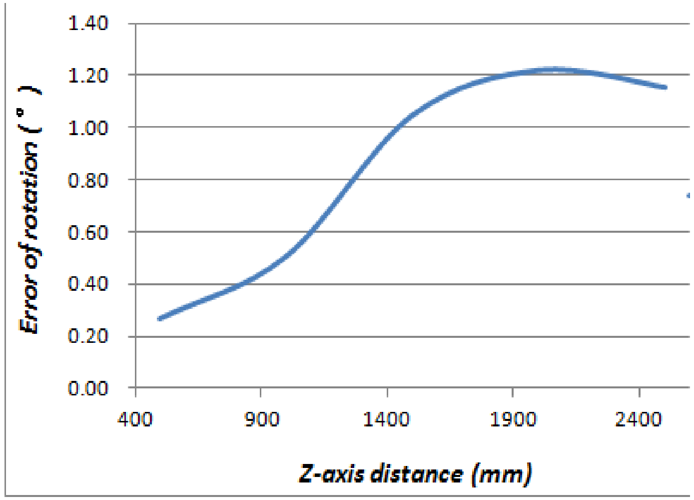
Experimental Results

- Rotation (Relative Roll) estimation:

  1.2 degree deviation in lab

  1.3 degree deviation outdoors

Conclusions: Within experimental error using the protractor. Small increase in angular error with increasing range.



Camera with 850nm NIR Filter attached

MVS/Glyphs/LEDs

- Using a NIR filtered camera with NIR LEDs is superior to using glyphs and works under all illumination conditions including bright sunlight – even with the Sun in the FoV.
- The range estimates and roll angle estimates are very good, and within the 10%/ $\pm 10^{o}$ tolerance we hoped for.
- The algorithms used in the experiment could be improved – in particular moving to the Planar POSIT algorithm would allow relative Yaw and Pitch to be established.
- The maximum active range over which the system works (using a 90^{o} wide angle lens) varies from ~4m in the laboratory to ~ 1.5m in full Sunlight. The minimum goes down to ~30cm.
- This could be improved by:
  - Implementing better, more standard algorithms
  - Using a true NIR monochome camera (also a higher pixel count)
  - Optimising optics/camera for close in operations < 1m.

MVS/Glyphs/LEDs

- Next Steps:

- Using DS325 Camera with NIR (850nm) filter to establish resilience to the Sun when in Lidar mode and with LEDs.
- Evaluate best configuration for ultra short range accuracy – over the first few cm out to 1-2m.
- Establish if 640x480 pixels is good enough for the MVS/LED system – or do we need a separate 1280x720 camera.
- Close the control loop via the R-Pi compute module.
- Conduct Air Bearing Table trials.

Questions?

Surrey AAReST

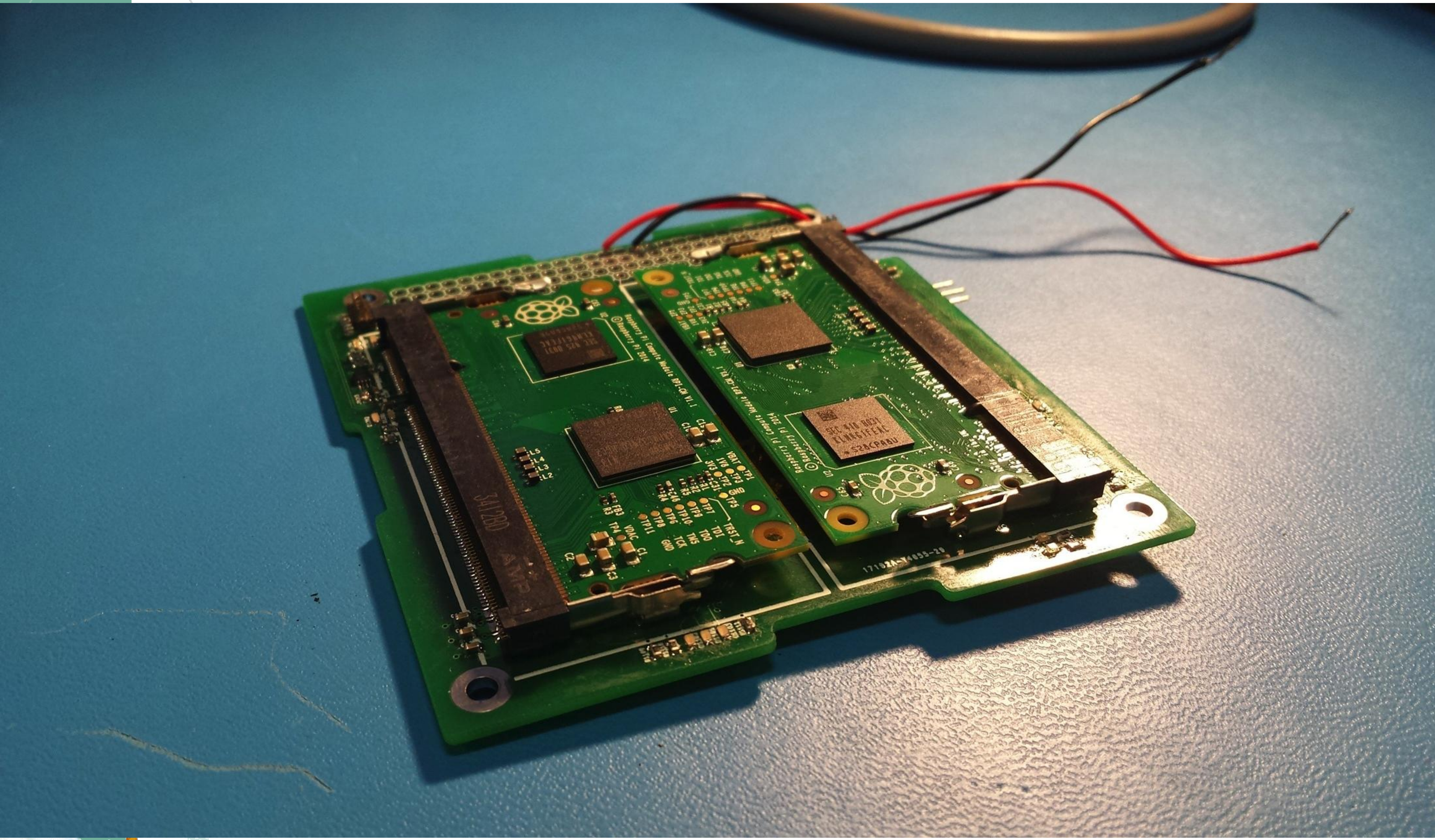
Payload Interface

Computer

2014 RPi-B > RPi Compute

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

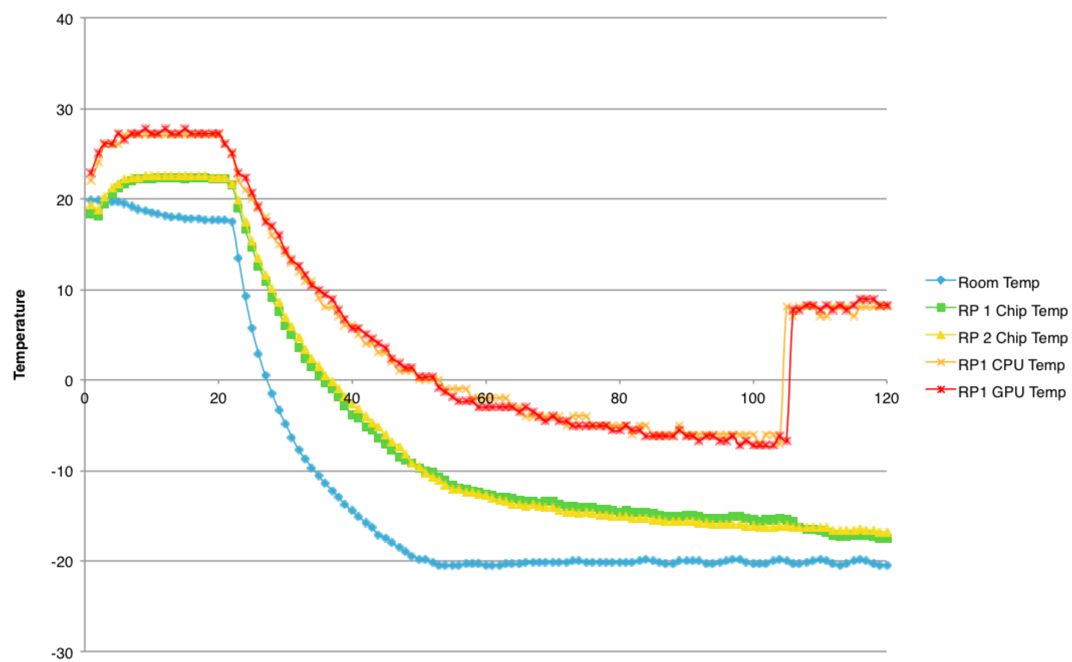
2014-2015 RPi Board Built



2015 RPi Software System

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

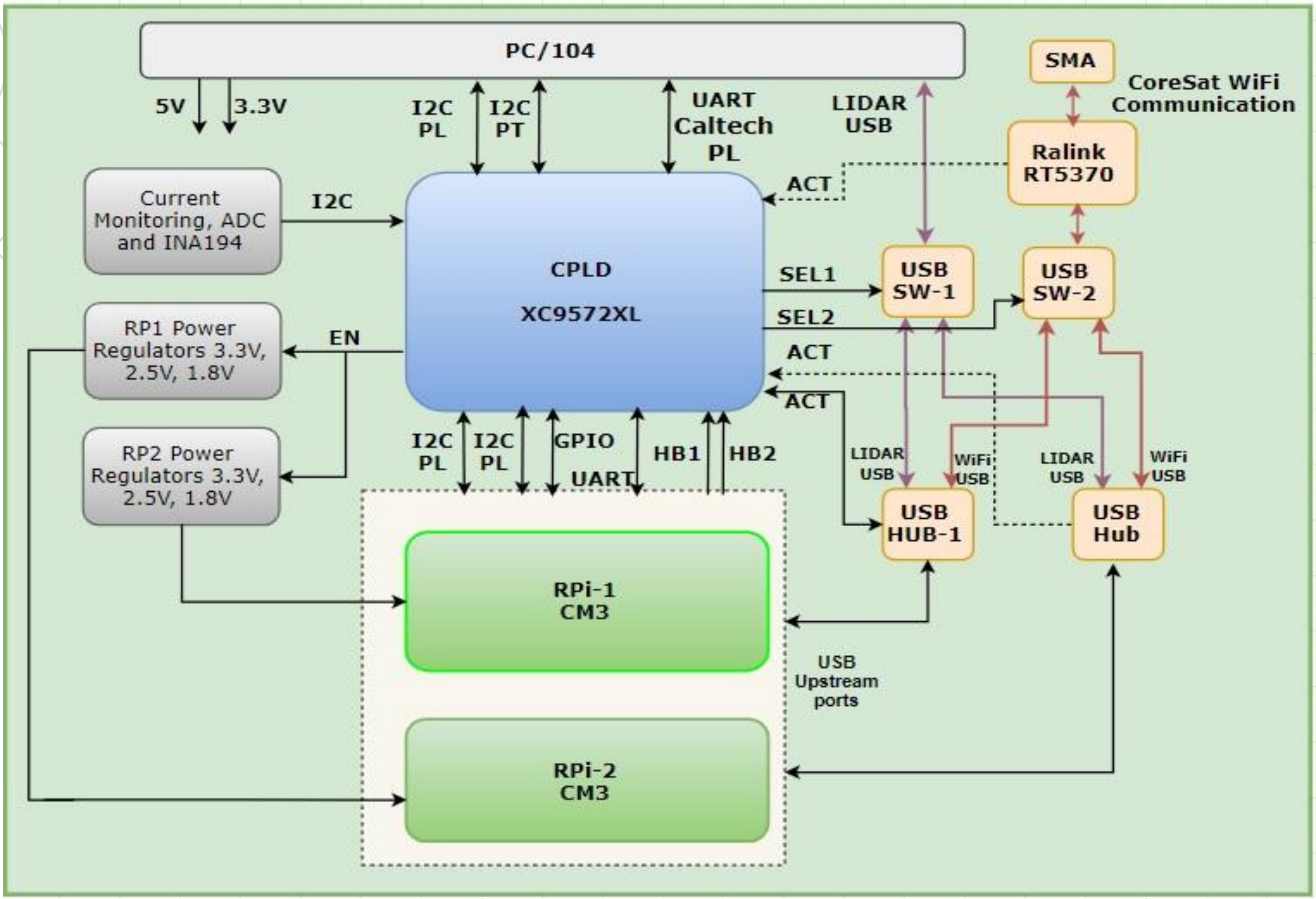
  - E.g. direct on-chip hardware control:
  - CPU & GPU Temp stable at 62° C
  - Turn ON/OFF at hot & cold (see right).
  - Core voltage & CPU freq. stable too.



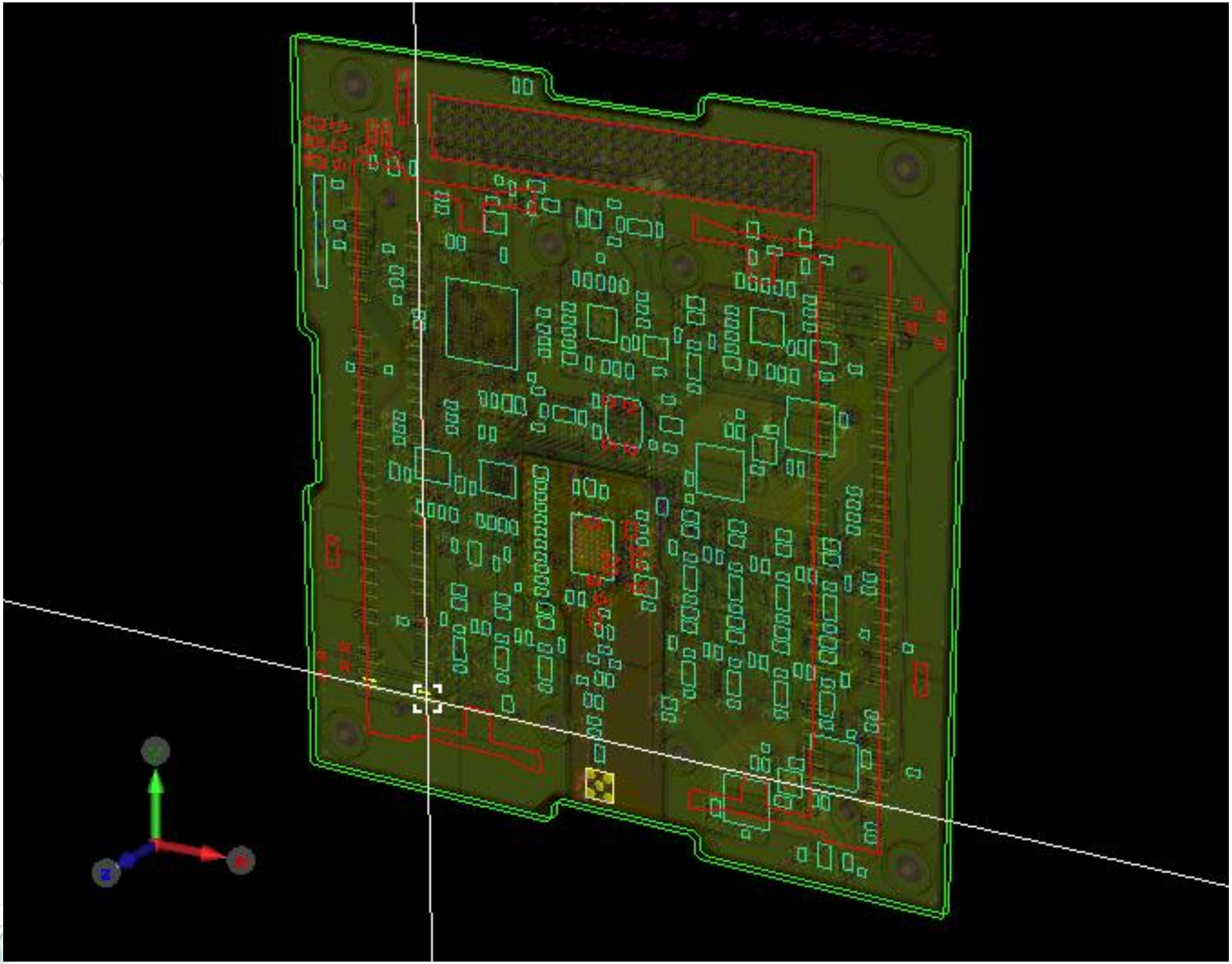
2017 PIC Board Spec.

- Key Specs:
  - Once ICD for payloads are finalised, the interfaces can be fixed
  - BCM2835 Processor (400-800 MHz)
    - NASA Goddard TID & SEE Radiation Tests, 4 RPi B+ DUTs
    - TID to 40 krad OK, 50-60 2 USB failures, 2 fine to 150 krad
  - 512 MB NAND RAM 46 GPIO (than 21) > + 4 GB NAND Flash.
  - Capacitor changes required > None required
  - External CPLD as:
    - Power up sequencing
    - 'Heartbeat' Watchdog on RPi-Computes
    - Power Monitoring & Switching via UART / ADC
    - I2C 'Router' (Multi-master buses)
  - Payload data/frame processing
  - RPi's perform EM Control in XY-plane during RDV

2017 Sept PIC Board Spec.

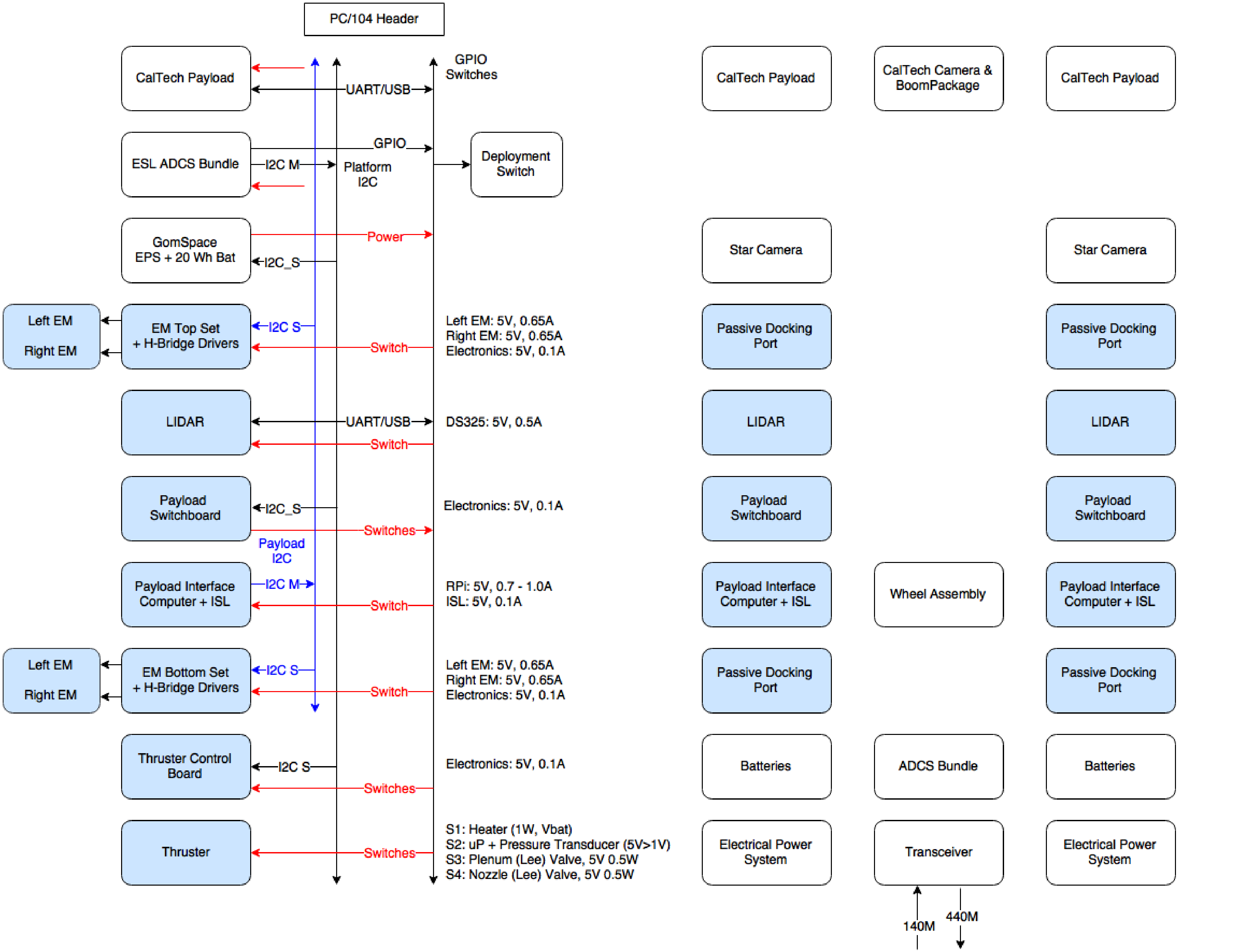


2017 Sept PIC Board Spec.



Questions?

Surrey AAReST MirrorSat System Budgets


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

SURREY SPACE CENTRE

Pins & Grounding

UNIVERSITY OF SURREY

- PC/104 Connector pins defined
- Payload power return is through power switch board
- Internal rods need to be non-electrical ground GND
- Electronics GND must be a single star point to –V Battery
- RF Ground is the chassis (forming full dipole from monopoles)

	UART_TX (Caltech Payload)	UART_RX (Caltech Payload)					CubeADCS ENABLE - Cubewheels/GPIO	CubeADCS ENABLE - Cubewheels/GPIO	CubeADCS ENABLE	CubeADCS ENABLE	CubeADCS UART_1	EMS -TOP 5V (switched)	5V_ MAIN
	2	4	6	8	10	12	14	16	18	20	22	24	26
	GPIO (Caltech Payload) optional	GPIO (Caltech Payload) optional					CubeADCS ENABLE - Cubewheels/GPIO	CubeADCS ENABLE - Cubewheels/GPIO	CubeADCS ENABLE	CubeADCS ENABLE	CubeADCS UART_1	EMS -TOP 5V GnD (switched)	5V_ MAIN
H2	1	3	5	7	9	11	13	15	17	19	21	23	25

	3V3_ MAIN	POWER GND (3v3)	POWER GND (5v)	LIDAR - USB 5V (switched)	EPS RX	EPS TX	EMS - BOTTOM 5V Gnd (switched)	CubeADCS BUVIN	THRUSTER - V_Batt Gnd (switched)	V_BAT		LIDAR - USB D+	LIDAR - USB D-
	28	30	32	34	36	38	40	42	44	46	48	50	52
	3V3_ MAIN	POWER GND (V_Batt)	ANALOG GND (EMS)	LIDAR - 5V Gnd (switched)	THRUSTER 3V3 (switched)	THRUSTER 3V3 Gnd (switched)	EMS - BOTTOM 5V (switched)		THRUSTER - V_Batt (switched)	V_BAT			
H2	27	29	31	33	35	37	39	41	43	45	47	49	51

	CubeADCS ENABLE	CubeADCS ENABLE	CubeADCS ENABLE	CubeADCS ENABLE			I2C_DATA (Payload)		CubeADCS UART_1	CubeADCS UART_1			PAYLOAD COMPUTER 3V3 (switched)
	2	4	6	8	10	12	14	16	18	20	22	24	26
	CubeADCS CANL	CubeADCS CANH	CubeADCS ENABLE - Cubewheels/GPIO	CubeADCS ENABLE - Cubewheels/GPIO	CubeADCS ENABLE - Cubewheels/GPIO	CubeADCS ENABLE - Cubewheels/GPIO	I2C_CLOCK (Payload)		CubeADCS UART_1	CubeADCS UART_1	CubeADCS I2C_ SCL_ ADCS	CubeADCS I2C_ SDA_ ADCS	PAYLOAD COMPUTER 5v Gnd (switched)
H1	1	3	5	7	9	11	13	15	17	19	21	23	25

	PAYLOAD COMPUTER 3v3 Gnd (switched)	CubeADCS SPI_ MOSI/ MISO	CubeADCS SPI_CS EPS 5V_in	THRUSTER 5V (switched)	THRUSTER 5V Gnd (switched)		CubeADCS UART_2				3V3_S	3V3_S	3V3_S
	28	30	32	34	36	38	40	42	44	46	48	50	52
	PAYLOAD COMPUTER 5V (switched)	CubeADCS SPI_CLK	CubeADCS SPI_ MOSI/ MISO	CubeADCS UART_2	CubeADCS UART_2		CubeADCS UART_2	I2C_SDA_SYS (Platform)	I2C_ SCL_ SYS (Platform)		5V_S	5V_S	5V_S
H1	27	29	31	33	35	37	39	41	43	45	47	49	51

H2	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51

H1	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51

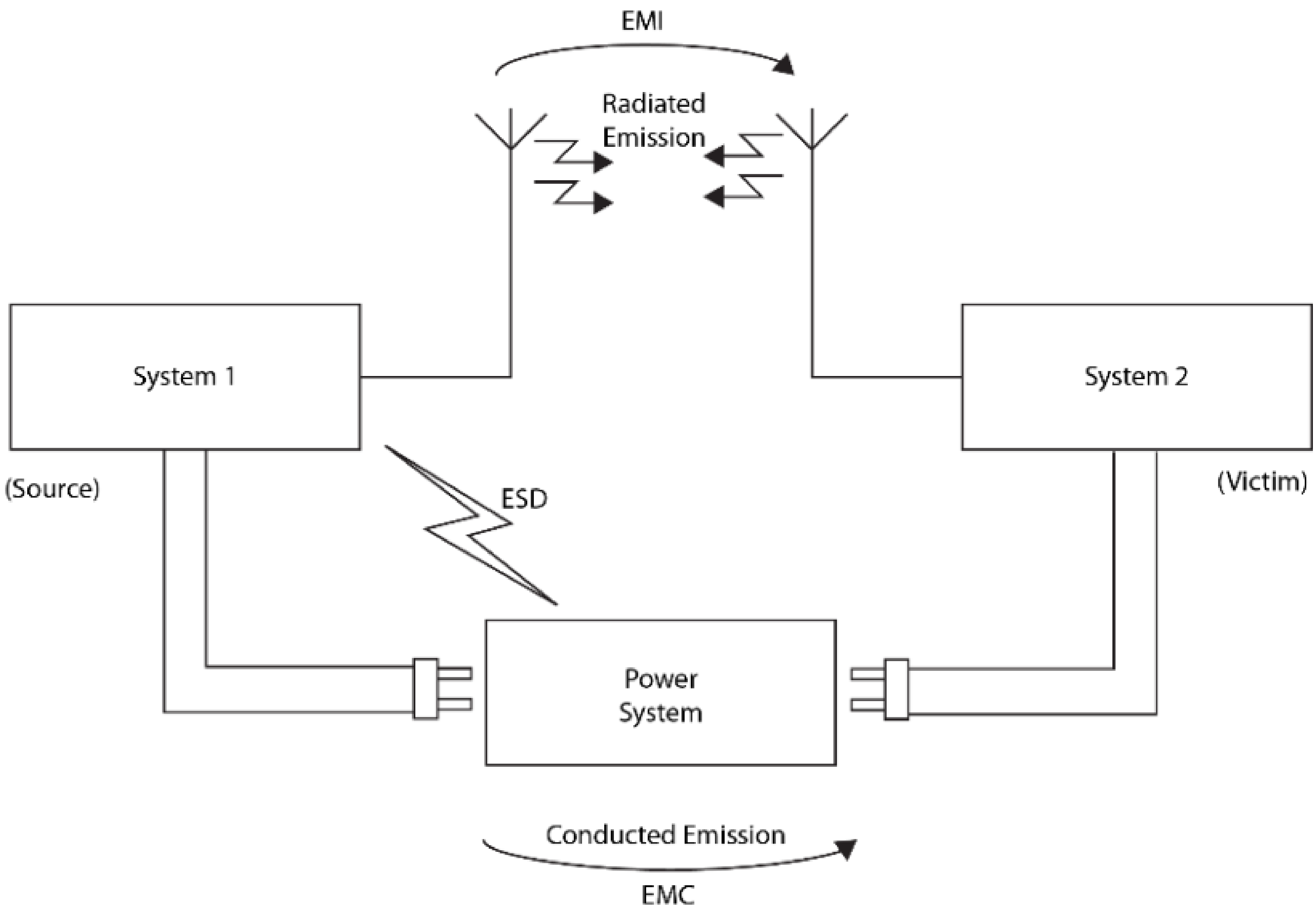
CUBE ADCS

GOMSPACE EPS

PAYLOAD

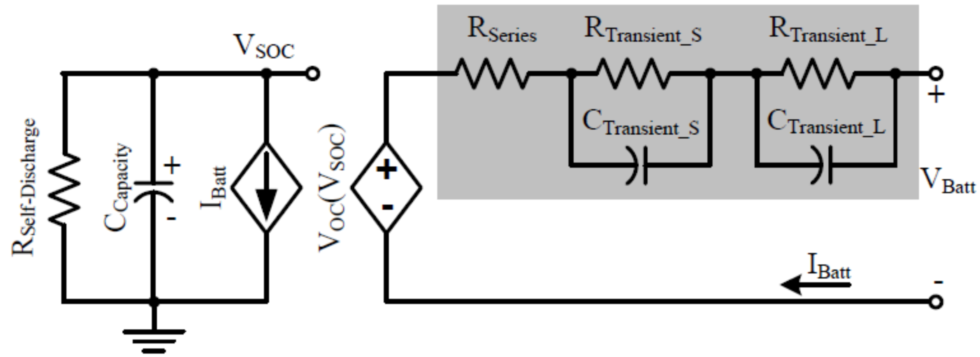
COMMON

Pins & Grounding



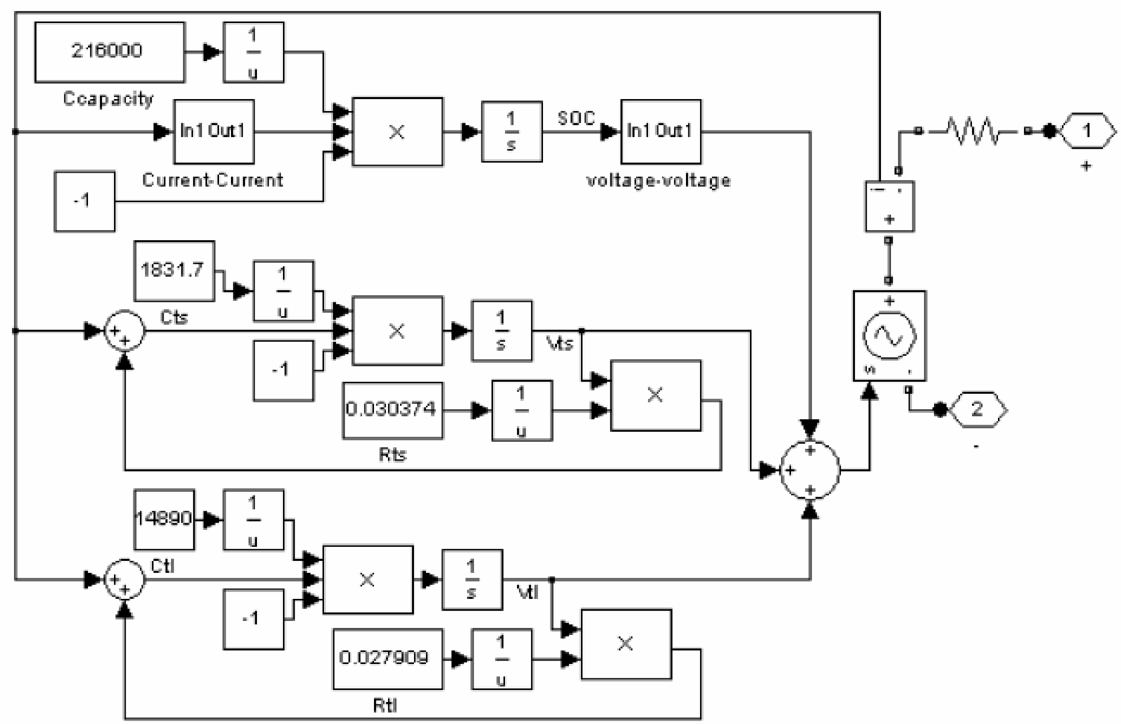
Power Budget Modelling

- Rincon-Mora
- 2006

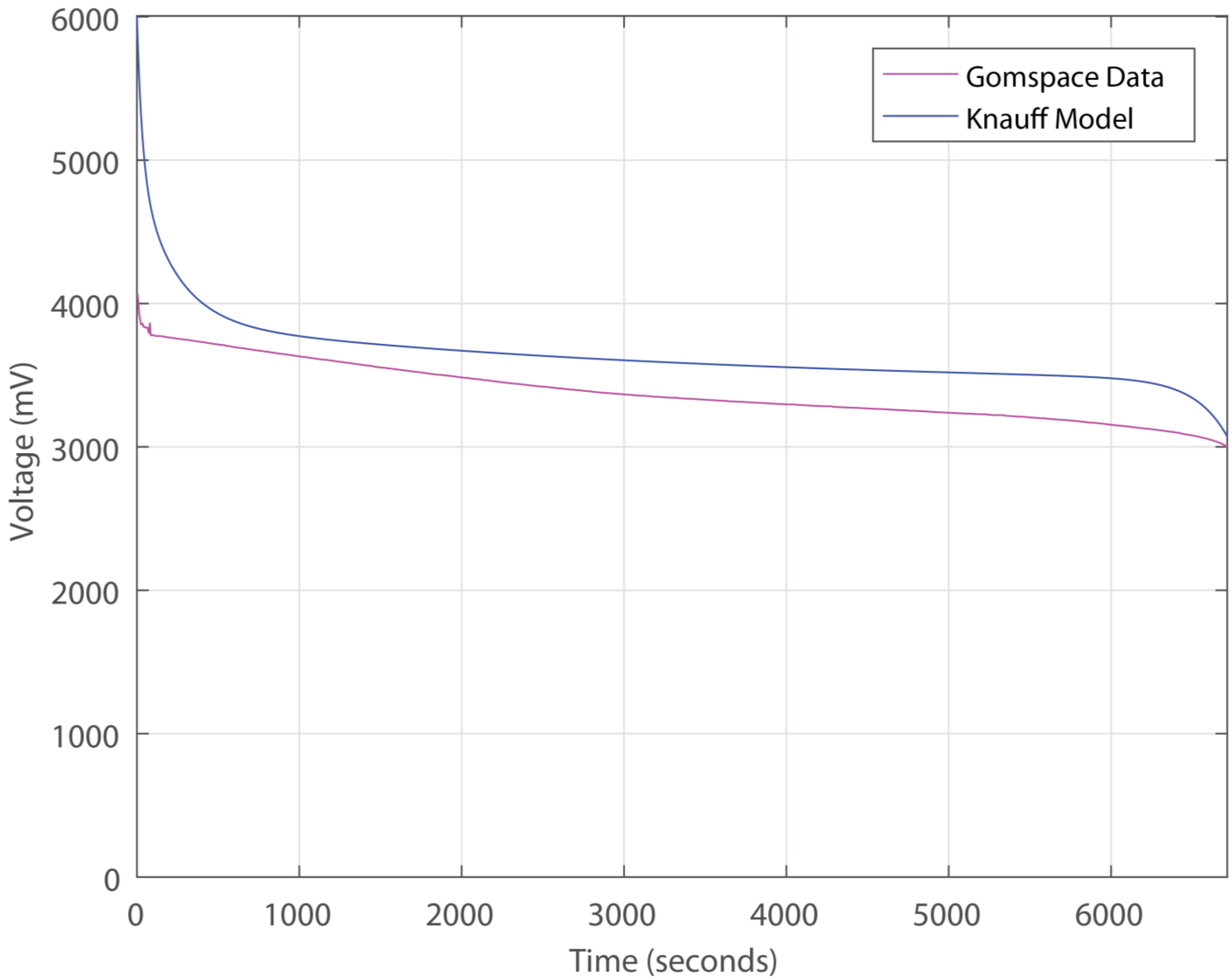


- Knauff-Mclaughlin
- 2007

- Tuned RC networks for:
  - State of Charge
  - 'Short' Transient
  - 'Long' Transient

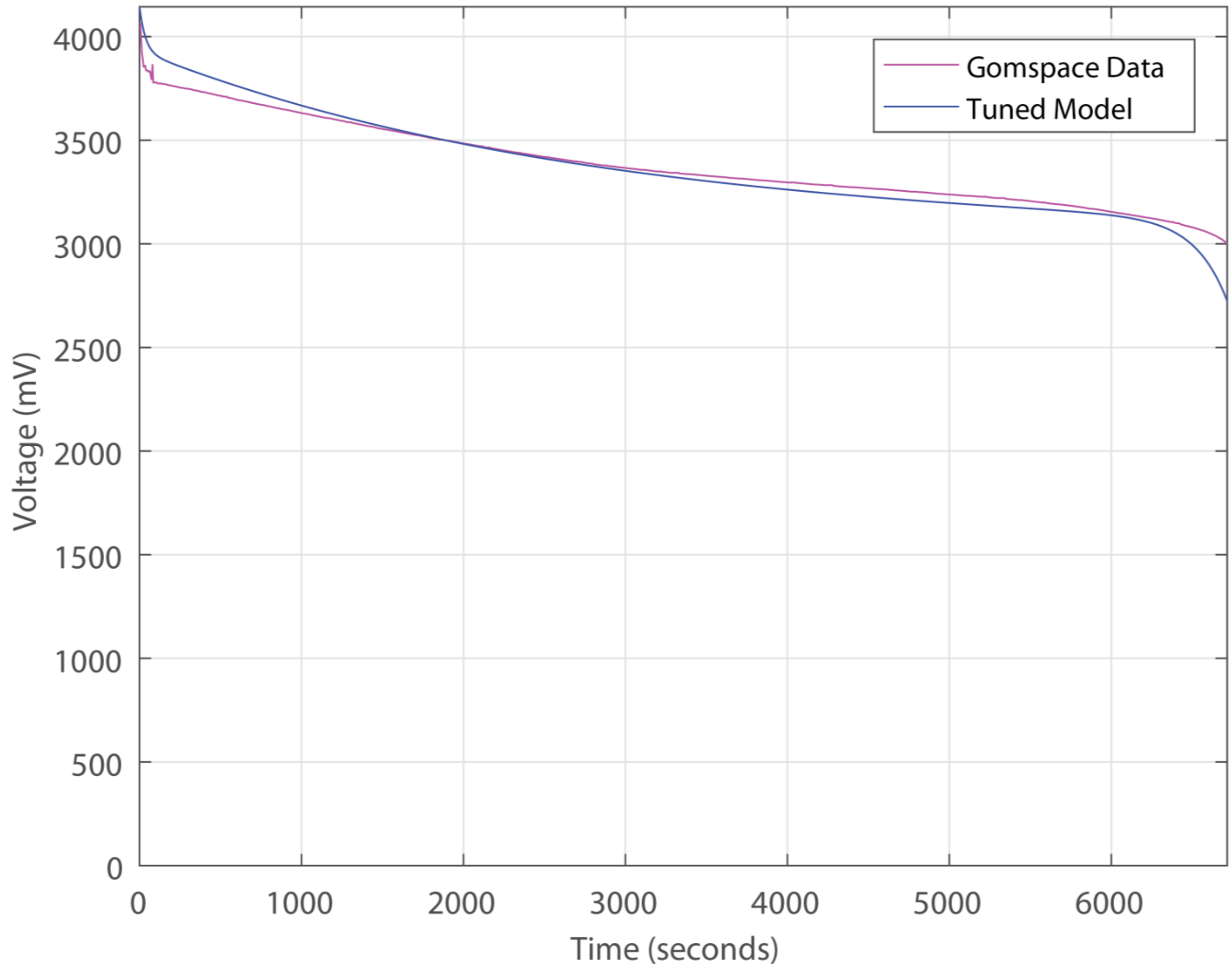


Power Budget Modelling



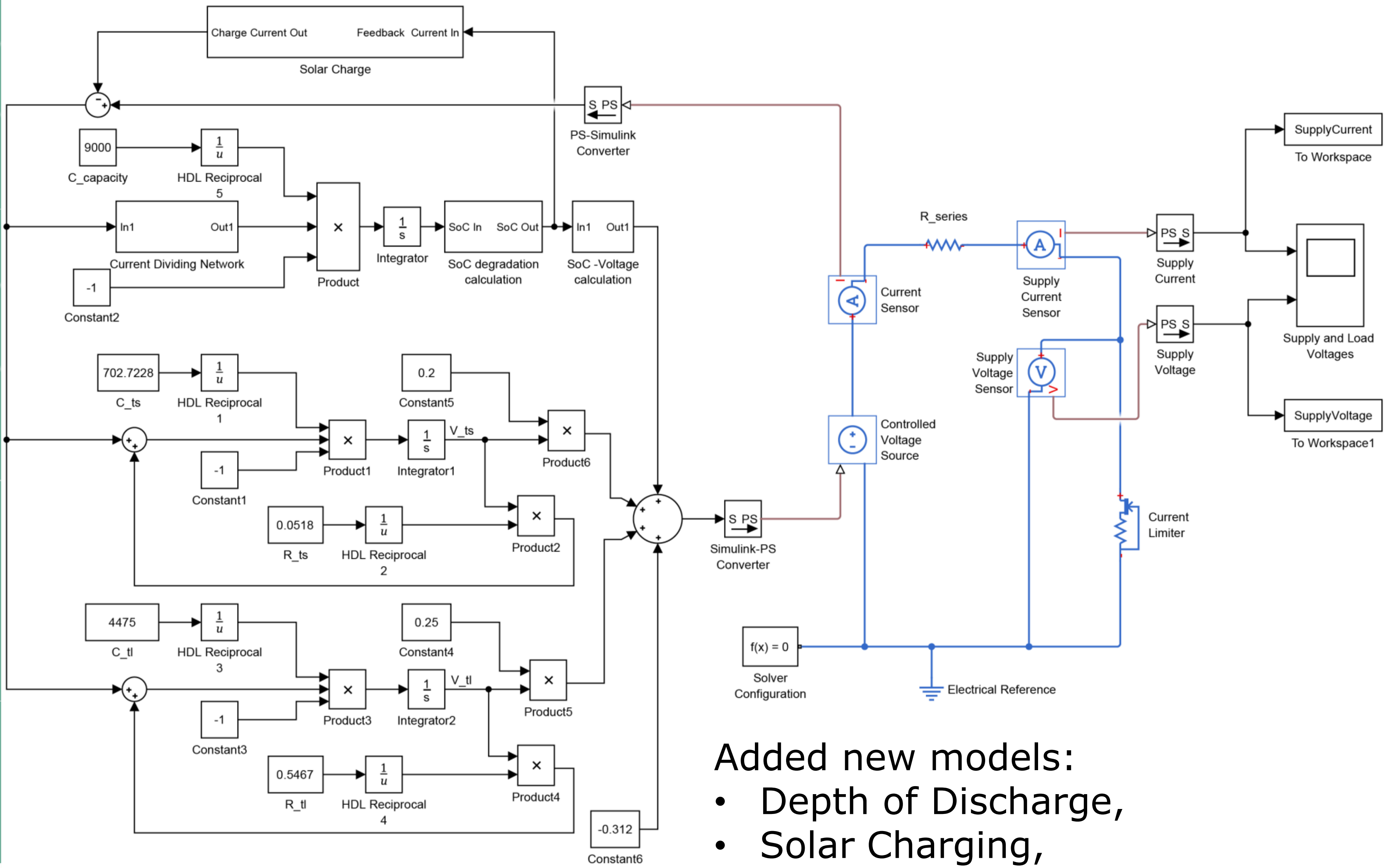
- Voltage readings under constant current discharge of 1.3 A

Power Budget Modelling



- Voltage readings under constant current discharge of 1.3 A

Power Budget Modelling



Added new models:

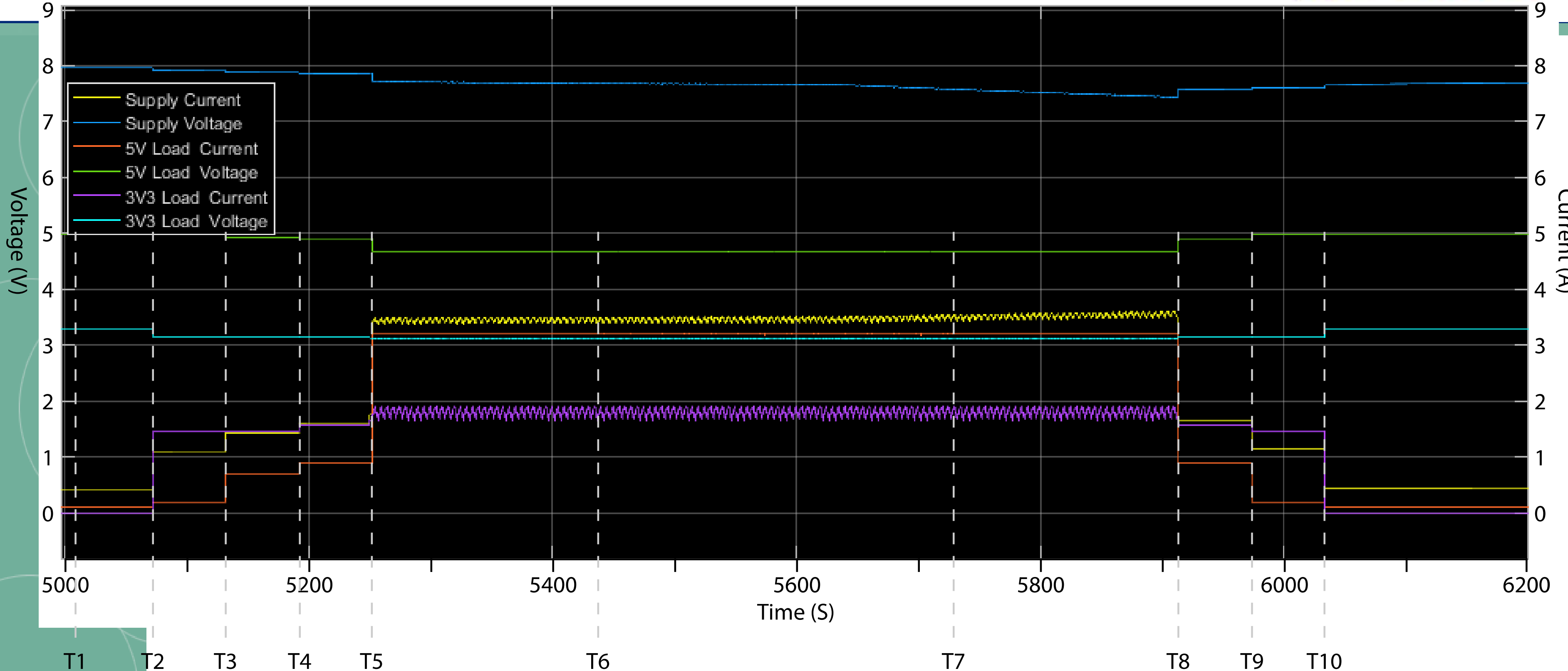
- Depth of Discharge,
- Solar Charging,
- Simulated Loads

System	Sub-System	Voltage (V)	Power (W)	Current (A)	Resistive Load (Ω)
Docking	Top Left EMS	5	3.25	0.65	7.692307692
	Top Right EMS	5	3.25	0.65	7.692307692
	Top EMS Electronics	5	0.5	0.1	50
	Lwr Left EMS	5	3.25	0.65	7.692307692
	Lwr Right Ems	5	3.25	0.65	7.692307692
	Lwr EMS Electronics	5	0.5	0.1	50
LIDAR	Lidar	5	2.5	0.5	10
OBC	Power Switchboard	5	0.5	0.1	50
	Payload I/Face Computer	3.3	4.9995	1.515	2.178217822
	Payload ISL	5	0.5	0.1	50
Thruster	Thruster Ctrl	5	0.5	0.1	50
Assembly	Thruster Heater	7.4	0.999	0.135	54.81481481
	Thruster Px Transducer	12	0.1248	0.0104	1153.846154
	Plenum Valve	12	0.99996	0.08333	144.0057602
	Nozzle Valve	12	0.99996	0.08333	144.0057602
ADCS	CubeComputer	3.3	0.200013	0.06061	54.44646098
	CubeControl	3.3	0.249975	0.07575	43.56435644
	CubeTorquer - X	3.3	0.363	0.11	30
	CubeTorquer - Y	3.3	0.363	0.11	30
	CubeCoil	3.3	0.134442	0.04074	81.00147275
	CubeWheel - start up	7.4	0.72000002	0.097297	76.05555344
	CubeWheel - mean	7.4	0.269064	0.03636	203.520352
	CubeWheel Electronics	3.3	0.33	0.1	33

Power Budget Modelling

Label	Time (Seconds)	Orbit Time	Activity	Details
T0	0	4825	Pow er Sw itch Board configuration	All simulation sw itches set open
T1	60	4885	RPi and ISL activate	
T2	120	4945	LIDAR activate	
T3	180	5005	EMS electronics and H-Bridge driver activate; CubeComputer and CubeControl activate;	
T4	240	5065	EMS actuators @ 100% duty Magnetorquers @ 40% duty CubeWheel @ 100% duty	Segments detach and repel
T5	420	5245	EMS actuators @ 50% duty	EMS actuators hold
T6	630	5455	Thruster control on Pressure Transducer on	
T7	660	5485	Thruster heaters on	
T8	720	5545	EMS actuators @ 100% duty Plenum and Nozzle Valves @ 50%	Thruster fire to return MirrorSat to EMS range
T9	780	5605	Plenum and Nozzle Valves @ 0%	Segments return and attach
T10	900	5725	EMS actuators @ 0% duty Thruster control off Thruster heaters off Magnetorquers @ 0% duty CubeWheel @ 0% duty	
T11	960	5785	EMS electronics and H-Bridge driver off; LIDAR off; CubeComputer and CubeControl off	
T12	1020	5845	RPi and ISL off	
T13	1021	5846	Manoeuvre complete	All simulation sw itches set open

Power Budget Modelling

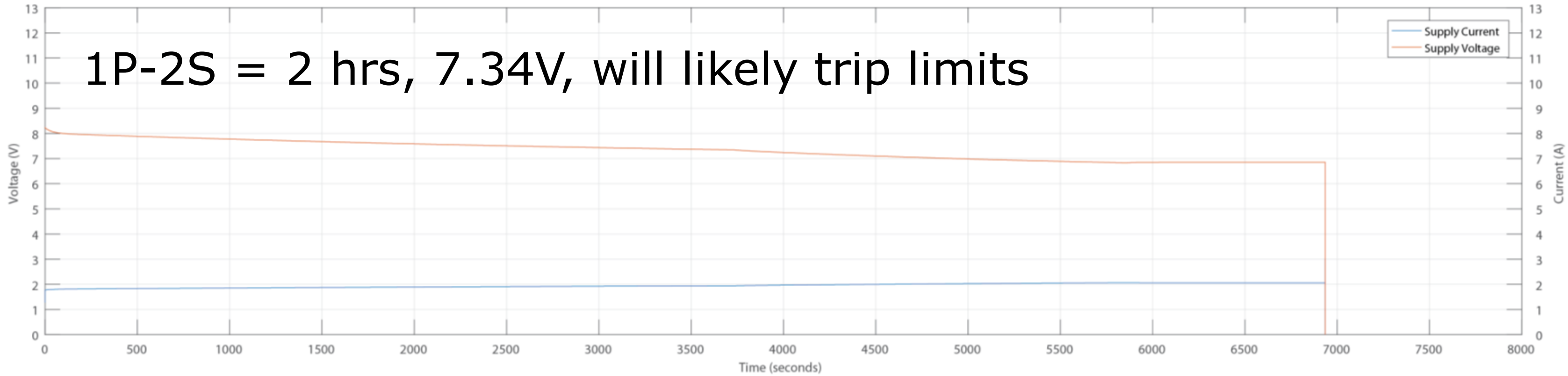


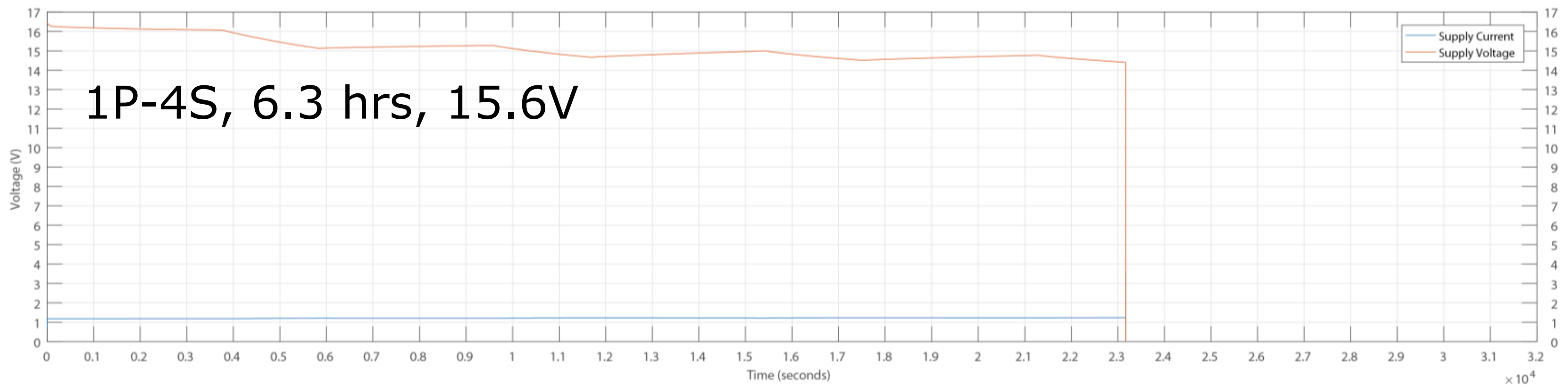
Note bus 'drooping' on 5V & 3V3

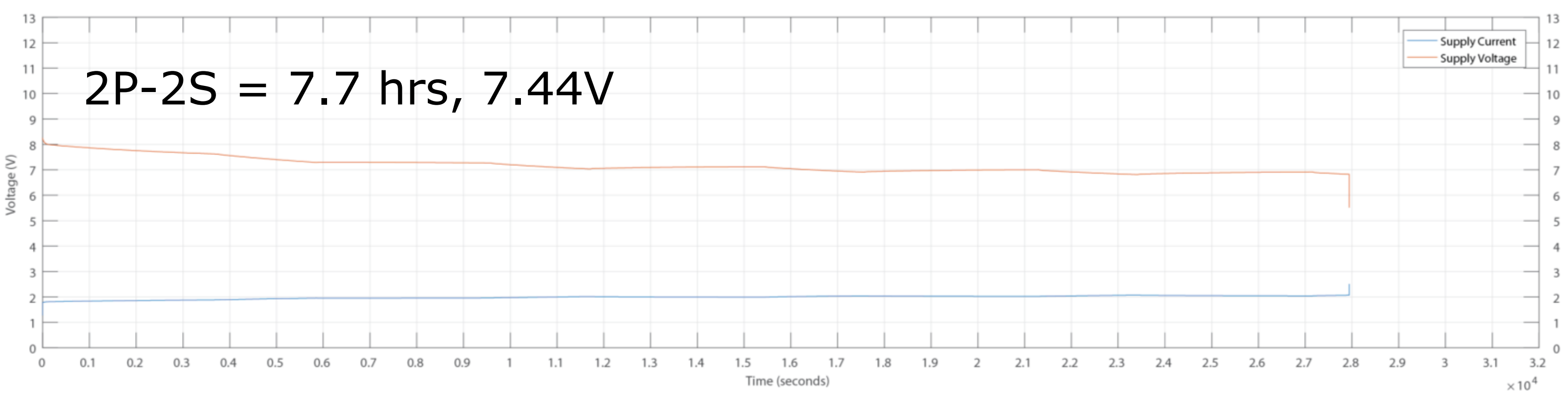
- T1: Power Switch board configuration
- T2: RPi and ISL power on
- T3: LIDAR power on
- T4: EMS and H-Bridge power on
- T5: CubeComputer and CubeControl power on; CubeWheel motor power on (100% duty); MTQ power on (40% duty)
  EMS repel at 100% duty
- T6: EMS hold at 50% duty
- T7: EMS return at 100% duty
- T8: EMS at 0% duty; CubeWheel power off; MTQ power off
- T9: H-bridge power off; LIDAR power off; CubeComputer and CubeControl power off
- T10: RPi and ISL power off

Max current is 3.5A on Vbat, 3.1A on 5V & 1.8A on 3V3

Power Budget Modelling



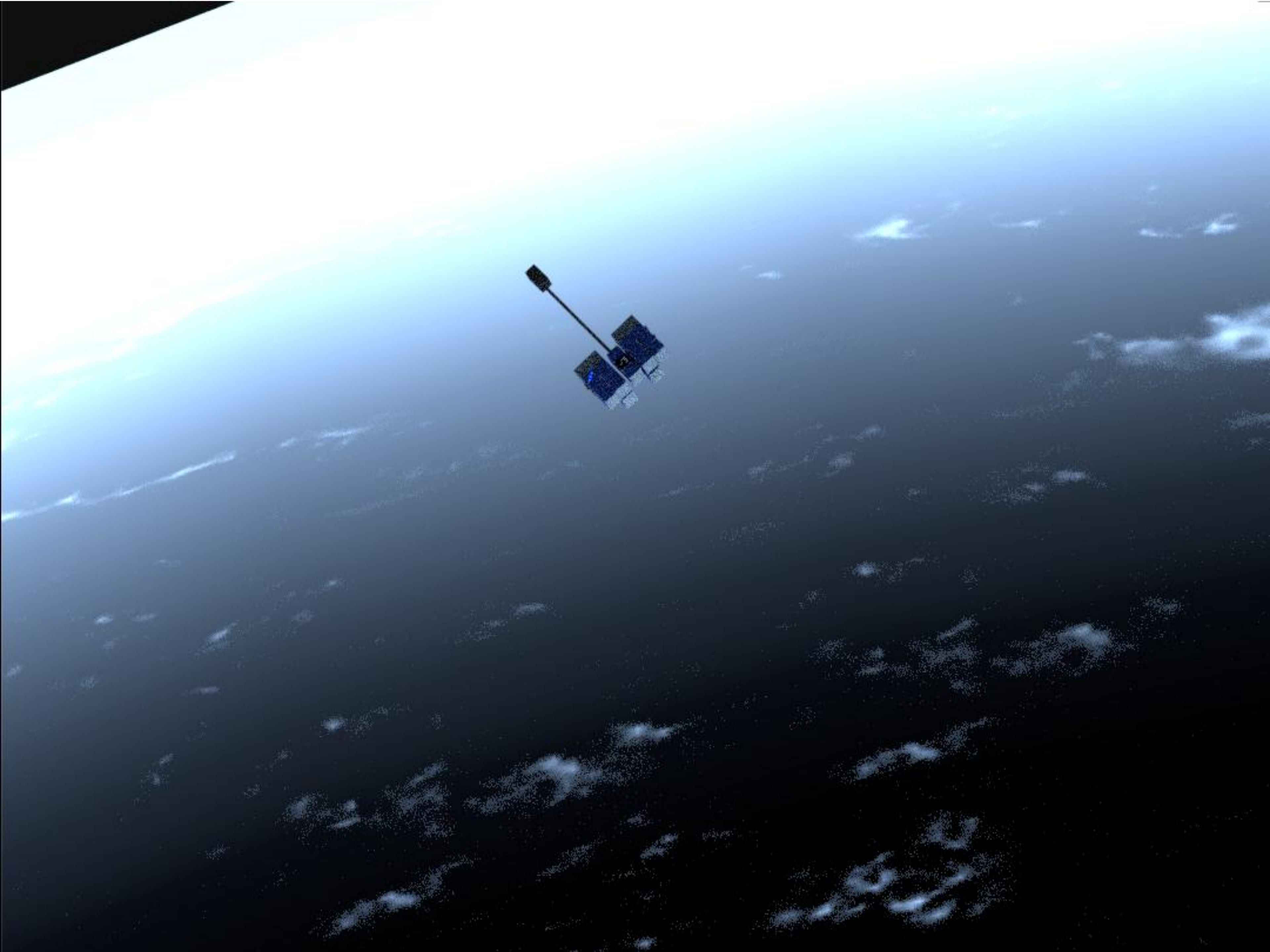


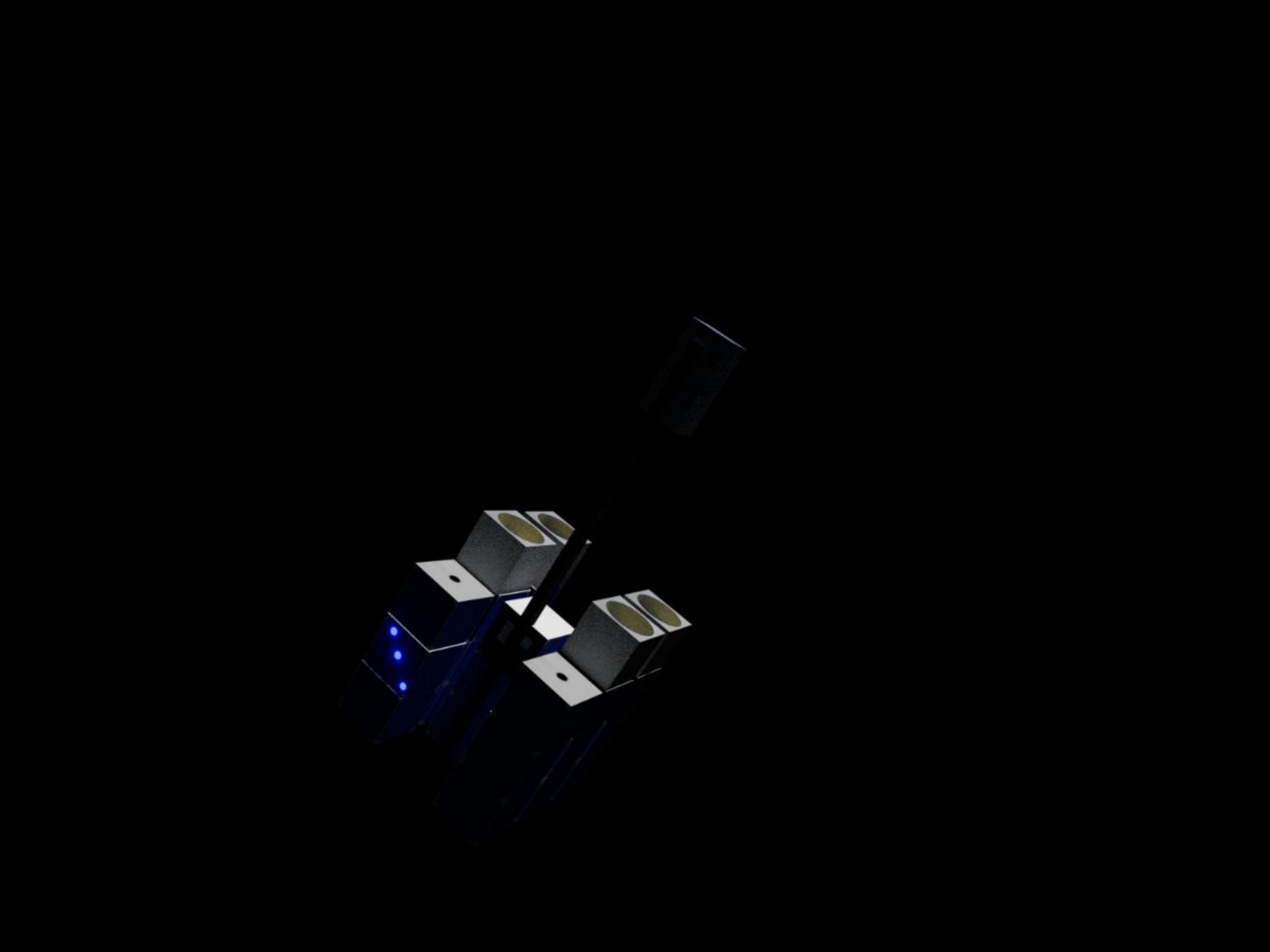


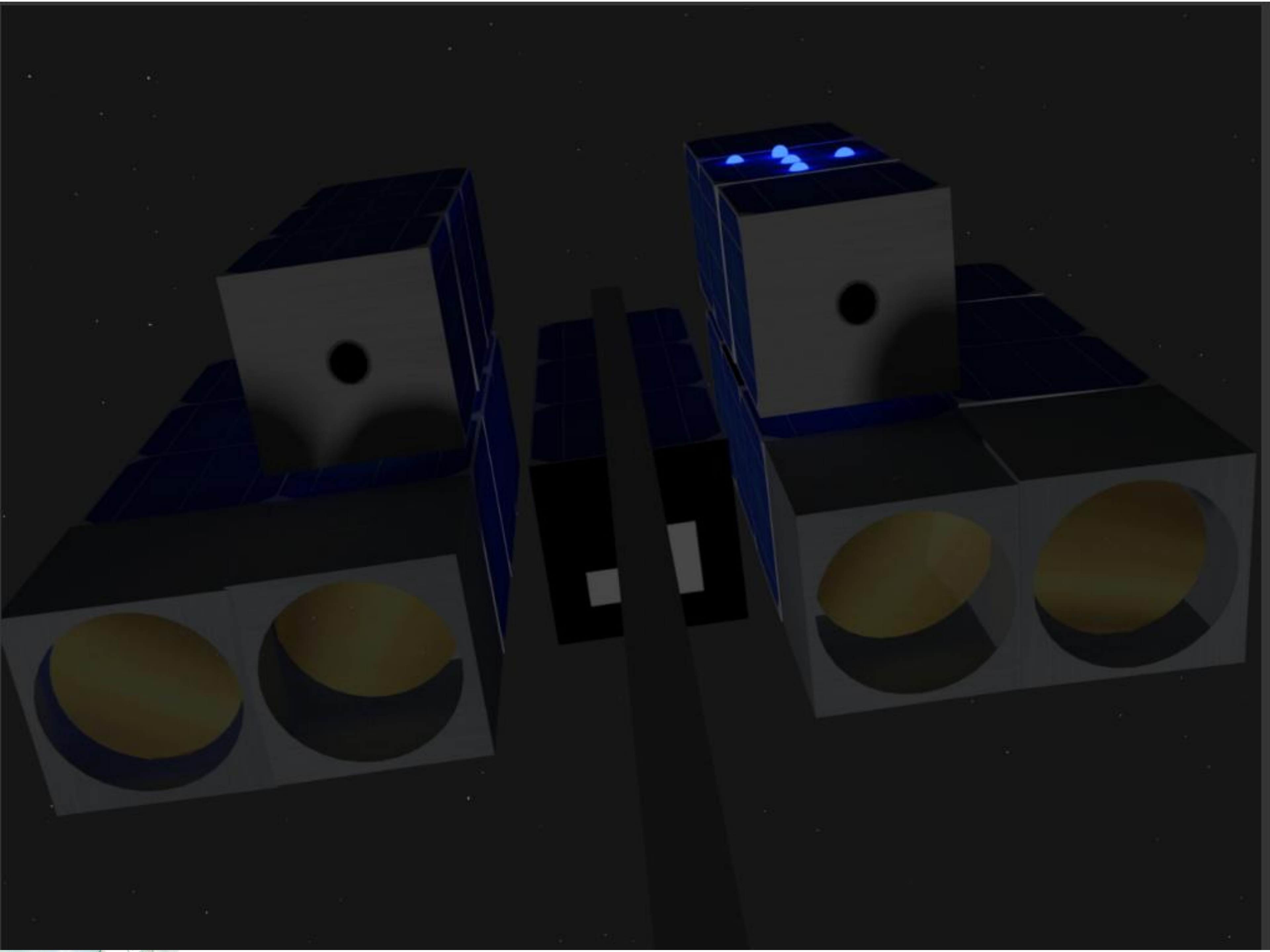
Surrey AAReST

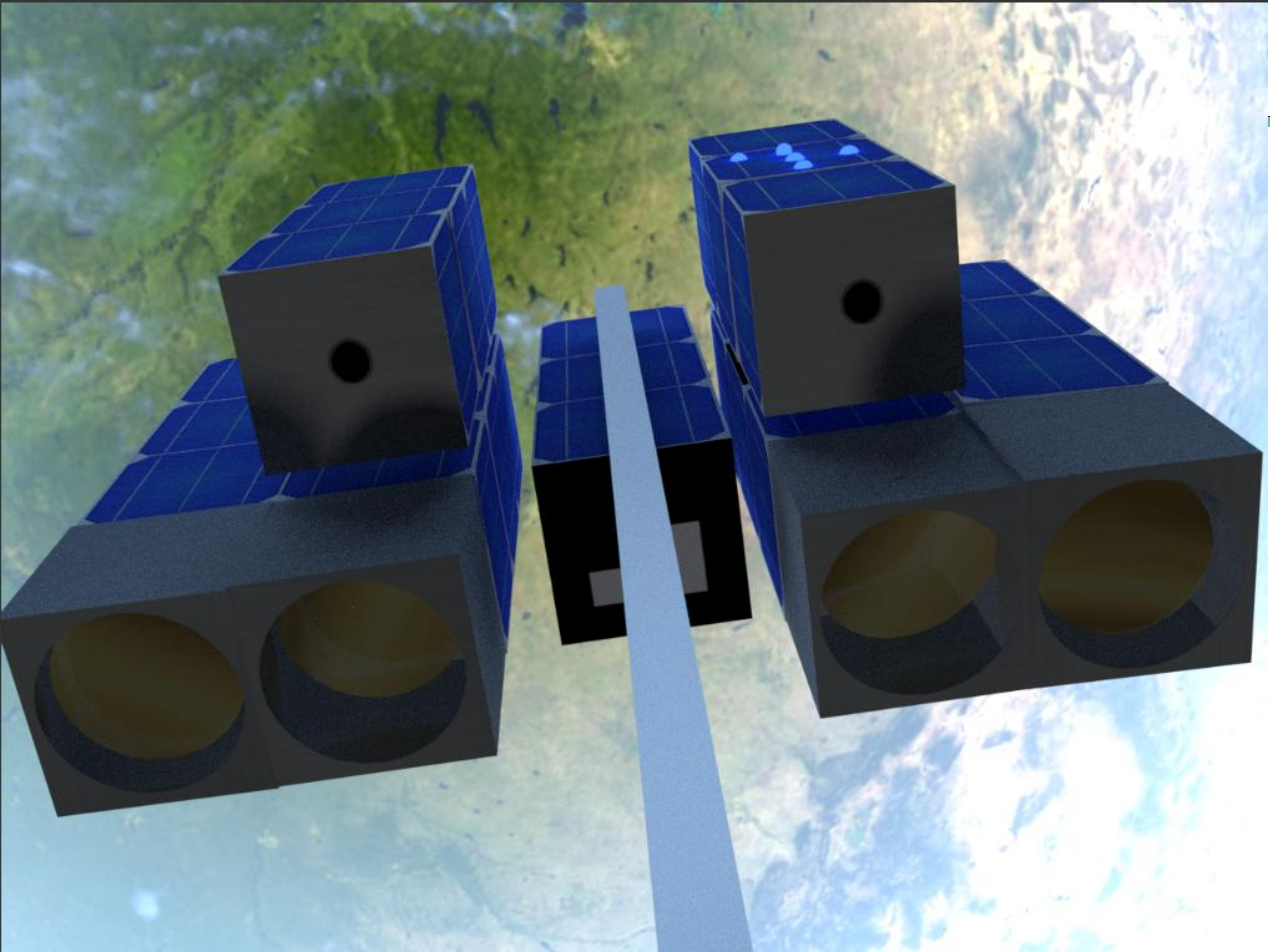
MirrorSat System

CONOPS Modeling

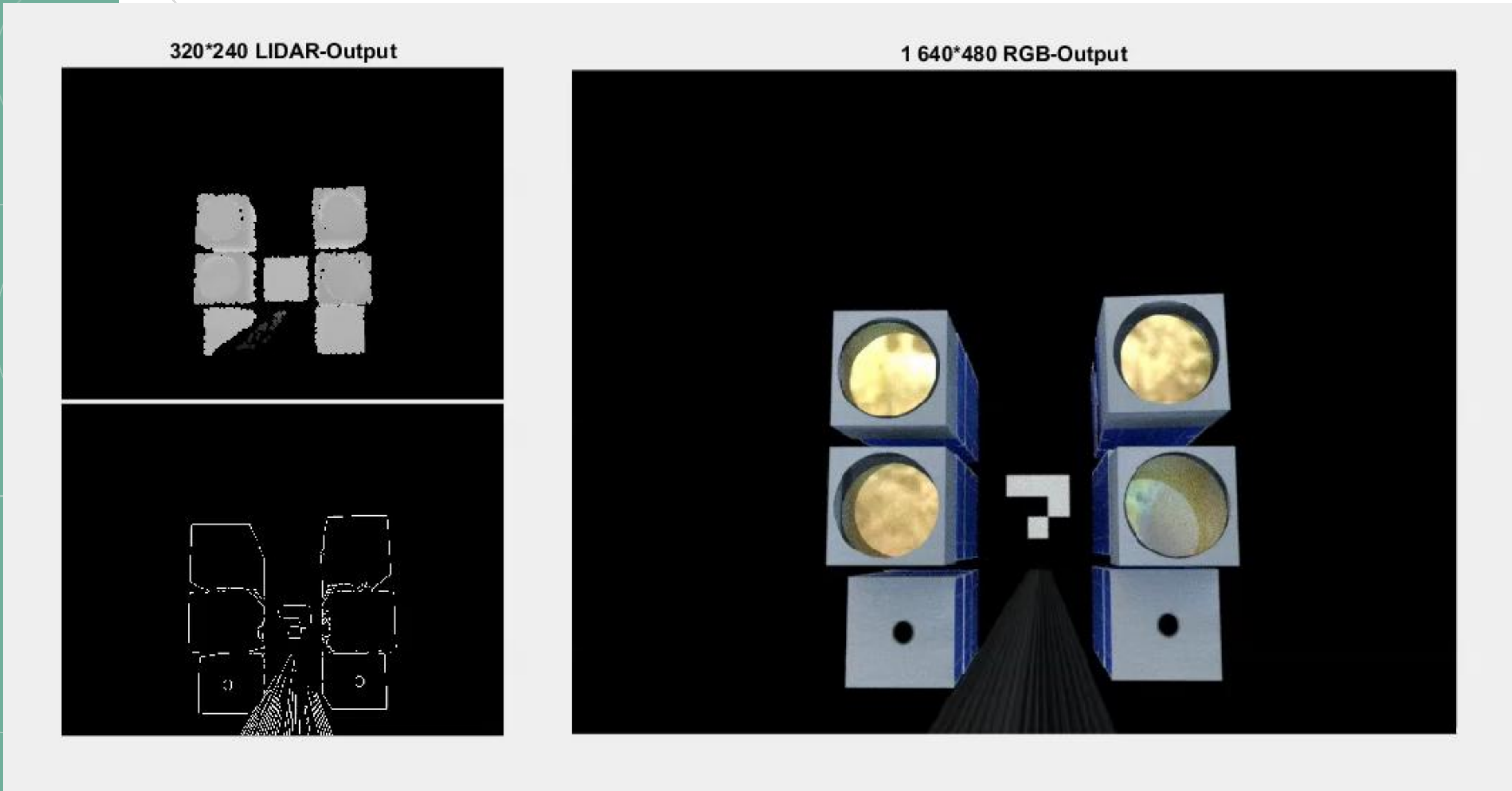




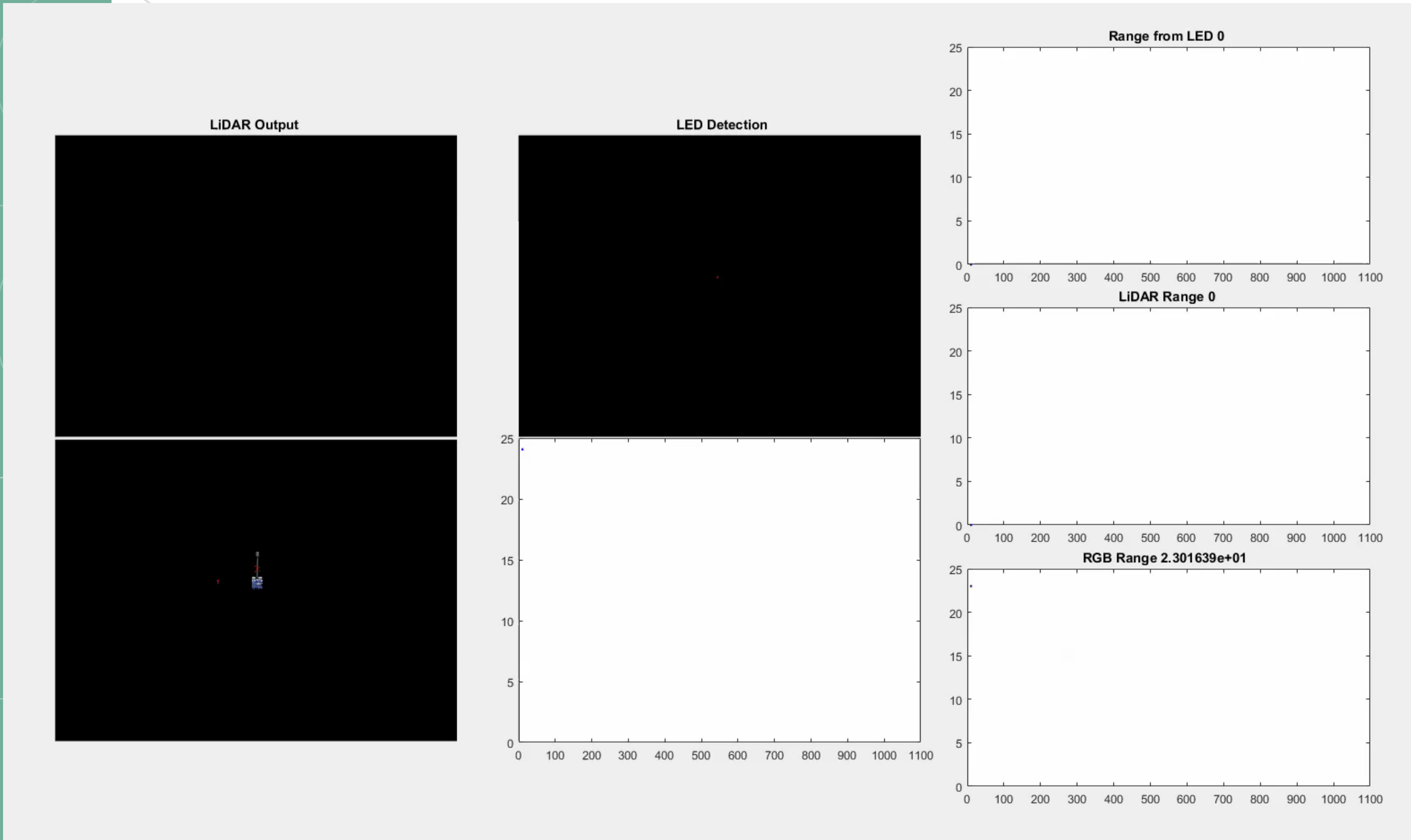




Imaging Modelling



Imaging Modelling



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Video Demo

Questions?

SURREY SPACE CENTRE

Acknowledgements

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Thank-You

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