Institution: University of Strathclyde		
Unit of Assessment: B12 - Engineering		
Title of case study: Growth of the Scottish small-satellite sector with global impact		
Period when the underpinning research was undertaken: 2004-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Malcolm Macdonald	Professor	01/07/2008 – present
Prof Colin McInnes	Professor	01/09/2004 – 30/09/2014
Dr Christopher Lowe	Research Fellow	01/07/2015 – present
Dr Ruaridh Clark	Research Associate	01/04/2017 – present
Dr Ciara McGrath	Research Associate	02/04/2018 – present
Period when the claimed impact occurred: 2014 – December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Research undertaken at University of Strathclyde since 2004 was applied in the development of the UK's first commercial CubeSat by Clyde Space Ltd., Glasgow, launched into space in July 2014. Over the next 5 years Clyde Space became a market leader, supporting around 30-40% of all CubeSat missions, and with a EUR7,600,000 annual turnover by the end of FY2019. The success of Clyde Space, together with availability of expertise from Strathclyde researchers, attracted other high value satellite and data analytics companies to the central belt of Scotland. Strathclyde research has led to capacity building and development of satellite technology in Mexico, South Africa, Namibia and Kenya, has influenced international strategy and planning, and has informed NASA's approach to small spacecraft.

2. Underpinning research

In 2013 the UK Government identified 'eight great technologies' which would propel the UK to future growth; one of these was 'satellites and commercial applications of space'. Since then, 'new space' has emerged as the term used to describe the private-sector driven, space start-up ecosystem that is leading the democratisation of space, with small, low-cost, high-performance satellites and their associated data products providing valuable information on the Earth's weather, oceans and ecosystems. When deployed as a fleet, small satellites can be used to provide near-real time global coverage and measurements. The reduction in cost and size of satellites, with advances in remote sensing technology, has been identified as a disruptive innovation by the National Academies of Sciences, Engineering, and Medicine. A CubeSat is one type of miniaturised satellite commonly used. The miniaturisation of components is continually improving and CubeSats are capable of increasingly advanced tasks, often replacing or complementing much larger satellites in scientific and commercial missions.

Since 2004, the Faculty of Engineering at the University of Strathclyde has established one of Europe's largest multi-disciplinary space engineering research clusters, focussed on the development and application of space systems. This cumulative expertise has given a 'technology push' to the space industry and supports the growth of commercial small and nano-satellite companies, by providing algorithms and identifying enabling characteristics of technology to be exploited. An important area of research ongoing since 2009 has been into the nanosatellite technology development process, with some key outputs (below) selected from a wide body of research which provides insights into:

- How to develop disruptive innovations, for example increase the technology readiness level of solar sailing, (where spacecraft are propelled by the radiation pressure of sunlight) and develop technology roadmaps that exploit the unique characteristics of these innovations [**R1**];
- Model-based and hardware-in-the-loop simulation [**R2**], to aid accelerated concept and hardware development, validation, and verification in the design and implementation of small satellite technology;

- Theoretical research on networked systems [**R3**, **R4**] with results which offer parallels with biological flocks and swarms, and with implications for the design of technological networks, for example, how fleets of spacecraft can be developed, deployed, and exploited [**R5**, **R6**];
- Algorithms that enable resource allocation within network systems [**R3**] and the structure of networks and algorithms for the identification of communities within them [**R4**]. In-turn, these algorithms and insights have enabled development of methodologies for agile and timely control and operation of fleets of small satellites [**R5**];
- Algorithms for near-optimal data routing through delay and distribution tolerant communication networks, characteristic of a spacecraft fleet, without the need for all spacecraft to communicate instantaneously, or for global system knowledge [**R6**].

Research findings were implemented through sustained collaboration with Clyde Space Ltd., supported by a Knowledge Transfer Partnership (KTP) and a series of industrial fellowships. From 2008 – 2011, McInnes had a KTP with Clyde Space Ltd., joined by Macdonald in 2010. On completion of the KTP in 2011, the KTP associate (S. Greenland) was employed by Clyde Space. From 2013 – 2015, Greenland held an industrial fellowship from the Royal Commission for the Exhibition of 1851 to continue work with Macdonald. In 2011 Clyde Space also sponsored an EPSRC iCASE PhD student (C. Lowe), under the supervision of Macdonald. Cumulatively, these projects supported and underpinned the development of Scotland's first spacecraft, and the UK's first commercial CubeSat, UKube-1.

3. References to the research (Strathclyde affiliated authors in **bold**)

R1 **Macdonald, M.**, **McInnes, C.** (2011) Solar sail science mission applications and advancement. *Advances in Space Research, 48*, 1702–1716. https://doi.org/10.1016/j.asr.2011.03.018 [REF2 in 2014]

R2 **Lowe, C.**, **Macdonald, M.** (2014) Rapid Model-based Inter-disciplinary Design of a CubeSat Mission. *Acta Astronaut, 105*, 321–332. https://doi.org/10.1016/j.actaastro.2014.10.002

R3 **Punzo, G.**, Young, G.F., **Macdonald, M.**, Leonard, N.E. (2016) Using Network Dynamical Influence to Drive Consensus. *Scientific Reports, 6*. https://doi.org/10.1038/srep26318

R4 **Clark, R.**, Punzo, G., **Macdonald, M.** (2019) Network Communities of Dynamical Influence. *Scientific Reports, 9*. https://doi.org/10.1038/s41598-019-53942-4

R5 **McGrath, C.**, **Macdonald, M.** (2019) General Perturbation Method for Satellite Constellation Reconfiguration using Low-Thrust Maneuvers. *Journal of Guidance, Control, and Dynamics, 42*, 1676–1692. https://doi.org/10.2514/1.G003739

R6 **Lowe, C.**, **Macdonald, M.** (2016) Resource considerate data routing through satellite networks. *Journal of Aerospace Information Systems, 14*, 472–482. https://doi.org/10.2514/1.I010423 [REF2]

Notes on the quality of research: All referenced outputs were peer-reviewed ahead of publication. The underpinning research was funded by over GBP6,000,000 of peer reviewed research income, and around GBP1,750,000 of KE income, including two prestigious GCRF/UK Space Agency projects to work with international partners in Mexico, South Africa, Kenya, and Namibia (Macdonald, M., Lowe, C., & Owens, S. R. FireSat. UK Space Agency, 01/06/2017 – 31/05/2020, GBP1,056,000; Macdonald, M., Anderson, P., & Khan, H. NANOBED-MX: UK-Mexico Nanosatellite Missions Laboratory. UK Space Agency, 01/08/2015 – 31/12/2016, GBP571,050.)

4. Details of the impact

Research findings were implemented through a KTP, a series of industrial fellowships, projects funded by RUK Global Challenges and the UK Space Agency, industry collaboration and knowledge exchange via the Scottish Centre of Excellence in Satellite Applications (SoXSA). Strathclyde research directly led to and supported the following benefits:

- Sustained **commercial success and economic benefit for Clyde Space Ltd**. This company, together with Spire Global, became a driver for the **expansion of satellite manufacture in Scotland**, with Glasgow becoming a global centre of space and satellite innovation.
- Satellite data provided by Glasgow-built spacecraft, and the data companies they enable, now serve a global customer base in the private sector and government, providing **efficient mapping and monitoring of the Earth's resources, ecosystems, and events**.

- The research has also been applied to support **international expansion of 'New Space'** technology in Low to Middle Income countries, and research-based expertise has informed policy and planning by organisations such as NASA.

Expansion of Clyde Space following success of UKube-1

With research translation through a KTP and industrial PhD projects supervised by Macdonald in collaboration with Clyde Space, UKube-1 was designed and built as an advanced micro-spacecraft suitable for a range of applications, including Earth observation. Launched from Kazakhstan in July 2014, the mission aimed to attract and train future generations of engineers, encourage collaboration across sectors and institutions, and accelerate the development of space technology. Following the successful completion of the 14-month UKube-1 mission, the UK Space Agency stated that UKube-1 is *'one of the most advanced CubeSats ever built… UKube-1 has also helped maintain the UK's leading position in the CubeSat sector. Participation in the mission places Clyde Space in an excellent position to capitalise on the fast-growing global nanosatellite market. The company has experienced 100% year on year growth, both in turnover and employees, as a direct result from involvement in UKube-1 and is firmly established as a global leader*' [**S1**].

The CTO of Clyde Space confirms that '*the KTP with Strathclyde was a fundamental building block that led to the development of UKube-1*' [**S2**]. UKube-1 established Clyde Space as a spacecraft manufacturer, and secured follow-on spacecraft orders for the company, with significant growth since 2014, as the company transitioned from a sub-system supplier to a spacecraft system integrator and service provider. By 2017, Clyde Space was a market leader with more in-orbit heritage than any other supplier and supporting around 30-40% of all CubeSat missions [**S2**]. In January 2018, the Swedish company ÅAC Microtec AB completed a share sale and purchase agreement to acquire 100% of the shares in Clyde Space [**S2**]. The acquisition was paid for with 30,500,000 newly issued shares in AAC, and GBP2,000,000 in cash to create the company now known as AAC Clyde Space. The merger of the two companies established a strong commercial presence in Europe, the US and Asia, and by the end of 2020, AAC Clyde Space employed over seventy staff in Glasgow [**S2**]. From January-September 2020 alone, AAC Clyde Space net sales amounted to GBP6,130,000 and the company is now an established leader in the global space sector. A Framework Agreement has also been in place since late 2019 with the University of Strathclyde to support and develop further collaboration. This resulted in the EUR19,700,000 (11-2020) xSPANCION project with the European Space Agency to manufacture ten spacecraft for a North American customer from December 2020, with University of Strathclyde as a project partner to apply research on novel inter-satellite data routing, and on constellation management and ground station selection [**S2**].

Growth and relocation of satellite and data analytics companies in Glasgow

With the success of Clyde Space, and the research expertise available locally, Glasgow came to be seen as an important global centre of space and satellite innovation, attracting investment from international satellite and data analytics companies. In July 2019, the CSO of AAC Clyde Space said: '*I can't say enough how important UKube-1 was to not only Clyde Space, but also to the Scottish space industry. I believe it was one of the most important catalysts to the fantastic growth we have since seen to the Scottish space sector - 13 years ago there was practically no industry and now we have one of the fastest growing space sectors in the world*' [**S5**]. Examples of this growth and relocation include:

- In 2015, Spire Global, a Silicon Valley start-up founded in 2012, opened its first European office in Glasgow, with the co-founder and CTO confirming: '*the relationship between Spire and the University of Strathclyde has been, and continues to be, strong ever since the company located to Glasgow in 2015*. *The availability of talent with local high-quality universities and the proximity of supply chain were key factors for Spire locating in Glasgow, and these continue to be significant motivators for the expansion plans*' [**S3**]. Spire designs and builds nanosatellites to collect data from space to identify, track, and predict the movement of the world's aviation, shipping and weather systems. Spire launched their 100th Glasgow-built spacecraft into orbit in April 2019, and in September 2019 the company announced that Glasgow office would expand to 320 staff over the following five years. By December 2019 Spire's Glasgow office

was operating the world's third largest private constellation of spacecraft, behind Planet and SpaceX, and by end 2020 had launched a total of 110 Glasgow-built spacecraft [**S3**].

- Bird.i, a global real estate data analytics company, relocated to Glasgow in 2016, recognising that *'Glasgow was becoming the space capital of Europe'* [**S4**].
- In 2019, Orbital Micro Systems (OMS) Inc., based in Boulder, CO, partnered with AAC Clyde Space to locate staff in the central belt of Scotland [**S2**], with Macdonald joining the company in 2020 as an Independent Non-Executive Director to support the company's growth plans.
- In 2014 the University of Strathclyde won the bid to host SoXSA, which was 1 of 5 centres opened by the Satellite Applications Catapult. The remit was to accelerate the development of the Scottish space sector, and broker links between academia and industry. Since 2014 there has been engagement with over 500 organisations, more than 100 workshops and events, over 60 collaborative projects [**S6**]. The iconic Tontine building in the centre of Glasgow was transformed into a tech start-up hub as part of the Glasgow Region City Deal, a GBP1,130,000,000 infrastructure funding agreement between the Westminster and Holyrood Governments. In 2016, SoXSA received funding from the UK Space Agency to work with Glasgow City Council and the Tontine incubator to support the creation of new space-related companies [**S6**]. By 2020, this incubator had supported the creation of 12 new space sector businesses. An average start-up in Tontine increases turnover by GBP126,000, and 2 employees, in contrast, Strathclyde-supported space start-ups in Tontine on average increase turnover by GBP274,000 and four employees [**S6**].

The combination of new space companies coupled with the expertise at Strathclyde provides Glasgow with an exceptional, end-to-end capability, rarely found elsewhere in the world, to take an idea from concept, through development and build, into operations in space, and data or service exploitation. This ultimately provides easier access to and more cost-effective space-enabled data and services for existing and future customers. As a consequence of the success of AAC Clyde Space and Spire, more spacecraft are built in Glasgow than anywhere else in Europe [**S4**].

Improved nanosatellite design, and commercial products underpinned by satellite data

Glasgow-built spacecraft enable the creation and improvement of a wide range of data applications, notable examples are:

- Based on the UKube-1 design and with project review support from Macdonald, AAC Clyde Space developed the SeaHawk CubeSat for the University of North Carolina, to monitor the health of the Earth's oceans. SeaHawk is 130 times smaller, 45 times lighter, has a ground resolution 7-15 times better, and has a Signal/Noise Ratio approximately 50% better than the spacecraft it replaces. This provides the University of North Carolina greater accuracy to measure ocean colour data, which plays a critical role in marine ecosystem monitoring [**S2**].
- Orbital Micro Systems' Global Environmental Monitoring Satellite (GEMS), using AAC Clyde Space's CubeSat platform, launched in July 2019, provides actionable weather data to a markets including aerospace and maritime transportation, who use the data to plan routes that optimize real-time weather conditions, reducing delays, fuel consumption and emissions while operating with greater safety. By July 2020 the GEMS satellite had been operational for one year, delivering '*precise, unique datasets that translate into highly reliable weather intelligence*' [**S7**].
- Data generated by Spire's Glasgow-built spacecraft is being used by partners around the world to track global shipping and trade patterns to help identify illegal fishing, and to better understand global weather patterns [**S3**]. This data supported a change in policy from the US Government's National Oceanic and Atmospheric Administration (NOAA), who assessed Spire's data and '*concluded that the commercial sector is capable of providing the quality of data needed to help support NOAA's operational weather forecasting needs'*, finding that the data improved the accuracy of one- and three-day weather forecasts [**S3**]. As a result, in November 2020 NOAA placed a two-year indefinite delivery-indefinite quantity contract with Spire worth up to USD23,000,000 (11-2020) to procure commercial data for operational use for the first time [**S3**].

International expansion and capacity building in 'new space' technology

Macdonald and Lowe have directly supported the development of satellite technology and regional expertise in low- and middle-income countries, with UK Space Agency GCRF funding for these

collaborations. Macdonald has also held several advisory roles, which influenced wider national and international level approaches and policy on small satellites and new space.

- Between 2015 and 2017, Lowe and Macdonald collaborated with MX-Space, Universidad Autónoma de Chihuahua, Mexico, and commercial partners in Glasgow to develop mission design software for the NANOBED Missions Laboratory [**S8**]. The resulting NANOBED was the first of its kind to be deployed in Latin America and significantly accelerated the validation process of the Mexican-built AzTechSat-1 nano-satellite [**S8**]. From 2017, Strathclyde researchers supported the development of a Globalstar CubeSat terminal for the AzTechSat-1 [**S8**]. This terminal allows CubeSats to send data to Globalstar, a constellation of satellites used for phone and low-speed data communications, enabling CubeSat data to be downloaded continuously, rather than 2 - 3 times daily when the CubeSat itself passed overhead. This led to the first collaboration between the Mexico Space Agency and NASA on a spaceflight project, which saw AzTechSat-1, with the Globalstar CubeSat terminal on-board, deployed from the international space station in February 2020 [**S8**].
- Building on this collaboration and funded by the UK Space Agency, Clyde Space led the FireSat project in collaboration with Macdonald and Lowe, alongside Government and University partners in South Africa, Namibia and Kenya, to support the deployment of the ZACube-2 spacecraft by South Africa [**S2**]. Launched in December 2018, the ZACube-2 serves as a technology demonstrator for remote sensing applications such as ocean colour monitoring, large fire tracking, and ocean vessel detection.
- On the basis of his research expertise and support to the 'new space' sector, Macdonald was invited to advise on Ireland's first national space strategy and supported University College Dublin's successful submission for funding in June 2019 to Science Foundation Ireland. The prestigious Frontiers for the Future grant (EUR1,000,000 (06-2019)), together with Macdonald's continued input, will support the development of a new Centre for Space Research and growth of Ireland's space sector from 2020 onwards [**S9**].
- From 2015 - 16, Macdonald was technology lead on the US National Academies of Sciences, Engineering, and Medicine committee on 'Achieving Science Goals with CubeSats' [**S10**]. The subsequent report, commissioned by NASA, made a number of recommendations, including how NASA should better structure itself to embrace this form of disruptive innovation. In 2018, as a direct result of the committee's recommendations, NASA created a new role of Special Advisor for Small Spacecraft Missions [**S10**]. According to the Special Advisor, '*the University of Strathclyde's research on nano-satellite technology and space mission analysis, conducted by Prof Malcolm Macdonald and his team, has been instrumental in informing NASA's approach to small spacecraft*.' [**S10**]

5. Sources to corroborate the impact

S1 UK Space Agency. UKube-1 completes mission. https://bit.ly/38gYHHH

S2 Corroborating statement from CTO, AAC Clyde Space (02/12/2020).

S3 Corroborating statement from Co-founder and CTO, Spire Global and appended announcement on NOAA contract (09/02/2021).

S4 Collated news articles related to the Glasgow space sector.

a. The National. How startup Bird.i brings satellite imagery to the mass market. https://bit.ly/32jUsra

b. Satnews. Weather Stream Birthed by Orbital Micro Systems. https://bit.ly/36c9RuQ

c. The Scotsman. Glasgow builds more satellites than any other European city. https://bit.ly/3ezskoT

S5 AAC Clyde Space statement on CubeSats for Ireland (EIRSAT-1). https://bit.ly/36cbiJK

S6 Collated internal reports relating to SoXSA.

a. Scotland in Space Startup: Final Report (2020)

b. Centres of Excellence Final Report April 2017 – March 2020

c. Overall SoXSA engagement figures for 2014 - 2020

S7 Earth Observation Portal Directory. IOD-1 GEMS. https://bit.ly/3l9UDg4

S8 Corroborating statement from Former Space Technology Coordinator, MX- Space, now Director of Industrial and Commercial Development, Mexican Space Agency (20/11/2020).

S9 Corroborating statement from Professor of Astronomy, University College Dublin (15/12/2020).

S10 Corroborating statement from Associate Chief Technologist, NASA (23/12/2020).