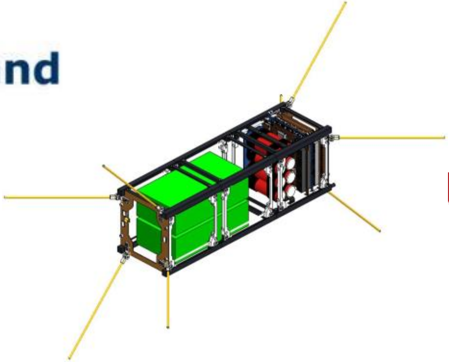


Nanosatellites for Quantum Space Science and Technology

Dr Daniel Oi

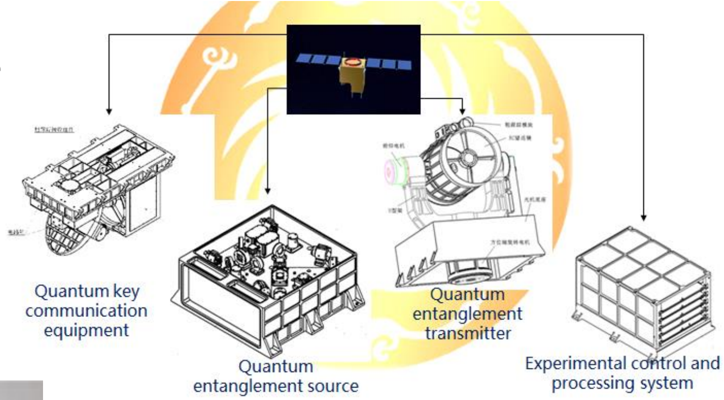
Computational Nonlinear & Quantum Optics

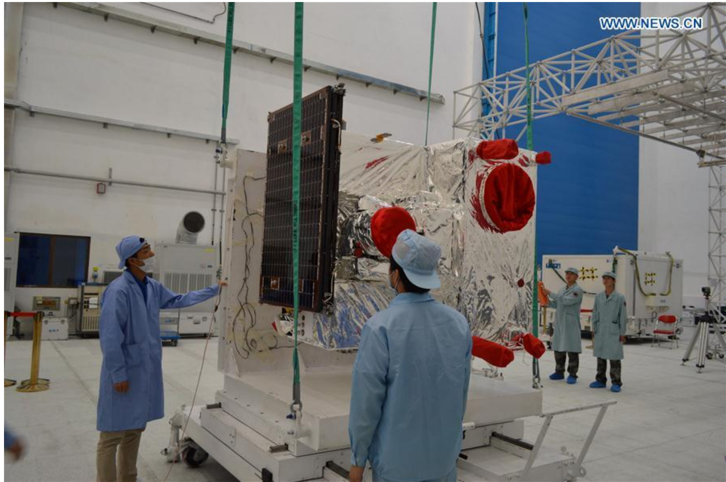
SUPA Department of Physics

COST Action CA15220 Malta 27-30 March 2017

Elephant In the Room

- Quantum Entanglement at Space Scale
- Launch August 2016
- Results?
- 640kg USD100M++?
- How to catch up?





Review Article

See also:
Achieving Science with CubeSats:
Thinking Inside the Box
National Academies of Sciences, Engineering, Medicine

University of Strathclyde Science

CONTEMPORARY PHYSICS, 2016
http://dx.doi.org/10.1080/00107514.2016.1235150

Nanosatellites for quantum science and technology

Daniel K. L. Oi[a], Alex Ling[b,c], James A. Grieve[b], Thomas Jennewein[d], Aline N. Dinkelaker[e] and Markus Krutzik[e]

[a]SUPA Department of Physics, University of Strathclyde, Glasgow, UK; [b]Centre for Quantum Technologies, National University of Singapore, Singapore; [c]Department of Physics, National University of Singapore, Singapore; [d]Department of Physics and Astronomy, Institute for Quantum Computing, University of Waterloo, Ontario, Canada; [e]Institute of Physics, Humboldt-Universität zu Berlin, Berlin, Germany

ABSTRACT

Bringing quantum science and technology to the space frontier offers exciting prospects for both fundamental physics and applications such as long-range secure communication and space-borne quantum probes for inertial sensing with enhanced accuracy and sensitivity. But despite important terrestrial pathfinding precursors on common microgravity platforms and promising proposals to exploit the significant advantages of space quantum missions, large-scale quantum test beds in space are yet to be realised due to the high costs and lead times of traditional 'Big Space' satellite development. But the 'small space' revolution, spearheaded by the rise of nanosatellites such as CubeSats, is an opportunity to greatly accelerate the progress of quantum space missions by providing easy and affordable access to space and encouraging agile development. We review space quantum science and technology, CubeSats and their rapidly developing capabilities and how they can be used to advance quantum satellite systems.

ARTICLE HISTORY
Received 3 May 2016
Accepted 7 September 2016

KEYWORDS
CubeSats; quantum; space; science; fundamental physics; technology; nanosatellites; communications

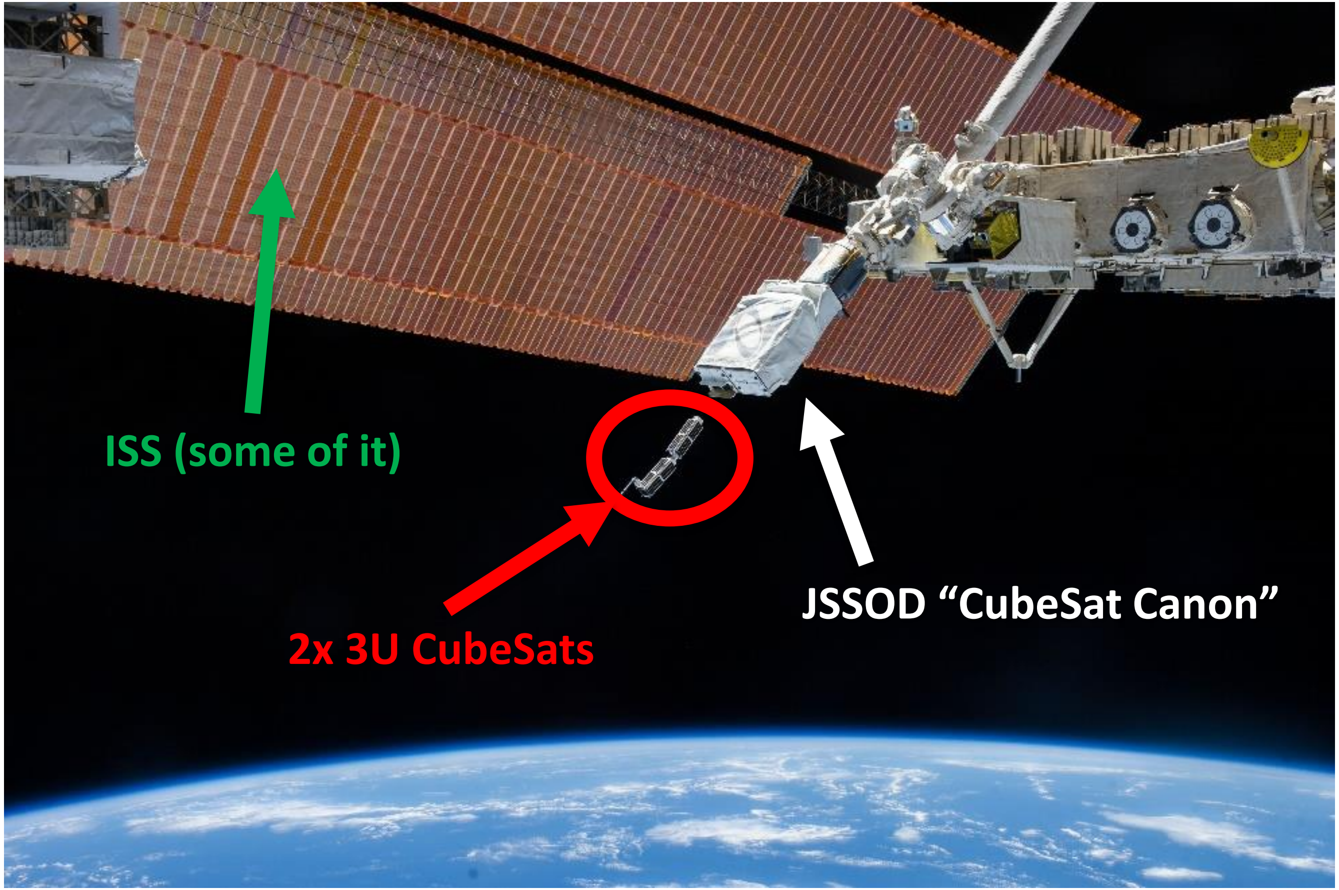
Topics Covered

University of Strathclyde Science

- What, Why, How, NanoSats?
- It's not just size that counts! Development Ethos
- Platform Characteristics
- Launch and Operations
- CubeSats in Action

As of 14/3/2017 (nanosats.eu)
Nanosats launched in total: **685**
CubeSats launched in total: 613
Nanosatellites in orbit: 405
Operational nanosatellites: 321
Nanosats destroyed on launch: 71

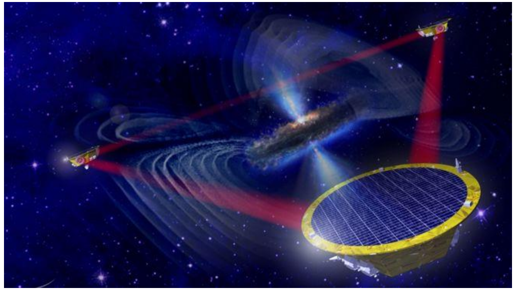
CubeSats vs ISS

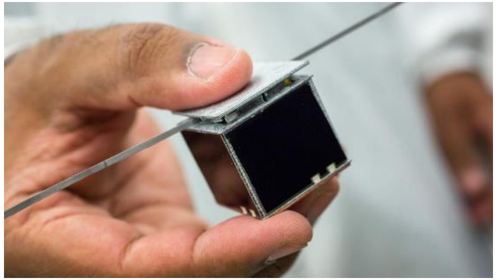


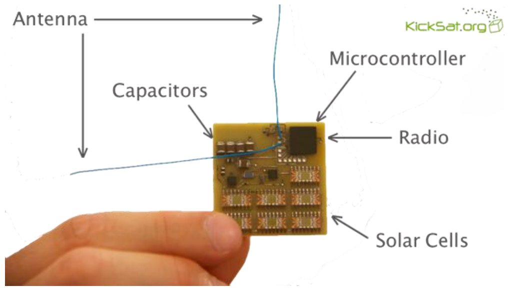
CubeSat Uses

- Education/Outreach
- Sputniks
- Earth Obs\ervation
- AIS Tracking
- Tech Demo
- Astronomy
- Atmospheric Science
- Radio Relay
- Testing
- Many more…

Satellite Zoology





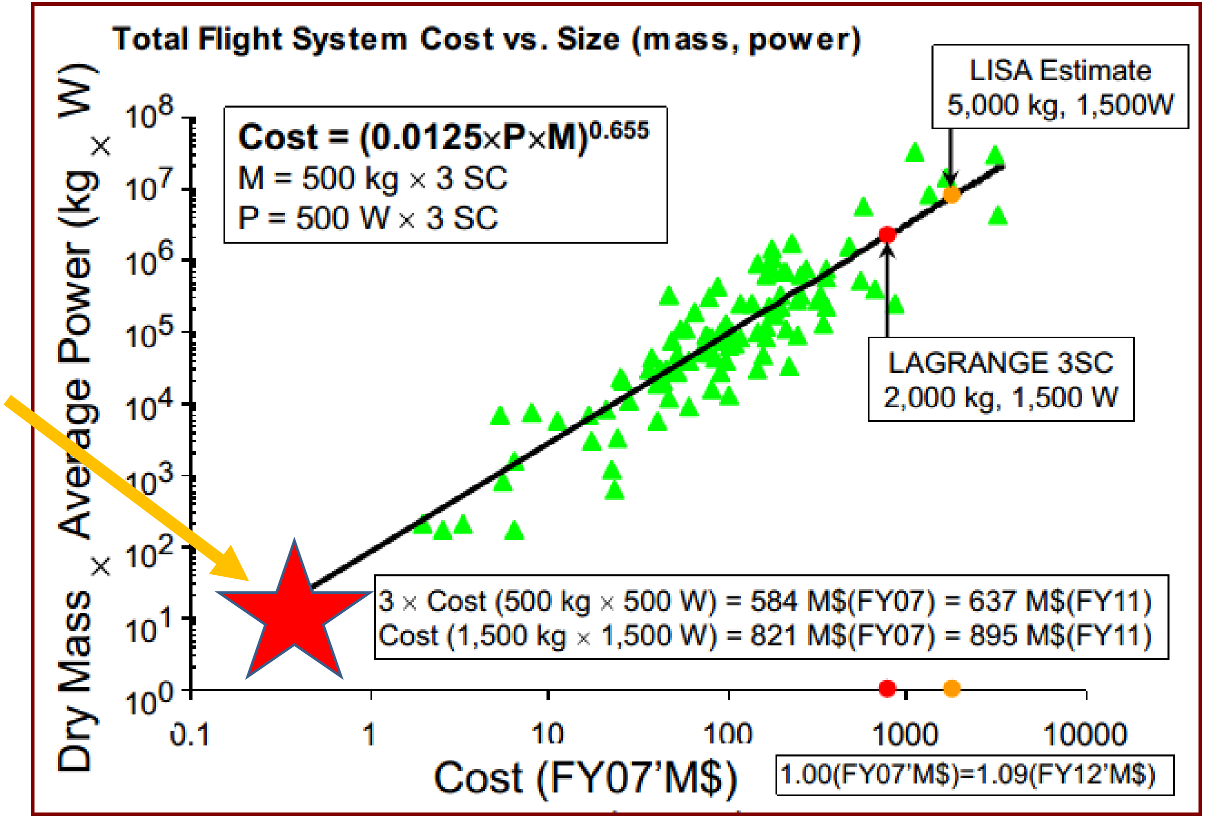


- LargeSat (LISA, Hubble) 10^3 - 10^4kg $\$10^9$
- MediumSat (GP-B) 5×10^2kg - 10^3kg $\$10^8$
- MiniSat (MICROSCOPE) 10^2 - 5×10^2kg $\$10^7$
- MicroSat 10^1 - 10^2kg $\$10^6$
- NanoSat (CubeSat) 10^0kg - 10^1kg $\$10^5$
- PicoSat 10^{-1}kg - 10^0kg $\$10^3$
- FemtoSat (ChipSat) < 10^{-1}kg $\$10^1$

LAGRANGE Cost Estimate

Complex Payloads cost more; DO NOT FIT model

Typical NanoSat

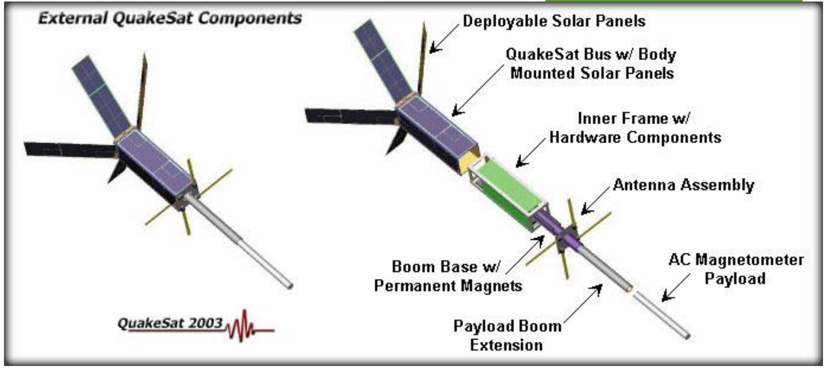


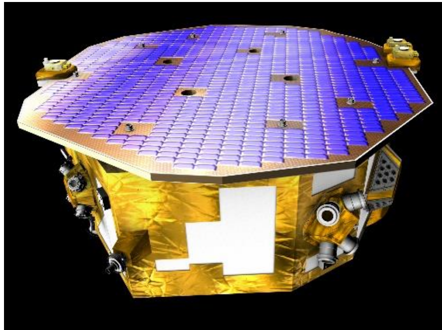
Big Space vs Small Space

- Big Space
  - High capability, Long Duration (typically), High Stakes
  - Dedicated vehicle, launch
  - Long development, costly, "over-engineered"
- Small Space
  - Leaner missions, *short duration* (typically), low stakes
  - Ride-share, availability of standard buses and components
  - Short(er) development, cheaper(?), "fly it and see" (not really, but the view of a traditional space engineer?)

CubeSats vs LargeSats

- Not just a smaller sat doing a (worse) job of a large one (cheaply)
- Opens up new missions
  - Component, device, subsystem testing (wasteful to launch a largesat to perform)
  - Test risky concepts, highly acceptable level of failure
  - Multiple satellites (simultaneously or in time)
  - Large-scale constellations, formations
- Support LargeSat Mission development in parallel
  - Pathfinding missions, proof of principle

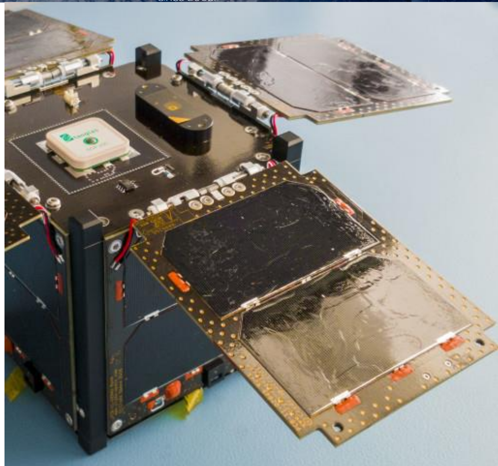




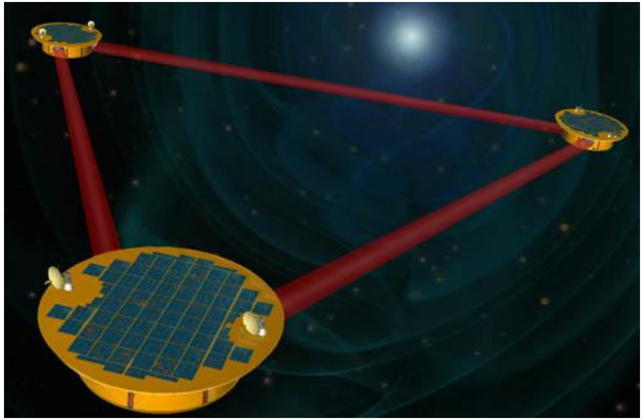
Why CubeSats?

- Zeitgeist
  - Smaller, *faster*, cheaper! COTS components
  - Thriving CubeSat Ecosystem
  - Commercial launch and ride-share expansion
  - Democratization of Space (do it yourself)
- Developmental Programme Advantages
  - Allows baby steps, flight heritage, experience
  - Short Failure-Learning Cycle, iteration
  - Reduced Risk Aversion
- NASA, ESA, Other Space Agencies Interest

University of Strathclyde Science



Why Not CubeSats



- Platform Constraints
  - Volume, Mass, and Power limits
  - (Current) lack of sub-systems, e.g. DFS
- Ultimate Performance
  - Benchmark tests require larger missions (But STEP vs MICROSCOPE?)
- Easier to develop without needing to miniaturize
  - Extra development effort to make compact outweighs savings on platform and launch

New Space Revolution

- Launch as a commodity
- Californian start-up mentality
  - Rapid Iteration
  - Agile development
  - Less ground engineering and testing, more in-orbit monitoring and evaluation of actual service performance (Beta test in space)
- Containerization!

Small satellite launch efforts

- Firefly
- Rocket Labs
- Avio Spa (Vega)
- Virgin Galactic
- Airbus-Safran
- Nammo Raufoss

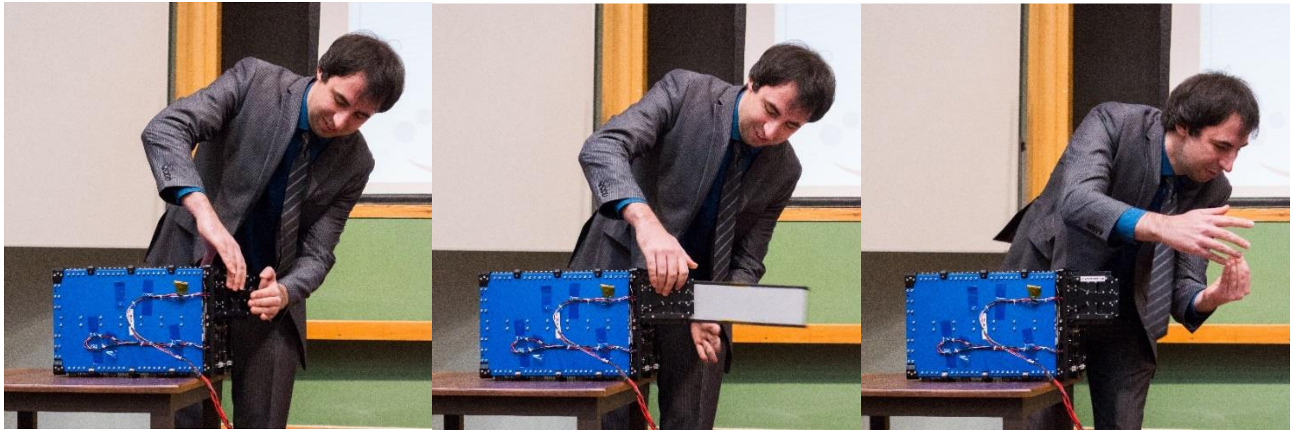
PSLV-C37 Satellite Deployment

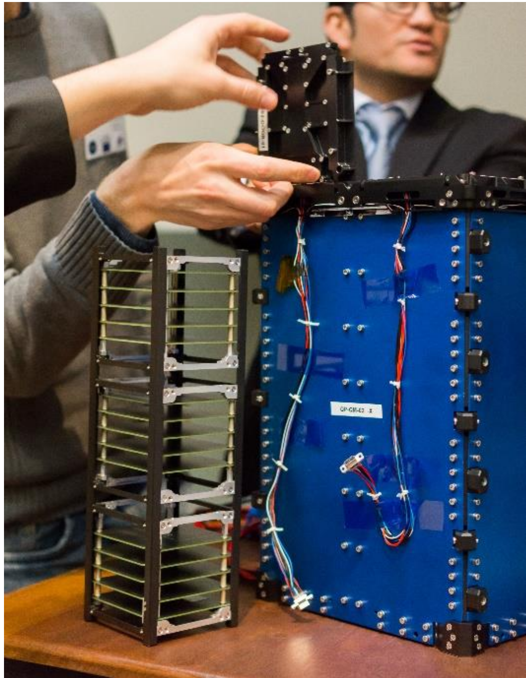
https://youtu.be/c0BpjPUT5FE

PSLV C-37 launches 104 satellites Feb 2017 including 88 from Planet

Containerization

- Key Enabling Technology
  - Weeks to load a ship, now hours (Shipping Container, 1956)
- Canister delivery and integration with Launch Vehicle
- Launch brokering (shipping agent), lowers cost
- Flexibility of launchers, dates

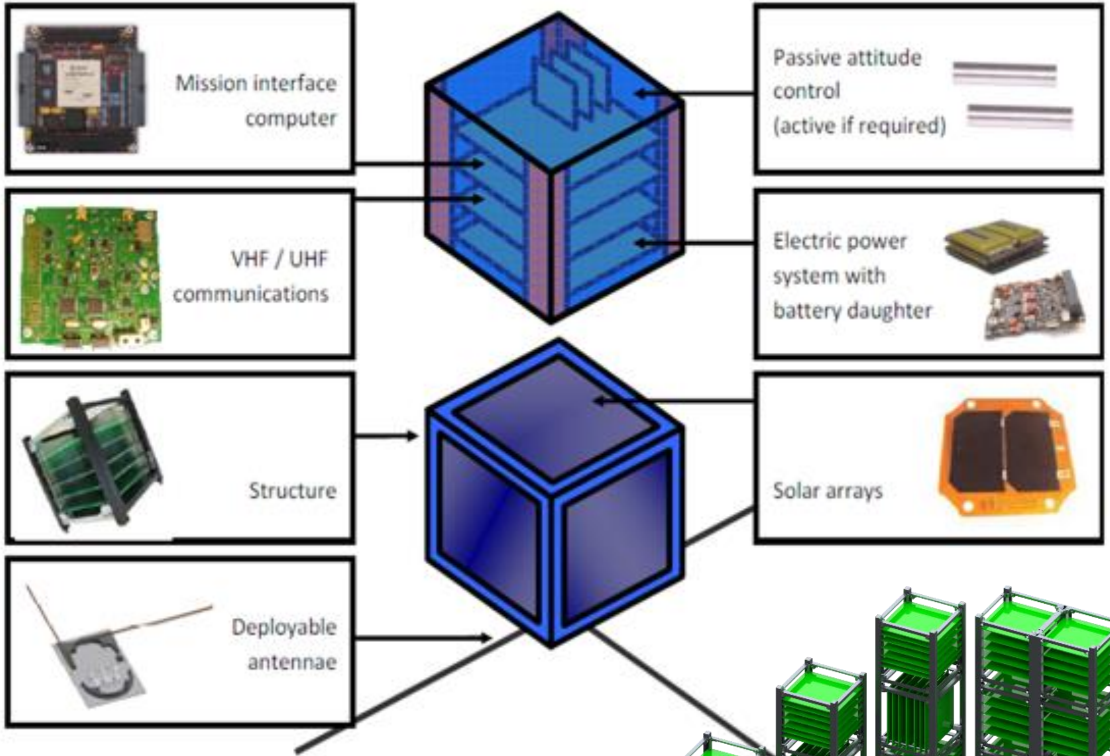


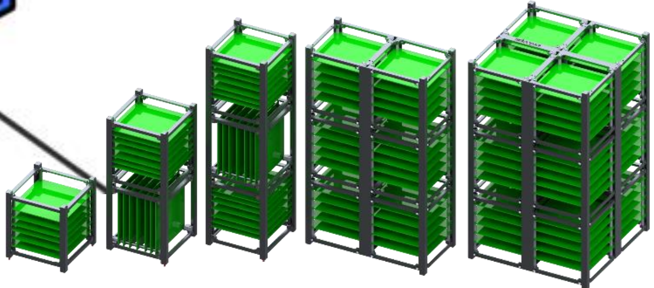


University of Strathclyde Science

CubeSat Anatomy

Basic building block 1U ($10x10x10\ cm^3$)





Often stacked to form 2U, 3U, 6U, 8U etc.

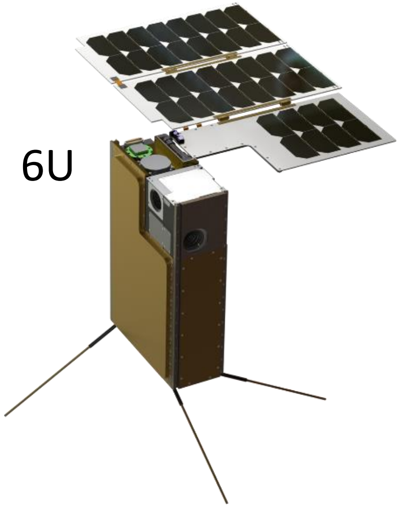
Steve Greenland testing 3U UKube-1 at Clyde Space

SoA COTS CubeSat

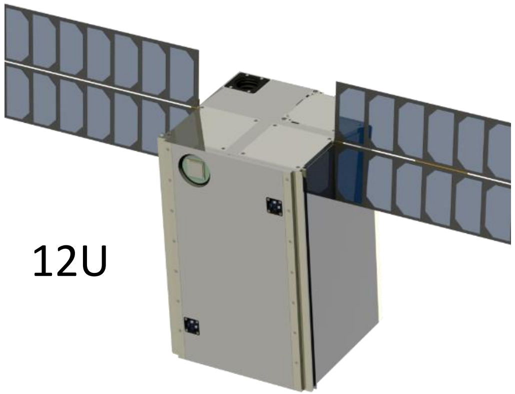
1U Systems,
rest Payload

Parameter	XB3	XB6	XB12
Class	3U	6U	12U
Available Payload Volume	2U	5U	11U
Pointing Accuracy	±0.002° (1-sigma), 3 axes, 2 Trackers		
Pointing Stability	1 arc-sec over 1 sec		
Maneuver rate	10 deg/sec (typical 3U)	5 deg/sec (typical)	5 deg/sec (typical)
Orbit knowledge	4m, 0.05m/s	4m, 0.05m/s	4m, 0.05m/s
Data Interfaces	Serial, LVDS, Spacewire, HDLC, I2C or SPI available		
Onboard Data Processing	Configurable via user loadable software		
Telemetry Acquisition	4 12bit Analog, 10 discrete inputs/outputs	4 12bit Analog, 10 discrete inputs/outputs (expandable)	4 12bit Analog, 10 discrete inputs/outputs (expandable)
Commands	Real-time, stored, macro		
Onboard Data Storage	32 Gbytes	32 Gbytes	32 Gbytes
System Bus Voltage	9 – 23 V (battery and array dependent)	9 – 23 V (battery and array dependent)	9 – 23 V (battery and array dependent)
Energy Storage	Standard: 25Whr, expandable	Standard: 50Whr, expandable	Standard: 75Whr, expandable
Solar Panels	Customer or BCT Provided Solar Panels (Details available per request)		
High Current Capability	Unregulated up to 60W	Unregulated up to 140W	Unregulated up to 140W
Payload Power Feeds	QTY 7 (12, 5, 3.3V or Bus voltage)	QTY 7 (12, 5, 3.3V or Bus voltage) (expandable)	QTY 7 (12, 5, 3.3V or Bus voltage) (expandable)
Frequency	UHF, Sband, Xband		
Uplink	CCSDS, SGLS, NSGLS		
Downlink	Up to 15 Mbps		
Encryption	AES 256		
Heater Controllers	Up to 7 independently controlled zones (using power feeds)		
Propulsion System Drive	Or up to 7 Thruster drivers or Latch Valves Drivers	Or up to 7 Thruster drivers or Latch Valves Drivers	Or up to 7 Thruster drivers or Latch Valves Drivers
Mass / Volume for Avionics	1.5 kg / 10 cm x 10 cm x 10 cm	1.5 kg / 10 cm x 10 cm x 10 cm	2.0 kg / 10 cm x 10 cm x 10 cm
XACT-Bus Nominal Power	< 6.3W		
Orbit Altitude / Orbit Lifetime	LEO / > 3 years		

3U



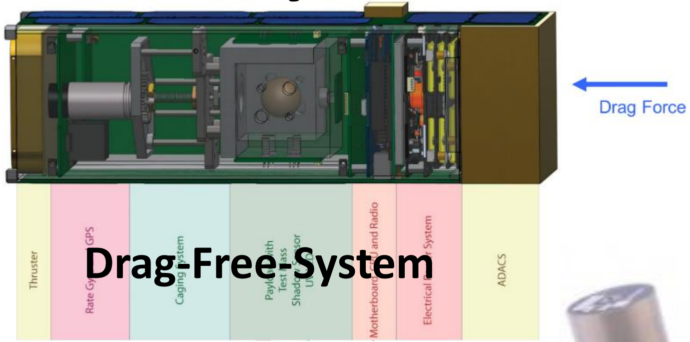
6U



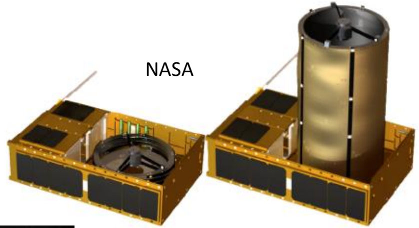
12U

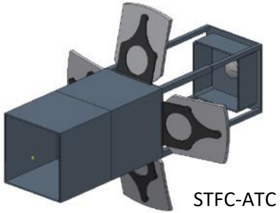
- OAP 10s of W
- ***Pointing better than 50µrad***
- 1.5kg per U
- X-Band 100Mb/s DL or more

Subsystems



Drag-Free-System





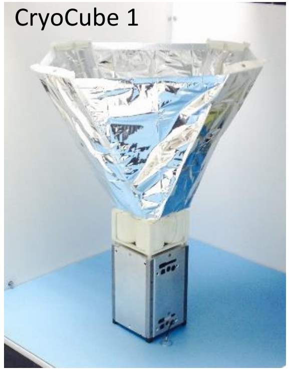
University of Strathclyde Science

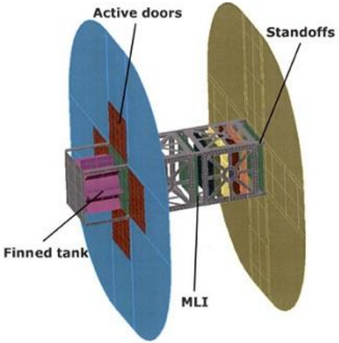
Deployables

Reciprocating or Pulse Tube

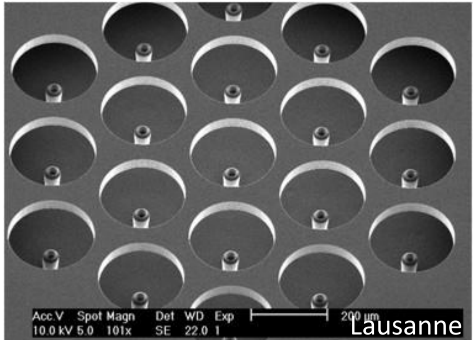
Coolers

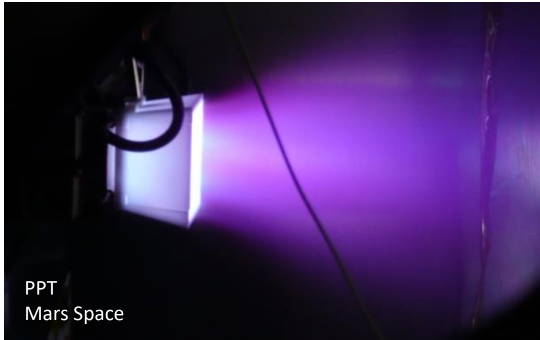
Power/Propulsion





Passive Cryo-cooling to 100K (LOX)





Launch and Operations

University of Strathclyde Science

- Free launch possible (e.g NASA ELaNa)
- Mostly rideshare as secondary/tertiary payloads
- Dedicated CubeSat launches as well (e.g PSLV-C37)
- Commercial launch brokers, e.g. Spaceflight, Nanonracks, GOMSpace, ISIS, JAMMS, CST etc.
- Months between launch contract and launch (in principle) due to containerization
- Can hire ground ops, ground stations, mission control (e.g. Spaceflight)
- Ground Segment important, do not neglect.

Ticket to Ride

	Containerized			Satellite Class							
Payload Type	3U	6U	12	50 kg	100 kg	150 kg	200 kg	300 kg	450 kg*	750 kg*	1000 kg*
Length (cm)	34.05	34.05	34.05	80	100	100	100	125	200	300	350
Height/Dia(cm)	10.00	10.00	22.63	40	50	60	80	100	150	200	200
Width(cm)	10.00	22.63	22.63	40	50	60	80	100			
Mass(kg)	5	10	20	50	100	150	200	300	450	750	1000
Price – LEO	$295	$545	$995	$1,750	$3,950	$4,950	$5,950	$7,950	$17,500	$22,000	$28,000
Price – GTO	$650	$995	$1,950	$3,250	$5,950	$6,950	$7,950	$9,950	CALL	CALL	CALL
Price – GSO/LLO	$995	$1,990	$3,250	$6,500	$9,950	$12,950	$15,950	$19,900	CALL	CALL	CALL

Prices are in thousands (USD).

Prices shown are standard list prices and do not account for launch specifics.

Standard payment structure

- 10% at Launch Reservation Down Payment
- 30% at Launch minus 24 months (or at Launch Service Agreement signing if less than 24 months)
- 20% at Launch minus 19 months
- 20% at Launch minus 13 months
- 15% at Launch minus 7 months
- 5% at Launch

While the majority of the price listed is the cost associated with booking a launch reservation, our pricing includes the following services:

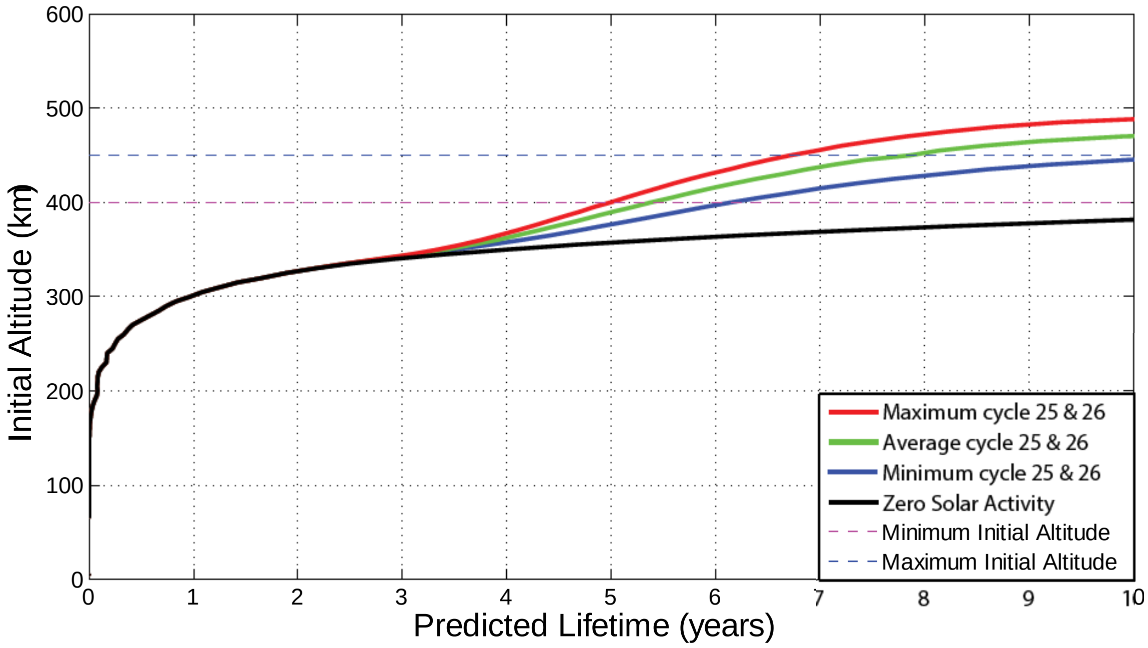
- Procurement of separation system
- Physical integration of the spacecraft to the launch vehicle
- Management of the launch campaign
- ITAR guidance
- Support for spacecraft registration, FCC & NOAA licensing

Nominal*	Orbit Nominal parameters*			MicroSats					
Date (CY)	Orbit	Type	CubeSats	50 kg	100 kg	150 kg	200 kg	300 kg	>300 kg
Q2 2017	600 km SSO	Foreign	Y	Y	Y	Y	N	N	N
Q3 2017	600 km SSO	Foreign	Y	Y	Y	Y	N	N	N
Mid 2017	500 km SSO	Foreign	Y	Y	Y	Y	N	N	N
Q3 2017	720 km SSO	Foreign	Y	Y	Y	Y	N	N	N
Q2 2017	400×600 km 24-27.5°	USA	Y	Y	N	N	N	N	N
H2 2017	575 km SSO	USA	Y	E-mail	E-mail	E-mail	E-mail	E-mail	E-mail
H2 2017	600 km SSO	Foreign	Y	Y	Y	Y	N	N	N
H2 2017	400-600 km 60°	USA	Y	Y	Y	Y	Y	N	N
H1 2017	600 km SSO	Foreign	Y	Y	Y	Y	N	Y	N
H2 2017	515 km SSO	USA	Y	Y	Y	Y	Y	Y	Y
H2 2018	GTO	USA	Y	Y	Y	Y	Y	Y	Y
H1 2018	500 km SSO	Foreign	Y	Y	Y	Y	N	N	N
H1 2018	450 km 20°	USA	Y	Y	Y	Y	Y	N	N
H2 2018	500 km SSO	USA	Y	Y	Y	N	N	N	N
H2 2018	500 km SSO	USA	Y	Y	Y	Y	N	N	N
H2 2018	GTO	USA	Y	Y	Y	Y	Y	Y	N
H2 2018	500 km SSO	USA	Y	Y	Y	Y	Y	Y	Y

Decommissioning

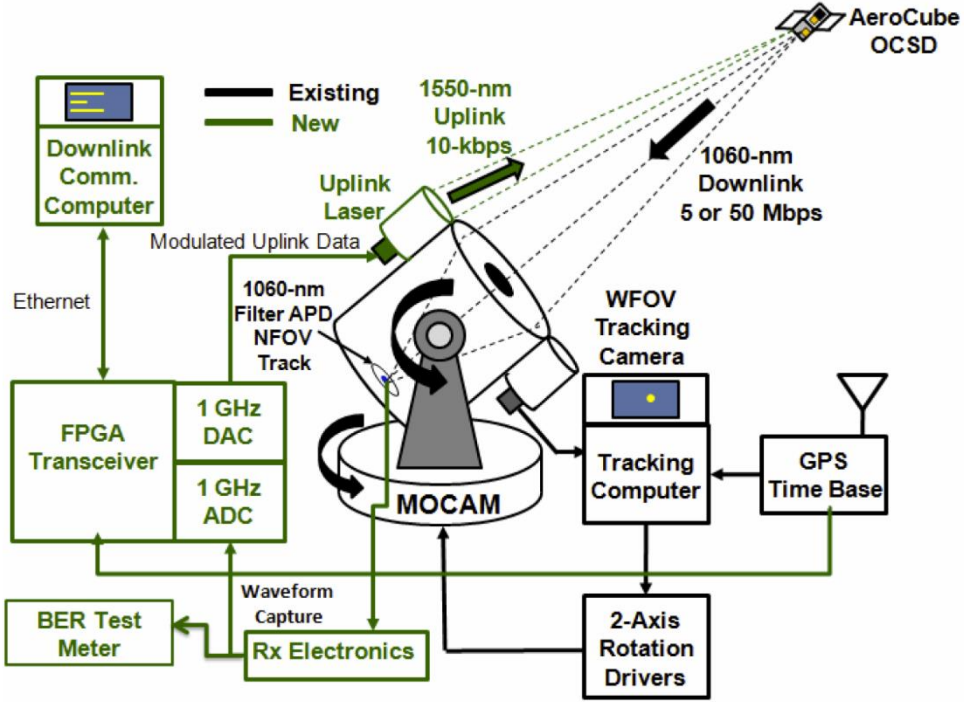
- Do not make "Debris-Sats"
- 25 year de-orbit requirement
- ISS deployment fulfils this
- Higher than 500-600km may require active de-orbiting

6U 10kg Minimum Drag Configuration



Selection of Advanced Missions

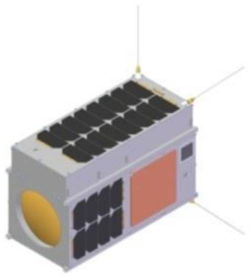
- Lunar CubeSats (Lunar FlashLight 6U, LunarH-Map)
- Mars (MarCO 6U Mars Telecomm Relay, with MRO InSight)
- Exo-planet search (BRITE)
- Optical Comms (AeroCube OCSD)
- Formation Flying (CanX-4&5)
- X-Ray Observation of Sun (MinXSS)
- Space Drugs (SpacePharma)

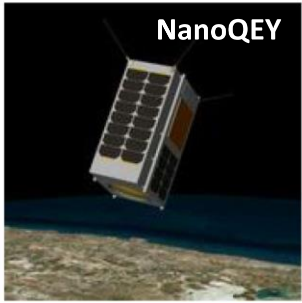


University of Strathclyde Science

Some QCubeSat Projects

- CQT NUS (Ling), SpoQySat + Joint Projects Australia, Germany, UK (QUARC Strathclyde+Bristol). See Rob's Talk
- Waterloo (Jennewein), NanoQEY
- CQuCoM (H2020 Proposal, EU Consortium+CQT)
- Humboldt U project. See Aline's Talk
- CAPSat (Kwiat), SPD performance and laser annealing
- European Project TBC
- CASPA (e2v, Birmingham)





CQuCoM Proposal (2015)

EU-Singapore Consortium

University of Strathclyde Science

RESEARCH Submitted to EPJ QT Thematic Series on Space Applications of Quantum Technology

CubeSat Quantum Communications Mission

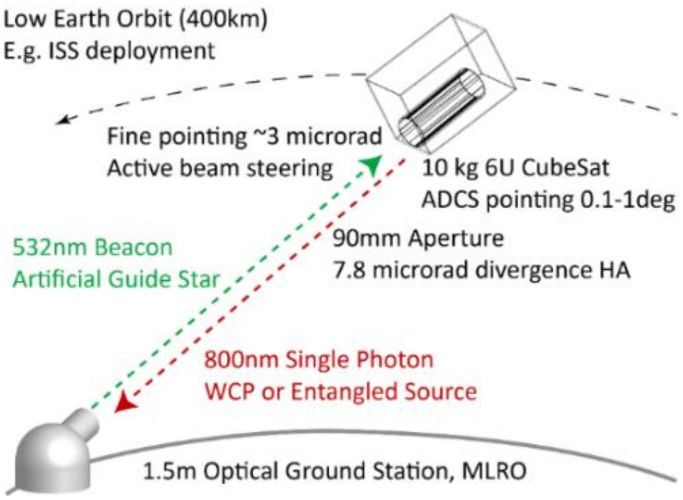
Daniel K L Oi[1,2*], Alex Ling[3,4], Giuseppe Vallone[5], Paolo Villoresi[5], Steve Greenland[6], Emma Kerr[6], Malcolm Macdonald[7], Harald Weinfurter[8], Hans Kuiper[9], Edoardo Charbon[10,11] and Rupert Ursin[12]

*Correspondence: daniel.oi@strath.ac.uk
[1]SUPA Department of Physics, University of Strathclyde, John Anderson Building, 107 Rottenrow East, G4 0NG Glasgow, UK
Full list of author information is available at the end of the article

Abstract

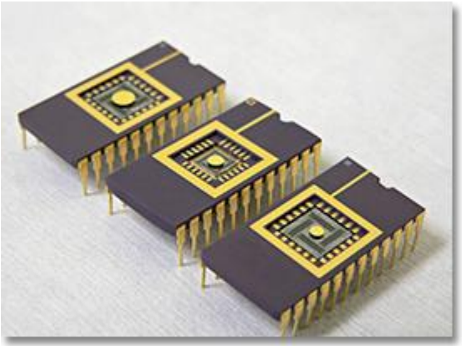
Quantum communication is a prime space technology application and offers near-term possibilities for long-distance quantum key distribution (QKD) and experimental tests of quantum entanglement. However, there exists considerable developmental risks and subsequent costs and time required to raise the technological readiness level of terrestrial quantum technologies and to adapt them for space operations. The small-space revolution is a promising route by which synergistic advances in miniaturization of both satellite systems and quantum technologies can be combined to leap-frog conventional space systems development. Here, we outline a recent proposal to perform orbit-to-ground transmission of entanglement and QKD using a CubeSat platform deployed from the International Space Station (ISS). This ambitious mission exploits advances in nanosatellite attitude determination and control systems (ADCS), miniaturised target acquisition and tracking sensors, compact and robust sources of single and entangled photons, and high-speed classical communications systems, all to be incorporated within a $10kg$ $6litre$ mass-volume envelope. The CubeSat Quantum Communications Mission (CQuCoM) would be a pathfinder for advanced nanosatellite payloads and operations, and would establish the basis for a constellation of low-Earth orbit trusted-nodes for QKD service provision.

Keywords: CubeSat; quantum; entanglement; cryptography



EUR7M (could do it for much less now)

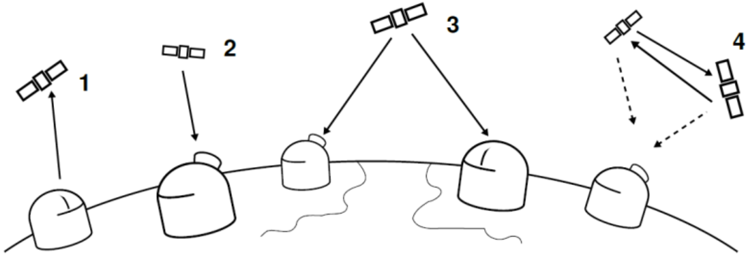
QUARC



Combine millirad coarse platform pointing with microrad fine pointing with active beam steering

- Quantum Research CubeSat
- Strathclyde University Lead
  - Bristol University (experiment)
  - Scottish Centre of Excellence in Satellite Applications (mission analysis)
  - Support from STFC Astronomy Technology Centre (adaptive optics) and Craft Prospect (platform engineering)
- Goal: Establish Free-Space Quantum Optical Link in CubeSat form-factor
- Challenge: Acquisition, Tracking, Pointing (ATP) on smallsat + turbulence
- Solution(?): MEMS Micromirror, multi-stage pointing, blended-rate sensors
- TRL3-4

Summary



- Disruptive development in space business, Space 4.0
  - "Mismatch between QTech development and current space programmes"
  - CubeSats can supplement conventional satellite development
  - Integrate within or conduct alongside large-scale project
- CubeSats advancing quickly, computing, comms, ADCS, power
- Development of subsystems, propulsion, DFS, cooling
- Deployables for optics and structures actively developed
- Gain success with a few smaller steps, not just a giant leap!