UK SPACE AGENCY

UK Space Facilities Review

December 2017

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FOREWORD

The UK Space Sector supports some £250 billion of the UK's GDP by providing space-enabled data and applications that are widely used in other sectors of the economy to improve efficiency, increase the tools available for businesses and consumers in critical activities and, in some cases, to introduce all-new ways of working. This activity is supported by space manufacturing companies that are smaller in scale but are crucial in producing the infrastructure we need for these services and applications. This report is the first national survey we have undertaken to ensure that we are all aware of the facilities we have in the UK to support the design, development and testing of space hardware and to identify where we need to invest further to meet the new demands of emerging markets.

The need for an audit of the UK's space facilities was first identified by the industry-led Space and Innovation Growth Strategy in 2010. This was subsequently confirmed in the Space Growth Action Plan 2013 as a vital factor in ensuring the future health of the UK space sector. The Plan called for a nationwide strategy to coordinate investment in facilities and infrastructure to support space exploitation and growth.

The UK Space Agency and the Rutherford Appleton Laboratory have worked closely together to produce this report that meets these objectives.

Starting necessarily with a representative sub-set of the entire sector, although the survey itself was broad, the review conclusions focus on three areas: system level assembly, integration, verification and test facilities; chemical propulsion test facilities; and electric propulsion test facilities. The approach we have adopted fits well with the Government's recently launched Industrial Strategy and is a good example of our sector coming together to undertake the analysis and subsequent actions we need to take to drive forward and invest in our sector.

Our intent over the next year is to continue to develop the partnership with RAL to update this report and cover additional areas such as satellite operations and related ground component, robotics and autonomous space systems, light launch test, and facilities that can manage and analyse the very large data sets that are very much becoming a feature of the sector.

I would like to thank the team at the Rutherford Appleton Laboratory for their dedication to producing an excellent report and also the many people in industry, academia and institutions who have contributed data and analysis to make this work possible.

Dr Graham Turnock, Chief Executive
UK Space Agency
December 2017

1 INTRODUCTION

1.1 Scope

This document is the 2017 Report of a UKSA study to assess the current facilities available in the UK for the development and test of space hardware, and thus identify any gaps constraining the UK institutional, academic or industrial space community in achieving the IGS objectives.

The study addresses a wide scope of facilities supporting the development and test of spacecraft systems, (deliberately omitting any 'downstream' application facilities) presented to the UK space user community at workshops held at the Satellite Applications Catapult. The workshops identified two high-level gaps in particular:

- a UK-based 'One-Stop-Shop' spacecraft-level environmental test facility, negating the need for systems integrators to transport spacecraft and teams to mainland Europe for extended periods; and
- a comprehensive and sustainable propulsion development and test facility to support both in-space and ultimately access-to-space technologies.

This study therefore concentrates on:

- System level environmental test and AIV facilities
- Chemical propulsion test facilities
- Electrical propulsion test facilities

In all, 57 significant UK entities involved in space R&D and space systems testing provided responses for the 2016 Report. What is clear from the interactions is that it is only possible to capture a snapshot, as the landscape is changing over time, with emerging new entities, subsidiaries of international companies starting up in the UK, mergers, acquisitions, and changes in strategy. However, where organisations were willing to discuss their plans and needs, it has been possible to identify some trends and to note that any national initiatives to provide additional testing facilities and services, will result in a response from the community to take advantage of those initiatives.

The study addressed most of the major players in the UK space ecosystem and provides a reasonably complete overview. The following organisations have been approached:

- Environmental test houses;
- Spacecraft systems integrators;
- Subsystem suppliers and SMEs;
- Research Organisations and Universities.

The following issues and facilities are not within the current study scope although some could be included in potential follow-on work for 2017:

- Downstream systems and services;
- Ground station systems and services;
- Planetary robotics and autonomous systems;
- Aeronautical or hypersonic facilities such as wind tunnels;
- Non-space avionics;
- Defence-specific technologies and facilities;
- Launch vehicle technologies and facilities.

Following analysis of the data gathered, the findings point towards possible outcomes regarding what may be done at the national level. It will be necessary to undertake specific market surveys in order to accurately establish the size, scope and characteristics of any new facilities, which is also beyond the scope of the current study.

1.2 Background

In 2010, a large sector-wide team of space experts published a 20-year strategic plan for space in the UK entitled the Space Innovation and Growth Strategy 2010-2030, RD1, referred to hereafter as the IGS. This led to a number of significant changes in the structure and governance of the UK Space sector, including the creation of the UK Space Agency, as illustrated in Figure 1.1 below.

In 2013 the IGS team reaffirmed its commitment to grow the space market and proposed an Action Plan with five high-level recommendations, also shown in Figure 1.1, each backed by a number of specific actions. One of these, Action 5.6, resulted in the UKSA commissioning this 'UK Space Facilities and Gaps Study':

- to assess the facilities currently available in the UK to support development, testing and integration of spacecraft platforms and payloads;
- to identify what gaps exist in the UK's space segment development and AIT (Assembly, Integration & Test) infrastructure; and
- to assess how those gaps may most effectively be filled, with the end goal of ensuring that the UK takes a global lead in exploitation of space infrastructure.

1.3 Reference Documents

RD #	REFERENCE DOCUMENT TITLE	DOCUMENT ID	ISSUE
RD1	Space Innovation and Growth Strategy 2010 to 2030 http://www.parliamentaryspacecommittee.com/media/publications/Space%20IGS%20Main%20Report.pdf		
RD2	Space Innovation and Growth Strategy 2014-2030: Space Growth Action Plan		
RD3	Government Response to the UK Space Innovation and Growth Strategy 2014 – 2030, April 2014		
RD4	National Space Technology Strategy, April 2014, The UK National Space Technology Steering Group		
RD5	Autonomy & Simulation Verification Facility Needs for Robotic Exploration Missions	SSL/8753/DOC/001	1.0
RD6	Harwell Robotics & Autonomy Facility (HRAF) Final Report, RAL Space/SCISYS/Astrium, 12 DEC 2012	PO-RP-RAL-HRAF-001	1.4
RD7	"SMALL IS THE NEW BIG", Nano/Micro-Satellite Missions for Earth Observation and Remote Sensing, Satellite Applications Catapult, May 2014		
RD8	2014 Nano/Microsatellite Market Assessment, SpaceWorks. Jan 2014.		
RD9	Space IGS 2015 Update Report https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/444918/_SPACE-IGS_report-web-JJF-V2.0.pdf		

2010 - Space Innovation & Growth Strategy (IGS): a partnership between industry, government and academia, to produce a 20-year strategic plan to develop and exploit space opportunities, aiming to secure 10% of the global space market, estimated to be worth £400 billion, by 2030.

The creation of the **Space Leadership Council**, bringing together Government, Industry and Academia as the most senior UK group advising on Space policy.

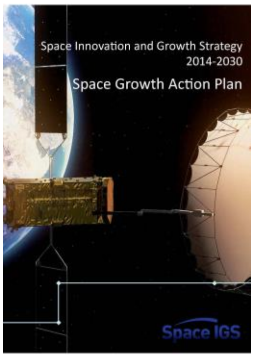
The creation of the **UK Space Agency** tasked with providing a unified voice in championing the sector, advising on policy, setting strategy and co-ordinating funding, with a budget of around £250m per annum.

The creation of the **Satellite Applications Catapult** centre at Harwell, Oxford, one of only nine Catapults in the UK, funded by the Technology Strategy Board - now Innovate UK

A **33% increase in optional funding** to the European Space Agency at the ESA Ministerial in 2012, increasing the UK's work and influence in crucial areas such as satellite communications and Earth observation.

The establishment by ESA of **ECSAT** (European Centre for Space Applications & Telecoms) at Harwell, in recognition of the UK's increasing commitment to space.

The establishment of a regulatory framework to enable the creation of a commercial **UK Spaceport** by 2018.



2013 - Space Growth Action Plan for 2014-2030: report by the IGS team, reaffirming its ambition to grow the space market, including a thorough analysis of that market, identifying the new actions necessary to deliver further growth, encompassed in five high-level recommendations:

1) *Develop the high-value priority markets identified in the Plan to deliver £30 billion per annum of new space Applications, plus a new interim target of 8% of the global space market by 2020, corresponding to £19 billion*
2) *Make the UK the best place to grow existing and new space Businesses*
3) *Increase the UK's returns from Europe by continuing to grow the UK contribution to European Space Agency (ESA) programmes*
4) *Support the growth of UK Space exports from £2 billion to £25 billion per annum by 2030 by launching a National Space Growth Programme*
5) *Stimulate a vibrant regional Space SME sector by improving the supply of finance, business support, information, skills and industry support*

2014 – UKSA Response to Space Growth Action Plan for 2014-2030, welcoming the five high-level recommendations from the Action Plan and setting out the UKSA position under each of the five themes.

The **Facilities Gap Study** was commissioned by UKSA as a specific response to Action 5.6 from the Plan to:

Develop a nationwide plan to coordinate investment in ground segment infrastructure and technology centres-of-excellence to secure facilities that support exploitation and growth, and provide value-for-money from Government investments and to ensure that the UK takes a global lead in exploitation of space infrastructure

Figure 1.1 Space Facilities and Gaps Study in the context of the IGS Framework

2 STUDY METHODOLOGY

The study is based on surveys, internet searches, telephone interviews and visits to UK organisations, together with facility presentations and brochures provided by the surveyed organisations. The interpretations and summaries of the survey responses have been submitted to the surveyed organisations for review, prior to incorporation of their entries into this 2017 Report.

This report is also supported by the Facilities Gap Study Workshops that were held at the Satellite Applications Catapult.

2.1 Target Organisations

The target organisations for the study were identified as:

- Environmental test houses
- Spacecraft systems integrators
- Subsystem suppliers and SMEs
- Research Organisations and Universities

Feedback from the target organisations accompanies the facility descriptions in Section 3, to include:

- the level of satisfaction with current facilities;
- obvious gaps;
- their current and future needs;
- how they might provide facilities to outside organisations;
- the consequences of new facility availability or non-availability for their future plans.

2.2 Initial Survey Questions

The following set of questions was used initially for this survey:

- What are the current capabilities of your facilities?
- What are your future plans, including investment plans?
- What are your future requirements and facility gaps?
- What are the quantitative and qualitative impacts of facility gaps if not addressed?
- What scope do you have for sharing of facilities?

AIV Facilities and Sub-System Suppliers			
Organisation	**Type and Interests**	**Main Website**	**Contacts**
ABSL/Enersys	Space battery supplier	www.abslspaceproducts.com	Tariq Sami
Airbus Ds - Portsmouth	Large satellite Prime	www.airbusdefenceandspace.com	Chris Ward
Airbus DS – Stevenage	Prime - ComSats	www.airbusdefenceandspace.com	Chris Ward
Airbus Group Innovations	Power and propulsion	www.airbusgroup.com/int/en/corporate-social-responsibility/airbus-group-innovations.html	Helen Swift
AVS UK	SME – subsystem supplier	www.a-v-s.es/areas/space	Alberto Garbayo
3C Test	EMC Test house	www.3ctest.co.uk	R Gordon-Colebrook
Clyde Space	SmallSats & CubeSat Prime	www.clyde.space	C Clark, Jenni Doonan
Cobham RAD Solutions	Radiation Test House	http://ams.aeroflex.com/pagesfamily/fams-rad.cfm	Richard Sharp
COM DEV International	Subsystem supplier	www.comdev.co.uk	Colin McLaren
Cyth Systems UK	SME, pyro test	www.cyth.com/MainPages/Contact_Europe.html	Wes Ramm
Deimos Space UK Ltd	SmallSats	www.deimos-space.com/en	Philip Davies
Element Matls Technlgy	Mechanical & RF Test House	www.element.com/locations/europe/wimborne	Damon Close
ESR Technology Ltd	Space tribology	www.esrtechnology.com/sectors/space	Grant Munro
Intertek	EMC Test House	www.intertek.com/uk/	Ranjit Bhambra
ISVR	Acoustic Test House	www.isvr.co.uk	Malcolm Smith
Lockheed Martin UK Ltd	Large satellite Prime	www.lockheedmartin.co.uk/uk/who-we-are/Locations.html	Nik Smith, Steve Gibson
Magna Parva	Space systems & structures	https://magnaparva.com/	Andy Bowyer
Neptec UK Ltd	SME, subsystems	www.neptecuk.com/about	Mike Kearns
NPL	Govt standards & test house	www.npl.co.uk	Carlos Mingo Roman
Oxford Space Systems	Booms, deployable structures	www.oxfordspacesystems.com	Mike Lawton, Mat Rowe
RAL Space, STFC	Govt research establishment	http://www.ralspace.stfc.ac.uk/RALSpace/	J Reburn, S Beardsley
Satellite Apps Catapult	Government	https://sa.catapult.org.uk/	L Moody, Vlad Stoiljkovic
Spur Electron Ltd	Space EEE components	www.spurelectron.com	Richard Matthews
STAR Dundee	Spacewire, Spacefibre	www.star-dundee.com	Steve Parkes
SSTL	Small & Medium Sat Prime	www.sstl.co.uk	Ben Stocker, R Goddard
Thales Alenia Space UK	Large satellite Prime	www.thalesgroup.com/en/worldwide/space/space	Rebecca Halls, L Houis
TWI Tech Centre, Wales	Materials research	www.twi-global.com/contact/find-us/twi-technology-centre-wales/	Chelly Reynolds
UK ATC, STFC	Govt research establishment	www.ukatc.stfc.ac.uk/UKATC/default.aspx	Andy Vick, Julian Dines
Vaeros Ltd	Space consultancy	http://vaeros.org/about/	Gina Galasso
Viper RF	SME, MMIC supplier	www.viper-rf.com	Simon Chan
Propulsion Facilities			
Organisation	**Organisation Type**	**Main Website**	**Contacts**
Airborne Engineering	SME, chemical propulsion	www.ael.co.uk	James Mcfarlane
European Astrotech Ltd	SME, chemical propulsion	www.europeanastrotech.com	Ms Sam Green
Falcon Project Ltd	SME, chemical propulsion	https://en.wikipedia.org/wiki/Daniel_Jubb	Daniel Jubb
Intnl Space Prop, ISP	Propulsion consultancy	www.ispropulsion.com	Paul Williams
Mars Space	SME, EP	www.mars-space.co.uk	Michel Coletti
Moog UK	SME, chemical propulsion	www.moog.com/markets/space/in-space-propulsion.html	Adam Watts
Portus Space Systems	Future EP Test House	www.aerospazio.com	S Tucker, F Scortecci
QinetiQ	EP and Multi-Test House	www.qinetiq.com/Pages/default.aspx	Keith Trevor
Reaction Engines Ltd	SME, chemical propulsion	www.reactionengines.co.uk	Ben Gallagher
Roxel Safran	SME, chemical propulsion	www.roxelgroup.com/corporate	John Ayris
Universities			
Organisation	**Organisation Type**	**Main Website**	**Contacts**
Cardiff University	Research, instrumentation	www.astro.cardiff.ac.uk/research/astro/instr	Peter Hargrave
Cranfield University	Propulsion research	www.crantalk.com/cranspace	Steve Hobbs
Glyndwr University	Research, space optics	www.glyndwr.ac.uk/en/campusesandfacilities/glyndwr universitystasaph	Paul Rees
MSSL	Research, space instruments	www.ucl.ac.uk/mssl/facilities	Alan Smith, Alex Rousseau
Open University	Planetary research	www.open.ac.uk/science/physical-science	Manish Patel, S Barber
QUB, ECIT	MEMS, space antennas	www.qub.ac.uk/sites/ECIT	Michelle McCusker
Imperial College London	Research, magnetometers, EO	www.imperial.ac.uk/space-and-atmospheric-physics	Helen Brindley, Chris Carr
Swansea University	Materials, propulsion	www.swansea.ac.uk/engineering/research	Kiyo Wada
Ulster University	Research, space composites	www.eri.ulster.ac.uk & www.niace-centre.org.uk	Freda Casey
University of Dundee	Research, OBDH	http://spacetech.dundee.ac.uk/	Steve Parkes
University of Kingston	Research, propulsion	http://sec.kingston.ac.uk/rocketlab/	Adam Baker
University of Leicester SRC	Research, space instruments	http://www2.le.ac.uk/departments/physics/research	John Pye, Mark Sims
University of Oxford	Research, space instruments	https://www2.physics.ox.ac.uk/research	Neil Bowles, Simon Calcutt
Univ of Southampton	Research, EP and chemical	www.ecs.soton.ac.uk and www.southampton.ac.uk/engineering/index.page	Steve Gabriel and A Grubisic
University of Strathclyde	Research, small sats	www.strath.ac.uk/space	Peter McGinty, B Hidding
University of Surrey	Research, small sats	www.surrey.ac.uk/ssc	Guglielmo Aglietti

Table 2.1: Organisations Surveyed

3 SURVEY

This section presents the results of the survey, and is effectively a catalogue of space development facilities available at each of the organisations surveyed. Table 3.1 presents a simple mapping of test facility types against organisation, although it is important to refer to the detailed descriptions which follow to gain an understanding of the scope and scale of existing facilities at each site, and to find information on their future needs and development plans.

	ABSL / Enersys	Airborne Engineering (Westcott)	Airbus DS Portsmouth	Airbus DS Stevenage	Airbus Group Innovations (Newport)	AVS-UK	3C Test Ltd	Cardiff University	Clyde Space	Cobham RAD Solutions	COM DEV International (Honeywell)	Cranfield University	Cyth Systems	Deimos UK	Element Materials Technology	ESR Technology	European Astrotech Ltd	Falcon Project Ltd	Glynd'wr University
Clean rooms	Y		Y	Y				Y	Y		Y					Y			
Mass properties				Y															
Vibration			Y	Y							Y				Y				
Shock			Y	Y											Y				
Pyro-shock													F						
Acoustic																			
Thermal-Vacuum	Y		Y	Y				Y			Y					Y			
Planetary environment chambers																			
Thermal chambers			Y	Y				Y	Y		Y					Y			
EMC			Y	Y			Y												
RF			Y	Y				Y			Y				Y				
Magnetic testing facilities																			
Radiation testing facilitites										Y									
Instrument design & development			Y	Y				Y			Y	Y							
Instrument characterisation & calibration								Y											
Molecular spectroscopy																			
Subsystem supplier	Y		Y	Y					Y		Y								
Small spacecraft & instrument-level test facilities			Y	Y					Y			Y							
Large spacecraft-level facilities			Y	Y															
Very large vacuum chambers																			
Specialist test facilities	Y		Y	Y	Y			Y	Y		Y					Y		Y	
Chemical propulsion design, development, test		Y		Y								Y					Y	Y	
High power chemical engine testing																		F	
Cold gas design, development, test																			
Electric propulsion design, development, test																			
Mission design & systems engineering			Y	Y	Y			Y	Y			Y							Y
Mechanical design & development facilities			Y	Y	Y			Y	Y		Y	Y				Y		Y	Y
Space optics design & development								Y											Y
Space electronics design & development			Y	Y				Y	Y		Y								
Thermal design & development			Y	Y				Y											

	Imperial College London	International Space Propulsion (ISP)	Intertek, Leatherhead	ISVR's Rayleigh Laboratories	Lockheed Martin Space Systems Co UK	Magna Parva	Mars Space	Moog UK (Westcott)	National Physical Laboratory	Neptec UK	Open University	Oxford Space Systems Ltd (OSS)	Portus Aerospace Ltd, Portsmouth	QinetiQ	Queen's University Belfast	RAL Space	Reaction Engines Ltd	Roxel (Safran-MBDA), Kidderminster	Satellite Applications Catapult
Clean rooms	Y					Y					Y			Y	Y	Y			
Mass properties																F			
Vibration																Y			
Shock																F			
Pyro-shock																			
Acoustic				Y												F			
Thermal-Vacuum	Y															Y	Y		
Planetary environment chambers											Y								
Thermal chambers																Y			
EMC			Y						Y							F			
RF									Y						Y	F			F
Magnetic testing facilities	Y								Y										
Radiation testing facilitites									Y										
Instrument design & development	Y					Y					Y					Y			
Instrument characterisation & calibration	Y								Y		Y					Y			
Molecular spectroscopy																Y			
Subsystem supplier	Y					Y	Y											Y	
Small spacecraft & instrument-level test facilities	Y															Y			Y
Large spacecraft-level facilities																F			
Very large vacuum chambers																Y			
Specialist test facilities	Y	Y				Y	Y	Y			Y			Y	Y	Y	Y	Y	
Chemical propulsion design, development, test		Y						Y									Y	Y	
High power chemical engine testing																	F	F	
Cold gas design, development, test								Y										Y	
Electric propulsion design, development, test							Y						F	Y					
Mission design & systems engineering						Y					Y					Y		Y	
Mechanical design & development facilities	Y					Y					Y				Y	Y	Y	Y	
Space optics design & development						Y					Y					Y			
Space electronics design & development	Y										Y				Y	Y	Y		
Thermal design & development						Y					Y					Y	Y		

	Spur Electron Ltd	SSTL – Surrey Satellite Technology Ltd	STAR Dundee	Swansea University	Thales Alenia Space – UK	TWI Technology Centre (Wales)	UK-ATC Edinburgh	Ulster University	University College London, MSSL	University of Dundee	University of Kingston	University of Leicester SRC	University of Oxford, Dept. Physics	Univ of Southampton - Astronautics Group	Univ of Southampton - Plasma Group	University of Strathclyde	University of Surrey	Vaeros Ltd	VIPER RF
Clean rooms		Y			Y		Y		Y			Y	Y				Y		
Mass properties																			
Vibration							F		Y				Y	Y					
Shock																			
Pyro-shock																			
Acoustic																			
Thermal-Vacuum							Y		Y			Y	Y	Y	Y				
Planetary environment chambers												Y							
Thermal chambers		Y																	
EMC																			
RF																			
Magnetic testing facilities																			
Radiation testing facilitites																F			
Instrument design & development					Y		Y		Y	Y		Y	Y						
Instrument characterisation & calibration									Y			Y	Y						
Molecular spectroscopy																			
Subsystem supplier		Y			Y												Y		
Small spacecraft & instrument-level test facilities		Y		Y	Y		F		Y			Y	Y		Y	Y	Y		
Large spacecraft-level facilities		Y																	
Very large vacuum chambers																			
Specialist test facilities		Y				Y	Y	Y	Y			Y	Y	Y	Y		Y		
Chemical propulsion design, development, test				Y	Y						Y			Y			Y		
High power chemical engine testing																			
Cold gas design, development, test																			
Electric propulsion design, development, test					Y									Y	Y		Y		
Mission design & systems engineering		Y		Y	Y		Y		Y			Y	Y	Y		Y	Y	Y	
Mechanical design & development facilities		Y		Y	Y	Y	Y	Y	Y			Y	Y	Y			Y		
Space optics design & development							Y		Y			Y	Y						
Space electronics design & development	Y	Y	Y		Y		Y		Y	Y		Y	Y				Y		Y
Thermal design & development		Y										Y	Y						

Table 3.1: Summary of facilities available at each organisation (Y = existing, F = future planned)

3.1 ABSL / EnerSys, Culham

3.1.1 ABSL / EnerSys Company Background

ABSL Power Solutions Ltd, including its space group ABSL Space Products, was acquired in 2011 by the US company EnerSys, a global leader in stored energy solutions for industrial applications. EnerSys believes that lithium batteries represent a significant growth driver for the coming years, complementing the growth of its existing business in lead-acid and nickel-based batteries. Space and terrestrial batteries, together with an expanding range of space instrumentation products manufactured by ABSL are valued as a diversified, specialist product mix supplied by the company into space and defence markets around the world. ABSL has supplied batteries for over 70 space satellite systems along with instrumentation system products for various space missions. ABSL has operational sites at Culham, Oxfordshire and in Longmont, Colorado.

3.1.2 ABSL's COTS Approach to Battery Design

ABSL pioneered the use of COTS Li-ion cells for space applications by recognising that lower-capacity higher reliability cells could be connected in a series/parallel configuration to enable a flexible modular design that met the battery capacity and volume requirements of a large variety of different missions. One of ABSL's favoured cell types is the 18650 cell which is 18mm in diameter and 65mm in length. The Company procures thousands of these cells, mostly via a special agreement with Sony, and then puts them through a comprehensive lot-acceptance testing process, followed by initial cell screening to produce a stock of space-qualified cells. These cells then go through detailed cell screening and matching before being assembled and rigorously environmentally tested to produce the flight-qualified batteries.

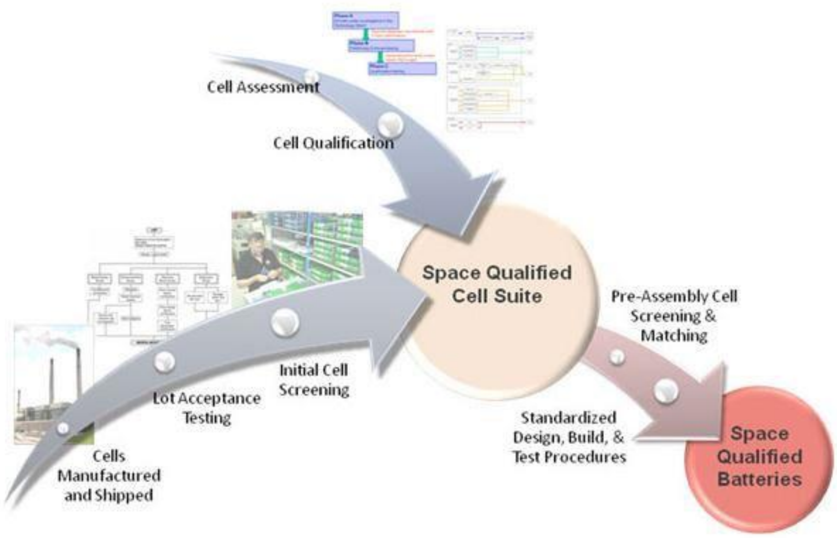


Figure 3.1 ABSL's COTS cell qualification process

3.1.3 ABSL Facilities

ABSL's space operations in the UK are based at the Culham Science Centre in Oxfordshire. The Culham facility has evolved from more than 40 years of continuous involvement in the space industry and includes a full suite of space hardware design, build, and test facilities to support the COTS battery design approach, as summarised below:

Battery Design Software:

- **BEAST (Battery Electrical Analysis Software Tool)** – allows users to perform snapshot simulations of battery behaviour under given operating conditions, based on defined fade parameters. Output data includes electrical performance parameters such as voltage, current, power, state-of-charge vs time and thermal dissipation data for use in system thermal analyses.

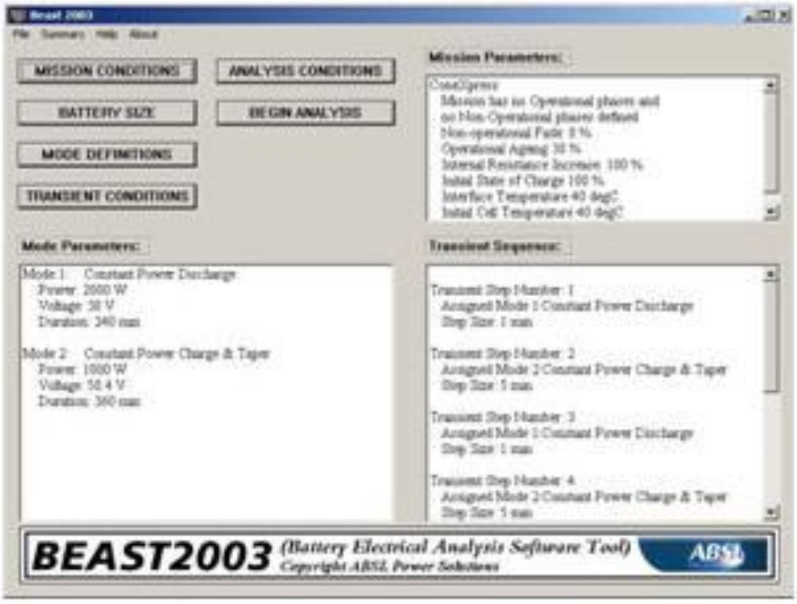


Figure 3.2 ABSL's BEAST battery design tool

- **LIFE (Lithium-Ion Fade Evaluator)** – a sophisticated fade tool allowing varying phases of operation to be modelled, based on an extensive database of in-orbit and life test data compiled by ABSL, allowing sensitivities to depth-of-discharge, temperature and state-of-charge to be evaluated, calculating fade against mission duration as an input to BEAST for performance predictions at any point during a mission.

Production Manufacturing

- Cleanroom 1: 54m^2, ISO-8 (Class 100,000), specifically designed for the manufacture of single or small-volume space hardware, with 190m ESD-safe bench space
- Cleanroom 2: 13m^2 , ISO-5 (Class 100) for assembly of high quality optical products complete with a laminar flow bench and access to a thermal vacuum chamber
- Engineering support: clean mechanical and electrical areas for assembly of jigs and harnesses required during manufacture and test of space hardware
- Bonded Store: for holding space-qualified components and materials with identification and barcode traceability for certification.

Testing

- Thermal vacuum chambers: x3 chambers; temp range -80°C to +100°C; pressure 1 x 10^{-6} torr; which are fully programmable for long term temperature cycling of hardware. All chambers are equipped with integrated battery power supplies.
- Thermal chambers for environmental testing of equipment capable of temperature cycling from -40°C to +100°C, fully programmable for long term cycling of hardware
- Maccor and Bitrode computer-controlled battery testers for monitoring and electrically cycling batteries up to 110 volts / 120 Amps
- Maccor single-cell formation rigs to enable testing of over five-hundred cells at any one time
- Battery impedance characterisation equipment covering a range of 10Hz to 100kHz

3.1.4 ABSL View on Facilities

ABSL has a World-class suite of design, build and testing facilities for cell screening, matching and acceptance testing for the production of space-qualified Lithium-ion batteries. These facilities are mostly for use by ABSL engineers working on batteries for commercial or scientific space applications but some, such as the BEAST battery design tool, are available for users to install at their own premises as a valuable addition to their space systems engineering design portfolio.

3.2 Airborne Engineering Ltd, Westcott

3.2.1 AEL Company Background

Airborne Engineering Ltd is a UK company based at Westcott Venture Park in Buckinghamshire, site of the former Rocket Propulsion Establishment (RPE Westcott) and its staff have over 70 years combined experience in rocket systems design and testing. The company's principal areas of expertise are:

- the provision of static testing services for propulsion research such as low-NOX hydrogen/air combustion tests and CO/O2 engine testing;
- propellant handling and pressurised gas systems; and
- manufacture of electronic and electro-mechanical instrumentation for propulsion systems.

3.2.2 AEL Propulsion Test Facilities

The Westcott site has a number of reinforced concrete test bays for live testing of rocket engines and two of these are assigned to Airborne:

- **J2 Test Bay**, has a specially built high pressure air flow system for air-breathing rocket engine research. It has a high flow rate air and hydrogen supply up to 10 kg/s, water cooling, water-spray sound suppression, and automatic metering valves on all propellant lines. The digitally controlled metering valves can either follow a specific mass flow profile to high accuracy or else set to allow closed loop control of engine operating conditions such as chamber pressure.

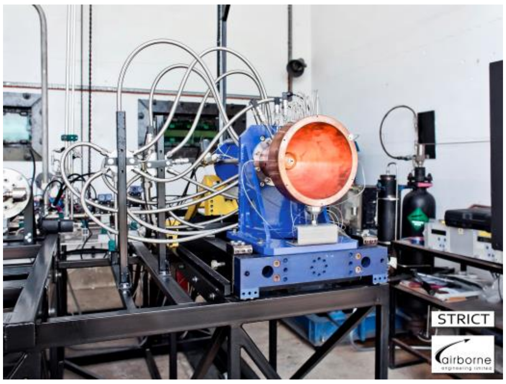


Figure 3.3 Lapcat engine firing and STRICT expansion-deflection research nozzle in AEL's J2 Test Bay

- **J1 Test Bay**, used for anything other than air-breathing engines. Cranfield University is currently using half of J1 Test Bay for testing a 600N bi-propellant engine. The facility has a modular test stand and modular rail system and has some availability for external users.

3.2.3 AEL View on Facilities

Airborne believes there should be a National Propulsion Test Facility, in which it would have a key role, to provide turnkey solutions to customers, in particular for academia, emphasising quick, low-cost projects. Airborne already works with Bristol University, Cranfield University, University of Surrey, University of Southampton, and Cambridge University (for which it has tested a small hybrid engine). Airborne would like to upgrade its J1 and J2 test bays as part of such a facility and estimates this would require a £1M to £1.5M investment.

Airborne is developing a 1.1kN engine. If a high-altitude vacuum test facility for this class of engine is not implemented in the UK, the testing will need to be carried out elsewhere in Europe or USA. Some of the testing would likely take place at Lampoldshausen, but experience has shown that their altitude chamber is problematic to book, resulting potentially in schedule delays. The high cost of setting up such a facility supports the case for a shared National Test Facility for 1-2kN engines.

Future testing facility requirements which are not currently being met include: short-duration 5kN engine tests; REL's Sabre engine testing; and full scale launch vehicle engine testing up to 100kN.

3.3 Airbus DS Portsmouth

3.3.1 ADS-P Facilities Background

Airbus DS Portsmouth offers a complete suite of Dynamic, Thermal, and EMC testing facilities. The extensive range of facilities provides customers with a 'one stop' test house capable of handling products from mobile phones to spacecraft payloads. Airbus DS services cover a variety of environmental simulation tests (including thermal vacuum, vibration, and shock), as well as Electromagnetic Compatibility (EMC) tests. Airbus DS has been conducting tests at the Portsmouth site for over forty years. This experience has allowed Airbus DS to create one of the most well-equipped and expertly staffed facilities of its kind. The Vibration, Shock, Thermal, Climatic and Centrifuge facilities are UKAS accredited and fully backed by consultancy support.

3.3.2 ADS-P Vibration Facilities

ADS Portsmouth has a range of shakers with advanced digital control and analysis systems able to test a wide range of products ranging from component level, to large payloads of several tonnes. The shakers can handle thrust levels up to 160kN, allowing a great deal of flexibility to meet customer requirements. Test procedures are tailored to suit the specific test needs of a product. Complex test profiles and levels can be achieved to suit each individual unit. The shakers are driven by sophisticated digital controllers capable of sine, random and shock profiles in three dimensions. Multiple channels of data may be recorded and analysed in real time from the control room. The latest system allows up to 64 channels of data to be analysed simultaneously. The cleanliness environment is Class 2 (10,000), with moveable hood dimensions 4m x 3.4m x 4.1m high. Vibration equipment includes:

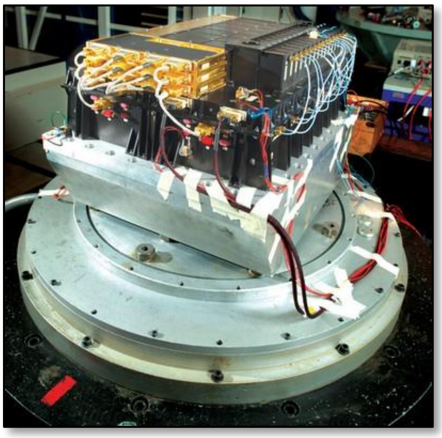


Figure 3.4 ADS-P V964 Vibrator

- Ling Dynamics V980 Vibrator
  - Max Thrust : 160kN
  - Frequency Range : 5- 2000Hz Acoustic Facilities
  - Max Acceleration : 100g
  - Max Displacement : ±12mm
  - Hydrostatic Slip Table: 1.525 x 1.525 m
  - Head Expander : 1.22m Diameter
- Ling Dynamics V964 Vibrator
  - Max Thrust : 75.26kN
  - Frequency Range : 5 to 3000Hz
  - Max Acceleration : 100g
  - Max Displacement : ±12mm
  - Hydrostatic Slip Table : 0.61x 061m
  - Head Expander : 0.762m Diameter
- Derritron VP2500 Vibrator
  - Max Thrust : 111.2kN
  - Frequency Range : 5 to 2100Hz

- Max Acceleration : 100g
- Max Displacement : ±12mm
- Head Expander : 0.762m Diameter

- Derritron VP1200 Vibrator
  - Max Thrust : 55.6kN
  - Frequency Range : 5 to 3000Hz
  - Max Acceleration : 100g
  - Max Displacement : ±12mm
  - Hydrostatic sliptable : 0.61x0.61m

- M+P International VXI Controller
  - 32 Channel Analysis System
  - Sine, Random and shock control and analysis

- M+P International VXI Controller
  - Portable 16 Channel Analysis System

- M+P International VXI Controller
  - 64 Channel Analysis System
  - Sine, Random and Shock control and analysis

3.3.3 ADS-P Shock and Drop Test Facilities

Airbus has been conducting shock tests at the Portsmouth site for over forty years. This experience has allowed Airbus DS to create one of the most well-equipped and expertly staffed facilities of its kind, able to perform a wide range of shock tests, drop tests, and data analysis. The shock test facilities have been developed to reproduce the mechanical shock environments that occur when pyrotechnic devices are fired during spacecraft launch and deployment operations. The shock facilities are UKAS accredited and fully backed by consultancy support. There are two main facilities available and they are selected depending on the test levels required and unit size. The facilities have a flexible design and can be tailored to suit individual customer requirements based on the nature of the testing, variety of units and shock levels required. The facilities are continually being expanded and upgraded to suit all types of test articles. The shock rig's main components are a hammer and resonant plate. The shocks are produced via a free falling mass (hammer) striking an anvil attached to the ringing or resonant plate. The test article is attached, usually directly, to the ringing plate. Half-sine shocks can also be produced using a free-fall drop rig. Classical shock profiles are generated using conventional electro-dynamic vibration systems.

General Performance Details:

- Frequency Range: 10 Hz to 10 kHz, higher frequencies may be analysed depending on customer requirements
- Shock Response Spectrum (SRS) acceleration levels: 1 kHz to 10 kHz, 4000 g; 2 kHz to 10 kHz, 8000 g
- Equipment mass: up to 45kg
- 5m drop test system
- Drop shock half sine

Figure 3.5 ADS-P Shock Test Facilities

Airbus DS recognises that there is significant outside interest in shock test facilities and is hoping to add another shock test facility to help address this demand. The company is open to working with government agencies, academia, industry and all other organisations driving the UK IGS actions, to help ensure alignment of facilities utilisation with UK growth targets.

3.3.4 ADS-P Clean Rooms

The Portsmouth site's principal space integration area is a large clean-room known as 'Neptune' used for the integration of spacecraft sub-systems, payload modules and instruments. The clean-room has a reconfigurable secure capability, enabling commercial and classified projects to run in parallel. The facility is air-conditioned and contamination-controlled and complies with ECSS-Q-70-01A. Sections of Neptune and/or other smaller clean rooms may be used by external companies subject to availability and normal commercial arrangements.

Figure 3.6 ADS-P Neptune Clean-Room

Neptune's characteristics as follows:

- Clean room environment: Class 100,000
- Dimensions(LxWxH): 41m x 28mx 12 m
- Crane hook height / max load: 10m / 6.3 tonne
- Temperature / humidity: 20°C ± 3°C / 30-55 %
- Load limit of floor: 1 tonne/m^2 and 10m x 8m seismic block
- Air lock door: 6.6m x 6.0m

3.3.5 ADS-P Thermal Vacuum Facilities

Simulating the severe conditions of space, the computer-controlled thermal vacuum chambers can subject units to the extremes of their working environment. Mimicking the night and day experienced by the spacecraft as it moves in and out of sunlight, the chambers can cycle temperature from +100°C to -196°C whilst simultaneously maintaining a space vacuum of at least 1.3E-5mbar. An extensive range of hermetically sealed connector feed-throughs is available, enabling units to be powered and tested whilst enduring thermal vacuum simulation. The temperature of the test item can be constantly monitored and recorded throughout the test campaign, with the use of multiple T-Type thermocouples connected to a data logger, which also logs the pressure of the chamber. Test temperatures, dwell times and ramp rates are fully customisable to enable a wide range of products to be tested to specific customer requirements.

- Capabilities
  - Temperature Range: -196°C to +100°C
  - Pressure: <1.3x10^{-5} mbar
- Thermal Vacuum Chambers (x4)
  - Balzers, type RSK 1500 (x2)
  - Leybold, type VS 1677 (x2)
  - Maximum Unit Size: H 0.8m x W 0.75m x D 1.25m
  - Temperature Range: -60°C to +100°C or -196°C by means of LN2
  - 4 x Port Holes 0.15m diameter
- Lintott Chamber
  - Maximum Unit Size: H 0.3m x W 0.5m x D 0.5M
  - Temperature Range: -90°C to +100°C
  - 2 x Port Holes 0.15m diameter
- Data Logger
  - 32 thermocouple channels per chamber standard; extra channels on request

Figure 3.7 Airbus DS Portsmouth Thermal Vacuum Test Facility

All of the ADS Portsmouth chambers are potentially usable by external customers subject to availability.

3.3.6 ADS-P EMC Testing Facilities

The Portsmouth site has a comprehensive range of EMC chambers, test rooms, and equipment. Airbus DS test laboratories have a wide range of the latest technology in EMC test equipment to cover all customer needs. The Company has many years of experience providing EMC testing and has developed the facilities and expertise to provide accurate testing for space products. Capabilities include:

- Emissions testing from 20Hz to 40 GHz
- Susceptibility testing from 20Hz to 40GHz up to field levels of 150V/m
- Pre-compliance testing for a majority of commercial standards
- 10m CISPR 16 semi-anechoic chamber
- 3m CISPR 16 semi-anechoic chamber
- Mil Std 461 test chambers
- General-purpose screened rooms

Chamber 1 – screened, air conditioned, test chamber

- Dimensions : 4m(L) x 4m(W) x 4.5m(H)

- Access: single and double personnel doors: double 3.0m x 3.0m
- Screening Effectiveness: <100 dB up to 40 GHz
- Class 3 (100,000 clean room standard)
- Tests accommodated: Mil Std 461

Chamber 2 - screened, air conditioned, test chamber
- Dimensions : 6.41m(L) x 4.88m(W) x 3.66m(H)
- Access: Double personnel door 3.05mx 3.20m
- Screening Effectiveness : Better than 100dB up to 40GHz
- Tests accommodated: Mil Std 461

Chamber 3 - screened, air conditioned, test chamber
- Dimensions: 3m(L) x 3.8m(W) x 2.7m(H)
- Access: Single personnel door
- Screening Effectiveness: Better than 100dB up to 40GHz
- Tests accommodated: Mil Std 461

Triton Range – a multi-purpose, air-conditioned, fully or semi-anechoic test facility
- 10m CISPR 16 Semi-Anechoic Chamber
- Spherical Antenna Test Range
- Dimensions: 30m(L) x 15m(W) x 15m(H)
- Turntable: 8m diameter, 10 tonne static loading, 2 tonne rotation loading
- Access: 8m x 8m swing doors, external hydraulic and single personnel door
- Lift for seamless entry of equipment up to 10 tonne
- Screening effectiveness: < 100dB below 18GHz; < 60dB from 18 to 40GHz
- Class 3 (100,000 clean room standard)
- Adjacent Screened Control/Support test chamber
- Tests accommodated: CISPR 16, EN55022, EN61000-6-x, Mil Std 461
- Antenna measurements of Pattern, Gain and Return Loss
- Payload EMC Testing

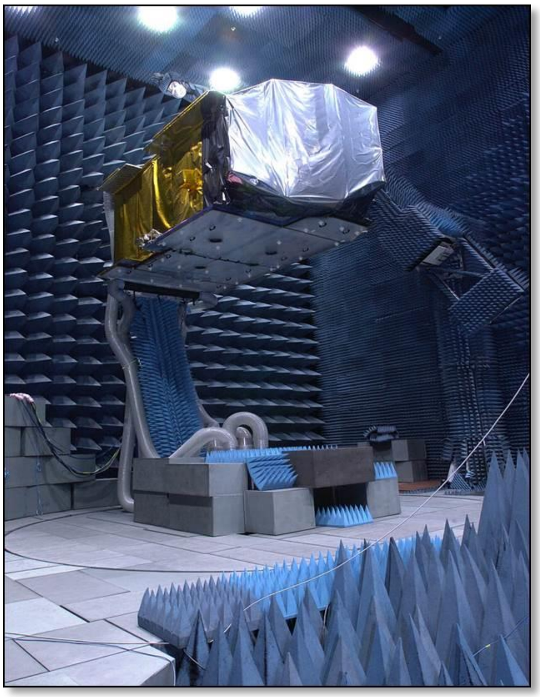


Figure 3.8 Triton Range at Airbus DS Portsmouth

3.3.7 ADS-P Space Electronics Manufacturing Facilities

Both the Stevenage and Portsmouth ADS sites have a full complement of production facilities for space electronics; the Portsmouth facilities are summarised here:

- Two dedicated ESD-protected clean-room areas:
  - Class 100,000 (ISO Class 8)
  - Class 10,000 (ISO Class 7)
- Floor Area:
  - 2200 m^2 for space electronics manufacture and test and 200 m^2 for hybrid manufacture and test
- Utilises MRPII controlled business systems with state-of-the-art MES (Manufacturing Execution System) paperless control
- Allows Parts traceability from component supplier through to manufacture

Figure 3.9 Airbus DS space electronics manufacturing facilities

- ESA approved manufacturing processes include:
  - Film and paste adhesive bonding
  - Parallel gap bonding of Au tape
  - Encapsulation and conformal coating
  - Component preparation and wiring
  - Marking labelling and packaging
  - Laser marking
- Access control:
  - Flight equipment manufacture and EGSE manufacture is undertaken in the Main Cleanroom, which is an access controlled cleanroom with limited access to manufacturing cleanroom engineering staff

3.3.8 ADS-P View on Facilities

The Airbus Portsmouth site has a very extensive range of space development and test facilities which effectively constitute a one-stop-shop for many of its own programmes, although it recognises that its thermal vacuum facilities in particular are not large enough for spacecraft-level testing. Airbus already makes its vibration, shock and EMC facilities available to external customers and is keen to add access to its clean rooms to this list. It can appreciate the benefit that the larger testing facilities currently under discussion, both existing and planned, for the Harwell site, will provide for its own programmes and for the UK space community as a whole, with the exception of the possible EMC/NF antenna test range since it believes that its Portsmouth facility already satisfies that demand.

3.4 Airbus DS Stevenage

3.4.1 ADS-S Company Background

For over six decades the Airbus Defence and Space site of Stevenage in Hertfordshire has been the lynchpin for the development and construction of Telecommunications, Scientific, Earth Observation and Metrology Satellites, structures, propulsion systems, mechanisms and antennas. The Stevenage site has an AIT workforce of over 300 highly qualified and skilled employees who operate in some of the best equipped and state-of-the art development, assembly, test and production facilities in the space industry. The AIT facilities offer a comprehensive suite of manufacturing and test capabilities from piece part manufacture, construction of light weight honeycomb panel composites; CFRP filament wound composites, to full structure assembly, including propulsion, harness and thermal subsystems, to the assembly integration and test, of complex satellites in clean rooms of cleanliness class ISO 8. The Environmental test facilities include vibration, shock, thermal vacuum, climatic, static and high powered RF testing in vacuum to support the qualification of components, equipment's, mechanisms and antennas.

The extensive range of facilities provides customers with a 'one stop' test house capable of handling products from individual components (ADTMs / SADMs / Cryogenic Coolers) to spacecraft payloads (CSO Propulsion Module) and complete satellites (Clyde Space and SSTL). ADS services cover a variety of environmental simulation tests with the ability to meet bespoke monitoring requirements for the articles under test.

3.4.2 ADS-S Mass Properties and Structural Test Facilities

Airbus DS Stevenage has comprehensive facilities for measurement of mass properties, including mass, centre-of-mass and moment-of-inertia. In its Structural Test Facility it is has 3 structural test beds able to conduct qualification and proof-loading tests of spacecraft using precisely controlled load applications up to 600kN with dynamic and static data logging of displacement measurements on up to 100 channels.

Figure 3.10 ADS Stevenage Structural Test Facility

3.4.3 ADS-S Vibration Facilities

There are two vibration facilities available capable of delivering 160kN and 40kN of dynamic force in 3 orthogonal axes. This enables testing of a wide range of products ranging from small components, of a few grams, up to large payloads of several tonnes.

Both vibration tables are driven by the latest digital controllers capable of sine, random and shock profiles, which can excite at levels from 0.1 to 100g up to 2000 Hz. Multiple channels of data may be recorded and analysed in real time from the control room. The latest system allows up to 120 channels of data to be analysed simultaneously, or by the addition of a second recorder, a further 40 channels can be added.

- Ling Electronic Industries C340 Vibrator (Large Shaker)
  - Max Thrust: 160kN
  - Frequency Range: 5 to 2000Hz
  - Max. Velocity: 1.9m/s
  - Max. Displacement: ± 19 mm
  - Hydrodynamic Slip Tables: from 1.2m x 1.2m to 2.4m x 1.52 m using outrigger bearings
  - Head Expanders from 0.61m to 1.06m diameter with Hydrodynamic Guidance System and Pneumatic Mass-Cancelling System.

Figure 3.11 ADS Stevenage V954 Vibrator

- Ling Dynamic Systems V954 Vibrator (Small Shaker)
  - Max thrust: 40kN
  - Frequency range: 5 to 2000 Hz
  - Axial velocity: 1.77m/s
  - Max displacement: ± 12mm
  - Hydrodynamic slip table 0.9m x 0.6m
  - Head expanders: 0.35m diam to 0.5m x 0.5m

- M+P International VXI Controller x 2 off
  - 120 and 64 channel analysis system
  - Sine, random and shock control and analysis

- Data Channels
  - 72 channels of data physics real-time shock and vibration data capture
  - 46 channels of strain instrumentation
  - 18 channels of force instrumentation

3.4.4 ADS-S Shock Test Facility

ADS Stevenage has a shock test machine with the following characteristics:

- SRS Shock Generation via a Swing/Drop Hammer
- Equipment mass: up to 30 kg

- Frequency Range: 3 Hz min to 46,000 Hz max
- Resolution: typically 1/12th octave spacing
- Max Acceleration: 3000g
- Swing Arm Length: 1.5m
- Max Drop Height: 3m
- Measurement Channels: 64

3.4.5 ADS-S Clean Rooms

ADS Stevenage has a number of clean rooms of various sizes for unit level and system-level AIT. The largest is the Perseus clean-room, used for spacecraft integration and test. Several of these are available for use by external customers subject to availability and normal commercial arrangements.

Figure 3.12 ADS-Stevenage Perseus Clean-Room

3.4.6 ADS-S Thermal Vacuum Facilities

The Stevenage site has a number of vacuum chambers capable of simulating the extreme conditions of space including:

- 2.2m Vacuum Chambers (x 2)
  - Volume available: 2200 mm diam x 2200 mm long
  - EUT max length x width x height: 2100 mm x 2100 mm x 2100 mm
  - EUT max weight: 1000 kg
  - Temp Range: -170°C to +100°C
  - Vacuum: <1*10^{-5} mbar
  - Measurement Channels: 100
- 1.5m Vacuum Chambers (x 3)
  - Volume available: 1500 mm diam x 1500 mm long
  - EUT max length x width x height: 1400 mm x 1400 mm x 1400 mm
  - EUT max weight: 600 kg
  - Temp Range: +180/-180 degrees C
  - Vacuum: <1*10^{-5} mbar
  - Measurement Channels: 100

Figure 3.13 ADS-S UHV Chamber

- Ultra-High Vacuum Chambers (x 2)
  - Volume available: 1000 mm diam x 1300 mm long
  - EUT max length x width x height: 1200 mm x 1200 mm x 1200 mm
  - EUT max weight: 60 kg

- Temp Range: -170°C to +150°C
- Vacuum: <1*10^{-5} mbar
- Measurement Channels: 100

Figure 3.14 Airbus DS Stevenage TVAC Facilities

All of these chambers are potentially usable by external customers subject to availability.

3.4.7 ADS-S RF Testing Facilities

Airbus DS has a comprehensive range of RF design and test services at Stevenage, including EMC, RF Compatibility and high-power microwave test facilities, most of which are located in a fully shielded 10m x 12m x 15m anechoic chamber. The chamber is suitable for EMC and RF testing of electronic components, antennas and complete spacecraft and has the following characteristics:

- Fully welded Faraday cage providing 100dB screening up to 40GHz
- Access doors 8m x 10m
- Temperature controlled to 20°C ±3°C
- Relative Humidity controlled to 50% ±10%
- Area controlled to ISO 8 (Class 100,000)
- Includes thermal chamber with temperature range ±140˚C for PIM testing
- Power handling capability 1500W/m^2
- RAM temperature monitoring using thermal imaging

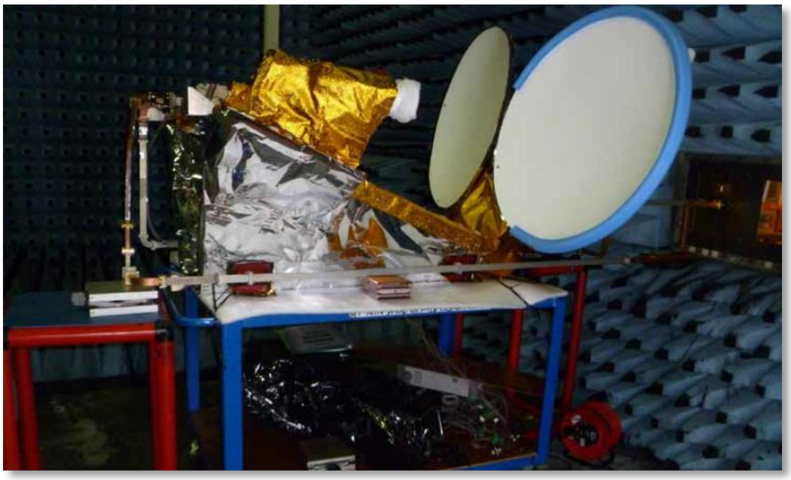


Figure 3.15 ADS Anechoic RF testing chamber

The chamber is typically used for:

- Passive Inter Modulation (PIM) testing at L, C, Ku and Ka-band
- Thermal PIM testing at C, Ku and Ka-band
- Thermal PIM temperature range currently ±/140˚C
- PIM testing of reflectors, feed chain assemblies and complete antennas
- Power handling of feed assemblies

- Two high power Ku-band amplifiers are available as follows:
  - 2 x 4000W Ku-Band amplifiers
  - Frequency range of 10.0 to 12.75GHz
  - Configurable to provide 2 x 2000W per amplifier
  - Combinable to provide 8000W output
  - Protected with internal isolators but can withstand a full short circuit up to 57dBm
  - The Amplifiers can be configured in the Anechoic Chamber free radiating with power handling capability 1500W/m^2 and with RAM temperature monitoring using thermal imaging cameras
  - Or in the dedicated TVAC chamber for power handling of waveguide components and multipaction testing of waveguide components

Figure 3.16 High power Ku-band amplifiers

3.4.8 ADS-S Propulsion Activities

In the field of spacecraft propulsion, ADS Stevenage provides support to spacecraft system design, platform engineering, manufacture, assembly and integration. It provides full end-to-end testing and launch site preparation and fuelling at various launch sites including Kourou, Baikonur, Plesetsk and US sites in California and Florida. ADS undertakes full system integration of large bipropellant, monopropellant, cold gas and plasma propulsion systems. The Propulsion Team is a multi-project group encompassing 22 propulsion system platforms currently in build at Stevenage including all 39 Eurostar Telecoms programmes: 10 UK MoD platforms, MetOp, Aeolus, Aeolus ICS, LISA PF, Bepi Colombo, SWARM, GAIA, CSO and EarthCARE. The Company is experienced and fully qualified in the transportation and handling of hazardous materials in accordance with COSHH, REACH and IMDG.

Figure 3.17 ADS-S Propulsion System Test and Propellant Loading

3.4.9 ADS-S Thermal Design and Manufacturing Facility

Airbus has vast experience in internal and external thermal design to meet the thermal requirements of the harsh space environment. The Thermal Blanket team has been responsible for the design and manufacture of varying different lay-ups of Multi-Layer-Insulation (MLI), with experience in the delivery and installation of both test and flight blankets for over 30 years, in support of many spacecraft programmes. The team also has the responsibility for the design and manufacture of spacecraft antenna sunshields, which combine effective thermal protection with RF transparency and total ESD protection for all sizes of antenna reflectors. The Thermal Blanket facility is located in the Phoenix clean room with the following characteristics:

- Clean room dimensions (W x L x H): 10m x 45m x 3m
- Temperature controlled: 20°C ± 3°C
- Relative Humidity controlled: 50% ± 10%
- Central monitoring and control of temperature and humidity to ISO 8
- Ultrasonic cutting machine Multi-Layer Insulation (MLI), Dual-Layer Insulation (DLI) and Single-Layer (SLI)

Figure 3.18 ADS-S MLI Facility

3.4.10 ADS-S View on Facilities

Like ADS-P, the Airbus Stevenage site has an extensive range of space development and test facilities which effectively constitute a one-stop-shop for many of its own programmes, although it too recognises that its thermal vacuum facilities, although larger than Portsmouth's, are still not sufficient for testing large spacecraft. The Airbus Stevenage vibration, shock, thermal-vacuum and EMC facilities are routinely available to external customers and it too is keen to add its clean rooms to this list of accessible facilities. Its views on the large testing facilities at Harwell are akin to those of ADS-Portsmouth.

3.5 Airbus Group Innovations, Newport and Bristol

3.5.1 Airbus Group Innovations Background

Airbus Group Innovations is a Global Network of research facilities, scientists, engineers and partners focused on delivering leading-edge research and development to the wider Airbus Group. It operates a global network of corporate Research and Technology (R&T) laboratories that guarantee its innovation potential with a focus on the long term. The structure of the network is consistent with the Airbus Group R&T strategy and covers the skills and technology fields that are of critical importance to the Group. Its teams are organised into seven transnational Technical Capabilities Centres:

- Composites Technologies
- Metallic Technologies and Surface Engineering
- Structures Engineering, Production and Aeromechanics
- Engineering, Physics, IT, Security Services and Simulation
- Sensors, Electronics and Systems Integration
- Innovative Concepts and Scenarios
- Energy and Propulsion

Within the UK, Airbus Group Innovations concentrates on the last of these capabilities, Energy and Propulsion research, which is split across two sites – Filton, Bristol and Newport, South Wales. Its core competence is system-level simulation and modelling of a wide range of platforms, focusing on the energy architecture. Highly integrated systems offer a new opportunity to optimise energy distribution and management in order to maximise the performance of a system in an energy-limited environment. Recent case studies include the ExoMars Rover (Project Endover), a Single Aisle passenger aircraft (Project; IPPA), a Small Fuel Cell Hybrid UAV (Project: SUAV), and a distributed propulsion future aircraft (Project: DEAP).

3.5.2 Airbus Group Innovations Facilities

In order to support these activities, Airbus Group Innovations offers a capability to include hardware-in-the-loop testing and simulation. Past activities have included batteries, fuel cells, solar panels and electric motors. Its highly configurable lab at the Newport Campus is equipped with a range of controllable power supplies and electronic loads, alongside a comprehensive suite of test and measurement equipment. Past hardware investigations have included a 250W PEM fuel cell (complete with a 10L/min hydrogen electrolyser), 3kW UAV electric motors for main propulsion, and various other electronic loads and energy systems such as solar, thermoelectric, and lithium batteries. The Newport site also has access to a wide range of technical facilities in the wider Airbus community (Power Campus, Battery Lab) and through its academic partners.

Figure 3.19 Hardware-in-the-Loop simulations at Airbus Group Innovations

3.5.3 Airbus Group Innovations View on Facilities

Airbus Group Innovations' Newport Campus has World-class facilities to support its energy and propulsion research activities and is happy to work with external users whenever appropriate.

3.6 AVS-UK, Harwell

3.6.1 AVS-UK Company Background

AVS-UK is a UK subsidiary of the Spanish company AVS (Added Value Solutions) based in Harwell and is an ISO 9001 and EN 9100 certified engineering consultancy company, offering full lifecycle development from conceptual design to manufacture, assembly, integration and commissioning. It makes mainly one-off products such as mechanisms for ground telescopes, fibre positioners, ion sources, control and diagnostics/measurement systems, optics and electric propulsion systems. It has only recently set up in the UK and at present may be considered a facility user rather than provider. Its plan is to ramp up to 20 employees over the next 5 years, when it expects to be involved with deployable optics, and engineering for international facilities such as ESRF, CERN, ILL and SKA. The company also has an increasing interest in electric propulsion, especially the niche technology of electron cyclotron resonance (ECR) plasma thrusters and the plasma diagnostic facilities required to evaluate their performance.

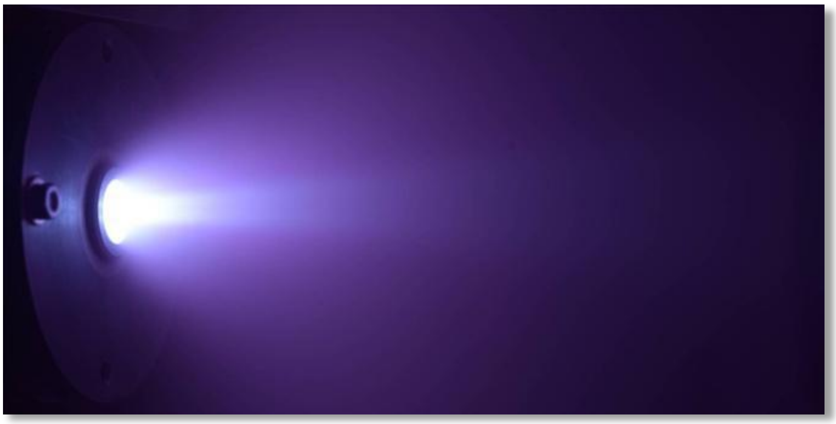


Figure 3.20 ECR plasma thruster

3.6.2 AVS-UK View on Facilities

At present AVS-UK has no facilities in the UK for manufacturing or testing its specialist mechanisms or optical products and so it plans to take advantage of the existing and planned development and test facilities which are currently being established within the Harwell Space Cluster. Similarly the lack of electric propulsion test facilities suitable for its ECR work, represents a facilities gap for AVS, which may possibly be met by modifications to and access to the QinetiQ or TAS-UK facilities.

3.7 3C Test Ltd, Silverstone

3.7.1 3C Company Profile

3C Test Ltd is a fully independent EMC test house, originally known as Triple C Ltd which was located in Grendon Underwood, Bucks, until it moved to Silverstone, Northants, in 2006, changing its brand name as it did so. Major investment of over 1.5 million pounds signifies how 3C Test has evolved to become one of the UK's leading EMC test houses, underlining the company commitment to delivering first class EMC testing for a wide range of industries, including space, for companies such as COM DEV. 3C Test is UKAS accredited to BS EN ISO 17025: 2005 and holds many other country and manufacturer specific accreditations.

3.7.2 3C Test EMC Facilities

3C's EMC facilities include:

- 3m CISPR 16 Semi-Anechoic Chamber
- 10m CISPR 16 Semi-Anechoic Chamber
- Three CISPR 25 Semi-Anechoic Chambers
- Five Automotive Electrical Test Laboratories
- ESD Test Laboratory
- General Purpose Screened Room
- Radio Laboratory
- Safety Laboratory
- High Voltage Test Laboratory

Figure 3.21 Typical 3C Test Anechoic Chamber

Within these facilities the Company can offer the following tests:

- Radiated Immunity: 20Hz - 18GHz up to 600V/m (depending on frequency range and test method)
- Test methods include tri-plate, bulk current injection, stripline, electric and magnetic free field
- Radiated Emissions: 20Hz – 26.5GHz Conducted Emissions: 20Hz – 400 MHz
- Transients: Configurable systems covering all pulses specified by ISO 7637
- ESD: Variable networks up to ± 30 kV, contact and air
- DC Electrical Performance testing using fully variable set-ups with function generators in tandem with DC-10kHz amplifiers of up to 5kW capability

3.7.3 3C Test View on Facilities

3C Test has become one the UK leading EMC test houses and fully intends to maintain that position. It can provide a comprehensive EMC testing service at unit or subsystem level.

3.8 *Cardiff University*

3.8.1 Cardiff University Background

Cardiff University was formally established by Royal charter in 1884, and is recognised in independent UK government assessments as one of Britain's leading teaching and research-intensive universities. Its world-leading research was ranked 5th amongst UK universities in the 2014 Research Excellence Framework (REF 2014) for quality and 2nd for impact. The University is the acknowledged leader of higher education in Wales. It is the Principality's only member of the Russell Group of research-led universities and has two Nobel Laureates on its staff. It has approximately 20,000 undergraduates, 8,000 postgraduate students, 6,000 staff and an annual turnover of around €525M. In terms of income, Cardiff had research grant income of €145M in 2013/14, a European portfolio in excess of 150 FP7 projects with a value of €70M, and 26 Horizon 2020 projects to date with a value of €16M.

The University comprises 3 Colleges, each with a number of Academic Schools. The College of Physical Sciences & Engineering is where the University's space activities are concentrated in two of its Schools: the School of Physics and Astronomy, which includes the Astronomy Instrumentation Group (AIG); and the School of Engineering, which includes the Gas Turbine Research Centre (GTRC); both of which are described below.

3.8.2 Astronomy and Earth Observation Instrumentation Group (AIG)

The School of Physics and Astronomy hosts a large and World-leading astronomy and Earth observation instrumentation group. The instrumentation group consists of approximately 40 researchers with expertise in the development and integration of new technologies for ground-based, balloon-borne and space-borne instruments for astronomy, Earth Observation and security applications. Cardiff has much experience in the development of technology for space-borne astronomy, with key roles in a number of past, ongoing and future instruments and missions such as SCUBA, ISO, Herschel, Planck, SCUBA-2, SPICA-SAFARI, JWST-MIRI, EChO, ARIEL, Twinkle and COrE+.

As well as astrophysics applications, the group is currently developing major hardware components for the MetOp-SG series of operational meteorology satellites, due for launch starting in ~2021. The group has also proposed a novel Earth observation instrument concept for satellite-borne atmospheric observations, for meteorology and climatology applications, following a feasibility study funded by UKSA via CEOI-ST.

The Cardiff instrumentation group has an excellent global reputation for building instrumentation for space, covering design, development, test and calibration. Much of this work has been funded by STFC, UKSA, and by the European Space Agency, working collaboratively with industry partners.

The group has particular expertise in:

- Sensors and detectors
  - State-of-the art detectors arrays for FIR-Submm wavelengths
  - Development and precision characterisation of low-dark-current MWIR-VLWIR detector arrays
- Cryogenics and thermal design
  - Cryogenic system design and engineering for satellite applications
  - Overall instrument thermal design and analysis
  - Cryogenic thermal testing
  - Precision thermometry for satellite applications
  - Thermal control systems
- Satellite data
  - Image processing expertise
  - Satellite image analysis expertise
  - Big data workflows and decision-support
  - Data security

  - Geophysical mapping and remote sensing
  - Astronomical image processing and data analysis expertise

- Optics and coatings
  - World-leading capability in THz optics and quasi-optics
  - THz filters, dichroics, beam dividers, polarisation analysers etc.
  - General optical design expertise
  - Space-qualified coatings for optics and for thermal engineering
  - High-temperature metal-oxide coatings – preparation and characterisation
  - Materials for X-ray polarimetry – investigation of X-ray dichroism in crystals – for development of polarisation analysers in astronomical instruments

- Satellite instrument system design and engineering
  - Expertise in overall satellite instrument system design and engineering
  - Space project management and quality assurance

- Mission design and planning
  - Expertise in planning astronomy and Earth observation missions

- Satellite hardware qualification and product assurance
  - Expertise in qualification of components and hardware for spaceflight
  - Expertise in product assurance for space instrumentation

3.8.3 AIG Facilities

Cardiff AIG has a range of facilities to support its space research activities, including:

Cleanrooms: Several fully-equipped cleanrooms from ISO-8 to ISO-5 (Class 100,000 to Class 100) available for device manufacture, component assembly, metrology, and instrument integration.

Figure 3.22 Typical AIG cleanrooms

Antenna test range: Antenna test range and Vector Network Analyzers available. Test range is suitable for frequency range 20 GHz – >1 THz; VNA coverage 0 GHz – 330 GHz.

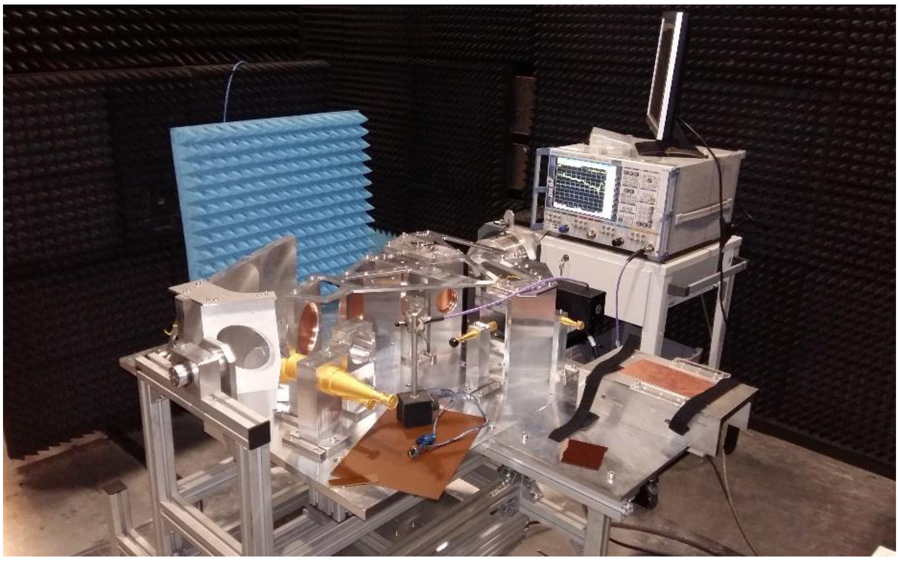


Figure 3.23 Antenna test range and VNA test set-up

Optical metrology and testing: Numerous optical tables and a full range of metrology equipment.

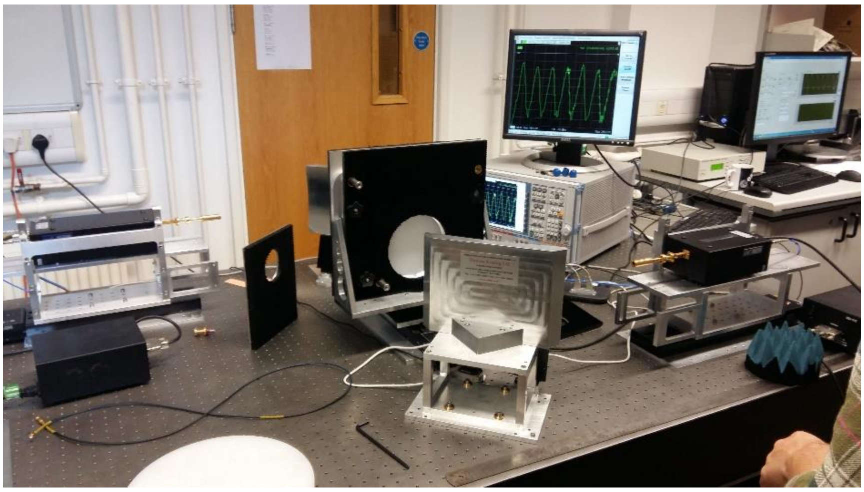


Figure 3.24 Typical optical test set-up

Spectroscopy suite: Spectroscopy covering the visible to millimetre wavelength range, and sample temperatures down to ~ 2K.

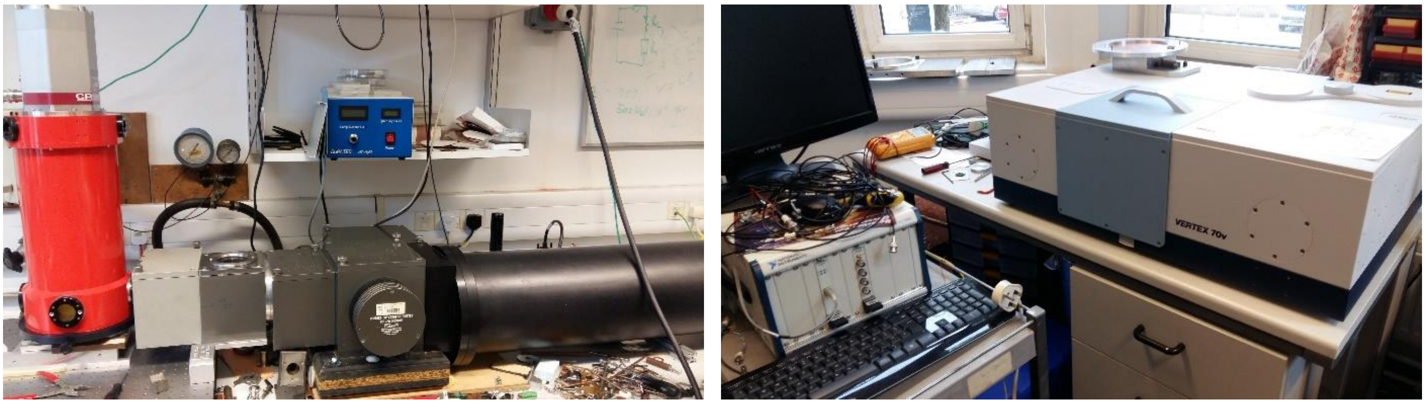


Figure 3.25 AIG Spectroscopy suite

Cryogenic test facilities: Large range of test beds available, with and without optical ports, for characterisation down to ~8mK.

Figure 3.26 AIG Cryogenic test facilities

Thermal/Vacuum facilities: There are a variety of vacuum ovens and thermal control chambers available. The large thermal chamber has internal dimensions 3m x 3m x 3m, and an operating temperature range of -40°C to +60°C.

Figure 3.27 AIG large thermal test chamber

Detector characterisation and calibration: Full suite of facilities for testing and calibrating detector arrays. Existing facilities for characterising arrays in the wavelength range from visible to ~3mm, and in the temperature range from 8mK up to room temperature. These facilities have been used for calibration of satellite-borne detectors and arrays.

3.8.4 Gas Turbine Research Centre (GTRC)

Cardiff's combustion researchers are building on over half a century of research history inherited from the National Gas Turbine Establishment at Pyestock, near Farnborough, to meet the sustainable energy challenges of the 21st century. The Gas Turbine Research Centre (GTRC), part of Cardiff School of Engineering, replaced the combustion capability originally created to support the UK Government and aerospace industry in the development of gas turbine technology. These facilities were commissioned in 2007 as a strategic investment in experimental hardware for future energy systems. The centre's mission is to generate original data to enable model validation or empirical model development, and the potential contribution of GTRC is distributed over a variety of impact areas including propulsion, power generation, alternative fuels and the environmental impacts. For 10 years (1994-2003) the University was the only EU-recognised academic partner in the EU consortium designated to increase access to training and research on large-scale combustion facilities (with co-partners ENEL and International Flame Research Foundation (IFRF)). Cardiff also chaired the EU 'Round Table on Energy' for 10 years, until 2003.

Cardiff has been developing optical, non-intrusive laser-diagnostic techniques for use in power-generation applications for almost 30 years, and successfully engages with a range of industrial companies on collaborative R&D programmes utilising these skills, hardware and expertise (LDA, PDA, LIF, PIV and Schlieren). Cardiff School of Engineering operates a successful ongoing partnership with the Danish advanced diagnostics developers and manufacturers, DANTEC Dynamics. In terms of combustion expertise, the Cardiff University group is known for characterising and developing understanding of combustion instabilities, combustion of difficult fuel mixtures, swirl flows and combustion, large-scale combustion hazards (e.g. explosions) and characterising / modelling fuel sprays and spray combustion processes.

3.8.5 GTRC Facilities

The key experimental test rig comprises a **High Pressure Optical Chamber (HPOC)** allowing for the observation and optical analysis of gas and liquid flames operating in diffusion and premix modes. The combustion air is supplied by a 2.2MW Joy compressor capable of delivering up to 5kg/s of air at 16bara. This air is pre-heated by a non-vitiating heater capable of raising the air temperature to 900K. A convergent-divergent nozzle pf diameter of 45mm accelerates the flow to Mach 5. Liquid fuel is delivered via a pressurised accumulator which can supply different liquids including kerosene, and bio-derived oils. Oxygen enhancement is supplied either unmixed or pre-mixed with the air upstream of the inlet, where the fuel is then introduced to the oxidant mixture via a specific mass flow controller. Downstream of the combustor in the exhaust there is an R-Type thermocouple to give representative entry temperatures and upstream of this the gas analysis sample is taken. Combustor acoustics are measured using dynamic pressure transducers at multiple configurable locations.

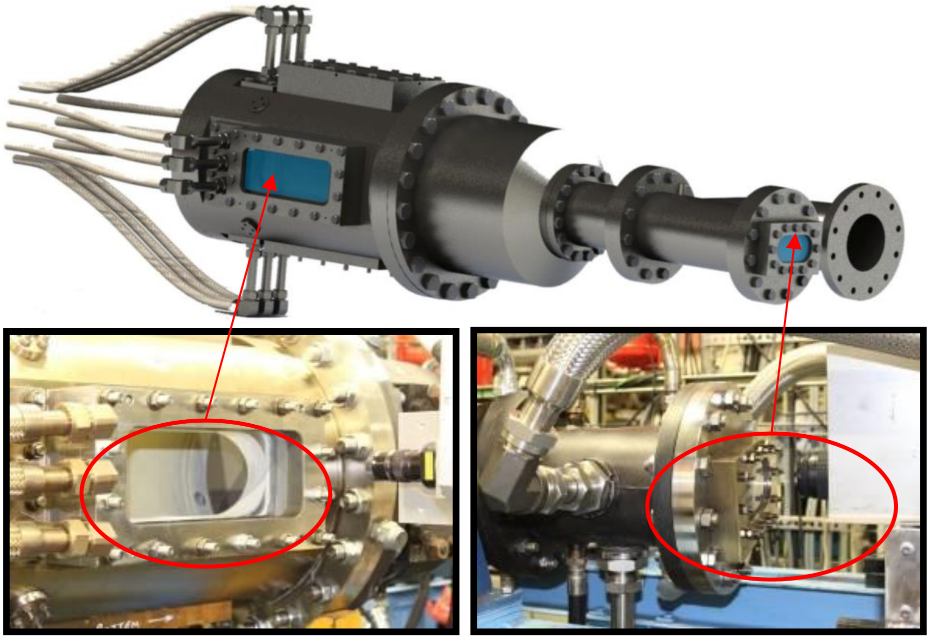


Figure 3.28 GTRC's High Pressure Optical Chamber (HPOC)

This setup was intended to demonstrate the velocity distributions in the flow-field and flame-front location, which allows for the determination of critical combustion parameters such as integral length scales and turbulence intensities.

Phase-resolved particle-imaging velocimetry (PIV) – integrated with a suitable triggering device such as a hot-wire probe (isothermal), pressure transducer (hot), enables efficient generation of temporally-resolved planar flow fields. There is considerable time benefit in using a planar characterisation technique such as PIV in this instance, as it is now easier to build fully 3-dimensional plots of these complex structures by systematically traversing downstream. However phase-locked laser Doppler anemometry (LDA) has many advantages and is often complementary to PIV for phase-locking purposes.

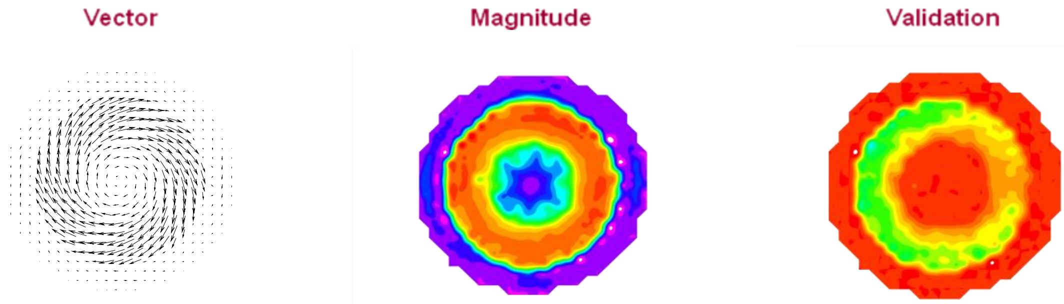


Figure 3.29 Processed Radial Velocimetry Images

GTRC's **Atmospheric Spray Rig** can handle a variety of gases and liquids at pressured delivery up to 150barg and a bulk flow rate up to 250g/s for ambient atmospheric measurements. The injector bulk temperature can be controlled via a thermostatically-controlled, actively-heated, water circuit arrangement around the injector mounting point, affording injector delivery temperatures of up to 90°C.

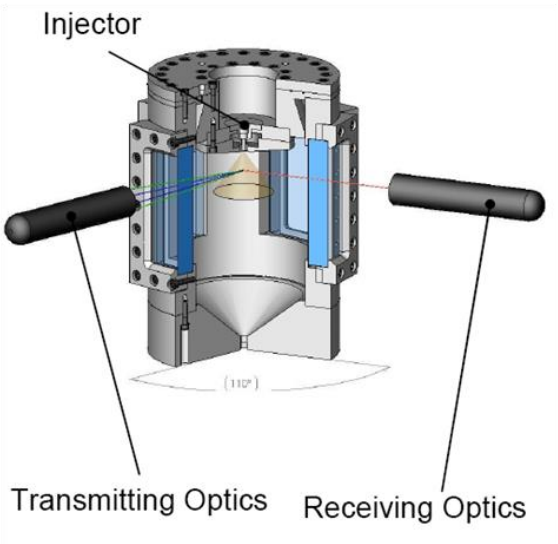


Figure 3.30 GTRC's Pressurised Spray Rig

The bespoke spray characterisation test rigs were designed to facilitate multiple optical access options affording, if required, the capability of simultaneous laser sheet imaging and Phase Doppler Anemometry (PDA). The Dantec PDA system facilitates measurements of droplets in the range 0 to 2132µm with a resolution of 0.02µm at velocities of -100 to 650m/s in 2 dimensions, more than sufficient as the expected velocities from a Pintle injector are in the range 10-50m/s.

The spray rigs also benefit from a custom-designed air curtain which facilitates improved acquisition times for both undisturbed, uninterrupted multiple transient injection characterisation or steady state injection characterisation options.

3.8.6 Cardiff University View on Facilities

The AIG has excellent facilities, potentially available to external users. AIG has significant experience of collaboration with industry and research institutions in the UK and abroad, and is very happy to work with external customers subject to resource availability and standard commercial arrangements. AIG is recognised as a World-class provider of IR and FIR/Submm instrumentation for space. The Group would like to upgrade its thermal infrared array cryogenic test facility to run from a cryogen-free cooler, and add the capability for precision characterisation of individual pixel response using a cryogenic spot-projector system and 3-D nano-positioning system, to position itself well for upcoming mission opportunities such as ARIEL. This would be an upgrade to a general-user calibration facility available to the community.

The GTRC provides an exemplar of an off-site university-industry Science and Innovation Centre, delivering circa £1M of contracts per annum. Since its launch in October 2007, the GTRC has a proven track record of delivering research and commercial projects on time and on budget e.g. £150k European Union FP5 project AFTUR, €2.0m SAMPLE I, II, III.1-5 projects for European Aviation Safety Agency (EASA), €2.0m DG MOVE on Aerospace, TATA combustion training courses, £1.8m Low Carbon Research Institute (LCRI) from the Welsh European Funding Office (WEFO), various EPSRC grants and contracts with Rolls-Royce, Ricardo and the HSE.

3.9 *Clyde Space, Glasgow*

3.9.1 Clyde Space Company Background

Founded in 2005, Clyde Space is an award winning British SME that has grown to become a leading supplier of nanosatellite and small satellite technologies. It is renowned for its extensive heritage, cutting-edge products, and robust management approach within the nanosatellite and small-satellite market, in particular in the CubeSat area of nanosatellites. Clyde Space hardware supports 40% of all CubeSat missions and Clyde Space is regarded to have more hardware in space than any other small satellite provider. It designed and manufactured Scotland's first satellite, UKube-1, commissioned by the UK Space Agency. Launched in July 2014 it has now successfully completed its mission, and has helped Clyde Space grow to the point of constructing an average of 6 spacecraft per month.

Clyde Space supports space missions at all levels, from conceptual design, development, integration, testing, through to launch and on-orbit operations, enabling a truly 'turn-key' mission offering. The Clyde Space product offering has two halves: its off-the-shelf products consisting of subsystems and full platforms, available at the click-of-a-button, and its bespoke solutions, which are designed specifically to meet its customers' requirements. These range from tailor-made subsystems to full mission design, integration and test.

Clyde Space off-the-shelf products range from subsystems of all varieties, to fully-integrated platforms. These affordable flight-proven spacecraft consist of off-the-shelf platform solutions and bespoke designs offering shorter development times and reduced costs. Clyde Space recognises that each customer's mission is different and feels that a 'one-size-fits-all' approach is out-dated; which is why its modular platforms can range from 1U to 27U and combine space-qualified off-the-shelf subsystems with its unique nanosatellite systems engineering expertise.

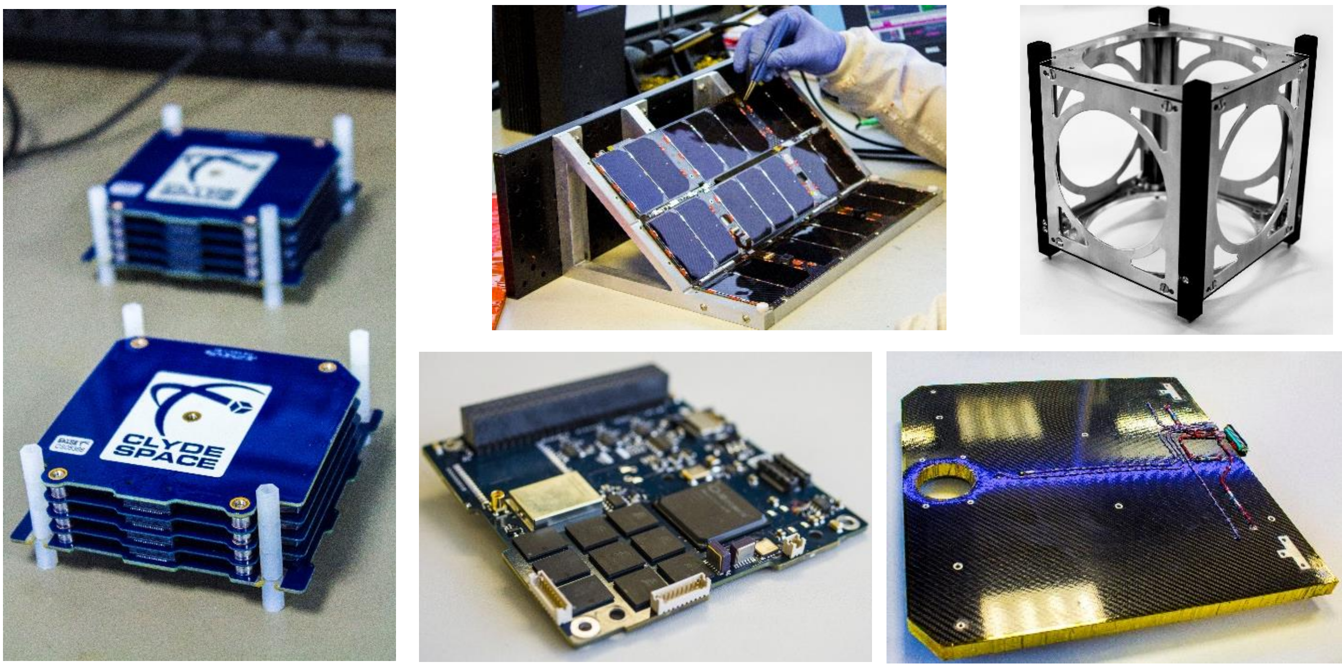


Figure 3.31 Clockwise from left: CubeSat Battery, Double-Deployable 3U Solar Panel, 1U CubeSat Structure, Nanosatellite OBC, Small Satellite Solar Panel

Clyde Space has over a decade of experience as a leader in the field of nanosatellite design and subsystem provision, and has supplied over 2,000 subsystems for small spacecraft ranging from 0.5kg to 250kg in size to a global customer base that includes NASA, ESA, JAXA, UKSA, US Navy, LuxSpace (OHB), KARI, Spire, Outernet, and many more.
Clyde Space customers include international universities, commercial companies and government organisations, with over 90% of sales being outside of the UK, and two-thirds to repeat customers. Clyde

Space has a proven track record of developing high quality flight hardware to challenging delivery deadlines at a market-disrupting price-point, adding real and immediate value to customers' mission developments.

Key to the company's success is the Clyde Space Quality Management System, fully compliant with ISO-9001, which covers all of its products from development through manufacture and delivery, ensuring that its business is conducted in a sustainable manner within a culture of continuous improvement, fostering innovation and growth.

3.9.2 Clyde Space In-house Facilities

Based at Skypark in the heart of Glasgow, Clyde Space premises include a 600m^2 Class 10,000 clean-room and 200m^2 of electronics labs. These facilities allow Clyde Space to both manufacture and test in-house with its ESA-qualified technicians.

Figure 3.32 Clyde Space Cleanroom

Clyde Space headquarters has recently expanded by a further 250m^2 to accommodate a new clean room dedicated to its environmental test facilities. This expansion comes after the company's most successful year to date and just 13 months after moving from its previous base. With further expansions of 400m^2 previously announced the total cleanroom capacity will be 1000m^2 in 2016. The clean room and component stores are fully ESD controlled and strictly monitored.

Clyde Space offers a complete on-site environmental test capability. The facilities include: on-site light sources for testing solar panels; a thermal test chamber suitable for performing thermal cycling tests on both EM and flight hardware, which can cycle over a temperature range of -70°C to -180°C; a thermal vacuum chamber and vibration testing rig. These have been sized for qualification testing of nanosatellite spacecraft platforms up to 6U (12kg) in size.

In addition to its manufacturing and test facilities, in order to support the growing fleet of Clyde-built spacecraft, the company is also establishing a satellite command and control ground station at its headquarters. This facility is expected to come on-line in late 2016 and will initially feature VHF, UHF, and S-band communications capabilities.

3.9.3 Clyde Space View on Facilities

Clyde Space's in-house facilities are fully committed to its own extensive manufacturing and test programmes and so the company does not offer stand-alone testing services, instead primarily offering these as subsets of larger programmes. The main testing elements still performed at external facilities are EMC testing, radiation testing, and environmental testing of solar panels for larger spacecraft.

The low-cost philosophy behind nanosatellites drives a need for a cost reduction in environmental testing compared to the more traditional approach to space; in addition to expanding their own facilities, Clyde Space is working to establish a network of external test facilities prepared to address this market need.

3.10 Cobham RAD Solutions, Harwell

3.10.1 Cobham Company Background

Cobham RAD Solutions (formerly Aeroflex RAD), with a new base in Harwell, is the UK arm of the US radiation effects company Cobham RAD of Colorado Springs. Cobham RAD Solutions offers a radiation testing capability unmatched in the UK for assessing the effects of ionising radiation on materials and components for use in the challenging environment of space. The Company specialises in building a test and measurement system around a customer's samples in order to derive data on their performance before, during and after exposure to radiation. This process provides the data needed to complete the design and qualify products for space.

Cobham operates its own gamma irradiation facility for total dose testing and undertakes frequent tests in other facilities, e.g. for single event effects testing and electron or neutron testing. Offering a data acquisition service, as well as basic irradiation, means Cobham can help customers understand the radiation-induced changes that take place. This knowledge can be used to assess equipment designs before testing so as to improve the chances of it passing the test. The synergistic effect of irradiation and other factors can lead to more rapid degradation than the sum of the individual effects would indicate. Hence, the Company also offers the possibility to irradiate in a range of gaseous environments and vacuum, with heating or cooling, with or without electrical stress and, for example with solar cells, under illumination.

3.10.2 Cobham Radiation Test Facilities

In addition to its existing total dose facility, Cobham plans to expand this capability during 2016/2017 to enable the irradiation of larger samples and at higher dose rates. Coupled with improved dosimetry and lower noise electrical measurement options, this will complement the space environmental test facilities currently under development on the Harwell campus. For high energy heavy ion and proton testing, Cobham has established access to a number of external facilities including University of Jyväskylä in Finland, Université Catholique de Louvain in Belgium, the Paul Scherrer Institute in Switzerland, the Lawrence Berkeley National Lab in California and the Cyclotron Institute at Texas A&M University.

Figure 3.33 Cobham Radiation Test Cell

Specific radiation test facilities and capabilities include:

- Total ionising dose (TID) RLAT (50 to 300 rad/sec or 3.6 to 36 krad/hr) according to

  – MIL-STD-883 or -750, test method 1019, condition A
  – ESA ESCC 22900, standard dose rate
- TID ELDRS (10 to 100 mrad/sec or 36 to 360 rad/hr) according to
  – MIL-STD-883 or -750, test method 1019, condition D
  – ESA ESCC 22900, low dose rate
- Neutron displacement damage testing
- Electron testing (1 to 23 MeV)
- Heavy ion single event effects testing (SEL, SET, SEGR, SEU, SEB, SEFI)

Figure 3.34 Heavy ion SE testing chamber used by Cobham at University of Jyväskylä

- Proton SEE and displacement damage testing (from 1 MeV)
- Gamma and alpha effects on materials
- Certificated to ISO 9001 and DLA Laboratory Suitability

3.10.3 Cobham View on Facilities

Cobham believes that being able to offer a full radiation testing service that includes not simply the irradiation of samples, but also their instrumentation, monitoring of performance degradation and analysis and interpretation of results, fills an important gap in this aspect of component and sub-system performance in space.

Cobham believes that its larger, high dose rate irradiation facility to be installed at Harwell in 2016 will provide an important capability and contribution to the proposed one-stop-shop in the Harwell Space Cluster.

3.11 COM DEV International (now part of Honeywell), Aylesbury and Edinburgh

3.11.1 COM DEV Company Background

COM DEV International Ltd is a global designer and manufacturer of space hardware and systems, and a world leader in the production of space-qualified passive microwave equipment, specialized electronics and optical subsystems. COM DEV has facilities in Canada, UK, USA, India and China, although this report concerns only the UK facilities, especially those in Aylesbury and Edinburgh (originally MESL Microwave, which COM DEV acquired in Dec 2014). COM DEV announced in November 2015 its acquisition by Honeywell Inc, and this may provide more opportunities for UK growth as Honeywell has targeted the European Space market as a growth area. The Company has also set up an office in Harwell in order that it may actively participate in the rapidly growing Space Cluster.

3.11.2 COM DEV Satellite Products

Although this report primarily concerns space test facilities, it does encompass space development facilities and in that context it is useful to include a top-level summary of COTS space subsystems available in the UK. COM DEV has a comprehensive range of passive and active RF components and complete subsystems, with over 1000 flight units delivered to date. Components designed, manufactured and tested at the Edinburgh facility include waveguides, diplexers, Microwave ICs, couplers, SAW filters, isolators, circulators, rotary switches and phase shifters.

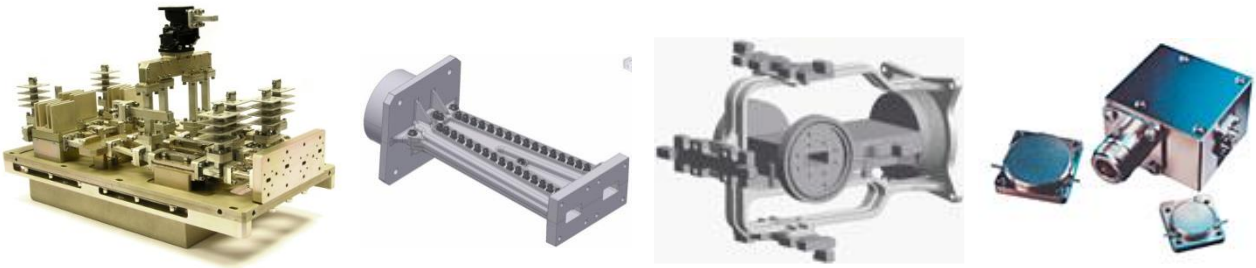


Figure 3.35 Typical COM DEV RF components: waveguide, diplexer, coupler, circulators

At the sub-system level, COM DEV produces a variety of space qualified equipment at the Aylesbury site including complex ferrite sub-systems for Earth Observation satellites, S-band transceivers for LEO satellites with a 5W transmitter, AIS receivers for this growing maritime application and an 8W 20Mbps C-band transmitter.

Figure 3.36 COM DEV S-band transceiver, C-band transmitter and typical Ku band RF sub-assembly

COM DEV's Canadian parent has built a number of small satellites in collaboration with the University of Toronto's UTIAS Space Flight Laboratory, based on a low-cost, adaptable multi-mission micro-satellite platform known as AIM, Advanced Integrated Micro-satellite. There is a possibility that such micro-satellites could be assembled, integrated and tested in the UK, with contributions from a UK supply chain, if the Company has access to suitable facilities, such as those existing and planned for the Harwell site.

Figure 3.37 COM DEV /SFL AIM Micro-satellite

3.11.3 COM DEV Vibration Facilities

Edinburgh

COM DEV has a small vibration facility at its Edinburgh site dedicated to the mechanical testing of its microwave components. It has the following characteristics:

- Manufacturer: Data Physics Vibration Systems
- Typical tests: MIL-STD-202G, Method 204D
  - Test Conditions: A, B, C, D, E, G
- Shaker Control Limitations:
  - Frequency range: 5 to 2000Hz
  - Max displacement: 50.8mm
  - Max velocity: 1700mm/s
  - Max acceleration: 88g
- MIL-STD-202G, Method 214A Test Condition I-F (20.71Grms)
- MIL-STD-202G, Method 214A Test Condition II-E (19.64Grms)
- MIL-STD-202G, Method 213 Table 213-1
  - Test Conditions A, B, G, H, J or K

The facility was set up specifically for in-house testing and would not normally be available for external customers.

Figure 3.38 Edinburgh Vibration Test Facility

Aylesbury

The Aylesbury site has a vibration facility for testing its RF subs-systems but which is also available for external users given sufficient planning and commercial arrangements.

It has the following characteristics:

- Manufacturer: M&P VibRunner
- Capability: random (with notching and limiting); sine; classical shock; and mixed mode sine with random
- Measurement channels: 16
- Max Force: 53kN
- Max displacement: 63mm peak-to-peak
- Slip plates: 1m x 1m and 0.6m x 0.6m

Figure 3.39 Aylesbury Vibration Test Facility

3.11.4 COM DEV Thermal and Thermal Vacuum Test Facilities

At its Aylesbury site COM DEV has a number of thermal test and thermal-vacuum chambers used to simulate the space environment, all of which are available for use by external users given sufficient planning and commercial arrangements.

Thermal Test Chambers

- Number of chambers: 6
- Fully programmable: ramp at pre-set rates
- Temperature range: -70°C to +130°C
- Climate: dry-air-purged

Figure 3.40 Aylesbury thermal test chambers

Thermal-Vacuum Chambers x 2

- Chamber 1: 0.9m diam x 1m length
- Chamber 2: 1.5m diam x 1m length
- Vacuum: <10^{-5} torr
- Thermally controlled baseplates and passive shrouds
- Temperature range: -35°C to +120°C

Figure 3.41 Aylesbury TVAC chamber

The Edinburgh site has an excellent thermal shock facility which is dedicated to in-house component testing so not usually available for external customers.

- Manufacturer: Angelantoni Test Technologies Srl (ACS)
- Type: ACS Thermal Shock Chamber
- Programmable dual chamber oven with <5 second transit times from hot to cold
- Temperature range: -90°C to +180°C

Figure 3.42 Edinburgh thermal shock chamber

3.11.5 COM DEV Clean Room Facilities

COM DEV's Aylesbury site has two Class 100,000 (ISO Class 8) Clean Rooms for the assembly and testing of space hardware. All operators within these facilities have been certified to ESA standards for the assembly of space hardware. Rigorous processes and procedures control is implemented, which has been audited by ESA and many of the European prime contractors. The recent acquisition of MESL Microwave Ltd offers further 100,000 (ISO class 8) clean room facilities within the Edinburgh site.

Figure 3.43 COM DEV clean manufacturing and test rooms

Within COM DEV's Aylesbury site the test laboratory, located in the clean room environment, is equipped with all the necessary COTS test equipment with which to perform electrical and RF measurements. COM DEV utilises both LabView and proprietary CTS software, developed by COM DEV, now installed in several locations with many years of heritage on multiple space programmes. The Edinburgh facility also offers increased RF and electrical test capability.

3.11.6 COM DEV RF Testing Facilities

Between the Aylesbury and Edinburgh sites, COM DEV has a full suite of design, analysis, manufacturing and test facilities used to produce its comprehensive range of RF, microwave and electronic products. The assembly, processing and test facilities used to support these product developments include:

- High-power RF test facilities covering L, S, C, Ku and Ka-band
- RF Testing:
  - S-parameters
  - Vector network analysers: 2-port and 4-port, DC to >50GHz
  - Automatic data capture through PC link and integration with Labview software
- EMC testing of RF components
  - Radiated emission and susceptibility
  - Spectrum analyser and RF Synthesised source to cover DC to 40GHz
- Glitch Testing
  - Detect and record glitches (i.e. sudden changes in the insertion loss of the units under test with amplitudes >0.05dB and durations >100msec), as test items subjected to changes in temperature
  - Water cooled oven for fast thermal response
  - Automatic testing under PC control
- RF Power and Intermodulation Distortion
  - Pairs of amplifiers for testing in the following power levels and frequency bands:
  - 500W 200-500MHz
  - 300W 825-2300MHz
  - 100W 2.5-2.8GHz
- PC control for automated testing and recording of results
- Environmental Stress Screening (ESS)
- Testing at high and low temperatures:

  - Numerous Votsch climatic chambers -40°C to +130°C
  - ATE controlled, holding pre-set dwells and saving s2p files
  - Overlay plots to show drift
  - In-house software calculates gradient with frequency and over temperature
- Thermal Shock and vibration facilities as described above
- Altitude chamber:
  - to 50,000 ft (75 torr)
  - thermal measurements of reverse power into load
  - bell jar, vacuum pump and interface plate for thermocouples, RF and DC connections

High Power Microwave Testing
COM DEV has a world class reputation for issues related to High Power Microwave design and test, and has invested heavily in facilities for the design and testing of complex waveguide equipment. This includes:

L band:
- 1000MHz to 2500MHz coverage
- Single channel testing to 1kW peak power
- Dual channel testing to 800W peak power/channel
- Typical pulsed signal of 40μs width at 1.5kHz prf
- ‘Free electron’ seeding source using Strontium 90 beta emitter (~290MBq)
- Detection systems
  - Phase nulling
  - Third harmonic
- System verification samples
  - 3-section bandpass filters
  - Coaxial stripline (parallel-plate)
- 2 vacuum chambers available – typical working pressure < 8 x 10^{-6} mbar
- Temperature control typically -40ºC to +80ºC

Ku band:
- 13GHz to 14GHz coverage
- Use of wave guide resonant ring provides maximum of 1kW peak power (dependent on DUT loss)
- Typical pulsed signal of 40μs width at 1.5kHz prf

Ka band: for the SWOT programme a world class high power test facility is being assembled, including assembly of a High Power S-parameter measurement system
- 35.75GHz operation (+/- 500MHz)
- Initial operation at 80W with intention to increase to 200W (HPA isolator dependent)
- Both CW and pulsed test signals possible, in principle
- 1-path, 2-port calibration possible (enhanced response)
- Temperature cycling capability over -25ºC to +90ºC (ambient pressure)

In summary COM DEV has the following test facilities for high power testing of microwave devices and equipment
- 1kW pulsed at 1 – 2.5GHz, 2 x 400W CW at 1 – 2.2GHz
- 200W CW at 10 – 14GHz
- 200W CW at 18 – 23GHz
- 200W CW at 27 – 39GHz

3.11.7 COM DEV Space Electronics Manufacturing Facilities

In addition to its RF test facilities described above, COM DEV has extensive space electronics manufacturing and test facilities available to support external customers in addition to its in-house programmes. Electronics production facilities include:

- **Assembly and Test:** Class 10,000 clean room area with dedicated Bonded Stores; restricted access to trained staff and secure storage of paper records, excess parts, glue coupons, bond pull coupons
- **Bonders:** fully automatic, semi-automatic and manual; for gold or aluminium, using wire or ribbon; for connections to terminations or more complex assemblies; bond pull-test facilities
- **Dage Microtester:** for standard width wires or ribbons bonded or welded to circuit patterns; non-destructive testing to MIL-STD-883D / 2023; destructive testing to MIL-STD-883D / 2011
- **Soldering:** void-free using SRO-702 ATV chamber to achieve void-free solder joints for optimum heat transfer from high power MMIC devices; can also be used for flux-free solder assembly of large-area components such as substrate and heat spreader attachment to carriers; manual soldering with solder iron and/or hotplate and re-flow solder equipment
- **Sealing:** pyramid projection welding for any standard 'can' package; Slee seam-sealer for any standard 'can' package; epoxy sealing using preformed gaskets; indium wire seal
- **Seal Test:** PIND Tester for vibrating projection weld packages after sealing; testing to MIL-STD-883E Method 2020.7; gross-leak test uses Trioteck Tester with 3M FC-40 to MIL-STD-202 Method 112; fine-leak test uses Pfeiffer QualyTest HLT270 to MIL-STD-883C Method 1014.6; post-seal units gross-leak or fine-leak tested with helium
- **Cleaning:** plasma cleaning; or ultrasonic degreaser
- **Inspection:** Mitutoyo Crysta Apex C776 CMM for dimension checks, flatness, finish and tolerance checks; verniers, micrometers, microscopes; high magnification photography with record function; connector checks – SMA interfaces, centre contact retention, engagement and separation force

Figure 3.44 COM DEV electronics assembly

3.11.8 COM DEV View on Facilities

COM DEV is generally content with its in-house facilities and, where necessary, easily-accessible external facilities, that are required to support its RF component and subsystem manufacturing and test activities. Its in-house facilities have been established specifically for the manufacture and test of its own products, so potential external customers are accommodated on an 'as-available' basis. COM DEV is willing to provide sub-contract assembly and test capability if capacity allows.

However, COM DEV is working on programmes where the equipment is larger than its own facilities can accommodate and so periodically needs access to larger thermal and TVAC chambers, vibration facilities and general mass property measurement facilities. It would be ideal for logistical reasons if these facilities were in one location with accompanying space to accommodate GSE for system verification before, during and after the relevant environmental test campaign.

COM DEV also regularly performs EMC testing at a test house close to its Aylesbury location on a commercial basis and recognises that this is one key test that it cannot perform in-house.

Another test that is always difficult to source is Pyro Shock, so an additional close facility for that test would be ideal.

3.12 Cranfield University, Cranfield and Shrivenham

3.12.1 Cranfield University Background

Cranfield University is a research-based post-graduate university specialising in science, engineering technology and management. It focusses on specific domains such as aerospace, energy and manufacturing. It has two campuses: the main one is located at Cranfield, Bedfordshire; and the second is the Defence Academy of the UK based at Shrivenham, Oxfordshire. The main campus uniquely boasts an operational airport, Cranfield Airport, adjacent to it, which is used by the University's own aircraft for aerospace teaching and research. In 2016 Cranfield celebrates its 70th anniversary, and Cranfield's Space Group its 30th anniversary. The University started as the College of Aeronautics at RAF Cranfield in 1946, later becoming the Cranfield Institute of Technology in 1969, and finally becoming Cranfield University in 1993. The Shrivenham campus was previously the Royal Military College of Science, later becoming the Defence College of Management and Technology, and finally in 2009 being known by its present name 'Cranfield Defence and Security'. The main Cranfield campus hosts the Space Research Centre, where most space-related research activities take place. The Shrivenham campus has an active propellant research group which is relevant to space rocket engines, as well as expertise in subjects such as radar, sensing and autonomy.

3.12.2 Cranfield Space Research Centre

Cranfield's Space Research Centre is the principal focus for space engineering in the University although significant expertise in specific space technologies is distributed across all Schools. Cranfield SRC teaches the MSc in Astronautics and Space Engineering, from which alumni now work in almost all significant space organisations in the UK, Europe and globally.

Cranfield is a world-leader in the development and supply of de-orbit drag sails for small LEO satellites. Two of these devices are currently in orbit and a third is being built for ESA's ESEO satellite. These programmes were managed by Cranfield staff, using development and assembly facilities on-site and with support for specialist test facilities from other UK organisations (Open University, RAL Space, and University of Southampton). This builds on more than a decade of research into space debris and its mitigation by a variety of techniques. The Cranfield devices ensure that the orbits of the spacecraft will decay within 25 years from their end-of-mission, to meet the current international guidelines. Using Cranfield's devices has enabled the manufacturer to demonstrate compliance with these guidelines and thus to secure a launch licence. The UK's TechDemoSat-1 (TDS-1) satellite, based on an SSTL-150 spacecraft bus, approximately 160 kg, with dimensions 0.7m x 0.7m x 0.9m, carries Cranfield's Icarus de-orbit sail, shown stowed around the sides of the right-hand face in the figure below. The right-hand picture shows the Icarus sail deployed during one of its development tests.

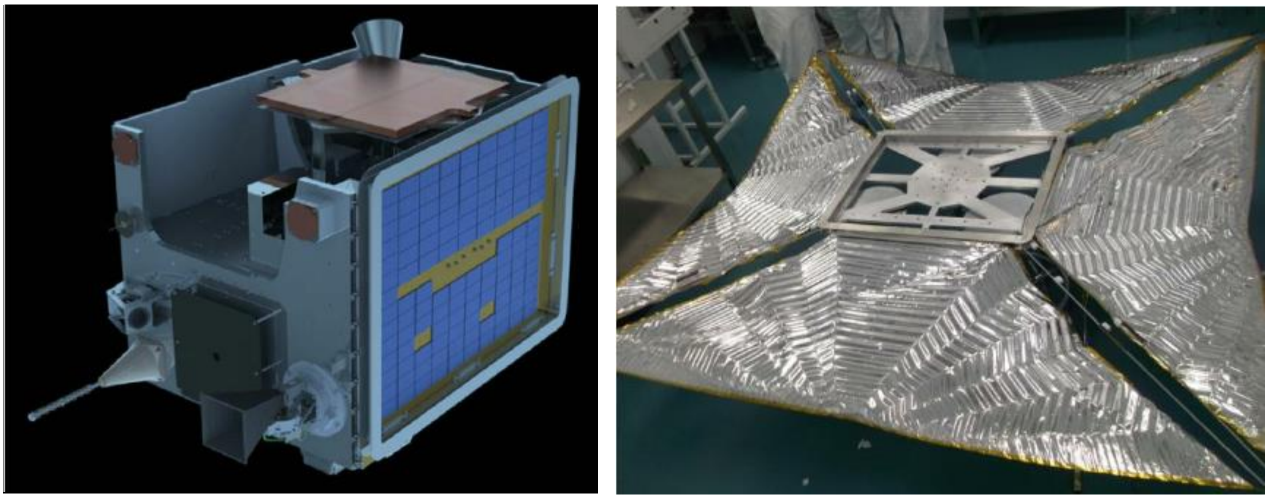


Figure 3.45 TDS-1 with de-orbit sail stowed around RH panel; and sail deployment trial

TDS-1's mission runs until July 2017 which is when the de-orbit sail will be deployed; the satellite's orbit decay will then accelerate and re-entry is expected after about a decade (the precise date depends on solar activity and the satellite's orientation).

The Space Group is also involved in developing Space Biotechnology solutions. Staff have been involved in leading the development of the Life Marker Chip instrument on the original ExoMars mission payload and flying bioscience payloads on ESA's Biopan facility. Current projects include the development of bio-CubeSats such as BAMMsat and CubeSat-like bioscience experiments on the ISS – specifically the GENESISS and ICEcube experiments.

3.12.3 Cranfield SRC Facilities

The Space Research Centre has a comprehensive range of support facilities including:

- Cleanroom (ISO 8, class 100,000): 4m x 3m x 4m working volume designed for assembly and integration of small satellites (≤100 kg) and payloads (and adjacent cleanrooms capable of providing working volumes to ISO 5 / class 100)
- Satellite ground station: Capable of receiving and transmitting on the amateur radio VHF and UHF bands, for work with CubeSats and other small satellites using these bands
- Airfield access: with National Flying Laboratory and Cranfield University aircraft
- Industry-standard engineering design tools: AGI's Satellite ToolKit, ESATAN, CATIA, NASTRAN/ PATRAN, I-DEAS
- Rapid-prototyping and instrumentation / electronics laboratory
- Hypersonic gun tunnel: for launch / re-entry simulation

3.12.4 Other Cranfield Facilities for Space Research

Cranfield University has notable world-class facilities in some areas relevant to space engineering:

- Ultra-precision surface manufacturing and metrology: Cranfield has world-leading capabilities in ultra-precision engineering. Its facilities were recently used to manufacture and test optical surfaces for the James Webb space telescope
- Off-road vehicle testing facility (e.g. for planetary rover development and test)
- Bioscience laboratories supporting Space Biotechnology activities
- UAV (Unmanned Aerial Vehicle): extensive expertise in UAV / aerobot development and operations

In addition to these there are other facilities which are of national importance:

- Ground-based radar for field experiments (Shrivenham)
- Material science analytical tools
- Engineering photonics: optical measurement facilities
- Hyper / high velocity impact
- Space propulsion: a bi-propellant test rig is being developed for research and teaching, and will be operated in collaboration with the national centre of propulsion expertise at Westcott.

3.12.5 Shrivenham Campus – Propulsion Research

Most activities on the Shrivenham campus are defence-related and therefore not of particular relevance to this study but at least one, namely the Propellant Research Group, undertakes research of interest to the space propulsion community. The Propellant Research Laboratories consist of four main laboratories:

Synthesis and Formulation Laboratory, specialising in the synthesis of binders and energetic materials to create advanced propellants, supported by a number specialist synthetic chemistry facilities.

Characterisation and Ageing Laboratory, specialising in the chemistry and thermal decomposition of nitrocellulose and nitrocellulose-based propellants, but including all aspects of solid propellant characterisation. Facilities include: chromatography, mass spectrometry, RAMAN spectroscopy, FTIR spectroscopy, UV-Vis spectroscopy and many other specialised test facilities.

Thermo-Mechanical Laboratory, which investigates the material and chemical properties of propellant materials to support physical/chemical ageing models. Facilities within the laboratory include: DSC, TGA, DMA, mechanical testing with high and low temperature heating control, rheometry, micro/nano hardness, CTE, SEM and optical microscopy, and CT X-ray analysis.

Ballistics and Combustion Laboratory, which researches propellant combustion chemistry, laser ignition mechanisms of propellants, propellant ballistics, and ballistic modifier chemistry. Facilities include laser ignition and propellant closed-vessel testing.

3.12.6 Cranfield View on Facilities

Cranfield expects to continue using a mix of its own facilities and specialist facilities at other organisations, since collaborations bring benefits to both partners. The University integrates its research and teaching and sees great value in exposing students to the practical aspects of test campaigns with space hardware. This is being developed in areas of mechanical testing (mechanisms, vibration, thermal / vacuum), space propulsion, and ground station operations.

As with all space organisations a balance must be made between the costs and benefits of acquiring, operating and supporting in-house test facilities against collaborating with other organisations to gain access as needed.

At national level Cranfield supports the development of centralised, specialist facilities for space technology where these enable world-class payloads and satellites to be developed by UK companies, research organisations and universities. Ensuring open access with transparent governance and charging is important in building a healthy user community. Mechanisms to improve access to national-class facilities which may be dispersed among a range of organisations are also of benefit.

3.13 Cyth Systems, Didcot

3.13.1 Cyth Company Background

Cyth Systems is a leading integration and engineering firm headquartered in Southern California with pioneering success in designing and building automated test systems, machine vision systems, and embedded control systems. Cyth creates purpose-built systems using 95% standard products as building blocks across both hardware and software aspects of a project. The resulting product is maintainable, flexible, reliable, and achievable within time and budget constraints. Cyth Systems recently opened an office in Milton Park, Oxfordshire.

3.13.2 Cyth Potential Pyro-Shock Facility

Cyth Systems intends to expand its presence in the UK by setting up a pyrotechnic shock testing facility to service the UK and European markets. It anticipates that many customers could potentially be from the Harwell Campus, with some overflow expected from the RAL Space test centre activities. Pyrotechnic shock facility is used for the qualification of space flight hardware. Pyrotechnic shock testing is necessary to qualify the survivability of any device that will experience pyro-shock, or for any of the component parts of a pyrotechnic shock source.

3.13.3 Cyth View on Facilities

Cyth Systems believes that the lack of a pyro-shock facility represents a real gap in the UK test scene and is currently undertaking a market study to explore interest in such a UK facility to inform the investment decision. Investment in a pyrotechnic shock facility would have to be justified and could in principle be implemented in conjunction with STFC/RAL Space.

3.14 Deimos UK, Harwell

3.14.1 Deimos Company Background

Deimos Space UK Ltd, founded in 2013, is a wholly owned subsidiary of the Spanish company Elecnor Deimos to address the UK market for space systems, services and applications. Deimos Space UK is located in the Harwell Space Cluster and offers expertise in the following areas:

- Mission and Flight Engineering
- Ground Segment Systems
- Flight Software Systems
- Global Navigation Satellite Systems
- Remote Sensing Applications
- Space Situational Awareness

Elecnor Deimos is now an established spacecraft AIV company, having integrated the Deimos-2 Earth Observation satellite, at its Castilla La Mancha plant in Spain. The 300kg agile (±30° off-nadir pointing) mini-satellite was launched in 2014, and produces high-resolution images of Earth from a multi-spectral push-broom imager to capture images on a 12km swath, achieving a resolution of 1m for panchromatic images and 4m in the visible and near infrared spectral range. Deimos-2 was integrated and system-tested at the Castilla La Mancha site using equipment mainly procured from Asian suppliers. Environmental testing took place at government facilities near Madrid before shipping to the launch site.

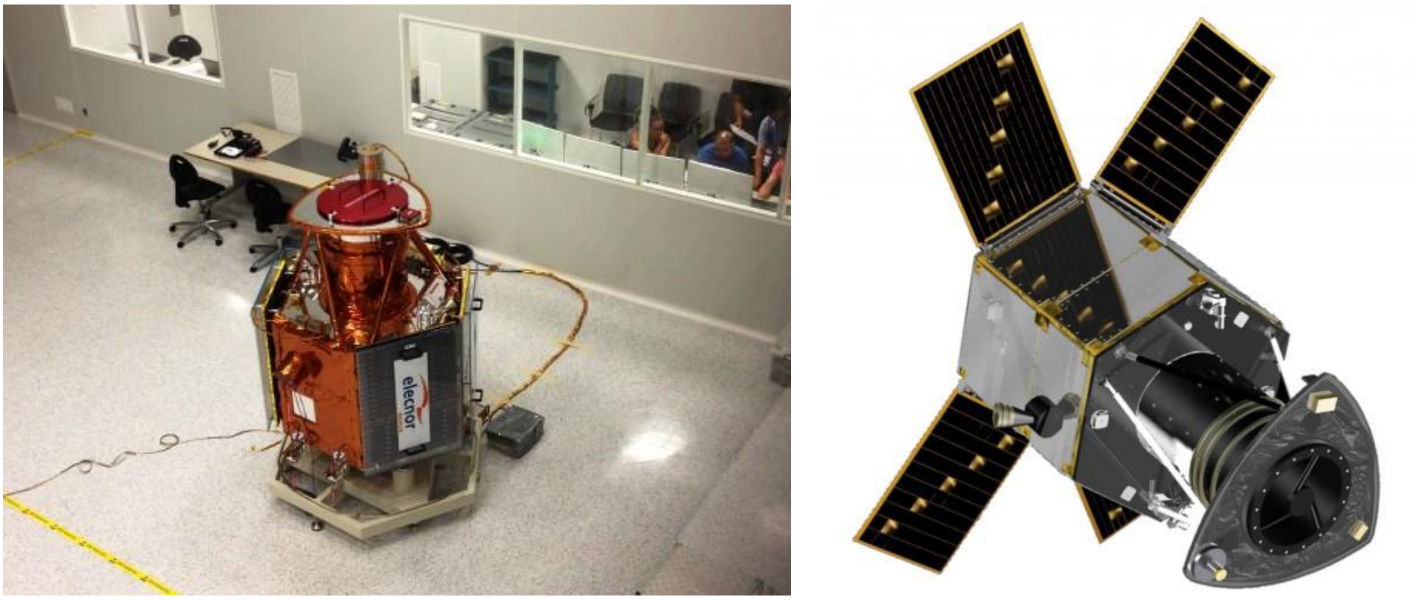


Figure 3.46 Deimos-2 FM spacecraft during final integration in Spain and in flight configuration

3.14.2 Deimos View on Facilities

Deimos currently has no plans to develop new facilities in the UK, but there is a possibility that future Deimos spacecraft assembled and integrated outside the UK could be environmentally tested in the UK on the Harwell site, especially if Harwell was able to offer a complete suite of test facilities, including EMC, at cost effective rates. A UK spaceport for small satellite launch would be a key enabler for such services offered by Deimos UK.

3.15 Element Materials Technology, Wimborne and Hull

3.15.1 Element Company Background

Element Materials Technology, hereinafter referred to as *Element*, is a global leader in materials and product qualification testing and certification with over 1,800 employes in 53 sites spread across the USA and Europe. In May 2015 Element acquired TRaC Global, which was the biggest independent aerospace testing and qualification organisation in the UK. Element is a UKAS-accredited testing and certification company, with several sites across the UK, two of which are of particular relevance to this study: Wimborne, Dorset; and Hull, East Yorkshire. The Element Wimborne site contains its main environmental test laboratories to form a European Environmental Testing centre-of-excellence and SC21 signatory. Environmental Testing at Wimborne can simulate a wide variety of environmental conditions to help determine product reliability. Its areas of technical expertise include Environmental Testing, Vibration and Shock Testing, Engineering Simulation, Early Stage Qualification (ESQ®) and Seismic Testing. The Element Hull facility is a European Radio and Telecommunications Testing Centre of Technical Excellence.

3.15.2 Element Vibration Facilities, Wimborne

The Element Wimborne facility houses three of the four commercially available LDS984 shakers in the UK which specialise in large and challenging specimen vibration tests. A range of electro-mechanical and electro-hydraulic vibration testing systems are used, with standard test frames, to apply dynamic vibration test loads suited to any requirement. The shakers can be fitted with thermal enclosures so that vibration testing can be combined with temperature testing over the range of -70°C to +170°C.

Figure 3.47 Element LDS V984 Electromagnetic Shaker

- Large Electromagnetic Vibration shakers (x3)
  - Frequency range: 5 to 2000 Hz
  - Maximum displacement: 38 mm pk-pk
  - Rated thrust: Up to 160 kN sine and random
  - Acceleration (Sine Peak): 100g
  - Slip Table: Combo and portable
- Medium Electromagnetic Vibration Shakers (x3)
  - Frequency range: 2 to 3000 Hz
  - Maximum displacement: Various from 12.7 mm to 50 mm pk-pk
  - Rated thrust: Various up to 89 kN sine and random
  - Acceleration (Sine Peak): 100g
  - Slip Table: Combo and portable

- Small Electromagnetic Vibration Shakers (x8)
  - Frequency range: 5 to 3000 Hz
  - Maximum displacement: Various from 11.4 mm to 50 mm pk-pk
  - Rated thrust: Various up to 40 kN sine
  - Acceleration (Sine Peak): 60g
  - Slip Table: Combo and portable
- High Displacement Vibration Shaker
  - Frequency range: 5 to 2500 Hz
  - Maximum displacement: 63mm pk-pk
  - Rated thrust: 67 kN
  - Acceleration (Sine Peak): 100g
  - Slip Table: Combo

3.15.3 Element Shock Testing Facilities, Wimborne

Element Wimborne has an extensive range of vibration and shock testing equipment that can reproduce low and high frequency conditions, replicating environments that subsystems may be subjected to whilst in operation. Shock Testing can be carried out using either a vertical-drop shock testing machine or one of its electromagnetic shakers, summarised below.

- Lansmont Vertical-Drop Shock Machine
  - Platform Size: 950mm x 950mm
  - Maximum Shock Level: 800g, dependent on duration and pulse
  - Shock Profiles: Half-Sine, Final Peak Sawtooth

- AVCO Vertical-Drop Shock Machine
  - Platform Size: 406mm x 406mm (16" x 16")
  - Maximum Shock Level: 1200g, dependent on duration and pulse
  - Shock Profiles: Half-Sine, Final Peak Sawtooth 'Trapezoidal'

- Electromagnetic Shakers
  - Platform Displacement: 63mm pk-pk
  - Maximum Shock Level: 100g, dependent on duration and pulse
  - Shock Profiles: Classical Shock, Time-Histories, Shock Response Spectra

3.15.4 Element RF Testing Facilities, Hull

The Element facility in Hull is a European Radio and Telecommunications Testing Center of Technical Excellence. Element Hull is UKAS-accredited to BS EN ISO/IEC 17025:2005, and is a Notified Body for the Radio and Telecommunication Terminal Equipment Directive, a Telecommunication Certification Body and a Conformity Assessment Body for Japan. The Hull testing facility helps manufacturers comply with the legal global market regulations for their products, and allows clients to stay on top of regional standards and statutory regulations and meet the evolving demands of product approvals. The Hull facility is able to offer EMC Testing, RF Testing, Safety Testing, Telecommunications Testing and ZigBee Testing.

3.15.5 Element View on Facilities

Within the UK, Element can provide a vast array of testing services of all types at its numerous locations, but in the context of this study it has been useful to focus on its Wimborne and Hull facilities, which are able to provide the UK space community with comprehensive mechanical and RF testing services respectively.

3.16 ESR Technology, Warrington

3.16.1 ESR Technology Company Background

ESR Technology is active in a range of markets covering space and terrestrial industries and specialises in tribology, the field of engineering related to friction, wear and lubrication. Activities in the space industry cover a range of services including consultancy, R&D, testing, bearing lubrication, and the design and build of mechanical hardware.

Much of this work is routed through the European Space Tribology Laboratory, ESTL, which has had a continuous frame contract with ESA for tribological research, for the last 43 years. This contract allows the provision of consultancy, historical research reports and access to test facilities for European space companies active in spacecraft mechanism development. ESTL also specialises in the production of thin-film solid lubricants applied to precision tribological components such as bearing, gears and screws. In many cases these are supplied fully assembled, run-in, and characterised as sub-assemblies ready for integration into the customer's mechanism system.

Commercial activities outside of the core space tribology discipline, including higher level mechanical systems and technologies, as well as MGSE and other vacuum mechanisms, are performed by ESR Space, a separate department, which is distinct from ESTL branded operations.

3.16.2 ESR Clean Room

In the summer of 2015, ESR Technology moved into new premises, which houses a 300m^2 Class 10,000 clean room. This includes a dedicated room for coating production, a test area for ESTL R&D activities and a mechanism assembly area with Class 100 flow benches for the integration of flight hardware.

Figure 3.48 ESR Cleanroom mechanism assembly area and Class 100 bench

3.16.3 ESR Thermal Vacuum Facilities

ESR's has 19 vacuum chambers, ranging from 150mm diameter to 1m diameter with typical test temperatures within the range -50°C to +80°C. However, this temperature range can be widened for particular projects such as BepiColombo or JWST where temperatures of +400°C and cryogenic testing down to 20K were achieved. While most chambers are configured for the testing of mechanisms and components such as bearings and gears, they can easily be configured for general thermal vacuum test use.

Figure 3.49 ESR thermal vacuum chambers

3.16.4 ESR Specialist Manufacturing Facilities

In addition to its clean rooms and thermal vacuum facilities described above, it has a number of specialist facilities associated with the manufacture, assembly and test of space mechanisms and bearings including:

- Coating facilities for the production of space qualified PVD (physical vapour deposition) solid lubricant coatings, mainly lead and MoS_2, with capability for other coatings such as silver

Figure 3.50 ESR Coating Facility

- Friction and wear research facilities, including:
  - Precision inspection and measurement facilities within the cleanroom include digital microscopy, CMM and other metrology, and an instrumented pre-loading press
  - Comprehensive metallurgical inspection and test facilities for forensic inspection and materials characterisation including fatigue, hardness, tensile testing and profilometry
  - X-ray Fluorescence (XRF) for the measurement of thin film thickness

- Specialist tribometers for the measurement of fundamental friction and wear properties in a representative environment

Figure 3.51 ESR spiral orbit tribometer

- Scanning Electron Microscopy (SEM) with Electron Dispersion Spectroscopy (EDS) capability for chemical characterisation

Figure 3.52 ESR scanning electron microscope

3.16.5 ESR View on Facilities

ESR has identified a number of specialist in-house facilities that are required to enhance and streamline its operations including:

- An additional Spiral-Orbit Tribometer (SOT), potentially with ESA support, to meet the increasing demand for specialist tribology testing; it would be a unique facility outside the US and equal to NASA, who have only 2 of these
- Specific (unconventional) vacuum chambers for adhesion testing
- Multiple bearing test rig for parametric or more statistically robust test programmes; ideally this would allow testing 5 to 10 samples at the same time, reducing the time taken for test campaigns by up to one year, and satisfying an ESA desire to do more numerical modelling, which would be easier with more samples and more data
- Laser Doppler Interferometer, which is a non-invasive measurement technique for dynamic measurements - ESA currently takes the view that it cannot justify the €100k investment required
- Micro-XRF for enhanced quantitative characterisation of thin transfer films
- Specialist bearing and mechanical seal test facilities (high speed and oxidising environments) for the development of longer life bearings for propulsion applications
- Enhanced cleaning capability for the precision removal of a range of preservative and lubricant oils and other contamination. These often require different solvents depending on the chemistry of the contaminant

3.17 European Astrotech Ltd, Westcott

3.17.1 EAL Company Background

European Astrotech Ltd (EAL) is a privately owned space propulsion company formed in 2007. It is based at Westcott Venture Park and provides technical support to the space industry and other sectors in the fields of spacecraft propulsion subsystem testing, propellant loading (supporting launch campaigns), ground support equipment design and build, propellant chemistry and compatibility, chemistry and materials technology, document preparation and support and safety support (risk assessment, site surveys etc).

3.17.2 EAL Propulsion Activities and Facilities

Specific activities and expertise include:

- Spacecraft propulsion subsystem testing
- Component level (bench) testing
- Design and build of propulsion GSE
- Launch campaign test and propellant loading activities
- Propellant supply, chemistry and analysis
- Metallic surface preparation (passivation)
- Contamination identification and control
- Corrosion and materials compatibility testing

Figure 3.53 EAL propellant-loading GSE and loading the Galileo spacecraft at CSG

3.17.3 EAL View on Facilities

EAL is generally content with its in-house design and test facilities and with the analysis capabilities of its main laboratory. Its B2 test bay is currently being upgraded to test subsystems associated with HTP (High Test Peroxide) green propellant.

EAL would welcome the opportunity to become an active participant in a National Propulsion Test Facility.

3.18 Falcon Project Ltd, Westcott

3.18.1 Falcon Project Company Background

The Falcon Project was founded by rocket engineer Daniel Jubb and Sid Guy in 1995 and incorporated in the UK in 2001. Falcon has bases at Westcott Venture Park in Buckinghamshire and in the Mojave Desert in California. The company designs and manufactures custom solid, liquid and hybrid propellant rocket systems with applications ranging from mine disposal and target drones to sounding rockets, mainly for the MoD and US customers. Probably the main interest for this study is the hybrid rocket, shown in cut-away below, developed originally for the Bloodhound supersonic car, but now a real candidate for a small vertical launch vehicle.

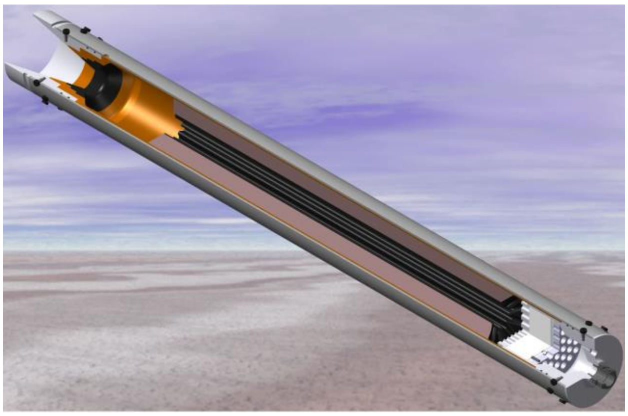



Figure 3.54 Cut-away of Falcon's hybrid rocket and test firing in the Mojave Desert

The 457mm (18-inch) diameter hybrid rocket is the largest hybrid to be developed outside the US and uses Hydroxyl-Terminated Polybutadiene (HTPB), a synthetic rubber, as the primary fuel and HTP, highly concentrated hydrogen peroxide (H_20_2), as the oxidising agent. HTP is non-toxic although it can cause burns; it was used extensively in the UK space programme of the 1950s, 60s and 70s in rockets such as Black Knight and Black Arrow, which used liquid fuel engines burning kerosene. The Falcon pump-fed, 457mm hybrid was static-tested in the UK in October 2013; it was the largest rocket to be fired in the UK for around 20 years.


Figure 3.55 6-inch hybrid rocket on test-stand at Westcott and 6-inch rocket motor test firing

In the process of developing the hybrid rocket, Falcon also produced the largest silver catalyst packs ever made in the UK and reverse-engineered and uprated the Stentor large HTP pump, shown in cut-away below. Falcon also reverse-engineered the turbine so, combined with experience in HTP:kerosene bi-propellant rockets, Falcon has the capability to rapidly redevelop the Black Arrow engine technology.

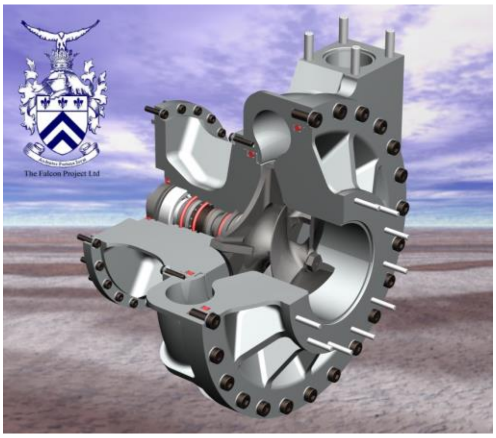


Figure 3.56 Reverse-engineered large HTP pump

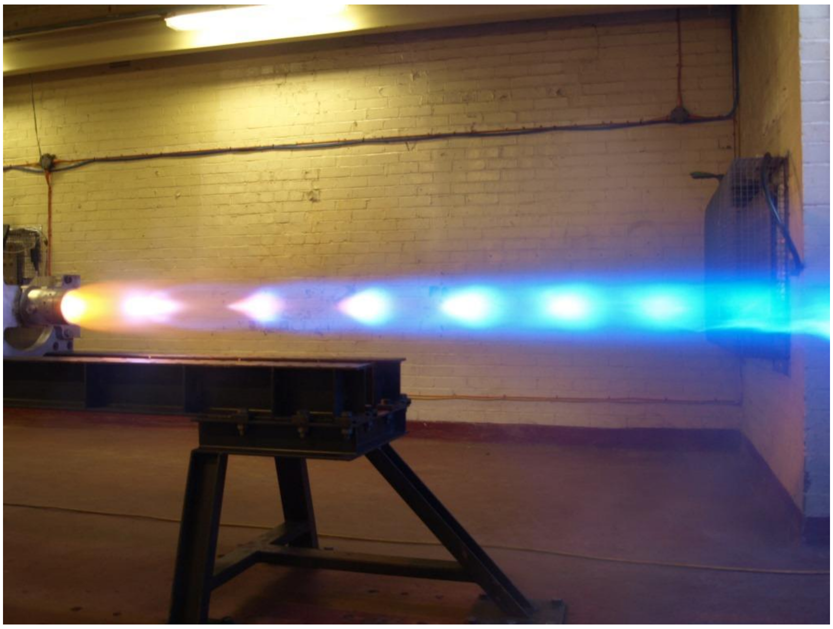


Figure 3.57 6-inch solid rocket motor firing at Westcott

3.18.2 Falcon Facilities

The Falcon Project Ltd has a static test bay on its 34-acre Westcott site; the test bay is licensed by the HSE for firings of solid-propellant rocket motors containing up to 800kg of solid-propellant or liquid-hybrid rockets with up to 1,000 litres of oxidiser. Falcon has fired solid propellant rockets with thrust levels of over 1 MN.

With a 5,000 kg production limit on the mix building and a 65-gallon mixer, Falcon has the capability to cast large sounding rocket motors and possibly small launch vehicle boosters at Westcott. Falcon is also world-leading in Resonant Acoustic Mixing (RAM) of solid rocket propellants.

3.18.3 Falcon View on Facilities

Falcon supports the development of a high altitude test facility at Westcott. Falcon also proposes to redevelop ‘K Site’ at Westcott, which includes K2 a horizontal test stand, K1 a vertical test stand and R Site which comprises two smaller firing bays. The K and R Site redevelopments require an investment of around £400k.

3.19 Glyndŵr University St Asaph

3.19.1 Glyndŵr University Background

Now (since 2016) officially known as Wrexham Glyndŵr University, the University's origins date back to the opening of Wrexham School of Science and Art (WSSA) in 1887. Since then it has evolved and been through several name changes, including Denbighshire Technical College and then, in 1975, the North East Wales Institute of Higher Education. NEWI became a full member of the University of Wales before being officially renamed Glyndŵr University in 2008 after being granted degree-awarding status. It has campuses at Wrexham, Northop and St Asaph in north-east Wales; and at Kingston-upon-Thames in London. It offers both undergraduate and postgraduate degrees, as well as professional courses. The St Asaph campus is a hub for high technology and scientific innovation, offering bespoke engineering design and consultancy services and the manufacture of large optics and is the principal subject of this survey.

3.19.2 Glyndŵr University St Asaph

Forming part of the University's North East Wales 'knowledge corridor', Glyndŵr University St Asaph, also known as the OpTIC Centre, is located just off the A55 and boasts: a well-equipped Conference Centre; an Incubation Centre supporting local businesses with facilities for company start-ups; and a well-equipped photonics Technology Centre. The Centre is a leading business and cutting-edge facility bringing together academics conducting research into highly specialised areas of technology and businesses looking to develop that technology for commercial purposes.

Figure 3.58 Glyndŵr University St Asaph campus

The Technology Centre performs both academic research and industrially-commissioned R&D alongside an industry-facing Engineering Projects Group trading as Glyndŵr Innovations Ltd.

Glyndŵr Innovations Ltd has completed design, fabrication and integration projects for a number of leading Institutions and Companies in the fields of Aerospace, Space Science and Medical, including innovation projects for the CDE (Centre for Defence Enterprise).

The OpTIC Centre is part of the funded UK Space Agency Incubation Network.

3.19.3 Glyndŵr University St Asaph Capabilities and Expertise

The capabilities offered by Glyndŵr University at its St Asaph campus are:

- Engineering Design and Analysis
- Optical Fabrication
- Verification of Optics and Optical Systems

These areas are summarised in what follows.

Engineering Design and Analysis includes the design of Airborne Optical Systems, Satellite Pre-flight Systems, Precision and High-performance Actuation, Thermal Design and Engineering, and Design for Additive Manufacture. The Engineering Projects Group based at the OpTIC Centre provides a multi-disciplinary design service to the UK aerospace and precision engineering sectors. Its links with the optics industry and its history of delivering innovative high precision engineering solutions make it a clear choice for the design, supply and integration of both airborne systems and ground support equipment. The team is staffed by professional engineers with substantial industrial and science-sector experience, including the design of large optical telescopes and instrumentation, vacuum and cryogenic system design and integration, and high performance structural engineering.

The team uses a full range of analytical and modelling software for the design of both optical and mechanical systems. Software in regular use includes:

- Zemax

- FRED
- Ansys
- Autodesk Inventor
- Solidworks
- Matlab

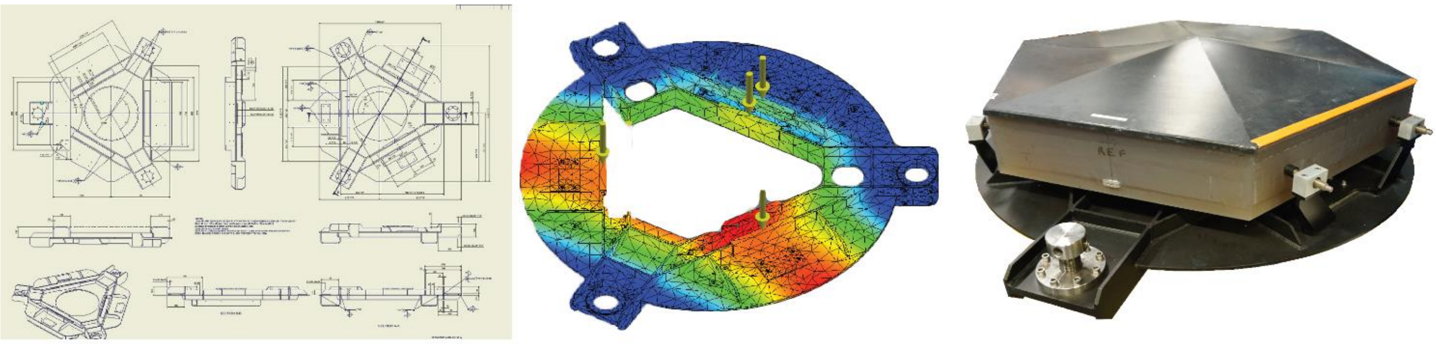


Figure 3.59 Mechanical design and analysis

Light-Weighted Optical Systems: The team has unique UK expertise in designing and fabricating light-weighted optics for satellite and airborne imaging systems. Light-weighting of optics between 70% and 80% can be both designed and fabricated at the OpTIC Centre, up to a current size limit of 380 mm diameter. Light-weighting of optical systems for space-borne applications includes the design and analysis of light-weighted support structures, modelled to withstand demanding operating environments.

Figure 3.60 Light-weighted optics

Satellite Pre-flight Verification Systems: The team has experience of providing both optical components and opto-mechanical assemblies for use in pre-flight ground support systems.

Precision and High-performance Actuation Design: The team has commercial experience in designing precision actuation for aerospace applications, with high-performance actuators being designed to operate in challenging environmental conditions including high torque, acceleration and vibration.

Thermal Design and Engineering: Recent client projects include the design and implementation of passive cooling of a high brightness UV LED system for a medical application; the design and integration of vacuum and cryogenic systems for nuclear research applications; high-precision optical mounting and actuation mechanisms designed for harsh environments, including the use of adhesives for mounting optics for operation at 77 Kelvin with high vibrational and impact loads.

Additive Manufacturing: The team is capable of creating designs optimised to take advantage of the unique properties that additive manufacturing can offer for applications requiring low mass rigid structures. It has recently undertaken studies into the applicability of additive manufacturing processes to aerospace applications.

Optical Fabrication at the OpTIC Centre is focussed upon the small volume fabrication of large and challenging optics. The optical fabrication facilities are able to manufacture optics up to 1.6 m in diameter, using both conventional polishing methods and also CNC processing. The optical fabrication team is able to develop manufacturing processes for the fabrication of highly aspherical optical surfaces using CNC-based methods.

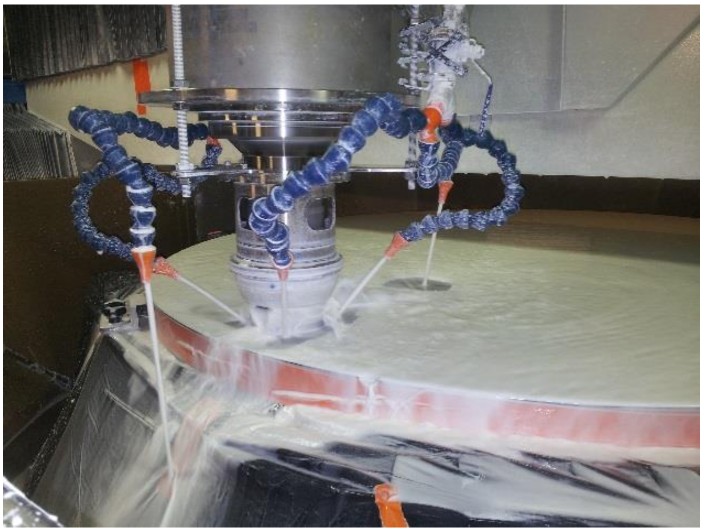


Figure 3.61 Polishing large diameter optics

Verification of Optics: This optical fabrication capability is complemented by a high level of competency in surface metrology, both form and texture, with a comprehensive suite of metrology instrumentation in use. Both profilometric and interferometric measurement methods are in use. For the fabrication of large optics and systems, the OpTIC Centre offers a high level of expertise in the critical mounting of optics required for both processing and verification. The metrology team is able to develop novel verification methods for challenging applications, from optical design through mechanical design to implementation.

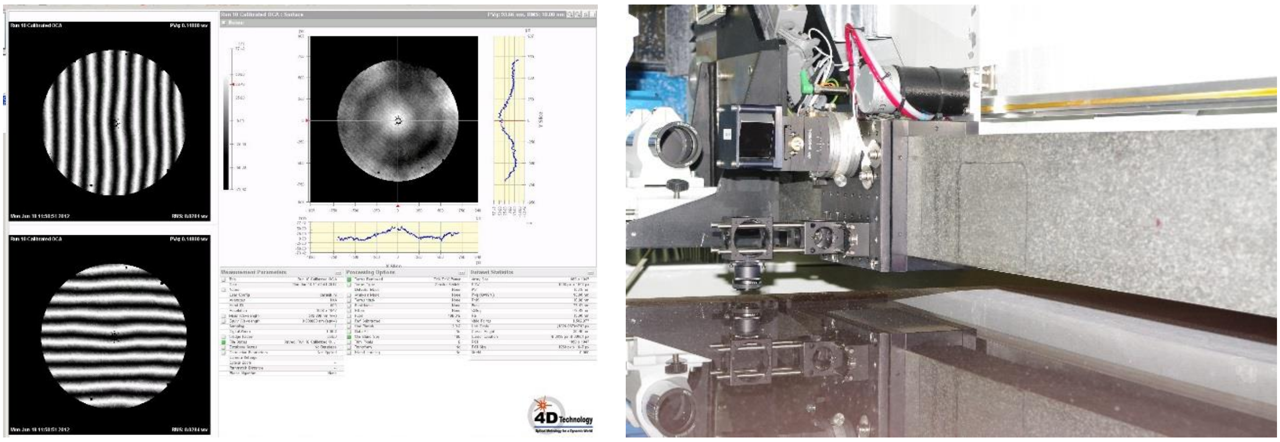


Figure 3.62 Optics verification

3.19.4 Other Capabilities

Composite Materials Research at Glyndŵr University is focussed upon developing lightweight, dimensionally stable mirrors from Carbon Fibre Reinforced Plastics. Glyndŵr University has completed a Framework 7 funded project for a feasibility study into the fabrication of a lightweight cryogenic mirror for space deployment. The mirror’s dimensional stability was computationally modelled after cryogenic material tests were conducted. Current and future projects include CFRP mirrors for high altitude surveillance and also for active and adaptive optics (with University College London). All CFRP fabrication is undertaken at Glyndŵr’s Advanced Composites Training and Development Centre, run in conjunction with Airbus, Broughton.

Capabilities Sited on University Wrexham Campus: In addition to the team located at the OpTIC Centre, there is significant engineering design and analysis capability in the CoMManDO research group, which is primarily comprised of research-active academic staff based on the Wrexham campus. Software in regular use for research and teaching enhances the overall capability that can be offered:

- CATIA V5
- Abaqus, Isight, FE Safe
- Ansys Fluent & Mechanical

Research capabilities include multi-physics modelling, impact analysis, structural dynamics and vibration, manufacture simulation, microwave cure simulation, and multi-objective optimisation

3.19.5 Glyndŵr University St Asaph Optical Fabrication and Verification Facilities

Wrexham Glyndŵr University has the following facilities at the OpTIC Centre in St Asaph, available for the support of the UK space programme:

- Optical Fabrications facilities
- Optical and Dimensional Verification facilities

Optical Fabrication facilities comprise polishing and metrology facilities for the fabrication of large optics.

Polishing facilities include:

- large bridge-type CNC machines: a Zeeko IRP1600 machine, capable of polishing optics up to 1600 mm diameter; and a Zeeko IRP1200 machine, capable of polishing optics up to 1200 mm diameter
- Conventional polishing machines: two Bryant Symons dual-spindle GP300 polishing machines and two 600 mm single-spindle polishing machines.

These polishing facilities are unique within the UK for the manufacture of large optics.

Metrology capabilities situated at Glyndŵr University St Asaph include the following:

- Contact Metrology
- Interferometric Metrology
- Bespoke Metrology
- General Facilities

Contact Metrology facilities include:

- Leica AT901 Absolute Tracker (currently integrated into a 10m optical test tower): Measurement volume >10 m radius; in-line measurement accuracy of 10 µm; angular accuracy of approximately 40 µm, SpatialAnalyser software.
- FARO Ion Laser Tracker: Measurement volume >10 m radius; in-line measurement accuracy of 10 µm; angular accuracy of approximately 40 µm, CAM2 Measure software.
- DEA Pioneer 6.10.6 CMM, offering a first term traceable measurement accuracy of 5 µm, PC-DMIS software.
- Taylor-Hobson Form Talysurf: One of a small collection of long range contact profilometers made by Taylor-Hobson. The Form Talysurf is a linear profilometer able to give a traverse of up to 300 mm, with a measurement precision of <100 nm.
- Taylor-Hobson Talysurf Intra: Contact profilometer made by Taylor-Hobson giving a traverse of up to 50 mm, with a measurement precision of <100 nm.
- NT-MDT standalone SMENA Atomic Force Microscope: Measurement footprint 100 µm x 100 µm; height measurement accuracy 0.1 nm or better.

Interferometric Metrology facilities include:

- Fisba µPhase 2 HR compact Interferometer: 1024x1020 camera resolution; associated diverger lenses, µShape software.
- 4D PhaseCam 4000 Interferometer: Stabilised Twyman Green interferometer; 473x475 camera resolution, 4Sight software.
- 4D PhaseCam 6000 Interferometer: Stabilised Twyman Green interferometer; 995x1003 camera resolution, 4Sight software.
- 4D PhaseCam 5030 Interferometer: Stabilised Twyman Green interferometer; 1967x1946 camera resolution, 4Sight software.
- 4D diverger lenses available for the 4D interferometers: F/1, F/2.5, F/4, F/6, F/8.
- Nikon ADE MicroXam Optical Surface Profiler: White light interferometer; measurement footprint approximately 1 mm x 1 mm height resolution of 0.1 nm.

Bespoke metrology facilities include:

- NOM optical profilometer: Capable of measuring a sagittal distance of 70 nm over a scan length of 1.4m. Calibrated with a sagittal measurement accuracy of 350 nm (one standard deviation).
- Bespoke 10m optical test tower: Currently configured to interferometrically measure ESO E-ELT primary mirror segments, but can be reconfigured for other interferometric applications.
- Bespoke interferometric beam expander: Working beam diameter 183 mm.

General metrology facilities include:

- A temperature-controlled optical metrology laboratory with two actively isolated optical benches, one approximately 5.4 m in length, and several non-isolated optical benches. Other optical facilities exist at Glyndwr University St Asaph, including other isolated optical benches that are not currently in use.
- Ocean Optics USB2000+ Spectrometer: The spectrometer operates at a range of integration times (1 ms to 65 s) with an optical resolution of 0.3 nm (FWHM). The spectrometer is configured for best efficiency over 350nm-850nm spectral range, with a grating blaze wavelength at 500 nm, making it ideal for spectral analysis within the visible spectrum and for applications such as fluorescence analysis.
- Taylor Hobson Talyvel 6 Differential Electronic Level System.
- Taylor Hobson Small Angle Generator Type TA48 – Certified to 0.1 arc seconds.

3.19.6 Glyndŵr University View on Facilities

Wrexham Glyndŵr University offers significant design, fabrication and verification capabilities that can be utilised for the UK space programme, and has an active track record in commercially exploiting these capabilities in this sector through Glyndŵr Innovations Ltd. The University has encouraged and supported this activity for some years and the OpTIC Centre provides a geographical location appropriate to its activity in the UK photonics sector.

3.20 Imperial College London

3.20.1 Imperial College Background

Imperial College was created as a constituent college of the University of London in 1907, by merging the City and Guilds College, the Royal School of Mines and the Royal College of Science to form the Imperial College of Science and Technology, in South Kensington. On its 100th anniversary it formally seceded from the University of London to become an independent public research university, Imperial College. It is comprised of numerous departments within three Faculties: Engineering, Medicine and Natural Sciences, together with the Imperial College Business School. The space activities of relevance to this report mostly take place in the **Space and Atmospheric Physics Group**, part of the Physics Department, known as the Blackett Laboratory, within the Faculty of Natural Sciences.

3.20.2 Space Magnetometer Calibration Facility

The Space and Atmospheric Physics Group's **Space Magnetometer Lab** comprises a team of scientists and engineers, together with the necessary support facilities, for the research and development of magnetometers for flight on scientific spacecraft. The group has supplied magnetometers for numerous missions including Cluster, Cassini, Venus Express, Double Star, Ulysses, Bepi-Colombo, Solar Orbiter and JUICE. Most of the Group's magnetometers are fluxgate designs, because of their lower power and mass, but some optically pumped designs such as the Vector Helium Magnetometer (VHM) shown below have been provided by US co-investigators and flown on Ulysses and Cassini. The JUICE scalar sensor will be provided by a co-investigator at the University of Graz.

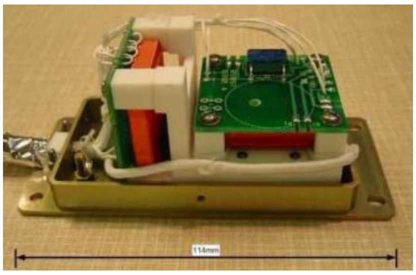
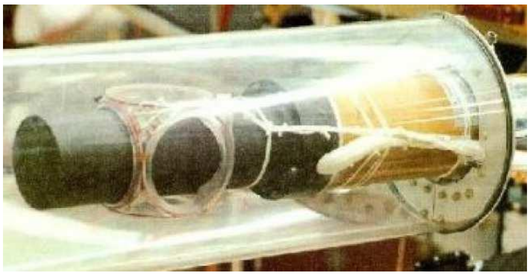



Figure 3.63 Double-Star fluxgate magnetometer and Ulysses VHM sensor

The Lab's ground calibration facilities for magnetometers are located at a magnetically-quiet site outside London in Staffordshire, belonging to a company specialising in magnetic sensors, Ultra Electronics Ltd, who also manufacture the fluxgate ring-cores used in the Group's sensors. The calibration facility comprises a 3-axis Helmholtz coil which compensates for the Earth's magnetic field and can then apply a field up to ±25µT in all 3 axes at frequencies up to 100Hz. It has a thermal enclosure enabling it to measure magnetometer offset, noise and scale factor over a range -50°C to +125°C. Measurement accuracies achieved by the facility are: linearity ±60µT; scale factor better than 0.01%; and alignment better than 0.1°. The Lab also has a magnetically-shielded thermal test system developed for Solar Orbiter and soon to be used for testing the JUICE magnetometer.

Figure 3.64 Imperial's 3-axis Helmholtz coil magnetometer calibration facility in Staffordshire

3.20.3 Earth Observation and Characterisation Facility, EOCF

The 83m^2 **Earth Observation Characterisation Facility**, **EOCF**, at Imperial College, overseen by the Space and Atmospheric Physics Group, is a resource for the development of instrumentation across a broad range of research applications. The heart of the EOCF is the Vacuum Calibration Chamber (VCC), designed to support the calibration of space-based radiometers, with the highest standards of precision and hydrocarbon-free cleanliness. The quality of the vacuum environment is assured through constant monitoring of trace gas species from 1 to 200 AMU using a quadrupole mass spectrometer. Chamber internal dimensions are 0.8m diam x 0.9m height, with precision articulating table and ports for calibration sources; the Department is considering upgrading the vacuum chamber to make it more suitable as a general-purpose TVAC chamber.

Figure 3.65 Imperial's Vacuum Ca*libra*tion Chamber

The EOCF has an access-controlled cleanroom with 28m^2 of usable floor area and a volume of 60m^3 maintained at ISO 6 (Class 1,000). The cleanroom air is completely changed once per minute, making it safe for activities involving large amount of inert gas discharge (e.g. purging during spectral absorption measurements). The facility owns four high-grade optical work-surfaces (one inside the cleanroom, one in the main lab and two in the satellite laboratory) and maintains a core inventory of bench optics. The table decks are Melles Griot 07OTQ501 models measuring 1.25m by 2.0m. Deck material is ferromagnetic stainless steel. Dynamic deflection coefficient, relative table motion and deflection under load specifications are all excellent. The support systems are self-levelling active vibration isolation systems with a load capacity of 2500kg. The table deck will be relevelled for an offset load of up to 250kg. Vertical and horizontal resonant frequencies are extremely low, being on the order of 1Hz.

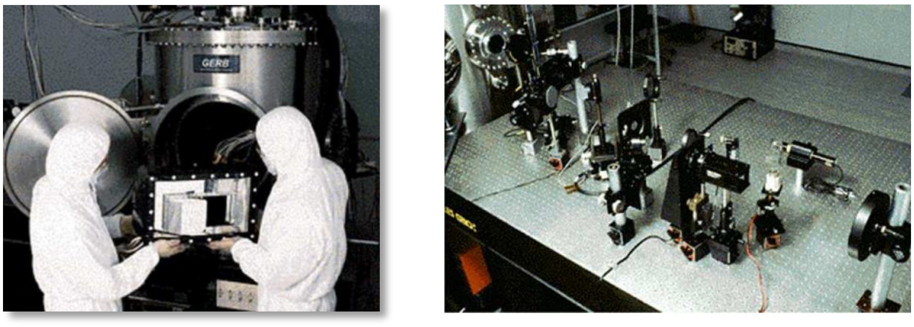


Figure 3.66 EOCF Clean Room (left) and typical 1.25m x 2.0m optics bench (right)

3.20.4 Imperial View on Facilities

Both the Magnetometer Calibration Facility and the EOCF are world class calibration facilities able to support a full range of active characterisation projects for Blackett Laboratory physicists. The University is happy to work with external users in a range of technical tasks, either by making the facilities accessible to external users, or by undertaking contract work by Blackett Laboratory personnel. It has identified a few gaps in its in-house capabilities: a) for more conventional thermal-vacuum testing it is considering upgrading its TVAC chamber to make it a general purpose environmental test chamber in addition to its EOCF calibration role; b) it would be useful to have access to a magnetically quiet site for its magneto-meter calibration activities, closer and more accessible than the Staffordshire site; and c) a vibration test facility would be useful and is being assessed by the Aeronautics Dept for space structures work.

3.21 International Space Propulsion (ISP), Marlborough

3.21.1 ISP Company Background

International Space Propulsion Ltd (ISP) was formed in October 2001 to provide knowledge-based engineering services to the space propulsion industry, primarily within Europe. ISP is a consultancy with particular expertise in all aspects of space propulsion, performing propulsion system design, development, procurement, and production and test of modules, or subsystems. Utilising a large network of propulsion partners, ISP's extended capabilities include: system engineering, materials testing and launch services; propellant procurement, analysis, test and shipping; and ground support equipment (GSE).

ISP founded European Astrotech Ltd (EAL), see section 3.17, as a wholly owned subsidiary in 2007, to perform chemistry and other propellant-based services, testing and equipment maintenance and to manage a new facility on behalf of the ISP Group. ISP divested its interests in EAL in 2010.

3.21.2 ISP Propulsion System Expertise

ISP is able to support the design and implementation of space propulsion systems in a number of key areas as follows:

- **Propulsion subsystem design:** ISP has been supporting the design, manufacture and production of propulsion systems in Europe since the 1980's, with involvement in many of Europe's successes in that time, including OLYMPUS, CLUSTER, Herschel/Planck, ATV and Galileo. This means that the Company has significant expertise in a wide variety of missions and subsystem types, configurations and layouts, scales and requirements, along with the inherent benefit of lessons learned on each programme.
- **Propulsion Ground Support Equipment:** ISP designs and builds GSE for satellite support services, including electrical/electronic explosion-rated (ATEX) precision gas flow and purge panels (as shown below), electrical control panels and other fluid control and monitoring devices.

Figure 3.67 ATEX-rated Precision Purge Panel Type 3992

- **Propulsion system documentation**: ISP has undertaken documentation support roles in many inter-European projects with great success. ISP has supported and implemented a pan-European standardisation of approach, allowing its personnel to assess and generate documents that demonstrate full compliance with current and historical norms, allowing high levels of understanding and traceability through programme heritage.
- **Parts, Materials and Process Management:** ISP's detailed knowledge of Parts, Materials and Process (PMP) philosophies, provides the technical team with an unequalled vision of past and potential material-related problem areas, concerning components, assemblies and complete systems alike. It uses this experience to apply a holistic approach to PMP performance, identifying areas of concern before they reach criticality and, by application of early detection techniques, mitigating problems before they arise.
- **Propulsion subsystem assembly and test:** ISP has a great deal of experience in the preparation and management of propulsion subsystem testing, either at module assembly level, or on the completed subsystem.
- **On-site propellant analysis:** ISP has developed a proprietary portable propellant analysis facility for ESA to certify propellants at the launch site, allowing transport of bulk loads for long-term storage and utilisation over a period of time (i.e. for series of satellites, or constellations).
- **Propellant awareness training:** ISP can provide training that covers propellant preparation, reliability and best practice, as well as component design and operation, hazards and precautions, and the importance of trend analysis and subsystem testing.
- **Business Development:** ISP has recently taken on a new mission to develop relationships with high-value Non-Space Entities, to introduce commercial products and services to the industry in support of the UK Government's National Space Policy, issued in December 2015. The successful outreach campaign intends to introduce novel and disruptive commercial approaches to problem areas within the space sector and thereby make the industry leaner and fitter in preparation for the new commercial space industry.

3.21.3 ISP View on Facilities

ISP’s consultancy expertise covers all aspects of space propulsion system design, manufacture, test and support services. Although ISP does not have facilities of its own, the Company maintains a network of relevant facilities and capabilities to fit any requirement and will offer to support any Customer who requires a complete test package, with additional interface, preparation and management services.

3.22 Intertek, Leatherhead

3.22.1 Intertek Company Background

Intertek is a global test house that has been in the testing business for 130 years, evolving from the combined growth of a number of innovative companies. It became Intertek Testing Services in 1996 and was listed on the London Stock Exchange in 2002 to become Intertek Group. In the UK, Intertek has become a trusted provider of quality and safety services for many of the world's leading brands and companies. With more than 1,500 expert staff working in over 50 locations throughout the UK and Ireland, it can provide responsive and local coverage. For the purposes of this survey, Intertek, Leatherhead has been selected since it specialises in EMC testing for the aerospace market.

3.22.2 Intertek Leatherhead, EMC test facilities

Intertek provides the capacity, proximity and engineering resources to streamline the customer EMC compliance testing process for the space market. The Leatherhead site offers fully anechoic and semi-anechoic chambers, with test item sizes ranging from 3 to 10 metres. Its EMC facilities include:

- 5 EMC chambers, where the main chamber dimensions are 12.25m x 7.7m x 6.5m
- Laboratory UKAS accredited for Military and Commercial EMC Testing
- DEF STAN 59-411 and 61-5 and EN Standards
- MIL STD 461 including: EMC radiated immunity/susceptibility; radiated emissions; bulk current injection; conducted immunity/susceptibility; conducted emissions; and the ability to perform radiated immunity testing up to 200V/m field strength in accordance with MIL STD 461 RS103 from 2MHz to 40 GHz and down to 10KHz
- Electromagnetic Interference (EMI) Testing
- Calibration Services
- Wireless Inductive Charging Testing

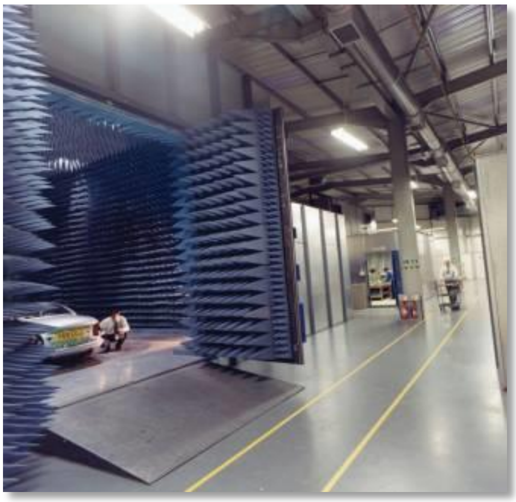


Figure 3.68 EMC Testing Facility at Intertek, Leatherhead

3.22.3 Intertek Leatherhead Environmental Test Facilities

The Leatherhead site offers an extensive range of chambers to test temperature (at ambient pressure), vibration, shock, mechanical wear and dust/moisture ingress and the effect of the light spectrum. It is also possible to bundle EMC tests with environmental tests if required.

3.22.4 Intertek View on Facilities

Within the UK, Intertek can provide an extensive array of testing services of all types at more than 50 locations, but within the context of this study it is useful to focus on its Leatherhead facility, which is able to provide a comprehensive EMC testing service at unit or subsystem level, combined with environmental testing if required.

3.23 ISVR's Rayleigh Laboratories, Southampton

3.23.1 ISVR Company Background

ISVR Consulting was established in 1968 at the University of Southampton as the Wolfson Unit for Noise and Vibration Control and, although the name was changed to the Institute of Sound and Vibration Research (ISVR) in 1987, the company has been providing a full-time professional service for more than 45 years. It is a commercial consultancy unit linked to the Institute of Sound and Vibration Research (ISVR) at the University and it operates the Rayleigh Laboratories' acoustic test facilities on the main campus of the University.

Many spacecraft components are exposed to high levels of noise-induced vibration during the launch phase, typically one or two minutes after lift-off. This can cause problems such as:

- Failure of micro-electronic component lead wires
- Chafing of wires
- Cracking of printed circuit boards
- Malfunction or failure of waveguides or Klystron tubes
- Vibration of optical elements
- Failure of joints in structures made from composite materials.

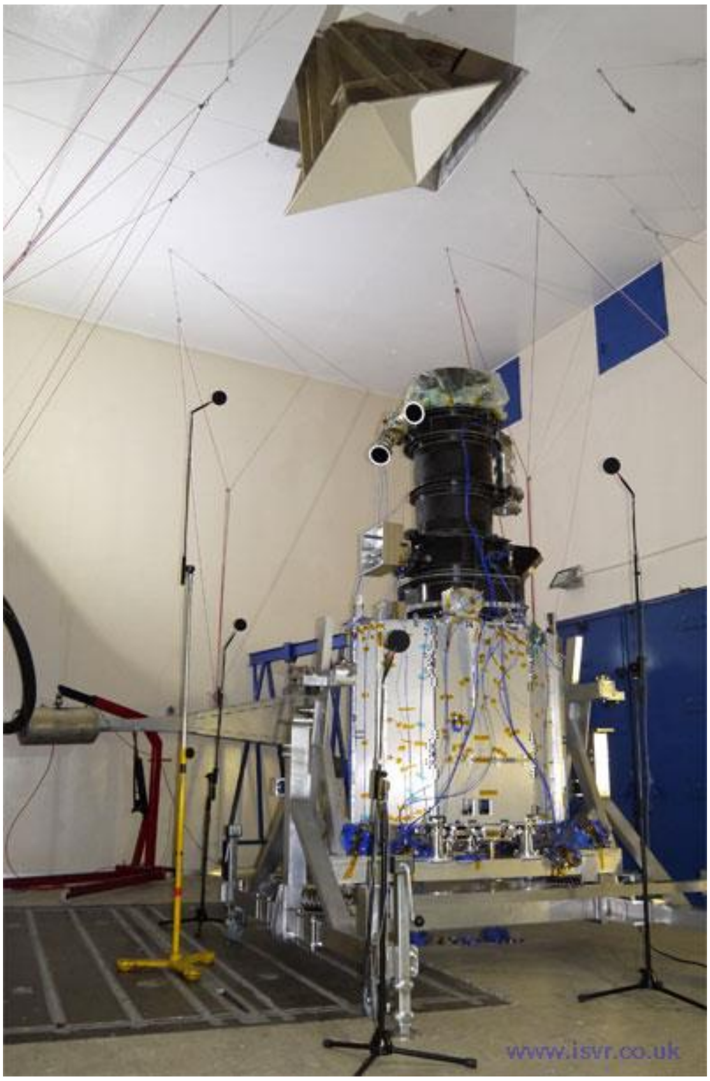
In order to ensure that spacecraft components don't fail under this acoustic stress they are tested under a high level noise field. During testing the noise exposure is made to be as close to real conditions as possible. For spacecraft components the excitation spectrum is usually specific to the launch vehicle, but some standard levels may be used if the actual spectrum is not well characterised. Overall noise levels up to 160 dB may be required in various frequency ranges between 25 Hz and 10 kHz. Ceiling-mounted and suspended horns are used as high-intensity noise sources.

Levels of up to 147 dB can be generated in ISVR's Large Reverberation Chamber (348 cubic metres). In the Small Reverberant Chamber (131 cubic metres) levels of up to 160 dB can be attained, depending on the sound spectrum required.

3.23.2 ISVR's Rayleigh Laboratories

ISVR has three acoustic test chambers, all with internal forced ventilation, as follows:

- **Large Reverberation Chamber**
  - Built as a box-within-a-box, isolated from the surrounding building
  - Non-parallel walls, 9.15m x 6.25m x 6.10m high
  - Access 2m x 2.4m high
  - High intensity testing in the reverberation room can achieve overall sound pressure levels of 147dB, and sound levels in excess of 170dB can be achieved in a progressive wave tube in which panels are excited by grazing incidence sound
- **Small Reverberation Chamber**
  - Similar construction
  - Non-parallel walls, 6.4m x 4.6m x 4.3m high
  - Access between reverberation rooms 2m x 2.4m high
- **Anechoic Chamber**
  - Dimensions inside wedges 7.3m by 7.3m by 5.1m high
  - Non-parallel walls, 6.4m x 4.6m x 4.3m high
  - The anechoic chamber floor has a removable grid floor above the wedges. This grid floor is at the same level as the floors outside the chamber. The grating is capable of supporting a spread load of several tonnes. Sections of the grid, or all of the grating, can be removed if necessary
  - Sound pressure levels of 160dB



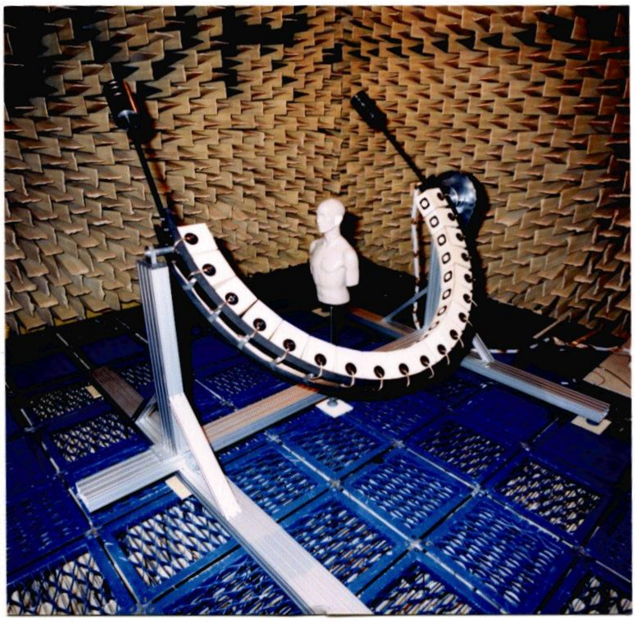


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Figure 3.69 ISVR Large Reverberation Chamber with SSTL300 S1 spacecraft (left) and Anechoic Chamber (right)

3.23.3 ISVR View on Facilities

Although ISVR's principal activities are centred on acoustics and vibration research, the Laboratory offers a comprehensive acoustic test facility for the space community, ranging from unit- or subsystem-level all the way up to spacecraft-level.

3.24 Lockheed Martin Space Systems Co UK (LMSSC-UK), Harwell

3.24.1 LMSSC-UK Company Background

Lockheed Martin UK, headquartered in London, is the UK-based arm of Lockheed Martin Corporation, a global security and aerospace company principally engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems, products and services. Lockheed Martin Space Systems Company UK recently opened a space technology office in Harwell to explore opportunities in the space sector as well as develop partnership opportunities with UK businesses and universities to support the UK's goal of maintaining and growing its national capabilities in space across the full spectrum of capabilities.

3.24.2 LMSSC-UK Possible Expansion

LMSSC-UK continues to expand its UK presence. In addition to working with the UKSA and ESA on a range of civil and commercial space projects, LMSSC-UK is also actively investigating the possibility of conducting final integration, assembly and test of complete medium-size 'geo' spacecraft in the 2-4 tonne class, using LMSSC's new low-cost A2100-TR spacecraft platform and leveraging the UK supply chain. The A2100-TR bus comprises a common framework that includes the satellite's solar arrays, propulsion system and core electronics. LMSSC-UK also intends to work with UK-based companies for the mission specific payloads. There are currently more than 40 A2100 spacecraft (the predecessor to the A2100-TR) in orbit with more than 400 collective years of on-orbit service, fulfilling both commercial and US Government missions.

Figure 3.70 Lockheed Martin A2100 Modular Spacecraft Platform

3.24.3 LMSSC-UK View on Facilities

At present LMS' space-related facilities in the UK are mostly located at Ampthill, Bedfordshire, and these include: 'Aeroshell' thermal protection systems for re-entry vehicles; payload release mechanisms; terrestrial and planetary landing systems; space-plane actuation systems; and hypersonic, aero-thermal dynamic and aerodynamic modelling. The decision on whether or not to build A2100-class spacecraft in the UK will depend crucially on the availability of suitable assembly and test facilities to support the assembly, integration and test of this class of spacecraft. Such support would include as a minimum: adequately sized clean rooms, vibration facilities, thermal-vacuum chambers and EMC facilities either co-located, or else in reasonably close proximity to each other.

3.25 Magna Parva, Leicester

3.25.1 Magna Parva Company Background

Magna Parva is a technology development company based in Leicester, with a strong space engineering capability, including systems engineering, structural and thermal design and analysis from initial concept through to manufacture and test. Its concept-to-production facilities include a 500m^2 design and analysis office, a 1000m^2 laboratory, temperature controlled CMM metrology room, clean room Cat 7, environmental test chambers, micro-crack propagation inspection facility and a high precision prototype manufacturing cell for both metal and plastic components. Examples of recent projects are shown below:

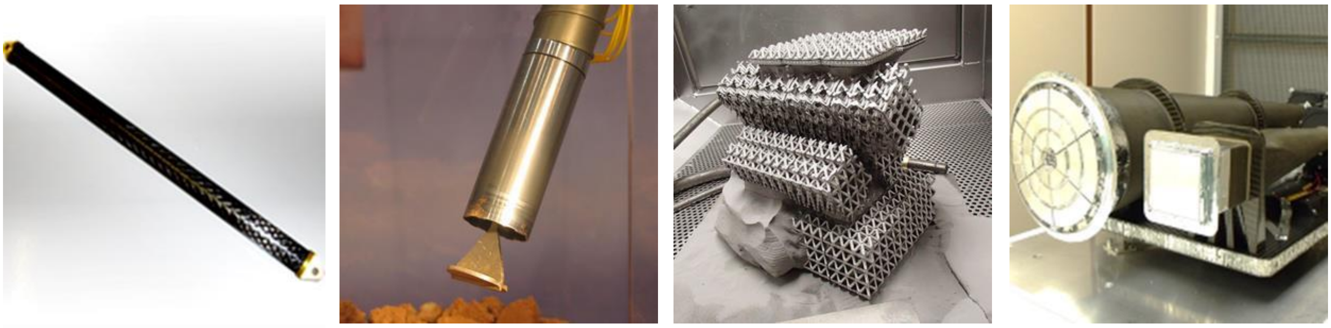


Figure 3.71 CFRP spacecraft component, ultrasonic drill, 3-D printed thermal hardware, Bepi Columbo optics

3.25.2 Magna Parva Manufacturing and Test Facilities

Magna Parva's manufacturing, environmental, validation and testing facilities, available to external users under suitable contractual arrangements, include:

- Clean assembly areas
- Rapid prototyping and mechanical testing
- Crack propagation laboratory
- Ultrasonic technology laboratory
- Biotech laboratory
- Electronics testing

Other test facilities, such the destructive test facility for testing windows for manned space flight, shown below, are very specific and may not be of interest to other organisations.

Figure 3.72: Rapid prototyping facility and destructive testing of window for manned spaceflight

3.25.3 Magna Parva View on Facilities

Magna Parva is generally content with its in-house design, manufacturing and testing facilities required to implement its own programmes and with its access where necessary to nearby external facilities. One exception is the lack of precision manufacturing facilities for CFRP in the UK, resulting in lead-times being increased and costs being driven up. This is further exacerbated by providers bumping smaller customers down the queue in favour of larger orders.

3.26 Mars Space, Southampton

3.26.1 Mars Space Company Background

Mars Space Ltd (MSL) is a spin-off company from the University of Southampton, formed in 2007, and although 100% independent of the University, it does collaborate with the University when mutually advantageous for joint projects such as some recent highly successful ESA projects. Furthermore MSL's MD, Steve Gabriel, also holds a personal Chair in Aeronautics and Astronautics, the only such post in the University. MSL is a fast-growing innovation-focused SME providing services and consultancy on space propulsion and plasma engineering and science. Its main areas of expertise lie in electric propulsion and plasmas, including the space environment. It is currently developing and qualifying a series of innovative propulsion concepts to increase the capabilities and commercial value of CubeSat, PicoSat, NanoSat and MicroSats by providing them with flexible and affordable propulsion systems to fit their needs. MSL, in collaboration with Clyde Space, has developed and fully space-qualified a pulsed plasma thruster (PPT) specifically designed for CubeSats.

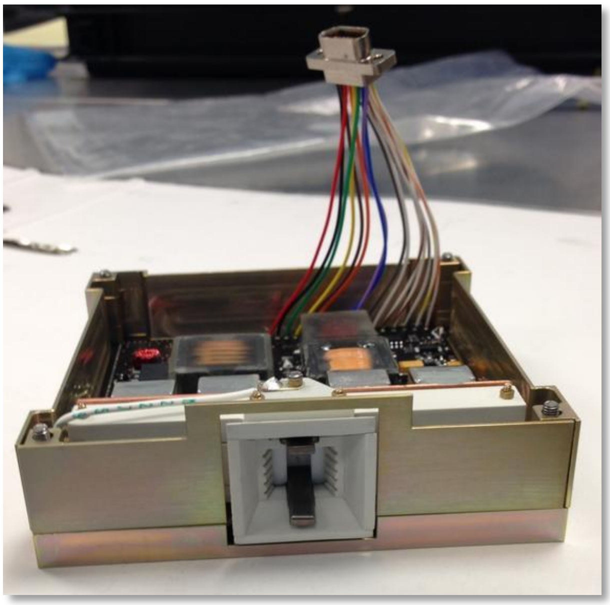


Figure 3.73 CubeSat Pulsed Plasma Thruster for CubeSat Propulsion (Mars Space and Clyde Space)

MSL is also actively working on the development of a new generation of UK ion engine in collaboration with QinetiQ, and in the development of a mini-ion-engine for NanoSats and of a very high temperature Xenon resistojet for telecommunication platforms in collaboration with MOOG.

3.26.2 Mars Space Propulsion Test Facilities

The MSL Electric Propulsion Laboratory is equipped with three vacuum chambers. Two vacuum chambers, named MSLC-1 and MSLC-2, are identical and are L-shaped, approximately 0.6 m diameter by 1.5 m long. The third chamber, MSLC-3, is cylindrical with a diameter of about 0.5 m and a length of 0.6 m. Other features and capabilities of the laboratory and its chambers, which are available for external customers under suitable commercial arrangements, are:

- **MSLC-1**
  - Pumping Speed 2,200 l/s
  - Base Pressure 1×10^{-7} mbar
  - MSLC-1 is equipped with a direct impulsive thrust balance (owned by the University) capable of measuring an impulse bit in the range 20 µNs to 120 µNs. The facility has been used to flight-qualify the first PPT for CubeSat applications and to test a PPT for nano-satellite applications. It is currently being used for delta qualification and acceptance testing of CubeSat PPT Flight Models
- **MSLC-2**

- Pumping Speed 4,300 l/s
- Base Pressure $<1x10^{-7}$ mbar
- MSLC-2 is used to perform tests on Hollow Cathodes and Hollow Cathode Thrusters, and will be used for tests on a Xenon Very High Temperature Resistojet and a Ring Cusp Ion thruster.

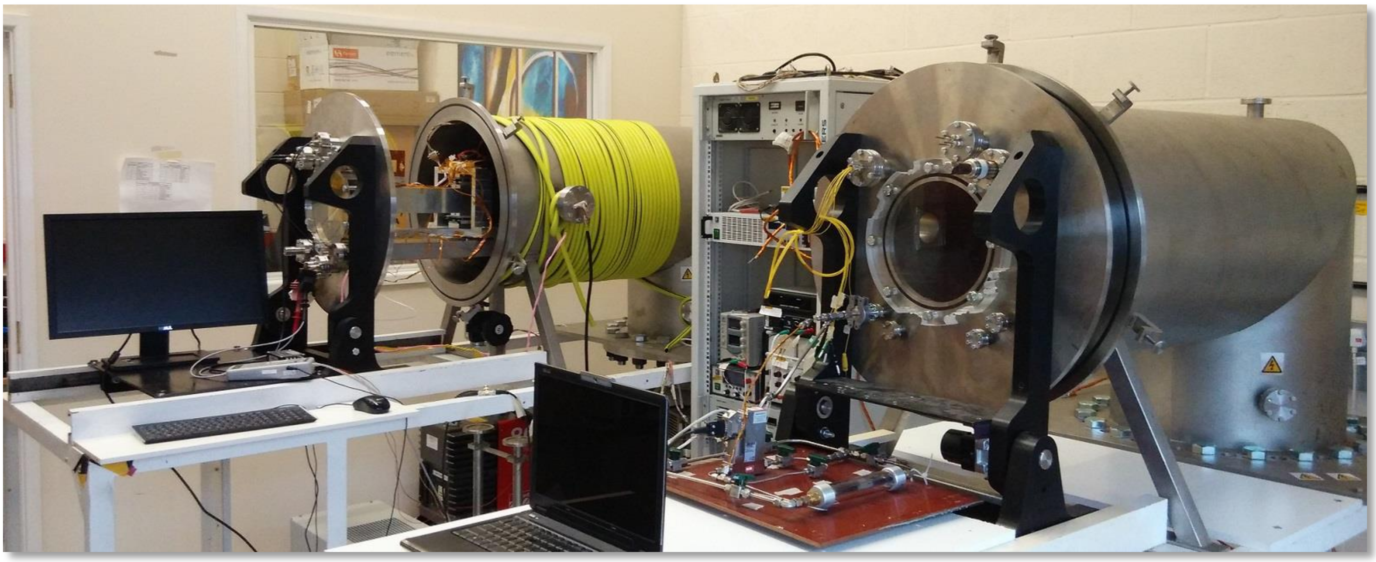


Figure 3.74 Mars Space MSLC-1 and -2 Test Chambers

- **MSLC-3**
  - Pumping Speed 2,300 l/s
  - Base Pressure $<1x10^{-7}$ mbar
  - MSLC-3 has just being assembled and will be used mainly for micor ion engine development and for hollow cathode testing. As with MSLC-2, this chamber also has a completely oil-free pumping system.
- **Power supplies and measuring instruments**
  - DC electric power supplies include low and high voltage supplies (up to 15 kV) necessary to operate PPTs and low and high current supplies to run HCs, HCTs, VHTRs and Ring Cusps (up to 60 A). RF power supplies are also available.
- **Diagnostic capabilities**
  - Two 12kV HV probes, one 7kV HV differential probe, two Rogowski coils (to measure the PPT discharge current) a 30A current probe, a high accuracy mass scale with a resolution of 10 µg and several digital multi-meters.
  - Two 4-channel digital oscilloscopes and NI-DAQ USB boards are also available for real-time data processing.

3.26.3 Mars Space View on Facilities

The Mars Space EP Lab has been recently upgraded and is considered to be sufficient for the work to come in the next two years. When necessary, it also has access to the University facilities (one of which is currently being used for 2 projects) via normal commercial arrangements. However Mars Space is conscious that it still lacks TVAC and EMC capabilities, although these capabilities are not needed on a daily basis but mainly for qualification campaigns when the cost of using an external facility can be accommodated.

3.27 Moog UK, Westcott

3.27.1 Moog UK Company Background

Moog Inc. is a global designer, manufacturer, and integrator of high-performance systems for military and commercial aircraft, satellites and space vehicles, launch vehicles, missiles, industrial machinery, wind energy, marine applications, and medical equipment. Moog's global space portfolio includes: systems, sub-assemblies and components for chemical, electric, and cold gas propulsion on satellites; positioning of antennas and solar array panels for spacecraft; and space-rated electronics, avionics, thrust vector control actuation systems, primary flight control actuators, electronic controllers, and fluid control systems and components for launch vehicles. This study focusses on Moog's UK space propulsion interests which are centred at its facility at Westcott Venture Park near to Aylesbury. In 2012 Moog acquired AMPAC In-Space-Propulsion (ISP), a leading developer and supplier of liquid rocket engines, tanks, and propulsion systems for spacecraft which has heritage dating back to the 1940's and continuing now at Westcott.

3.27.2 Moog Chemical Propulsion Engines and Thrusters

Moog-ISP produces a range of bi-propellant and mono-propellant chemical thrusters and engines for in-space propulsion which are manufactured and tested at Westcott. These include low-thrust engines for ACS applications and high thrust apogee engines examples of which are shown below.

Figure 3.75 The MHT-1N high reliability, high performance 1 Newton monopropellant thruster currently under final development at Moog Westcott

Figure 3.76 Moog-ISP test firing for High Thrust Apogee Engine development programme

3.27.3 Moog Cold Gas Systems

Moog's Cheltenham facility (previously Polyflex, then Marotta Europe and then AMPAC-ISP) produces a range of valves and cold gas thrusters based on its SVT01 thruster.

Figure 3.77 Moog SVT01 Cold Gas Thruster

3.27.4 Moog View on Facilities

Moog's Westcott facilities include high altitude pumped test cells, one for engines up to 3N, a second for engines up to 22N, and a sea-level (un-pumped) test facility for engines up to 30kN such as that shown in Figure 3.76 above. Other Moog facilities include flow test benches for the characterisation of injectors and complete engines, electron beam welding, a coordinate measuring machine, a vibration facility and a well-equipped state-of-the-art chemistry lab for the analysis of propellants. Moog also undertakes custom mechanical and electronic design instrumentation projects and works on Ground Support Equipment for satellite propellant loading.

Moog's high altitude and sea-level test cells at Westcott are all used to support in-house rocket engine development projects, but there is some capacity for taking on external work, subject to availability and normal commercial arrangements. Moog's current focus is on apogee engines (also known as kick motors) selling across the world, primarily to the USA. Moog is also developing a new low-cost, high performance apogee engine primarily for European telecoms missions.

Moog believes there is a critical need for a high-altitude test facility to test 1 to 2kN engines. The lack of such a facility may mean that the European 1kN engine being developed for Mars missions and other applications will be at risk. It also represents an obstacle to training more people and developing more skills in the space sector. Moog is keen to be part of such a 'National' facility, which could be ultilised by MOOG, Airborne Engineering, ESP, Airbus etc and which will require UK funding but would represent extremely good return on investment for the UK.

3.28 National Physical Laboratory (NPL), Teddington

3.28.1 NPL Background

The National Physical Laboratory (NPL) is the UK's National Measurement Institute, and is a world-leading centre-of-excellence in developing and applying the most accurate measurement standards, science and technology available, which it has been doing for more than a century. These standards underpin the National Measurement System infrastructure of traceability throughout the UK and globally, that ensures accuracy and consistency of measurement. NPL ensures that cutting-edge measurement science and technology have a positive impact in the real world. NPL delivers world-leading measurement solutions that are critical to commercial research and development, and support business success across the UK and the globe.

3.28.2 NPL Electromagnetic RF Testing Facilities

NPL runs one of the world's most comprehensive capabilities for traceable measurement of basic electromagnetic parameters at RF and Microwave frequencies. This is centred on the frequency range from 1 MHz to 110 GHz, but with many extensions at either end, e.g. up to THz frequencies.

The National Standards and measurement capability are maintained specifically to support UK industry, engineers and scientists. Experience gained in their development gives the RF and Microwave metrologists at NPL unique knowledge that can be invaluable when working with industrial collaborators and end-users to help remove their measurement barriers to innovation. This experience is passed on in many ways, e.g. through collaborations, workshops, publications, inputs to standardisation bodies and consultancies.

The wide range of facilities and measurement techniques for calibration, test and characterisation includes:

- EMC antennas (loops, monopoles, dipoles, bi-conical antennas, LPDAs, horns etc) and VHF antennas
- Power flux density measurements include: axial isotropy, frequency response, linearity, sensitivity
- Radiation hazard monitors, field-strength probes
- Power / Attenuation / Noise Standards to 110 GHz
- Conventional on-wafer measurements to 220 GHz
- Time-Domain Spectroscopy (TDS) from 100 GHz to 5 THz
- Vector Network Analysis (VNA) from RF to millimetre wavelengths and beyond (to 750 GHz)
- On-wafer Electro-Optic Sampling (EOS) / Time-Domain Reflectometry with sub-picosecond resolution (>600GHz)
- Test site validation and electromagnetic field site surveys
- Hire of NPL test sites and /or sales of various bespoke instrumentation

The Microwave Anechoic Chamber is a ±1°C temperature-controlled 7.5m x 7.5m x 15m anechoic chamber, providing a low reflection environment for the accurate characterisation of antennas. It is certified to ISO 17025, and has a very broad frequency spectrum capability from 250MHz up to 110GHz (can be extended to 220 GHz). It has a wide range of waveguide and coaxial feed types for applications ranging from remote sensing to radar and communications. The chamber has a 0.25mm rail spec; computer-controlled positioning with laser encoder measurement. Measurements include:

- gain pattern and measurements to ±0.05 dB
- sidelobes
- 3 dB beam width
- front-to-back and axial ratios
- tilt and reflection coefficients

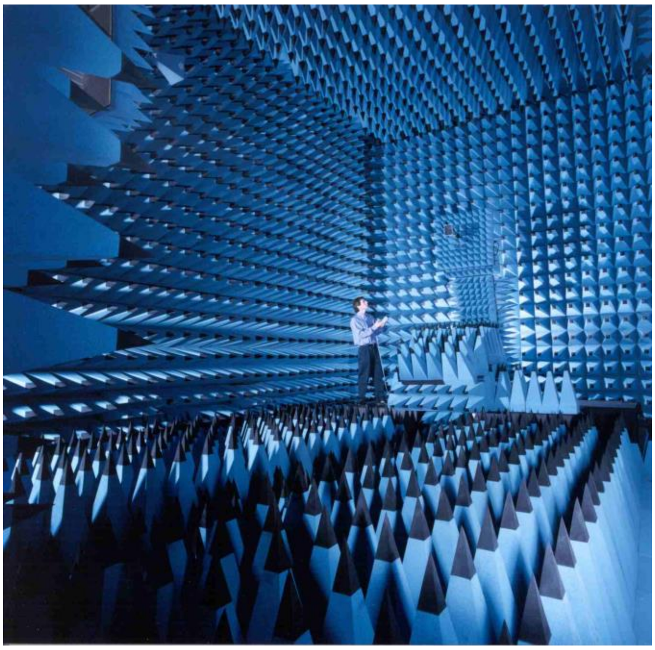


Figure 3.78 NPL Microwave Anechoic Chamber

The SMART (SMall Antenna Radiated Testing) range is a temperature controlled 7.15m x 6.25m x 6.25m anechoic chamber, providing a low reflection environment for the accurate characterisation of antennas over the range 400MHz to 26.5GHz (can be extended to 110GHz). Applications include electrically small antenna, smart antenna, MIMO and wireless communications. Measurements include:

- 3D radiation pattern (using either roll-over-azimuth or elevation-over-azimuth) with cable or unique non-invasive optical fibre solution
- Antenna and Propagation channel evaluation (i.e. with single-input-single-output (SISO), single-input-multiple-output (SIMO), multiple-input-single-output (MISO), multiple-input-multiple-output (MIMO) channel emulation capability up to 4 x 4 channel)
- Gain
- Directivity
- Radiation Efficiency

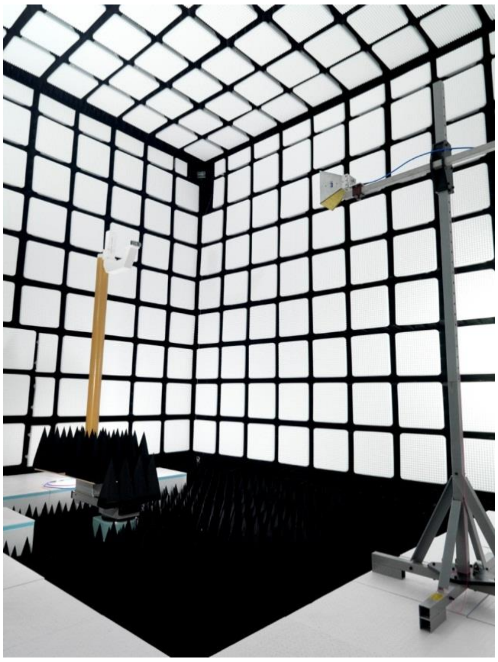


Figure 3.79 NPL SMART antenna range

The NPL Reverberation Chamber is a temperature-controlled 6.5m by 5.85m by 3.5m chamber providing an over-moded reflecting environment that gives statistically homogeneous and isotropic fields within its working volume with frequency spectra from 170 MHz (lowest usable frequency) up to 18 GHz.
Measurements include:

- EMC Radiated Emission and EMC Radiated Susceptibility testing
- Antenna radiation efficiency
- Total radiated power
- Wireless propagation channel characterisation

Figure 3.80 NPL Reverberation Chamber

3.28.3 NPL's Radiometric Calibration and Characterisation Facility

NPL is collaborating with STFC/RAL Space to establish the Centre for Calibration of Space Instrumentation, see Section 3.35.7, as a UK National facility on the Harwell site.

NPL's Radiometric calibration and characterisation facility provides direct access to SI traceability at the highest accuracy possible for a range of quantities in the optical domain (UV, 200 nm through to TIR, ~100 µm) both pre-flight and post-launch. The facility is constructed so that it consists, where possible, of transportable systems that can travel to other sites in the UK and elsewhere to facilitate delivery of measurement services at point of need e.g. at a vacuum facility, or in a desert. The measurement capabilities are underpinned by a cryogenic radiometer as the primary standard, which can measure the power of an intensity stabilised laser beam to better than 1 part in 104 or 0.01%. A version of the cryogenic radiometer measures total solar irradiance and is deployed at the World Radiation Centre in Davos to provide the reference for the World's solar radiometers.

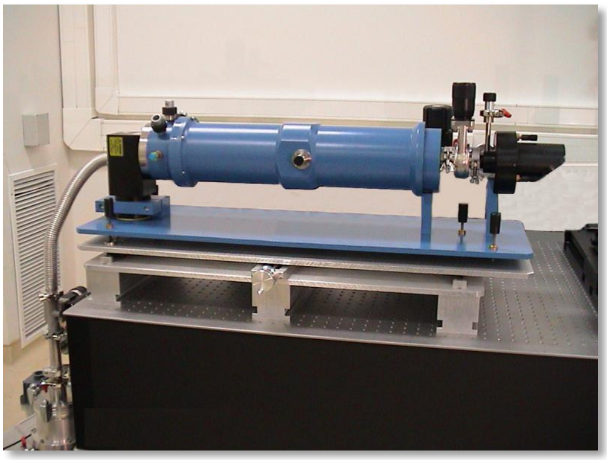


Figure 3.81 NPL Primary Standard cryogenic radiometer

The NPL facility provides calibration of: detector properties (responsivity, linearity, uniformity etc.) at ambient to cryogenic temperatures, high and low valued reflective and transmissive properties (angular, BRDF, polarised) of materials and surfaces (including land/snow surfaces in the field) spectral radiance/ irradiance/brightness temperature. The services can be delivered in a variety of ways through a range of systems, tailored to meet the user requirements be it a, sub-system or end-to-end calibration of a full instrument. The capabilities are all state-of-the-art, and are maintained and improved through resources of the national measurement system programme of BIS. They include the novel use of spectrally tuneable laser radiation capable of providing high spectral resolution for wavelength/band shape and radiance simultaneously and a variety of transfer standards, instrumentation, and infrastructure that can be loaned or utilised on an as-needs basis. As part of its work with ESA it has established, and will soon operate, a test site in Namibia for the post launch radiometric gain calibration of solar reflective imaging sensors such as Sentinel 2.

3.28.4 NPL Magnetic Test Facility

A low magnetic field facility has been established at NPL in which the Earth's magnetic field is cancelled to less than a nanotesla at the centre of a 3m diameter triaxial Helmholtz coil system. Field-generating coil systems can then be located inside the triaxial coils to characterise magnetic sensors. Sensor parameters including gain, offset, linearity, gradient and frequency response can be measured in addition to the sensor's noise performance. The Power Spectral Density (PSD) of the cancelled environment has demonstrated an existing noise floor of 12 pT/√Hz at 1 Hz, and the system allows for noise measurements to be made down to 0.1 mHz. The facility also has the capability to characterise magnetic sensors at the operational temperatures encountered in a range of industrial applications. A temperature control system has been integrated into the cancellation system that allows calibration of such sensors over the temperature range of –55°C to +125°C.

Measurements performed in the cancellation system exhibit a better measurement repeatability and lower uncertainty contributions for this type of measurement. The field-generating coil systems are calibrated using a proton resonance magnetometer to obtain the lowest uncertainties with traceability gained via frequency. The lowest uncertainty offered over the range 20 µT to 90 µT is ± 0.0030% (k=2, 95%). The majority of magnetic measurements made at NPL can be issued on calibration certificates covered by NPL's UKAS (ISO 17025) accreditation.

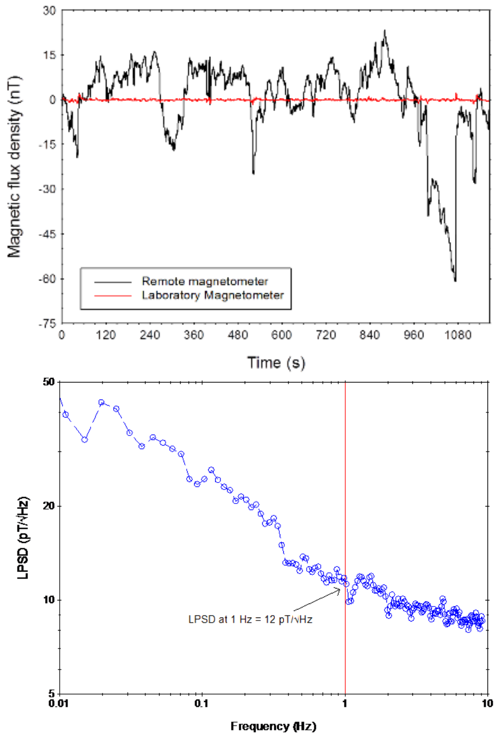


Figure 3.82 NPL Triaxial Helmholtz Coil System

The calibrated three-axis fluxgate magnetometer used to establish the zero of the cancellation system can also be used for magnetic signature measurements. The item-under-test is first removed to a position at which it can no longer be seen by the magnetometer and the zero condition established. The item is then brought up to a known distance for each of its three geometric axes and the magnetic flux density measured for forward and reverse directions. From these the magnetic dipole moment can be calculated. Either of these quantities can be compared to the customer requirements to see if the item passes for magnetic signature. Magnetic signature measurements have been made on various satellite components, including batteries, On-board computers and thrusters. The facilities also provide for customer specific 'Perming' and 'De-perming' profiles to be included as part of the measurement procedure.

In addition, a set of high frequency Helmholtz coils have been produced for the calibration of magnetic field meters up to a frequency of 120 kHz. This system is used to calibrate portable magnetic field meters that are used for compliance testing. The magnetic field range covered by the facility has been selected to meet that of the majority of meters available on the market. Limited measurements for non-sinusoidal waveforms are also available. Also available are the facilities to calibrate DC magnetic field instruments up to 3 T.

Other capabilities include both static (DC) and time-varying (AC) magnetic field surveys of customers' sites where the magnetic signature of the local environment is required to be known, and once known mitigation (e.g. screening) can be employed if required.

3.28.5 NPL Radiation Test Facilities

As explained above, NPL is the UK's National Measurement Institute, developing and applying the most accurate measurement standards, science and technology available and one such area, particularly important for space missions, is radiation testing.

A therapy level ^{60}Co Gamma-ray facility is maintained by NPL's Radiation Dosimetry group and is available for hire for short or long term gamma-ray irradiations with supporting dosimetry and technical services if required. The facility comprises a Theratron Radiotherapy irradiator and can be used for instrument, materials and components radiation hardness testing for space electronics.

Figure 3.83 NPL Radiation Test Facility

Research and investigations can be carried out with this facility by NPL staff on a contract basis. The unit may be hired on a half day, day or week basis and the hire fee includes the use of a Perspex or water phantom if required. Other dosimetric equipment can also be hired in conjunction with the hire of the Theratron itself. Any dosimetry required can be made traceable back to either the National Standards of absorbed dose and of air kerma (kinetic energy released per unit mass).

The characteristics of the radiation test facility are as follows:

- Manufacturer: Theratronics, Canada
- Source: ^{60}Co, fitted with a collimator to provide rectangular fields of up to 35cm x 35cm at 80cm source-to-surface-distance (SSD)
- Beam can be set up at any angle in a plane down the long axis of the 6m x 10m x 4m irradiation cell
- The temperature can be kept constant to better than 0.1°C in the range +15°C to +30°C
- Irradiations are controlled from a control room adjacent to the irradiation cell
- Both rooms are electrically screened from external radio frequency interference and communication between the equipment-under-test and its controller can be achieved using cables passing through 10cm diameter ducts in the radiation shielding
- Equipment for irradiation is mounted on a carriage system allowing test items to be moved in three dimensions to a precision that is a fraction of a millimetre. The carriage is mounted on 6m long rails enabling movement along the long axis of the irradiation room
- The cobalt head has high level of shielding and is loaded with a 300TBq (8.1kCi) source
- Dose rate to water is up to 1.0Gy min^{-1} at 80cm from the source (March 2011)

NPL's three ^{60}Co self-shielded irradiators are available for the irradiation of dosimeters or investigations and tests of materials. The irradiators provide ^{60}Co gamma-ray fields covering dose rates from 3 Gy min^{-1} to 120 Gy min^{-1} (as of January 2016).

For the irradiation of samples where the most accurate dose is required, for example as part of a dosimeter calibration exercise, small thermostatically controlled holders are available. These holders enable precise dosing to small volumes at a customer-selected temperature. Depending on the specific holder temperatures between -60°C and +70°C can be achieved.

For more general irradiations the full cylindrical irradiation volume of the three irradiators may be used. The volumes are approximately 1700cm^3 (12 cm diameter by 15cm high) and 3300cm^3 (15cm diameter by 19cm high). Cables can be fed into the irradiation volume if continuous monitoring of the sample is required. Dose distribution studies can be undertaken to determine exact doses and uncertainties at the time of irradiation.

Figure 3.84 NPL ^{60}Co irradiator

The NPL radiation facilities are complemented with a 3.5 MV Van de Graaff accelerator Neutron source.

3.28.6 NPL View on Facilities

The NPL range of facilities and measurement capabilities is not limited to those described above and covers a wide range of other areas such as advanced materials, quantum detection, time-and-frequency, mass, dimension and temperature metrology or acoustic measurements amongst others. As the UK centre-of-excellence for developing and applying the most accurate, internationally traceable, measurement standards, NPL is uniquely able to make its facilities and expertise available to the UK space community.

3.29 Neptec UK, Harwell

3.29.1 Neptec Company Background

Opened in Harwell, Oxfordshire in October 2014, Neptec UK Ltd. is a wholly-owned subsidiary of Neptec Design Group Ltd. of Ottawa, Canada, which is an award-winning technology innovator for the space market and NASA Prime Contractor. Neptec UK provides support to the Company's European-based customers as well as specialising in the UK development of space-qualified metrology instruments, IR cameras and other intelligent sensors.

Under contract to the Spanish company Sener, Neptec UK is currently developing the HAMS (Hi-Accuracy Measurement System) for the ESA PROBA-3 two-satellite precision formation-flying mission. HAMS is a derivative of an earlier instrument CAMS (Canadian Astro-H Metrology System) developed for the JAXA Astro-H mission. It is able to measure the nominally 150m distance between the two satellites to micrometre accuracy so that they are effectively flying joined to each other, even though there is no physical connection. It is expected that this technology will allow smaller satellites to be launched from Earth independently and then joined in space to form larger structures or platforms such as large telescopes. Neptec also intends to exploit potential terrestrial applications for this precision ranging technology.

Figure 3.85 ESA Proba-3 Mission using Neptec's HAMS sensor (left) and its predecessor CAMS (right)

Neptec UK recently won two contracts with the UK Space Agency: a) to develop model simulations of IR cameras in space; and b) to design and build a European space-qualified IR camera.

3.29.2 Neptec UK View on Facilities

Each of these space contracts will require extensive qualification testing and since Neptec UK is an SME without its own testing facilities, it will have to rely on other organisations in the UK to provide those services. These contracts will require the following tests to be performed on Neptec's equipment before delivery to the Customer: thermal-vacuum; vibration; shock; EMC; and radiation performance.

An important consideration for Neptec will be ease of access to suitable testing facilities, ideally co-located, and cost is certainly a major consideration for a small company. Also, Neptec plans to build its own development laboratories for preliminary builds of hardware but it will need access to clean rooms when assembling and troubleshooting space flight hardware. Neptec is hoping that clean room access for its staff will be available on the Harwell campus and is happy to share this with other small companies in order to ease the cost burden.

3.30 Open University (OU), Milton Keynes

3.30.1 OU Background

The Open University (OU) is a distance-learning and research university based in Milton Keynes and was established in 1969. With more than 250,000 students enrolled, it is one of the biggest universities in the UK for undergraduate education, with the majority of those students spread throughout the United Kingdom, studying off-campus. However, there are also a number of full-time postgraduate research students based on the 48-hectare university campus where they use the OU facilities for research, and it is these facilities that are of interest to this space facilities study.

The university comprises 11 faculties each containing a number of departments and one of these, the Department of Physical Sciences within the Faculty of Science is located in the Robert Hooke Building on the Milton Keynes Campus. It is this Department where most space research activities are conducted, supported by a number of specialist facilities, many of which are dedicated to the Department's particular interest, planetary research.

3.30.2 OU Clean Rooms

One of the great challenges of the study of extra-terrestrial materials is discriminating the indigenous signatures from terrestrial contamination, so much of the processing of samples and all curation and building of space instruments is performed in dedicated clean rooms:

Sample Curation Facility: comprising a suite of labs covering approx 60m^2 that is the main facility for handling and storage of meteorite, lunar and other extra-terrestrial samples; the main 30m^2 cleanroom is ISO Class 6 (Class 1,000), supported by an ISO Class 7 chemistry lab and two ISO 5 (Class 100) rooms.

Clean Fabrication Facility: dedicated to building space hardware, there is a 50m^2 ISO 6 clean room, supported by an ISO 7 chemistry, preparation and control laboratory.

Figure 3.86 OU clean room

Clean Petrography Suite: dedicated to the characterisation of rock samples prior to analysis by the OU mass spectrometers, there is a 45m^2 Class 7 clean room containing the main optical microscope systems, a laser Raman micro-probe and a UV-Vis micro-spectrophotometer.

3.30.3 OU thermal and planetary environment chambers

The OU has a number of vacuum chambers customised to become Planetary Environmental Simulators.

Large Mars Chamber: capable of recreating the Martian environment for large scale simulation of the Martian surface (aeolian transport etc) or to test large instruments or rover subsystems:

- Dimensions: 0.9m diam x 1.8m length
- Temp range: -70°C to +110°C
- Environment: CO_2/N_2 atmosphere at 6mbar
- Illumination: UV solar sim

Figure 3.87 OU's Large Mars Chamber

Small Mars Chamber: environmental chamber allowing automated simulation of the Martian surface environment.

- Dimensions: 0.7m diam x 1.2m length
- Temp range: -70°C to +110°C
- Environment: CO_2/N_2 atmosphere at 6mbar
- Illumination: UV solar sim
- Cycling: automated pressure and thermal control for thermal cycling
- Sterilisation: sustained temp >110°C for continuous periods for DHMR sterilisation (dry heat microbial reduction)

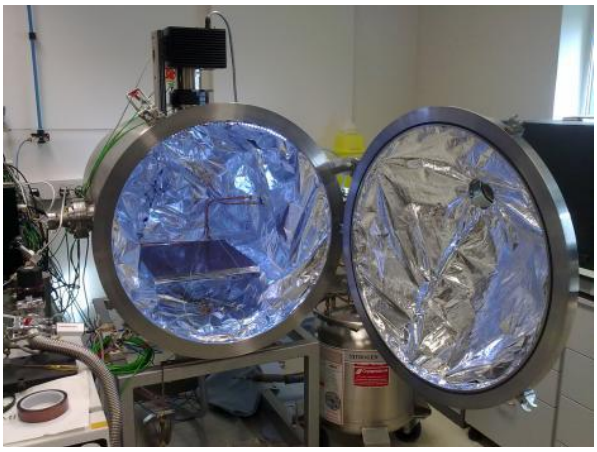


Figure 3.88 OU's Small Mars Chamber

Icy Bodies Chamber: environmental chamber allowing automated simulation of conditions on icy bodies such as Europa, Ganymede and Enceladus.

- Dimensions: 140mm diam x 150mm height
- Cold temp: -150°C
- Illumination: solar simulator via top port
- Cycling: automated pressure and thermal control for thermal cycling
- Viewports: horizontal and angled

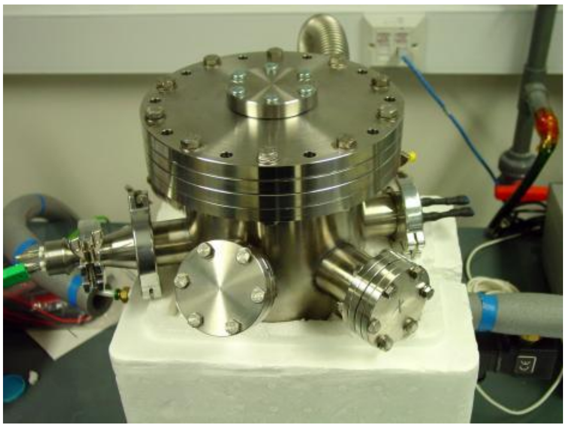


Figure 3.89 OU's Icy Bodies Chamber

Mercury Chamber: an upright cylindrical chamber allowing simulation of some of the conditions encountered on Mercury, and also for testing instruments that are going to be flown in an extreme space environment, where they will be subject to an extreme temperature range, as well as the vacuum of space.

- Dimensions: 0.7m diam x 0.8m height
- Temp range: -100°C to +180°C
- Illumination: high power xenon solar simulator
- Vacuum: <10-5 mbar

Figure 3.90 OU's Mercury Chamber

3.30.4 OU View on Facilities

The OU Department of Physical Sciences has excellent facilities to support its in-house planetary research programmes. It is happy to collaborate with external users subject to availability of resources and normal commercial arrangements. If larger test facilities are required for larger instruments it has good access to external facilities such as those at Airbus and at Harwell.

3.31 Oxford Space Systems Ltd (OSS), Harwell

3.31.1 OSS Company Background

Oxford Space Systems, OSS, formed in 2014 by the ex-Deployable Structures team at ABSL and based in Harwell, is an award-winning space technology business pioneering the development of next-generation deployable space structures that are lighter, less complex and lower-cost than those in current commercial use. Drawing on conventional wisdom, as well as fresh thinking, OSS is set on becoming the leading supplier of ITAR-free deployable space structures globally. Development collaboration contracts are underway with Europe's largest satellite builders as well as emerging players in the micro-sat and cube-sat markets.

3.31.2 OSS Deployable Systems

OSS currently works in three principal areas of development: deployable panels, flexible composite boom systems and large deployable antennas (LDAs). Until now, LDAs have only been available from two US companies and these are inevitably subject to ITAR restrictions. OSS has already built a prototype 4m diameter LDA that is readily scalable up to 12m and this is receiving massive attention from ESA and the international COMSAT community. OSS has also just been awarded a 1M€ matched-funding grant from the UK Space Agency under an ESA GSTP 6.2 contract to further develop its LDA technology at Harwell. The first variants of the OSS booms use space-proven carbon-fibre and resins, woven in an innovative way to produce a memory-shape material whose properties can be tuned to suit particular applications by changing the weave patterns and resins. The boom is rolled up in its stowed state and then deploys using a proprietary deployment mechanism to form a lightweight rigid boom with a precisely controlled length that can even be re-stowed if required. OSS will fly a 1m demonstration boom on the UK/Algeria CubeSat, ALSat, in 2016. This represents two records for the UK space industry: going from material concept to flight in under 30 months; and the World's longest retractable CubeSat boom system.

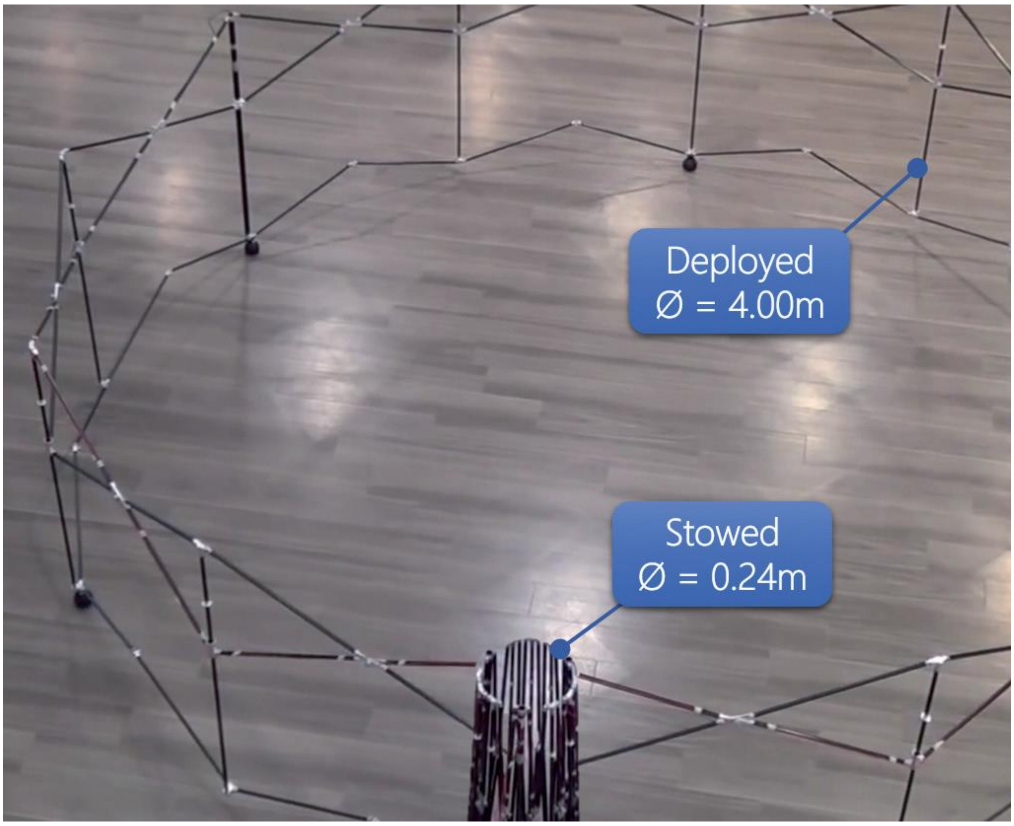


Figure 3.91 OSS Large Deployable Antenna structure and Precision Deployable Composite Boom

3.31.3 OSS Requirement for an LDA Deployment Test Facility

The principal facility gap identified by OSS is for a large deployable antenna (LDA) deployment test facility. Such a facility would need a large area such as RAL Space's R100 entrance bay. There is likely to be a future need to deploy structures up to 12m, although the current focus is on structures 4-6 m in diameter. The facility would need to have some kind of gravity off-loading, making use of cranes, or helium balloons or possibly positive pressure skates. RF testing would need to be done elsewhere such as at ADS Portsmouth. Examples of two types of gravity off-loading facilities are shown below: the GAIA sun-shield is suspended from a crane as it deploys, whilst the Harris facility in Florida uses helium balloons for gravity off-loading.

Figure 3.92 GAIA sunshield deployment gravity compensation facility

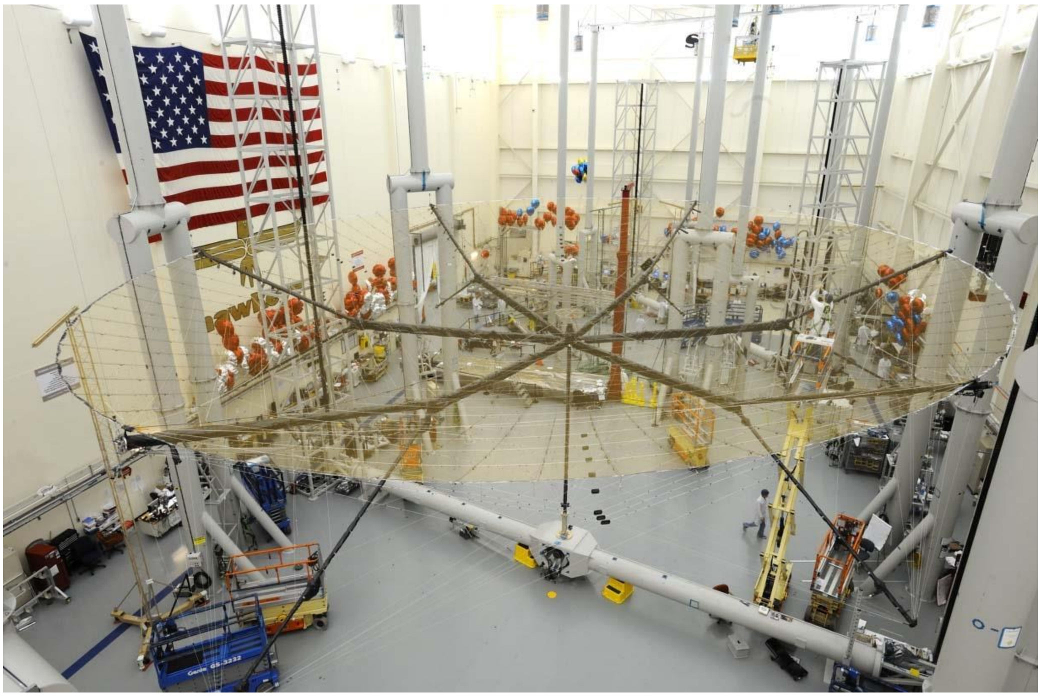


Figure 3.93 Harris antenna deployment facility using helium balloons

3.31.4 OSS View on Facilities

In addition to its need for a Deployment Test Facility as described above, OSS has identified difficulty in obtaining the PEEK material for its booms as an issue since there is only one UK supplier and that one tends to prioritise the spacecraft Primes at the expense of SMEs.

OSS has its own development laboratories for prototyping and initial assembly and test, but for flight hardware it will require cost-effective access to cleanrooms, clean gravity off-loading deployment facilities and environmental test facilities that include: thermal-vacuum, vibration, shock and EMC testing. OSS is hoping and expecting that it will have relatively easy access to such test facilities, ideally all on the Harwell campus, although cost and accessibility will be major drivers. OSS would be happy to share clean room facilities with other small companies if appropriate in order to ease the cost burden.

OSS is aware that there is an opportunity to make Harwell a 'one-stop-shop' for space hardware testing within the UK, in much the same way that both Germany and France have dedicated campuses able to offer extensive and complete ranges of test facilities. Currently, hardware builders are forced to add cost and risk to programmes because of the necessity to transport hardware to various parts of the UK because facilities either do not exist, are not available, or are not accessible. OSS understands that discussions are underway for a significant investment in a major extension of the R100 facilities to create such a one-stop-shop.

However, OSS has real reservations concerning the politics of accessing facilities already on the Harwell campus. Like most companies, OSS had assumed that the R100 facility was financed by HMG in order to provide a National Environmental Test Facility to help grow the wider UK space economy. However, after meeting with RAL Space officials recently, it was made clear that the test facilities in R100 are a resource specifically for use by RAL Space, who will always have priority access to them. Third parties may use the facilities, but only when RAL Space deems access is available. As RAL Space focus is on scientific missions, test facilities can be expected to be tied up for long duration tests associated with the needs of instruments for such missions.

OSS therefore wishes to emphasise that there are currently no environmental test facilities on campus for third party use where RAL Space does not have automatic priority. This situation will start to impact OSS commercially: for instance OSS has a potential significant contract from an overseas customer that is dependent on its ability to test a complex deployable structure. The Customer will be visiting Harwell campus in the summer of this year specifically to assess OSS's access to UK test facilities and any contract will be contingent on its ability to present a credible test capability.

OSS will therefore only be able to support any further investment in test facilities on the Harwell campus if they are truly part of a national environmental testing infrastructure controlled by a neutral third party and not simply an extension of RAL Space facilities.

OSS is of course aware that access to test facilities is always likely to be an issue for small companies working on small satellites since bigger missions generally have higher priority. Ultimately, as OSS grows, its investors may demand a transfer of some activity overseas, the most likely territory being the US, if facilities/funding do not materialise within the UK. The US CubeSat and MicroSat markets are predicted to be huge growth areas for the 'New Space' industry – OSS intends to aggressively target this market.

3.32 Portus Aerospace Ltd, Portsmouth

3.32.1 Portus Company Background

Portus Aerospace is a UK subsidiary of the Italian company Aerospazio Tecnologie s.r.l. based in Siena. The parent company was set up in March 2000 to provide high quality test services in the fields of electric propulsion, thermal-vacuum and space simulation. High power electric propulsion requires extensive investigation due to the complex phenomena that occur on the fully deployed satellite, so Aerospazio developed a large Vacuum Test Facility complex to allow high fidelity characterisation of high power Xenon electric thrusters. The Siena operational facilities, which are expected to be replicated at Portus, cover 4,500m^3 of laboratories and offices.

3.32.2 Portus Electric Propulsion Facilities

In Siena, Italy, Aerospazio has two large Vacuum Test Facilities specifically designed for space electric propulsion testing available: **LVTF-1,** with an internal volume of 120 m^3, allows high fidelity testing of electric thrusters of power level well above 10kW (possibly as high as 25kW) as well as high vacuum testing of large systems (such as an overall spacecraft); and **LVTF-2**, which is 12.5m long with a diameter of 3.8m giving a total volume of 140 m^3. Both of these chambers are fitted with a comprehensive array of plasma diagnostic equipment comprising Faraday probes and RPAs (retarding potential analysers).

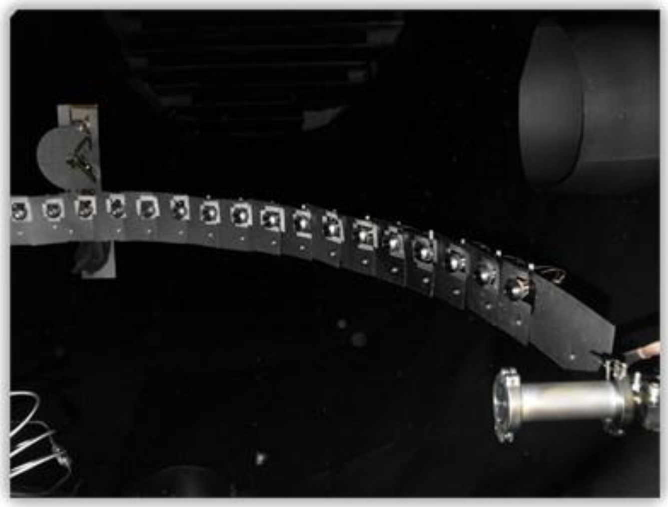


Figure 3.94 Aerospazio's LVTF-1 EP chamber and boom-mounted Faraday probes in Siena

In conjunction with its electric propulsion activities, the Company has developed specific expertise to design and manufacture state-of-the-art high-voltage DC/DC converters for space, military and other high reliability applications.

3.32.3 Portus View of Facilities

The business case for Aerospazio's decision to set up a UK subsidiary, Portus Aerospace, is based on their perception that there is a significant gap, especially as regards availability, of EP test facilities in the UK. They believe that their Portsmouth facility will go a long way to filling this gap. Portus expects to have two large TVAC chambers, similar to those in Siena, available in Portsmouth within 1 year. These will be aimed principally at electric propulsion testing but may be usable for other applications as well, although the Company is well aware of possible cleanliness issues after a chamber has been used for EP testing. Portus is hoping to be involved in developing a new thruster and if this happens, a third large chamber may be required in addition to those currently planned.

3.33 QinetiQ, Farnborough

3.33.1 QinetiQ Company Background

QinetiQ is based in the UK but is a global business, with an established US footprint and growing presence in targeted international markets. It is a people-based business, where service offerings account for the majority of sales, although its products division now provides technology-based solutions on a global scale. Through their technical expertise, domain know-how and rigorous independent thinking, its engineers and scientists are uniquely placed to help customers meet challenges that define the modern world. QinetiQ works across four key markets: defence, security and aerospace being the principal ones but with a growing position in select commercial markets. Its customers are predominantly government organisations, including defence departments, as well as international customers in specific targeted sectors. QinetiQ operates from a large number of different sites in the UK but for the purposes of this report it is sensible to concentrate on its space electric propulsion facilities at Farnborough. QinetiQ is very active in the field of electric propulsion and has developed a number of gridded ion engine electric propulsion systems. QinetiQ's thrusters are deployed in several high profile space projects including ESA's GOCE mission (Gravity and Steady State Ocean Circulation Explorer), and the ESA/JAXA Bepi Colombo Mission.

3.33.2 QinetiQ Electric Propulsion Facilities

QinetiQ has a number of EP test chambers at its Farnborough facility, available for use by external Customers on commercial terms. These include the LEEPs (Large European Electric Propulsion) chambers and a range of smaller vacuum chambers that together provide the capability to conduct a comprehensive range of qualification and acceptance tests for EP propulsion systems. Test capabilities include Direct Thrust Measurement, Thermal/Vacuum and EMC testing of EP thrusters and EP systems, as well as development, test and diagnostic systems for grids and cathodes. QinetiQ is currently investigating options for installing a Xenon recovery system to reduce EP testing costs.

- **LEEP1** – designed for thruster EMC testing in a specially modified thermal vacuum chamber incorporating a 3m long GFRP RF-transparent section of chamber wall. The RF transparent section is surrounded by a 4m × 3m × 3m screened enclosure lined with 300 mm RF absorbing material to achieve an RF anechoic test environment designed to meet Mil-Spec 461F, recognising that the intrusion of the vacuum chamber presents a compromise over a more ideal construction.

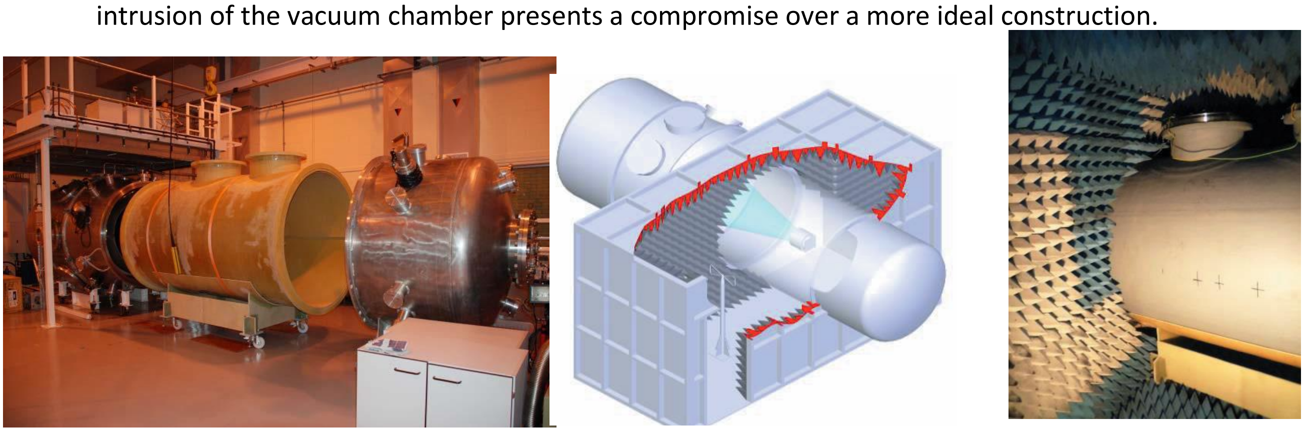


Figure 3.95 LEEP1 showing RF-transparent section and anechoic chamber

LEEP1 characteristics:

- 2kW water-cooled graphite target on chamber door
- LN_2 cold panels
- 6 x cryo-pumps, 2 x turbo-pumps, 2 x backing pumps
- Pressure <1 x 10^{-5} mbar with xenon flow rate of 3.5mg/s
- RF-transparent section 3m long x 1.6m diameter
- Copper-foil-lined anechoic chamber 4m x 3m x 3m, 120dB screening over 1-10 GHz

- **LEEP2** – this is the main chamber for thruster qualification and acceptance testing, shown in Figure 3.96 below. The largest section of the chamber is 3.8m diameter x 4m long. The conical section is 0.9m long and the small section is 2.6m diameter x 5m long. Thrusters are located at the junction between the 2.6m and conical sections and the ion beam(s) are directed towards the chamber door/target. This configuration minimises any thruster chamber interactions. The ion beam target is a water cooled graphite clad design and the walls of the chamber are protected using a stainless steel/graphite liner.

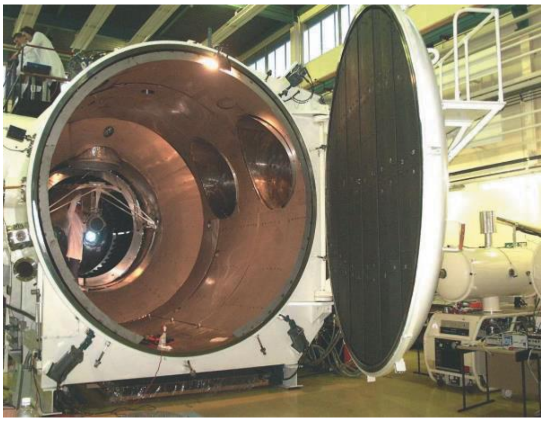


Figure 3.96 LEEP2 schematic and photo with T6 thruster installed

LEEP2 characteristics:

- Chamber dimensions: 3.8m diam x 9m long and 2.6m diam x 5m long
- Water-cooled graphite target on chamber door
- Pressure <2 x 10^{-4} mbar with xenon flow rates up to 30mg/s
- Pumping capacity equivalent to 100,000 l/s Xenon
- High Xenon flow rates suitable for large Hall-effect thrusters
- Measurements of plume characteristics such as thrust vector and beam divergence
- Thrust balance for real-time thrust measurements

LEEP2 can also be used for twin thruster testing as shown in Figure 3.97

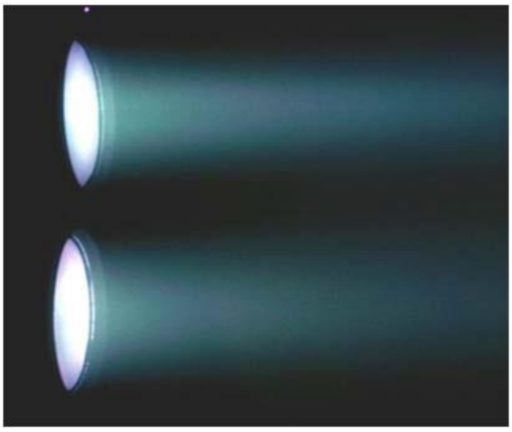


Figure 3.97 Twin T6 thrusters in LEEP2

- **LEEP3** – shown in Figure 3.98, has been developed specifically for long-duration EP testing, in particular for the BepiColumbo SEPS system testing. It has a water-cooled chevron-style graphite target to minimise back sputter, helping to reduce the beam out rate due to facility effects. Measurements with a Quartz Crystal Microbalance (QCM) have shown that the back sputter rate seen in LEEP3 is lower than that measured in LEEP2, verifying the improved performance of the target design.

Figure 3.98 LEEP3 chamber showing T6 thruster installed and chevron target on door

LEEP3 characteristics:

- Dimensions: 3.3m diam x 7.2m long
- Pumping capacity equivalent to 200,000 l/s Xenon
- Base vacuum level $5.0x10^{-7}$mbar, giving $9.0x10^{-6}$mbar with Xenon flow rate ~3.5mg/s (equivalent to a single T6 thruster running at 145mN)
- Water cooled chevron style graphite target to minimises back sputter

- **Small EP chambers** – in addition to the three large LEEPs, QinetiQ has a number of smaller chambers for the bake-out, evaluation, qualification and acceptance of thruster sub-components and other small items of equipment. These range in size from 0.5m to 1.0m diameter, the largest of which can be used to operate a T6-size of thruster in discharge mode for initial diagnostic tests. Figure 3.99 shows two of the most frequently used chambers, both of which can cycle components from -150°C to +200°C.

Figure 3.99 QinetiQ's 1m (left) and 0.5m (right) small EP TVAC chambers

3.33.3 QinetiQ View on Facilities

QinetiQ's position is that the need for acceptance testing of 5kW engines can be met with only modest updates to LEEP2 and LEEP3 to enable testing of 5kW Hall Effect Thrusters. However, there is a real facilities gap for testing higher thrust engines that will require either modifications to existing chambers or, more likely, a new vacuum vessel. If a new 20kW chamber is to be built, it should include an RF-transparent section, like that in LEEP1, for EMC testing. The thrust balance systems, beam probes, diagnostic facilities, cryo-plates, pumps and compressors etc. would be similar to those currently in use and QinetiQ already has the necessary EP know-how in-house. If a high-thrust EP test facility is not established in the UK, the gap can only be filled by using external facilities in Continental Europe.

3.34 Queen's University Belfast

3.34.1 Queen's University Belfast Background

Queen's University of Belfast (QUB) is one of the oldest universities in the UK, its roots going back to the Belfast Academical Institution in 1810. It is a member of the prestigious Russell Group of leading research universities in the UK, and in the top 1% of global universities. In 2014, the UK-wide Research Excellence Framework exercise (REF 2014) placed Queen's 8th in the UK for Research Intensity. Queen's academic structure is based on three Faculties containing a total of 20 Schools and one of these, the School of Electronics, Electrical Engineering and Computer Science, within the Faculty of Engineering and Physical Sciences (EPS), is where most of QUB's space-related activities take place.

3.34.2 The Institute of Electronics, Communications and Information Technology

Within the EPS faculty is ECIT (The Institute of Electronics, Communications and Information Technology, www.ecit@qub.ac.uk). ECIT was established in 2003 to extend world-level expertise in a variety of enabling digital communications technologies. ECIT has developed breakthrough space-related technology, including the World's first dual-polarized freestanding Frequency Selective Surface, and has introduced LCD technology to space applications, developing liquid crystal based reconfigurable reflect-arrays to replace antenna drive mechanisms. ECIT extends the significant links that QUB has developed internationally with major industrial partners and research centres. It also provides hot-desking and incubation facilities to encourage and support the establishment and development of new companies. Located on a flagship waterside site in the Northern Ireland Science Park, ECIT has received funding from the European Union, Invest Northern Ireland and the Department for Employment and Learning, Northern Ireland.

Figure 3.100 Institute of Electronics, Communications and Information Technology at QUB

3.34.3 QUB Clean Rooms: QAMEC (Queen's Advanced Micro-Engineering Centre)

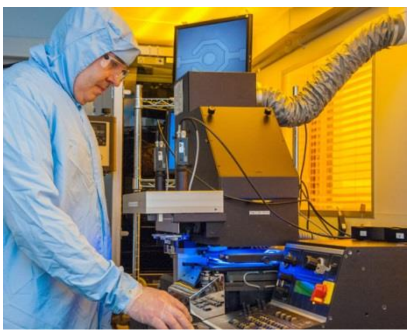
Also within the EPS faculty, QAMEC is a centre-of-excellence for research and development employing silicon technology and MEMS technology. The centre has established itself, in partnership with the Centre for Wireless Innovation, in the design and fabrication of Frequency Selective Surfaces serving the European Space Agency. Primarily a MEMS facility, the centre offers support through technology transfer, training and collaborative enterprise to industry in new growth areas.

Figure 3.101 Main QAMEC Clean room

QAMEC operates a 200m^2 ISO 5/6 cleanroom (class 400), which incorporates an ISO 5 (class 100) photolithographic room with independent humidity and temperature control. The remaining area houses processing stations from ISO 4 to 5 (class 10 to class 100) for front-end processing. The core equipment set can accommodate processing of silicon substrates up to 150mm in diameter, as well as offering the versatility of handling non-standard substrates such as Sapphire, Germanium and semiconductor grade Quartz and Glass. The Centre's test facility houses a suit of probe stations offering device testing such as CV, IV, CT, transistor characterisation and 4 pt probe measurements. Pyrogenic probe stations offer low temperature device measurements.

These MEMS-based activities have been utilised in the space industry for the fabrication of Frequency Selective Surfaces utilising both quartz and micro-machined silicon. Reflectarray antennas incorporating Liquid Crystal have also been manufactured using existing equipment sets.

Figure 3.102 QAMEC photolith area



Equipment available in the QAMEC facility includes:

EV420 Proximity Aligner: the EV420 aligner will print images with a resolution of >2µm. In combination with a second set of optics the system can perform double sided alignment for MEMS applications.

Figure 3.103 EV 420 Proximity Aligner

Alcatel I-SPEEDER ICP Etching system and STS RIE system: the ICP (inductively coupled plasma) allows for fast through etching of silicon. Incorporating the Bosch etch process allows high aspect ratio etching. The STS reactive ion-etching system allows controlled plasma etching of insulating layers such as silicon dioxide.

Figure 3.104 Alcatel Etch system

Other processing equipment includes:

- deposition systems for LPCVD, PECVD and APCVD which can deposit various insulators and semiconducting layers such as silicon dioxide, silicon nitride and polysilicon;
- sputtering and evaporation systems for deposition of metals such as Titanium, Copper and Aluminium; and
- for Liquid Crystal work the facility also houses a polyimide rubbing machine and liquid crystal vacuum fill system.

Material Characterisation

The facility also has a suite of measurement and analysis equipment for material characterisation including:

- a Leo Supra 25 SEM system;
- a Taylor Hobson White light interferometry system for non-destructive characterisation;
- a Nanometrics layer-thickness measurement system; and
- a Tencor Alpha Step 200 surface profiler.

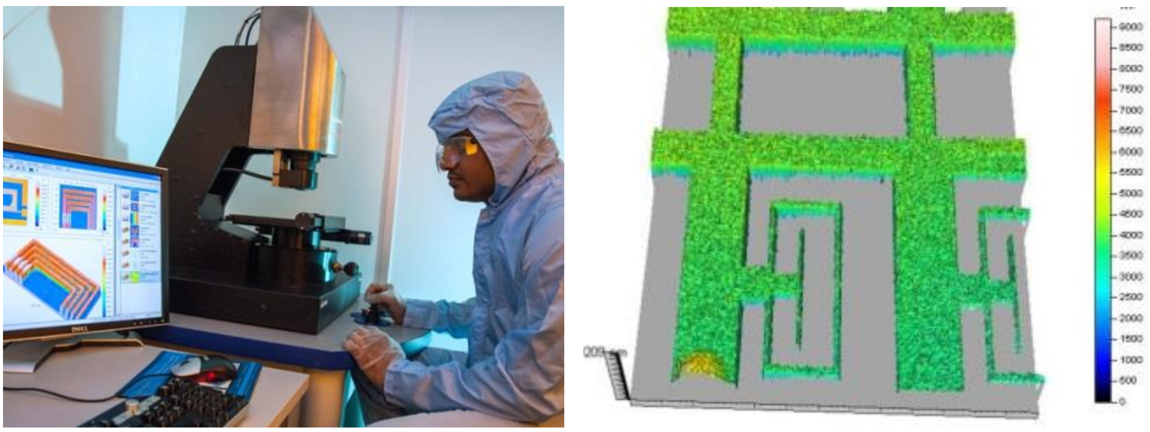


Figure 3.105 Taylor Hobson Talysurf surface profiler and image

3.34.4 ECIT TEST Laboratories

ECIT has five electromagnetic test laboratories housing state-of-the-art facilities including a thermally controlled probe station (dc to 110 GHz) and several Vector Network Analyser measurement systems, which cover the range from dc to 100 GHz. An AB Millimeter VNA and quasi-optical test bench, only one of two systems of its type in the UK, can be used to measure the spectral response of FSS and reflectors in the range from 100 GHz to 700 GHz with a frequency resolution down to 20 MHz and dynamic range of 60 dB. Other facilities equipment include a thermally controlled small/large signal V-band monolithic micro-wave integrated circuit (MMIC) probe station, and a microwave free-space reflection-based test setup.

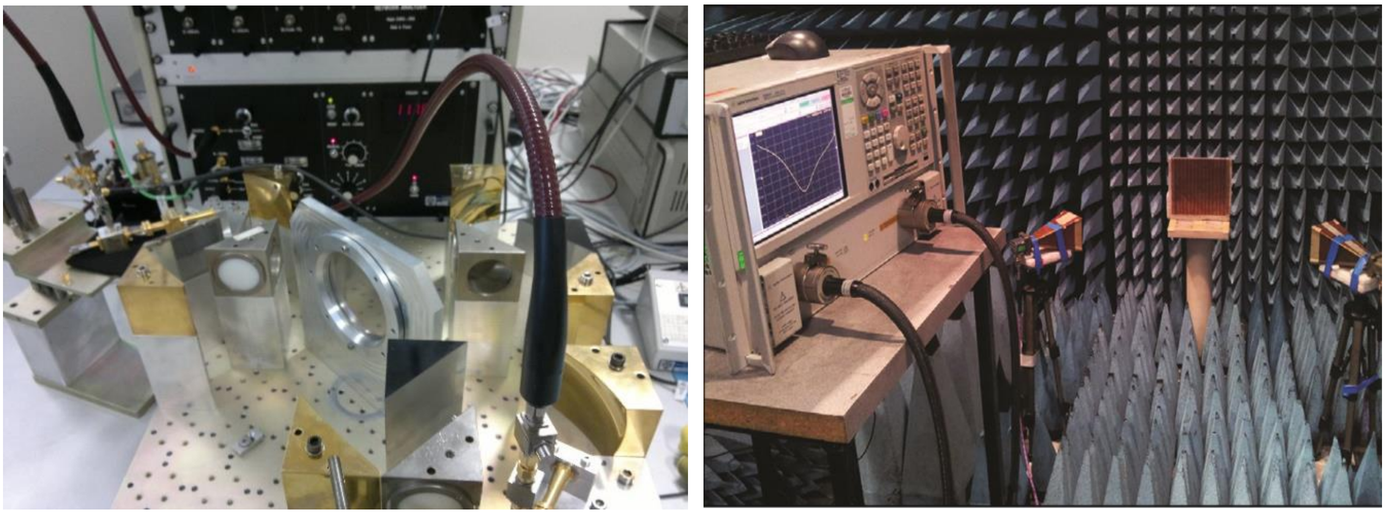


Figure 3.106 ECIT's VNA FSS measurement system (left) and free-space measurement test rig (right)

Two antenna measurement systems are available: a 10m anechoic far-field antenna test range; and a 1.5m planar near-field scanning antenna facility. These use Scientific Atlanta and NSI computer-controlled instrumentation and cover the frequency range 1 to 110 GHz.

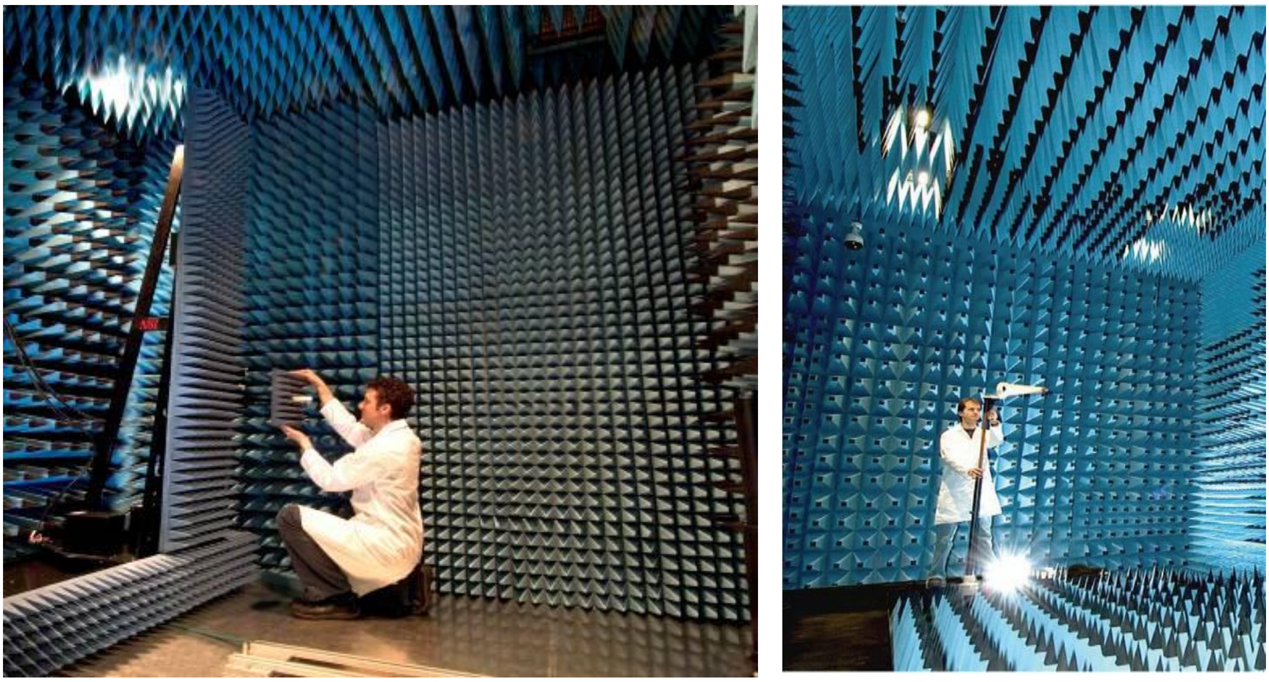


Figure 3.107 ECIT planar 1.5 m near-field scanner (left) and 10 m far-field antenna range (right)

3.34.5 QUB Workshops

Engineering Workshop: The engineering workshop has gained considerable expertise in machining test fixtures, waveguides, and antennas for space-borne communication systems. It includes:

- three vertical machining centres with envelopes ~1.0m in the x-axis, and 0.6m in the y- and z-axes;
- two 5-axis machining centres with envelopes of 0.5m in the x-, y- and z-axes;
- mill-turning machine with envelope of 0.2m diameter in x-axis, 0.5 m in z-axis and 0.6m in y-axis;
- EDM wire-eroder with machining envelope 0.5m in x-axis, 0.4m in y-axis and 0.3m in z axis;
- EDM die-sinking with machining envelope 0.4m in the x- and y-axes and 0.3 in the z-axis;
- three CNC 2-axis lathes with a machining envelope of 0.3 m × 2.0m;
- high-pressure water-jet cutter machine, envelope of 3.0m in x-axis, 2.0m in y-axis, and 0.1m in z-axis;
- programmable press-brake with capacity for 3.0m × 6mm in mild steel;
- guillotine with capacity to shear 2.5 m × 6 mm in mild steel;
- rolling of steel plate to 6 mm × 2 m in mild steel; and
- TIG and MIG welding facilities.

Electronics Workshop: The electronics workshop is able to process high frequency PCB-based substrates from suppliers such as Taconic and Rodgers, and provide through-hole plating of small vias for double-sided boards. It has also developed a number of proprietary processes that can be used to improve the resolution of the printed element shapes which are applicable for the manufacture of space hardware. The workshop has a large state-of-the-art range of equipment for patterning microwave substrates with photo-resist, depending upon the accuracy needed, such as spin-coating, dip-coating or dry-film lamination. With these methods it is possible to obtain double-sided coatings and PCB sizes from 300mm to 500mm square. It has an industrial standard 0.5m × 0.5m capacity LITTLEJOHN UV exposure unit with soft- and hard-vacuum to increase exposure resolution. The workshop also has a dedicated darkroom for producing photomasks with up to 10:1 reductions. Etching of the patterned boards is carried out by a 0.3m × 0.5m copper PCB etcher using specialised conveyor spray-processing equipment.

Figure 3.108 LITTLEJOHN UV exposure unit (left) and copper PCB etcher (right)

3.34.6 QUB View on Facilities

QUB has excellent facilities to support both its in-house research programmes and external users, subject to normal commercial terms. The ECIT is a world-leader in FSS antenna technology and reconfigurable reflectarrays, supported by an extensive suite of world-class manufacturing and test facilities. QUB's Engineering Workshop has comprehensive machining facilities and the expertise necessary to produce space-quality hardware, and its Electronics Workshop has particular expertise and facilities for the production of space-quality PCBs for its microwave work.

3.35 RAL Space, Harwell

3.35.1 STFC / RAL Space Background

The Science and Technology Facilities Council (STFC) is one of seven research councils in the UK. The research councils form part of UK government and report to the Department for Business, Innovation and Skills (BIS). STFC runs major science programmes using its own research capability and acts in support of the major UK physical science facilities, as a result of which it is able to offer access to world-class science expertise and facilities to UK industry and to other government agency customers. The major STFC sites are: Rutherford Appleton Laboratory, Oxfordshire; Daresbury Laboratory, Cheshire; Chilbolton Observatory, Hampshire; and UK Astronomy Technology Centre, Edinburgh, Section 3.44 below.

RAL Space is STFC's 'Space Department', supporting the programmes of STFC, as well as undertaking a large number of contracts for agencies, industry and other commercial customers. RAL Space provides world-leading research and technology development, space test facilities, instrument and mission design, and studies of science and technology requirements for new missions. RAL Space has been in the business of producing instruments and software for space flight, and in building and operating ground segments since the mid-1970s. RAL Space is also a prime technical institute of the UK Space Agency, and supports the space community by providing the complete range of skills and technology necessary for the construction, testing and calibration of space instruments for which it has ISO9001:2000 certification. It also conducts a number of key technology development programmes, aimed at advancing the state-of-the-art in areas of strategic importance to the space community.

RAL Space has a long history of providing AIV facilities at its Harwell site for the broad UK space community. The AIV Group is managed and operated by a team of people who use their knowledge and experience, balanced with enthusiasm, to provide customers with a high quality testing service which is both flexible and responsive. The AIV Group provides customer support to:

- define and understand test specifications;
- assist with the design and manufacture of test fixtures;
- adapt facilities to meet exacting test requirements;
- provide cost and schedule information; and
- ensure a professional and reliable service.

3.35.2 RAL Space Vibration Facilities

RAL Space has a 67kN 3-axis vibration facility which has recently been moved to the new R100 AIV Building. The vibrator has advanced digital control and analysis systems and is able to test a wide range of products ranging from component level to large payloads up to 700kg.

Ling Dynamic Systems LDS V8-440

- Max force = 67 kN
- Max acceleration = 140g
- Max velocity = 1.78 m/s
- Max displacement = 63mm peak-to-peak
- Max payload (including moving mass) = 700Kg
- Configuration options:
    - Head expander: 0.6m diam or 1.2m x 1.2m
    - Slip table: 0.75m x 0.75m or 1.22m x 1.22m
    - 64 channels as standard expandable to 128
    - Force limiting 6 triaxes

Figure 3.109 RAL Space LDS V8-440 Vibrator

- Facility properties:
  - Cleanliness: ISO class 5 or 6 (10,000)
  - Crane capacity: 1 Tonne
  - Crane hook height: 5.4 m
  - Access doors: size 3.5 m wide x 3.5 m high

RAL Space is currently assessing whether or not to purchase a more powerful shaker able to service larger satellites and payloads, with a view to installation in 2016.

3.35.3 RAL Space Shock Tests Facilities

RAL Space does not currently have any shock test facilities; however, it is planning to implement a shock test capability in its new R100 Environmental Test Building. Details will be made available in due course.

3.35.4 RAL Space Clean Rooms

RAL Space has an extensive suite of clean rooms, both on the Main site and in the new R100 building, which may be used by external companies subject to availability and normal commercial arrangements. On the Main RAL site, the Large Space Test Chamber is housed in a large clean room and the access areas at each end of the chamber are effectively assembly and integration clean rooms in their own right. Similarly the access areas for the smaller thermal vacuum chambers are also clean rooms. In addition to these areas, there are two dedicated instrument level build facilities available. Operated and maintained to ISO14644 these clean rooms are used for the assembly, integration and test of spacecraft instruments and sub-systems. The rooms are fully conditioned for temperature, humidity and pressure and benefit from the addition of carbon filtration to limit the transmission of airborne hydrocarbons into the facilities.

Figure 3.110 RAL Space Main Site Clean Rooms: Clean Room 1 (left) and Clean Room 2 (right)

Clean room 1

- Main area: 11m x 7m at ISO Class 6 (Class 1,000)
- Horizontal laminar flow unit: 5m x 5m at ISO Class 5 (Class 100)
- 2 Laminar-flow-benches: 1m x 0.5m and 2m x 0.5m at ISO Class 5 (Class 100)
- Central changing room: lockers for up to 20 people

Clean Room 2

- Main area: 12m x 7m at ISO Class 6 (Class 1,000)
- Horizontal laminar flow unit: 5m x 3m at ISO Class 5 (Class 100)
- 5 Laminar- flow-benches: 1m x 0.5m at ISO Class 5 (Class 100)
- Central changing room: lockers for up to 20 people

The new R100 building has numerous clean rooms including five 90m^2 clean rooms, one of which is blacked out for optical work as follows:

Typical R100 Clean Room

- Environment: Class 5 or 6 (100 or 1,000), temperature and humidity controlled
- Availability: case-by-case
- Floor dimensions: 15m x 6m
- Crane hook capacity: 1 tonne
- Access doors: 2m width x 2.4m height
- Access control: swipe card

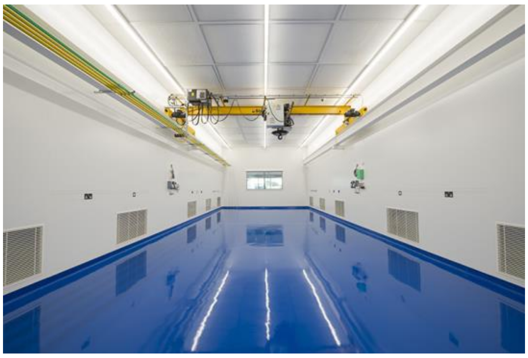


Figure 3.111 RAL Space: typical 90m^2 room in R100

In addition to the 90m^2 rooms, there are large assembly and integration clean rooms at either end of the 5m chambers. The picture below shows the large clean area just inside the access doors during installation of the first 5m chamber; the second shows the somewhat smaller blacked-out OGSE clean area at the other end of the chamber.

Figure 3.112 R100 clean integraton areas at either end of the 5m chambers (during installation)

R100 Clean Assembly areas either end of 5m chambers

- Environment: Class 5 or 6 (100 or 1,000), temperature and humidity controlled
- Availability: normally in conjunction with a 5m chamber test campaign
- Floor dimensions: 13m x 12m (access end) and 6m x 10m (blacked-out OGSE end)
- Crane hook capacity: 5 tonne
- Access doors: 6m width x 6.1m height
- Access control: swipe card

3.35.5 RAL Space Existing On-Site Thermal-Vacuum Facilities

In order to ensure the correct and long-term operation of instrumentation destined for space it is essential it is functionally tested in space-like conditions on the ground. This is achieved by thermal vacuum testing, whereby the vacuum is created either using turbo-molecular or cryo-pumps to simulate the conditions found in space and the temperature of the test item is varied through its operating range to ensure functionality. This is done by heating and cooling either radiatively using a thermal shroud, or conductively using thermal straps to link the test item to a thermal control plate. These facilities also lend themselves to thermal balance testing where the test item is surrounded by a number of thermally controlled plates which are allowed to stabilise whilst the temperature at several points within the test item are monitored for comparison with its thermal mathematical model.

RAL Space has several chambers which are suitable for thermal vacuum and thermal balance testing currently located on the main Rutherford Appleton Laboratory site, but which will be moved to R100 in due course. These include:

Small TVAC chambers:

- Size range: 0.6m to 1m diam; 1m to 3.5m length
- Temperature range: LN2 to +100°C
- Dry Pumped
- Multiple thermal plates
- Mass Spectrometer (Residual Gas Analyser, RGA) fitted at all times
- TQCM available to measure outgassing rate
- Class 1,000 cleanroom conditions for installation and preparation of contamination-sensitive payloads

Large Space Test Chamber (STC):

- Vessel size: 3m diam x 5.5m length
- Ultimate pressure: $< 1x\ 10^{-6}$ mbar (payload and temperature dependent)
- Dry pumped
- Temp range: LN2 to +150°C
- 200 monitoring channels
- Multiple thermal plates
- Mass Spectrometer (RGA) and TQCM
- Class 1,000 cleanroom conditions

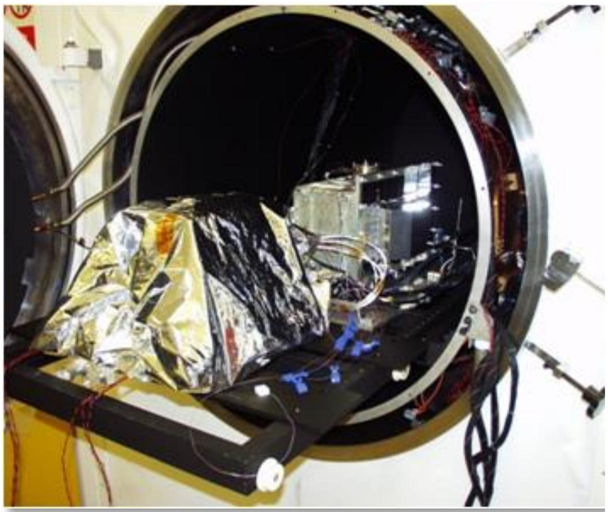



Figure 3.113 Typical small TVAC chamber (left) and 3m Space Test Chamber (right)

3.35.6 RAL Space R100 Thermal-Vacuum Facilities

Phase 1 of a very large purpose-built environmental test building, hereinafter known as R100, is nearing completion. This is a new and innovative addition to the Harwell Oxford Campus Space Gateway, accommodating a co-ordinated set of space facilities, supported by world-leading integration and calibration teams. In terms of thermal-vacuum facilities R100 will have three large vacuum chamber suites and a number of smaller TVAC chambers as follows:

Large TVAC Suites:

- STC-1 and -2: both 5m diameter x 6m length, with active vibration isolation
- STC-3: baselined to be the 'old STC' (3m diameter x 5.5m length) from the existing on-site facility which could be moved to R100, but it is possible that a larger chamber will be installed, TBD
- Temperature range -180°C +150°C
- Vacuum rating: 10^{-7} mbar (payload and temperature dependent)
- Dedicated Optical Ground Support Equipment (OGSE) rooms
- Direct Electrical Ground Support Equipment (EGSE) access areas
- Dry pumping system throughout, with molecular contamination control
- Clean Room support facilities
- Clean room suites 1200 m² each, ISO class 5/6
- High-performance vibration isolation for STC-1 and -2 designed into building:
    - Optically-sensitive instruments mounted on a set of 'quiet' rails in the chamber, which are directly coupled to a seismic block, isolated from the chamber body
    - All other equipment coupled to building structure via a set of 'noisy' rails mounted on chamber body
    - Overall seismic mass ~300 tonnes resting on 22 air suspension bags for each chamber
    - Seismic block extends beyond chamber at both ends enabling OGSE to be coupled to the block and to the quiet rails
    - Interfaces external to the vacuum chamber are steel plates with grid pattern of holes

Figure 3.114 Clean room suite and seismic block prior to installation and 5m TVAC chamber newly installed

Small TVAC Chambers:

- Up to nine smaller TVAC chambers will be installed in R100 over the next 2 years
- Size range: 0.5 to 2m diameter and 1 to 3m length
- Temperature range: -180°C to +150°C
- Vacuum rating: 10^{-7}mBar, payload and temperature dependent
- Dedicated accommodation for EGSE

3.35.7 RAL Space /NPL Centre for Calibration of Space Instrumentation (CCSI)

The UK Centre for Calibration of Space Instrumentation (CCSI) was established in response to the increasing need for measurements made by satellite instruments to be provided with uncertainty estimates and demonstrate their traceability to internationally agreed standards. The CCSI is a joint venture between STFC's RAL Space and the National Physical Laboratory (NPL), aiming to co-ordinate the existing UK space calibration activities with the close involvement of UK academic and instrument teams. The Centre is a National Facility that provides a nucleus to enable the UK to offer state-of-the-art calibration and validation services to agencies and instrument builders, illustrated pictorially below.

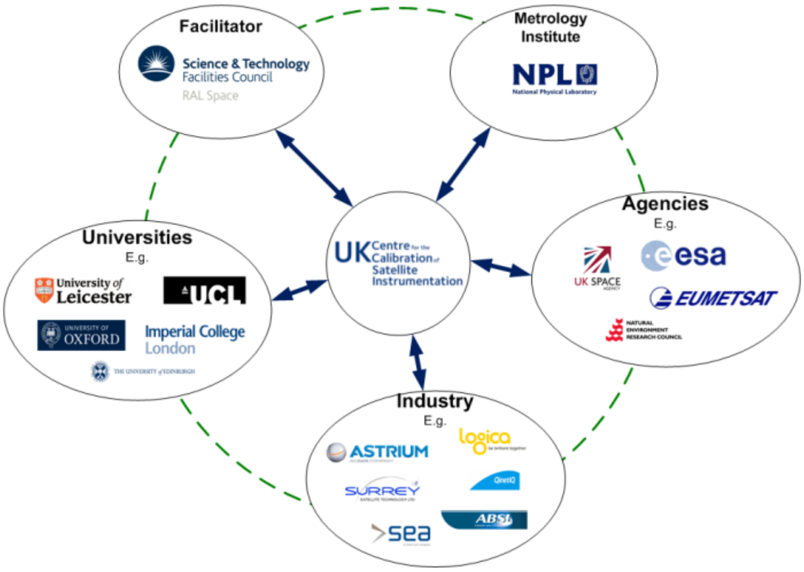


Figure 3.115 UK CCSI interfaces with external agencies, academia and industry

Currently, the UK CCSI covers the following areas:

- Design of EO sensors and their calibration schema
- Calibration of satellite sensors, both pre-flight and in-orbit
- Development and operation of surface validation instrumentation
- Data validation and quality assurance for a variety of satellite sensors

It supports the calibration of satellite sensors from x-ray wavelengths through to the far infrared and microwave; the development and operation of instrumentation for the validation of Satellite Sea surface temperature observations; and routine vicarious calibration of visible EO sensors using ground test sites.

Satellite sensors can be calibrated against a variety of ground calibration sources and sensors whose accuracy is traceable to international standards using techniques such as the pre-calibrated (at NPL) transfer standard shown below.

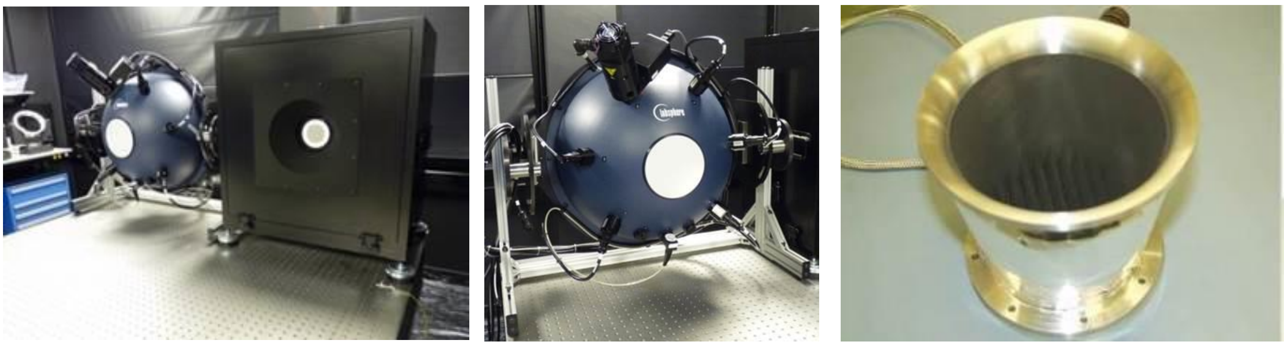
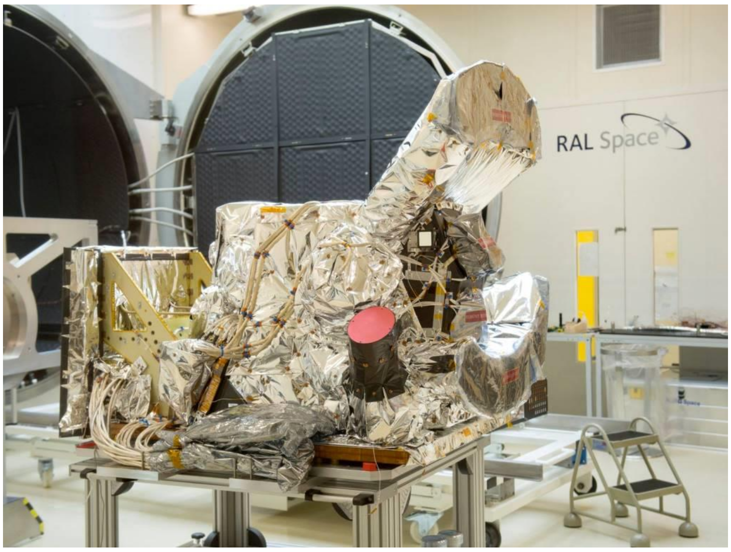


Figure 3.116 UK CCSI typical black body sources and transfer standards

The Centre also participates in instrument-level calibration campaigns, with close involvement in the design, build and certification of sometimes highly complicated and sophisticated calibration rigs such as that for AATSR and its successor, SLSTR (Sea and Land Surface Temperature Radiometer) shown below. In the past such campaigns have utilised the 3m Large Space Chamber but future large instruments will be calibrated in the new R100 5m chambers.



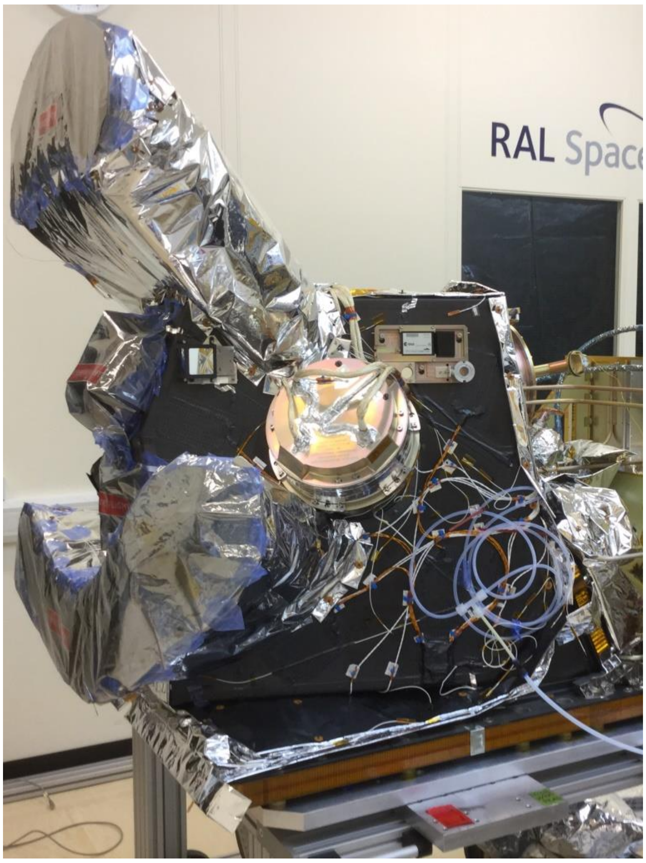


Figure 3.117 SLSTR calibration in RAL Space 3m Space Test Chamber

3.35.8 RAL Space Molecular Spectroscopy Facility

The Molecular Spectroscopy Facility (MSF) is a world-class facility for the UK environmental science community to conduct a wide range of interdisciplinary research, providing central laboratories, scientific equipment, training, scientific/technical support, and high-quality data. Infrared, visible, and ultraviolet spectroscopic data are increasingly important for studying the important chemical, physical, biological, and geological processes occurring in the natural environment. The MSF provides essential inputs to many key science and technology areas, in particular Earth observation of the atmosphere and surface using optical remote sensing techniques, atmospheric chemistry, and climate research.

Through the MSF, broadband, high spectral resolution Fourier transform and fibre-optic spectrometers are available for measuring the absorption, emission, and scattering properties of solid, liquid, gas/vapour, and aerosol samples contained in a range of spectroscopic cells. High-quality spectroscopic data over the entire spectral range from wavelengths (wavenumbers) of 1 mm (10 cm-1) in the far-infrared/sub-millimetre range to 180 nm (55,000 cm-1) in the far ultraviolet are generated at spectral resolving powers of up to 1 part in a million and time resolutions as high as 5 µs. Customised sample cells are available for specific temperature-dependent measurements over the range 77 to 350 K at optical path-lengths from 1 mm to over 1 km using multi-pass optical systems. For atmospheric chemistry studies, the chemical synthesis area and laser-safe laboratories permit a wide range of projects to be supported.

Fourier Transform Spectrometers

The MSF has two of the highest resolution Fourier transform spectrometers in the UK and a number of fibre-coupled miniature grating spectrometers:

Instrument	Spectral Range, Resolution
• Bruker IFS 125HR	10-40,000 cm^{-1}, 0.0015cm^{-1}
• Bruker IFS 120/5HR	10-40,000 cm^{-1}, 0.0015 cm^{-1}
• Bruker Vertex 80v	300-50,000 cm^{-1}, 0.07 cm^{-1}
• Bruker IFS 66v/S	300-50,000 cm^{-1}, 0.12 cm^{-1}
• Ocean Optics CCD	200-800 nm, 0.6 nm
• Ocean Optics CCD	550-1100 nm, 0.6 nm

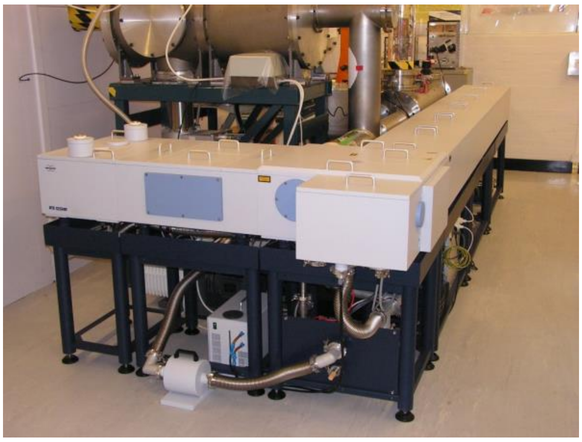


Figure 3.118 MSF Bruker 125HR FTS

Sample Containment Cells

A variety of sample cells for gases liquids and aerosols are available, operating at optical path lengths from less than a millimetre to one kilometre.

Many of the cells can be cooled or heated within the range 77K to 473K and some can operate at high pressures up to five atmospheres. Most of the cells are specifically designed to operate with MSF spectrometers, and all optical paths can be evacuated to eliminate spectral interference from atmospheric species. However, two larger diameter cooled cells have been built to operate with other instruments, and have been used for instrument validation.

All cells can be fitted with calibrated temperature, pressure and humidity sensors that are automatically logged during measurements.

Figure 3.119 Absorption cell with heater jacket

Quantum Cascade Lasers

Systems for operating pulsed and continuous-wave room-temperature quantum cascade lasers are available. These devices are high-power, tuneable and robust mid-infrared laser sources ideal for applications requiring a combination of high spectral resolution and high measurement sensitivity in a narrow wavelength band.

In addition a multi-pass gas cell is available that provides an optical path-length of up to 200 m.

Figure 3.120 Quantum cascade lasers

3.35.9 RAL Space Concurrent Design Facility

The RAL Space Concurrent Design Facility (CDF) is a multi-disciplinary facility for the quick and efficient conceptual design not only of complex space programmes, but also of non-space system-of-system design tasks. The CDF has been developed by RAL Space engineers and IT staff, but incorporates the experience and best practice of other CDFs located overseas such as those at ESTEC, JPL, ASI, CNES, JAXA and DLR. The RAL Space CDF comprises three elements:

- **the facility infrastructure:** which includes the room itself, the IT and communications hardware and the specialist space mission design software which enable engineers to design individual elements of a complex mission;
- **the CDF design database**: which includes the software which automatically links the design of the individual elements of a mission or other system into a coherent system; and
- **the methodology**: which is the process for efficiently co-ordinating the design activities of engineers, scientists and programme managers in a concurrent design environment.

These three elements of the CDF enable novel space concepts and other system-of-system challenges to be quickly and efficiently assessed from technical, financial and programmatic points-of-view.

Figure 3.121 RAL Space Concurrent Design Facility

The key benefits of utilising the RAL Space CDF for Mission Studies are:

- **Study Quality**: The rigorous and systematic approach to the design process helps ensure that the results are of a consistently high standard.
- **Efficiency**: ESA and other CDF operators report a reduction in assessment study costs by a factor of two and elapsed time by a factor of four.
- **Fostering Collaboration**: Teams of Scientists and Engineers from different organisations and countries are able to start work together on real projects quickly, build collaborations and profit from each other's strengths.
- **Stimulation of new scientific and business initiatives**: New ideas and concepts can be refined, elaborated and assessed from scientific, technical and business points-of-view and take them to the next level of maturity.

There are similar benefits for other system-of-system design problems such as town planning or hospital refurbishment.

3.35.10 RAL Space Precision Development Facility

The Precision Development Facility (PDF) was originally established within RAL Space's Millimetre Wave Technology Group to provide the very high accuracy machining required for the development of sub-millimetre wavelength receiver technology. However, in addition to this close project support role, it also undertakes development work for industry and a variety of government institutions. Recent investment in some of the very latest CNC machine tools has enhanced its capabilities, maintaining its position as experts in all aspects of precision machining and novel component prototyping.

Precision Machining Facilities

- Precision turning, milling on customised lathes, micro-milling machine and mini-jig borers
- Precision micro-drilling
- CNC Wire EDM
- High-speed EDM hole-drilling
- Optical inspection and non-contact measuring
- Design and manufacture of novel jigs and fixtures
- Diamond flat-lapping and polishing
- Manufacturing microwave calibration loads and interferometer grids

Figure 3.122 Precision Machining Facilities

CNC Nano-Machining Facilities

- KERN pyramid nano CNC Mill (50,000rpm positional accuracies ± 0.3µm)
- KERN Micro 5 Axis CNC Mill (40,000rpm positional accuracy ± 1µm)
- Hardinge Super Precision Lathe (8,000rpm positional accuracy ± 5µm)
- Non-Contact Tool Pre-setters
- Cutters as small as 0.1mm

Figure 3.123 CNC Nano-Machining

Project Support Facility

- DMG DMU 5-Axis full simultaneous CNC milling machine (18,000rpm spindle, 32 tool changer, positional accuracy ± 8µm
- HURCO VM10u 5-axis milling machine
- HURCO VMX30 milling machine
- Two HAAS Super Mini-Mills (15,000rpm positional accuracy ± 8µm)

Figure 3.124 Project Support Facility

3.35.11 RAL Space Thermal Manufacturing Facility

The RAL Space Thermal Engineering Group specialises in the design, manufacture and installation of multi-layer insulation (MLI) blankets. The ISO9001 accredited facility is located on the main RAL site, and will move to a new 83m^2 ISO Class 6 clean room in the new R100 building in the near future.

Figure 3.125 EarthCARE battery MLI (left) and EarthCARE BBR Betacloth MLI (right)

RAL Space thermal engineers:

- are specialists in the design and manufacture of MLI for payloads and small spacecraft, with particular expertise in the manufacture of MLI for higher cleanliness applications;
- have an extensive thermal database allowing them to optimise blanket performance by selecting the right combination of materials;
- are highly experienced and able to recommend the proper combination of space qualified materials and processes;
- ensure that requirements are properly analysed at the start of the process to ensure the best solution is used;
- able to install on or off site; and
- able to perform full thermal verification tests to confirm the design and performance of the MLI.

RAL Space has designed and manufactured MLI blankets for many important scientific missions over the years such as MIRI on JWST and the GERB instrument on MSG, shown in Figure 3.126 below.

Figure 3.126 MIRI Cryogenic MLI (left) and GERB with MLI installed (right)

3.35.12 RAL Space View on Facilities

As part of the *Science and Technology* ***Facilities*** *Council*, it is clearly part of RAL Space's mission to provide world-class space development and test facilities for the UK space community. Although RAL Space is a non-profit government research establishment, it is able to utilise any margin from its commercial contracts to maintain and, where practicable, enhance its facilities by replacing and upgrading equipment and smaller test facilities. This replacement / enhancement programme is, and will remain, an on-going process.

However, when it comes to major new facilities, especially capital projects such as the new R100 environmental test building, significant external funding, mostly government sourced, is required.

The R100 test facility is interesting for several reasons: a) it was designed principally with the assembly, integration, test and calibration of major space instruments in mind, particularly those with precision optics; b) it is right at the centre of the Harwell Space Cluster and as such, it has been seen and visited by a large number of space organisations, many of them with potential interest in the facilities it offers; and c) the feedback from these (mostly industrial) organisations has been universally positive.

Specifically, RAL Space has been approached by a cross section of UK industry keen at system integrator level to see R100 expanded to enable full spacecraft system-level environmental testing (potentially encompassing vibration, acoustic, EMC, RF, TVAC, mass properties and appendage deployment testing) and at subsystem and equipment-level more modest AIT activities.

RAL Space is currently evaluating with industry, STFC and UKSA the technical and financial feasibility of extending the R100 building to accommodate this request while releasing some clean room and other capacity to industry and other third-party organisations.

3.36 Reaction Engines Ltd, Culham

3.36.1 REL Company Background

Reaction Engines Ltd (REL) is a UK company based in Culham, Oxfordshire, formed in 1989 to develop the technologies needed for an advanced combined cycle air-breathing rocket engine class called SABRE (Synergetic Air-Breathing Rocket Engine), that will enable aircraft to operate at speeds of up to five times the speed of sound or fly directly into Earth orbit.

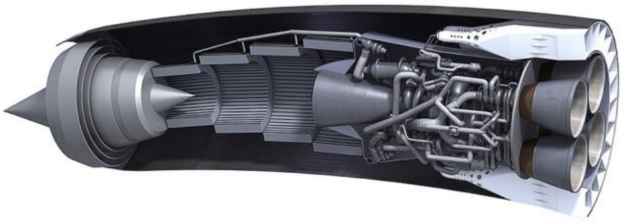


Figure 3.127 Reaction Engines' SABRE engine

REL achieved a breakthrough in engine technology by developing ultra-lightweight heat exchangers 100 times lighter than existing technologies allowing cooling of very hot airstreams from >1,000°C to -150°C in less than 1/100th of a second. Reaction Engines' technology has undergone extensive independent technical assessments, undertaken by the European Space Agency at the request of the UK Government, which have confirmed the viability of the engine technology and its vehicle applications, in particular for the Skylon launch vehicle.

Figure 3.128 Reaction Engines’ Skylon with upper stage deployed

3.36.2 REL Manufacturing and Test Facilities

Most REL capabilities and facilities at the Culham site are specific to the pre-cooler development including:

- Pre-cooler manufacturing and test for which:
  - precision tube manufacturing capability is being developed
  - a new vacuum furnace for full size SABRE pre-cooler brazing has been installed, potentially available to external users, see section below
- Subsystem/component manufacture and test:
  - propellant tanks for potential flight test programmes
  - TiSiC tube manufacture and NDT (non-destructive test capability)
- Additive Manufacturing
  - Stainless Steel injector plate manufactured and soon to be tested
- Aeroshell
  - Silicon carbide-reinforced glass ceramics - a programme with Imperial College London to develop hot isostatic pressing techniques

Other developments, either in place or planned at REL for the SABRE engine include:

- Hydrogen turbines:
  - An embrittlement investigation programme with the Welding Institute
  - Potential investment in a stir friction welding facility
- Liquid hydrogen:
  - Fuel tanks and insulation research
  - LH2 availability for hydrogen pumps
  - Cavitation testing
- A new propulsion test facility with fast data acquisition and multiple propellant options with potential for 10-60kN range engines
- 1kN testing for the Reaction Control System

3.36.3 REL Specialist Manufacturing Facilities

As explained above, REL's principal interest is development of pre-cooler technology for its SABRE engine. With this in mind, in addition to the high precision machining available at their subsidiary, Brite Precision, and their sheet-metal fabrication and welding facilities at another subsidiary, Crossman Engineering, described below, REL has recently taken delivery of a new state-of-the-art high vacuum furnace at the Culham site. The bespoke furnace was jointly funded by Reaction Engines' private capital, and the ESA GSTP programme, supported by UKSA and Innovate UK. It is capable of achieving temperatures up to 1200°C and a vacuum level of less than one ten billionth of the Earth's atmosphere (10-10atm). The furnace is unique in the UK, having an exceptionally clean processing environment and highly responsive thermal performance. Its main purpose is the manufacture of the SABRE engine pre-coolers, but there will be some spare capacity, potentially available to external users.

Figure 3.129 REL's new vacuum furnace

The principal characteristics of the furnace are:

- Temperature: 1200°C
- Vacuum: 10^{-10} torr
- Internal dimensions: ~3m diam x ~3m high

REL's two subsidiary companies are potentially able to support external customers in addition to their REL work.

Brite Precision, based in Didcot, offers precision engineering manufacturing services using state-of-the-art equipment including 5-axis CNC machining and CNC wire erosion. Its staff are experienced in working with a wide variety of materials including exotic nickel alloys and plastics and in the assembly of precision engineering and aerospace equipment.

Crossman Engineering, also based in Didcot, is dedicated to high quality precision welding and fabrication, including one-off and batch job services in sheet metal, structural and bespoke manufacturing work in a wide variety of metals including steels, aluminium, brass and copper.

Figure 3.130 Typical component from Brite Precision (left) and engine casing from Crossman (right)

3.36.4 REL View on Facilities

REL has a number of specialist manufacturing and test facilities that can be made available to external users subject to usual commercial terms. In particular they see the high-vacuum brazing furnace as something that is unique in the UK with potential applications in other fields.

The Company has identified a number of test facility gaps that need to be filled in order to proceed with its SABRE engine development programme. The most serious of these is the lack of any 2MN rocket test facilities in the UK – new facilities will have to be built for REL. Another important gap is that there are no UK wind tunnels in the Mach 5 range, although the transonic/subsonic/supersonic wind tunnels at Bedford and BAE Warton are potentially useful, although outside the scope of the current activity.

3.37 Roxel (Safran-MBDA), Kidderminster

3.37.1 Roxel Company Background

Roxel is an Anglo-French Group formed in February 2003 by the merging of the Royal Ordnance Rocket Motors of the UK (a division of BAe Systems) and Celerg of France (a JV born by combining the operations of SNPE and Aerospatiale in 1993).

It designs, develops, manufactures and sells solid propulsion systems and related equipment for all types of rockets and tactical and cruise missiles for air, sea and ground forces. It has proven capabilities in the chemistry of energetic materials and mechanical fields offering its customers bespoke solutions for all elements of propulsion systems. Roxel UK is based in Kidderminster and has a long history and an extensive knowledge in all aspects of rocket motor design, modelling, testing and analysis for the qualification and certification of rocket motors. Roxel's work spans a range of applications primarily for but not limited to tactical missiles. For example in 2007 Roxel conducted design work for the Exomars descent motors.

Figure 3.131 Typical rocket motor assembly at Roxel

3.37.2 Roxel Design, Modelling and Analysis

The company's design expertise covers all areas from propellant charges, nozzles, igniters and motor hardware to the thermochemistry of propellants. The company has experience in rocket motor performance and range modelling such as exhaust plume interaction and advanced tools for Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) and Fluid Structure Interaction (FSI). Following a firing test, Roxel is able to carry out analysis of firing data and sectioning and examination of fired hardware.

3.37.3 Roxel propulsion hardware and manufacturing facilities

Roxel has extensive facilities and capabilities for the manufacture of rocket-related hardware including: CNC machines, structural bonding, motor case manufacture, case lining and inhibition.

Igniters: Roxel has designed and manufactured many igniters for a wide range of applications, providing a good knowledge of pyrotechnics, pyrogens and Ignition Safety devices (ISDs).

Motor cases: Roxel UK's proprietary Steel Strip Laminate (SSL) technology, developed since the 1950's, can be used to make a wide variety of rocket motor cases of different lengths and diameters. The size of the case is limited only by the size of the mandrel. These cases deliver excellent strength and lightweight properties at a low cost.

Figure 3.132 Steel strip laminate rocket motor cases

Rocket bodies: Facilities include the manufacture of Kevlar Overwound Aluminium (KOA) bodies. These bodies exhibit the lightweight nature of aluminium with an enhanced hoop strength provided by overwound Kevlar fibres.

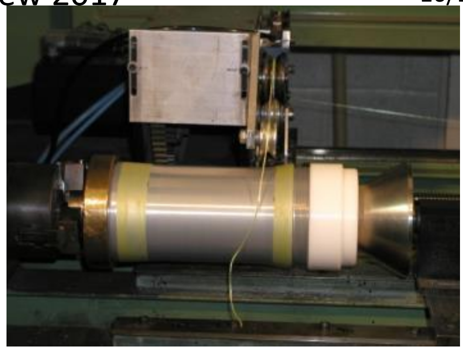


Figure 3.133 Kevlar over-wound aluminium (KOA) body

Additive manufacturing: as well as conventional hardware manufacture Roxel is looking to the future and has been developing rocket motor parts using additive manufacture. Roxel has recently installed a 3D printer capability. This printer is typically used to produce tooling parts. Roxel also has experience with metallic additive manufactured rocket motor parts. Critical rocket motor components such as nozzles have been produced and tested successfully.

Figure 3.134 Additive manufacture rocket nozzle

Propellants: Roxel has extensive knowledge and experience in the manufacture of a range of solid propellants and the capacity to manufacture all dimensions of solid rocket propellant charges. Nitro-glycerine paste is manufactured on site and Roxel has recently invested in a new novel propellant facility. Some of the propellants produced are Cast Composite, Extruded-Curable Composite, Cast Double Base (CDB), Extruded Double Base (EDB), Elastomer Modified Cast Double Base (EMCDB) as well as advanced smokeless composite propellants.

Figure 3.135 Typical propellant charges

Research: The company is engaged in several research projects to improve manufacturing methods, materials and technologies. Some of the projects being worked on are Discrete Variable Thrust (DVT) technology, shown below, Novel Propellants, Composite Rocket Motors Cases, Resonant Acoustic Mixing (RAM), Additive Manufacture and Propellant Modelling. In the past Roxel has worked on many other research projects such as Continuous Variable Thrust (CVT) and Pulse Rocket Motors.

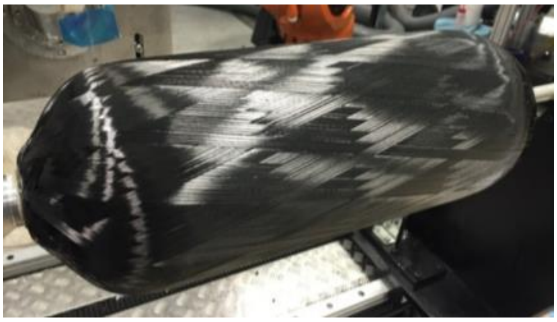


Figure 3.136 Filament-wound composite case

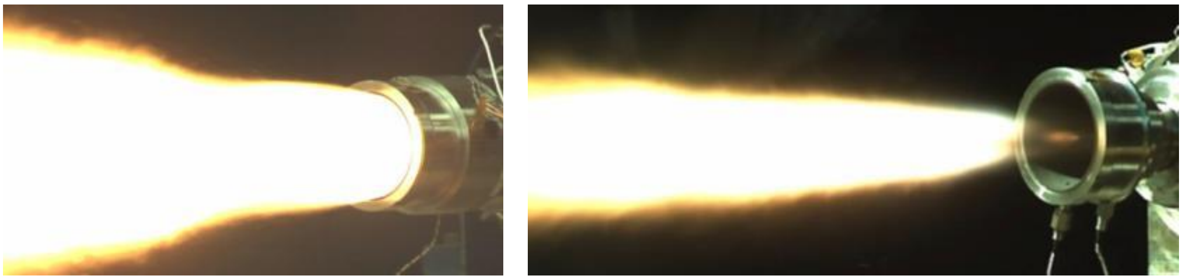


Figure 3.137 Discrete variable thrust: boost phase (left) and sustain phase (right)

Thrust Vector Control (TVC): Roxel has developed various TVC systems for rocket motors. The most notable being the TVC for the vertical launched Sea Wolf. The TVC is capable of turning the motor over by 90°C in any direction following a vertical launch.

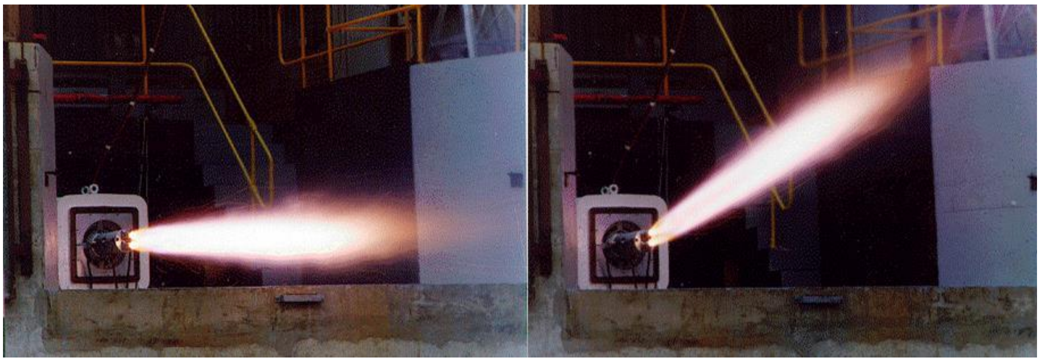


Figure 3.138 Thrust Vector Control (TVC)

3.37.4 Roxel Trials and Environmental Test Facilities

Roxel has well-established facilities and experienced staff available for performance testing of a variety of propulsion systems including solid propellant rocket motors, thrusters, hybrid engines and air-breathing systems. These systems can be trialled over a range of conditions to simulate the operating environment and include:

- Static and dynamic
- Operating temperature from –65°C to +80°C
- Simulated flight profile (e.g. aerodynamic heating or high altitude)

Rocket Test Ranges: The majority of Roxel's rocket firing and environmental trials take place on a 100 acre range in the Wyre Forest. On the Wyre Forest main range, static firings of motors with thrusts up to at least 200kN can be conducted. On the existing firing bed the maximum motor size that can be fired is 6m long and 1.5m in diameter but can be increased easily. The secondary range can be used to test motors up to 20kN of thrust and the TVC facility up to 200kN of thrust.

Figure 3.139 Roxel rocket test range in the Wyre Forest

Roxel has another test range on its Summerfield site offering: three main ranges up to 20kN thrust; a roll torque rig for up to 5kN thrust; a smoke tunnel for up to 5kN thrust; and a thrust misalignment rig up to 2kN thrust.

The majority of trials are carried out under static conditions but dynamic trials can also be conducted especially to simulate eject and launch conditions. A large number of measurement techniques have been developed that include, but are not limited to the following: pressure, thrust (axial and side), roll torque, acceleration, temperature, strain, blast over pressure (BOP), smoke measurements (i.e. visible, IR, UV and particulates), high speed video, real time X-ray. A state-of-the-art data acquisition system allows up to 32 data channels and 100kHz of data recording and can cater for the most demanding of trials.

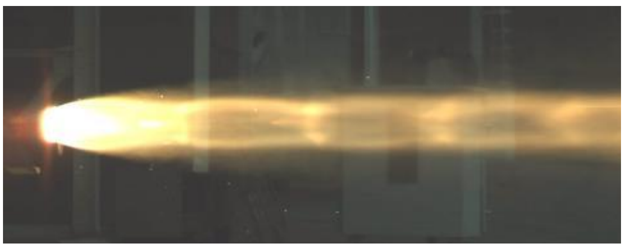


Figure 3.140 Rocket plume image from high speed video

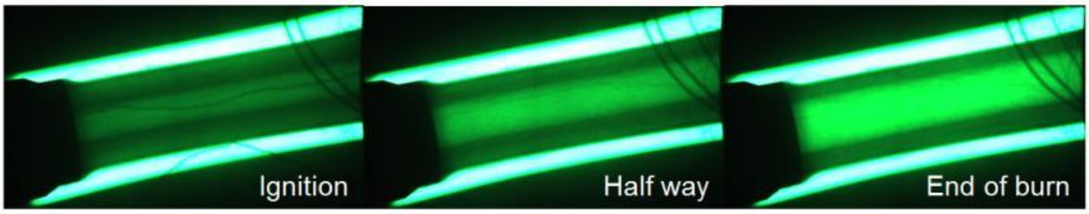


Figure 3.141 Insulation erosion during firing from Real-Time X-ray (RTX)

Centrifuge: The Wyre Forest site has the largest centrifuge in the UK with a 6.5m arm that is capable of accelerating payloads, depending on their mass, up to an acceleration of 60g and a speed of 92rpm. The centrifuge can be used for explosive or inert testing.

Figure 3.142 Wyre Forest Centrifuge

Vibration Facility: The Wyre Forest site also houses Roxel's vibration facility. The vibrator is capable of mounting full size propulsion systems. This can be combined with a conditioning chamber and Re-circulatory Air Conditioning System (RACS) to provide constant or varying thermal conditions and together provides a flexible facility to test both explosive and inert items. Some of the specific capabilities of the large vibrator are:

- Temperature ramp: -65°C to +80°C
- Sine force peak: 55.5kN
- Velocity sine peak: 1.8m/s
- Displacement: 63.5mm pk-to-pk
- Sine frequency range: 5Hz to 2000Hz
- Load capacity: 700kg

Figure 3.143 Rocket mounted on large vibrator

A limited capability for bump and shock testing is available using the large vibrator. This is suitable for low intensity bumps and shocks up to 200kN over long durations.

Climate chambers: A large number of climatic chambers are available to cater for a wide range of sizes and climatic conditions. A temperature range of -65°C to +80°C and a humidity range from 10 to 98% RH can be achieved for large test items. Larger ranges can be handled in collaboration with other organisations.

Figure 3.144 Typical environmental chamber

Cold gas thruster testing: For cold gas testing Roxel has an air rig of the blow down type which is suitable for short duration trials of up to about 30 sec depending on the pressure and mass flow rates required. An electrical heater is also available to increase the air temperature without contaminating the propellant.

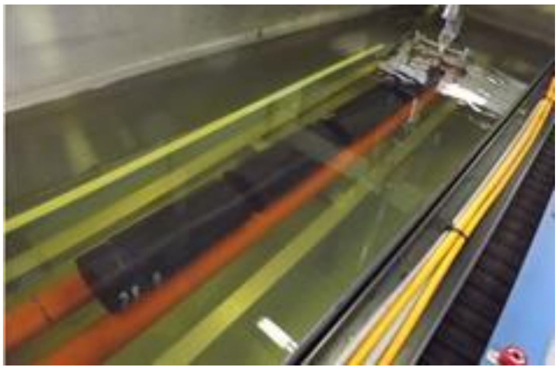
Specific capabilities of the air rig include:

- Maximum pressure unheated of 40 bar
- Maximum pressure heated of 12 bar
- Maximum temperature of 350°C
- Air storage capacity of 5.5m^3

Figure 3.145 Cold gas thruster testing air rig

Structural Testing: Roxel has a structural testing facility for the testing of loads on rocket motor hardware. Testing typically involves instrumented structural testing such as body pressure burst tests, bending and torsional loading over a temperature range.

Non-Destructive Testing (NDT): Roxel has an NDT facility which contains X-ray machines and ultrasonic instrumentation. Ultrasonic scanning can be conducted with dry probes or wet in an ultrasonic bath. The X-ray machines are capable of 30 to 400kV outputs. High resolution digital filmless radiography sets new standards in the capability of fault detection.



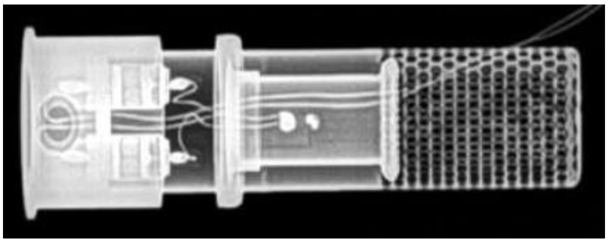


Figure 3.146 Charges being scanned in ultrasonic bath (left) and X-ray image of igniter (right)

Chemical Testing: Roxel has a modern chemical laboratory where technical experts analyse a wide variety of explosive and non-explosive materials using a range of methods. Some general tests include:

- Chromatography techniques: High Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Gel Permeation Chromatography (GPC)
- Spectroscopic techniques: Atomic Absorption Spectroscopy (AAS), Infrared Spectrometer (IR), Ultra-Violet Spectrometer (UV)
- Traditional analysis: volumetric and gravimetric analysis

Figure 3.147 Chemical Laboratory

Stability tests that can be performed include:

Compatibility tests that can be performed include:

- Abel Heat Test
- Vacuum Stability Test
- 80°C Self-Heating Test
- Bergmann and Junk Test & J test
- Mass Loss
- pH
- Vacuum Stability
- Stabiliser Consumption
- 10% Admixture Test
- Self-Heating / Silver Vessel Test
- Differential Scanning Calorimetry (DSC)
- Thermal Gravimetric Analysis (TGA)

Physical Testing: Roxel has a comprehensive physical testing capability with an excellent range of equipment and instrumentation supported by well trained staff. Tests can be carried out over a wide temperature range to characterise the properties of materials. Data is generated for Quality Control (QC) and Finite Element Analysis (FEA) design studies.

Mechanical testing can include tensile, compression, shear, flexure, fatigue, creep, stress relaxation and optical extensometry testing. For such testing Roxel have tensile test machines equipped with temperature conditioning chambers and a line-scan camera capability. This can be used to test explosive and non-explosive material. Other testing includes metallurgical analysis such as hardness and failure / corrosion analysis, fracture analysis and microscopy, bond testing, thermal analysis and Dynamic Mechanical Thermal Analysis (DMTA).

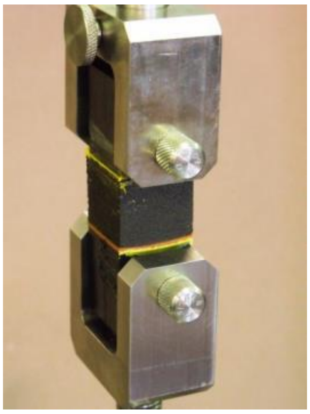


Figure 3.148 Sample being tensile tested

Hazard Testing: The hazard laboratory has achieved accreditation from DOSG to carry out small scale hazard testing as required by DEF-STAN 13-129/1. The laboratory has the ability to generate hazard data for all types of energetic materials with the exception of primary explosives. Testing includes Rotter Impact, Mallet Friction, Temperature of Ignition, Ease of ignition, Train Test, Electric Spark and Rotary Friction.

3.37.5 Roxel View on Facilities

Roxel's rocket motor design, manufacturing and testing facilities, which were established principally for its own development programmes make it ideally positioned to support external customers in all aspects of rocket propulsion systems, whether it is for solid, liquid, hybrid or air breathing motors. This support includes: consultancy for motor development and analysis, technical engineering support, safety and hazard analyses, propellant characterisation and sensitivity testing and all aspects of rocket motor testing.

Roxel UK believes its existing test facilities are capable of meeting the currently known requirements but could be easily expanded to meet future requirements for either increased loads (thrust, temperature, etc.) or additional specialist capability. It also believes its production facilities are similarly well placed with the exception that there is a need to increase propellant manufacturing capacity to cater for new propellants and larger motors.

3.38 Satellite Applications Catapult, Harwell

3.38.1 Catapult Background

The Satellite Applications Catapult, hereinafter referred to as 'the Catapult' which is how it is usually known, was established at Harwell in May 2013 by Innovate UK, as one of a network of Catapults to accelerate the take-up of emerging technologies and drive economic growth. It is an independent not-for-profit innovation and technology company, created to foster growth across the economy through the exploitation of space. This Catapult helps organisations make use of and benefit from satellite applications and technologies, which is an area of significant growth for the UK, bringing together multi-disciplinary teams to generate ideas and solutions in an open innovation environment. It is principally a down-stream satellite applications company with particular expertise in Smart Cities, intelligent transport and maritime applications, such as illegal fishing and coastal security. However it does have at least two up-stream facilities that are of particular relevance to this study: a far-field antenna test range and a development environment for CubeSats, described in the following sections.

3.38.2 Catapult Far-Field Antenna Test Range

The Catapult is setting up a 400m far-field antenna test range at its Harwell site, essentially replicating the now-closed Cobham (Leatherhead) antenna range. The Catapult test range will be used primarily for the development, characterisation and type approval of satellite communication antennas for use on satellite telecommunications networks. It will comprise two antenna towers and cover all satellite communication bands from C to Ka, helping British and international satcom terminal manufacturers develop and test new products. Expected antenna range characteristics as follows:

- Range length: 400m
- Transmit tower height: 3m
- Receive tower height: 13m
- Antenna characterisation for gain, co-polar/cross-polar discrimination and raster scan
- Waveguide switches for band switching, enabling reduced measurement times, higher capacity, and lower cost to customers

3.38.3 Catapult CubeSat Development Facility

The Catapult has a CubeSat mission development facility comprising a suite of avionics cards (power board, OBC, communications card) from a typical CubeSat, laid out on a flat surface (collectively known as a 'FlatSat'), together with the necessary support equipment (external power supply, RF communications equipment, oscilloscope and external control computer), which, together with the FlatSat and its on-board software are collectively known as a 'Nano-bed'.

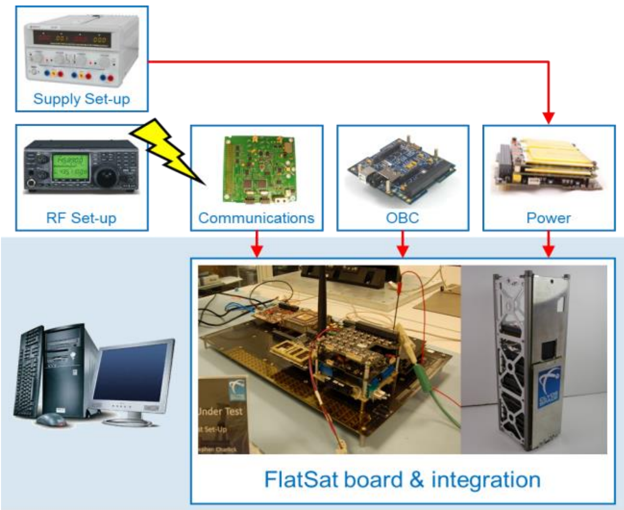


Figure 3.149 Catapult 'Nano-Bed' CubeSat Mission Development Facility (credit Clyde Space)

This facility allows CubeSat users, including payload or instrument providers, subsystem suppliers, detector suppliers, and on-board software providers, to plug in their device(s) and or software, to a set of avionics that behaves electrically in exactly the same way as an actual CubeSat does, so that they can test its interfaces and performance in a realistic CubeSat environment. By verifying its performance in this way, they can eliminate almost all potential interface issues, so that when they encounter the flight CubeSat, they can be confident that their device(s) can be integrated with a minimum of difficulty.

The Catapult has five designated Centres-of-Excellence, two of which also support CubeSat activities: Strathclyde University and the UK ATC. Both of these Centres have ‘Mission Labs’ with Nano-Bed development facilities, allowing northern CubeSat users the same benefits.

3.38.4 Catapult View on Facilities

The Catapult has many down-stream facilities including an operations control centre with spacecraft and payload control software, data processing facilities and data visualisation facilities including a large video wall and 3-D visualisation suite. However, as stated earlier, the current study is concentrating on up-stream facilities and in this context the Catapult believes that both its far-field antenna range and flat-sat development facility for CubeSats are filling an otherwise significant gap in the facilities available within the Harwell Space Cluster.

3.39 Spur Electron Ltd, Havant

3.39.1 Spur Company Background

Spur Electron, based in Havant, is an ISO 9001:2008 registered and approved company, with all operations controlled by a robust Quality Management System. It provides a comprehensive range of expertise covering all facets of component engineering, materials sciences and manufacturing capability for space electronics. Space assembly work is conducted in an ISO Class 7 (Class 10,000) clean room by ESA-certified technicians and inspectors.

3.39.2 Spur Space Electronics Manufacturing Facilities

Spur's space electronics manufacturing capabilities and facilities include:

- **Component Engineerin**g: reviewing DCLs; advice on component selection; physical analysis; screening and testing; radiation assessment and testing; component approval; long-term storage; obsolescence solutions; consultancy and technological studies
- **Component Procurement:** export compliance (ITAR); supplier control; supply chain management; logistics management and control; customer visibility and reporting
- **Inspection and Test:** visual inspection; mechanical inspection; pure-tin mitigation; solderability; radiographic inspection; data review; evaluation; re-lifing; life-testing; receiving inspection; non-conformance resolution and reporting
- **Analytical Laboratory:** component assessment; construction analysis; DPA (Destructive Physical Analysis), performed in accordance with ESA Standards, SSQ25000 and MIL STD 1580 including Residual Gas Analysis (RGA); electronic photographic records maintained; reports produced with results and observations; failure analysis; ESA Process Verification Assessment; materials and processes studies
- **EEE Component Testing:** visual inspection at high and low magnification; fine and gross leak-testing; marking permanency; solderability; lead integrity; X-ray analysis; particle impact noise detection testing; bond-pull/die-shear; scanning electron microscopy (SEM) analysis; micro-sectional analysis; materials analysis (energy dispersive X-ray analysis)

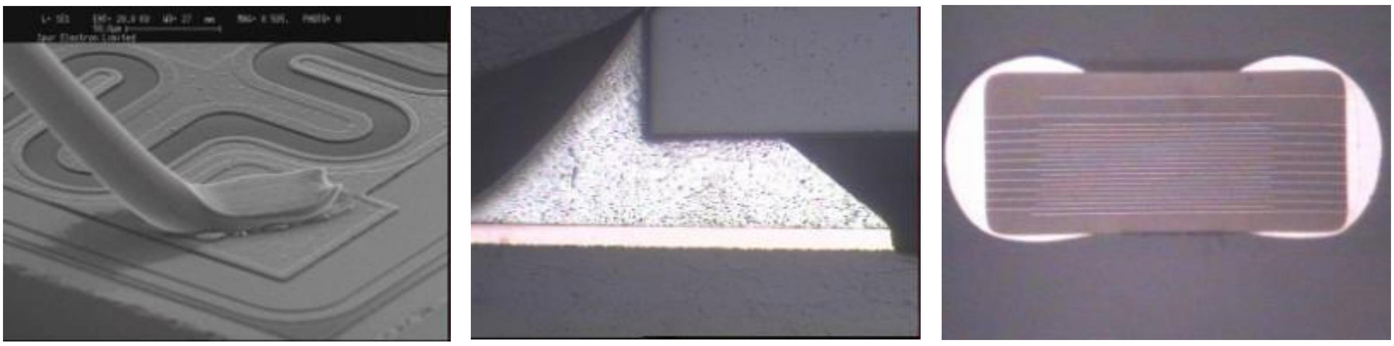


Figure 3.150 EEE component testing

- **Solder Verification:** verification in accordance with ECSS-Q-ST-70-38 comprising: preparation of verification plan; assembly of test vehicles; vibration; thermal cycling; micro-section. The Spur laboratory has ESA accreditation to perform micro-sectioning in accordance with ECSS-Q-ST-70-38.

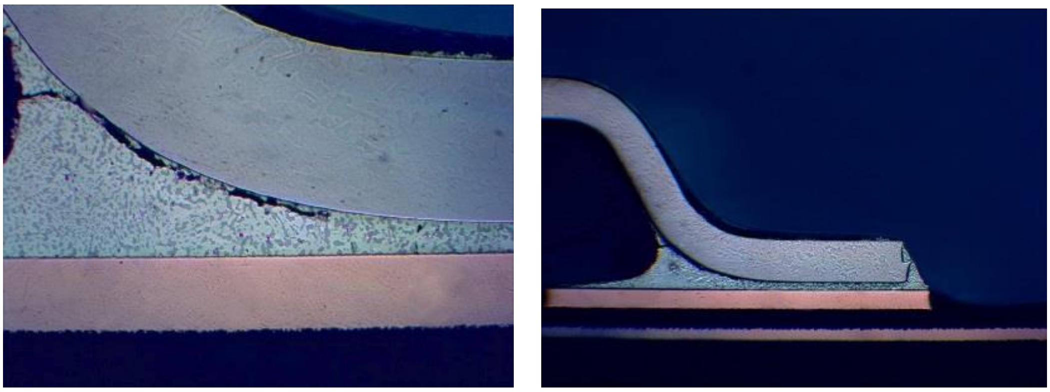


Figure 3.151 Micro-sectioning in Spur lab

- **PCB Assembly:** space-qualified PCB assembly; automated surface mount assembly; qualified hand-soldering by ESA-certified technicians; lead forming; high pin-count ceramic column grid array process; ISO Class 7 Cleanroom; conformal coating

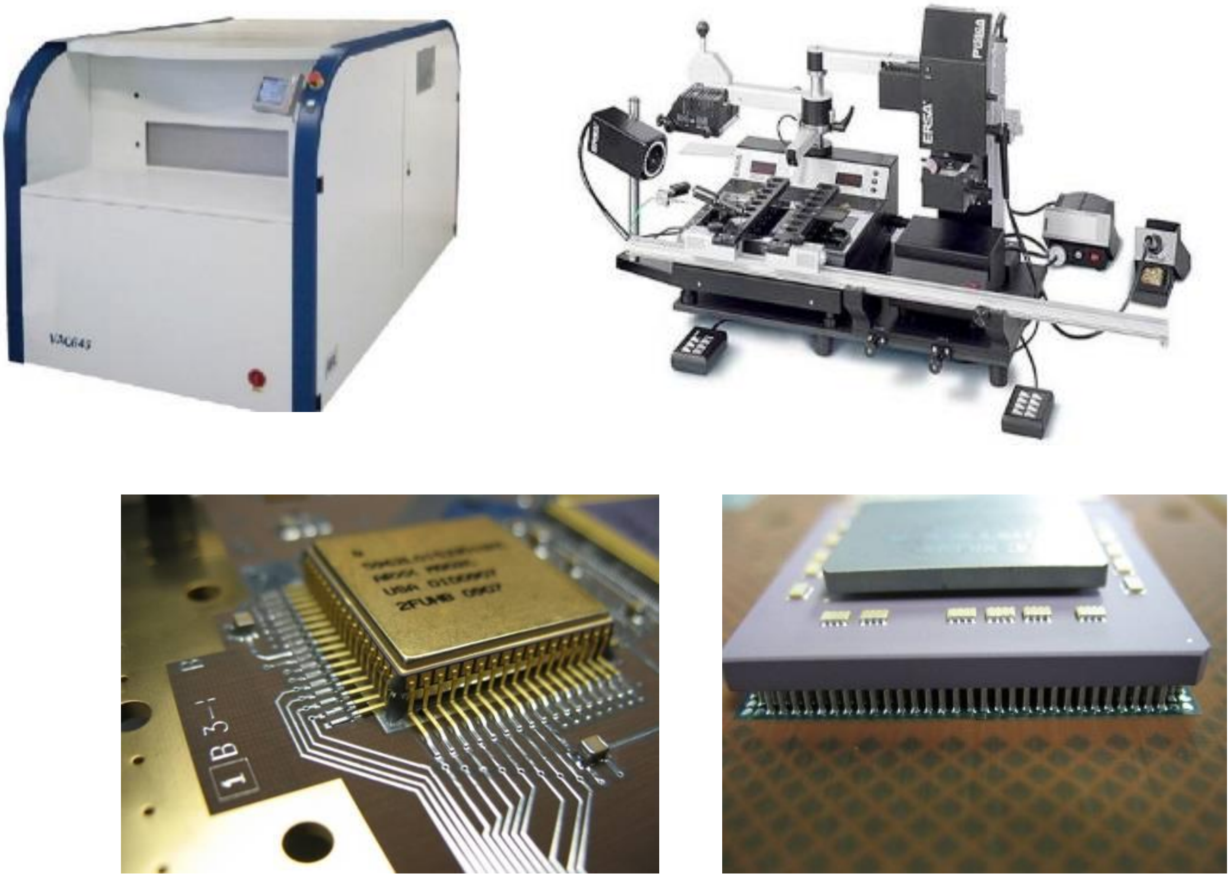


Figure 3.152 Spur's PCB assembly facilities

3.39.3 Spur View on Facilities

Spur Electron's expertise and facilities for EEE components and space electronics manufacturing at its Havant site constitute a world-class resource for the UK space community, especially SMEs and other companies new to the stringent requirements of space missions.

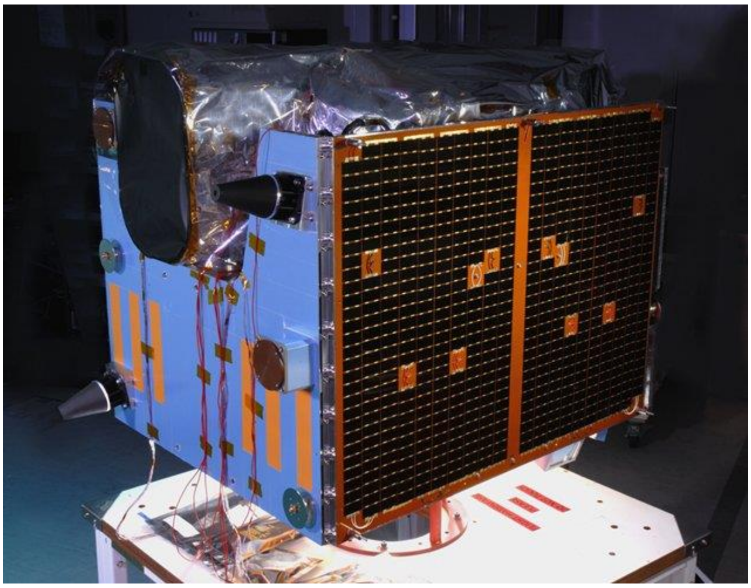
3.40 SSTL – Surrey Satellite Technology Ltd, Guildford

3.40.1 SSTL Background

The SSTL story began in the late 1970s when its founder, Martin Sweeting, and colleagues at the University of Surrey, decided to build a satellite using commercial off-the-shelf (COTS) components. That first satellite, UoSat-1, was launched in 1981 and was a great success, outliving its planned 3-year life by more than 5 years, demonstrating that relatively small and inexpensive satellites could be built rapidly to perform successful and sophisticated missions. In 1985 the University of Surrey formed Surrey Satellite Technology Ltd as a spin-out company, located in Guildford, to transfer the results of its research into a commercial enterprise. The growth of the company has accelerated, and its innovative approach to the design, build, test and operation of spacecraft has propelled SSTL to the forefront of the small satellite industry. SSTL is now an independent UK company within the Airbus Defence and Space group and has the following capabilities:

- Provides complete in-house design, manufacture, launch and operation of small satellites
- Delivers complete mission solutions for remote sensing, science, navigation and telecommunications
- Delivers space training and development programmes including on-the-job customer training
- Designs and builds remote sensing, navigation and communications payloads
- Supplies avionics suites and sub-systems
- Builds and installs ground infrastructure
- Provides consultancy services

SSTL has long been known for its small satellites such as the RapidEye spacecraft, but its expanding portfolio now includes medium-sized spacecraft such as NovaSAR, both of which are shown below; and these are soon to be followed by significantly larger geostationary comsats.



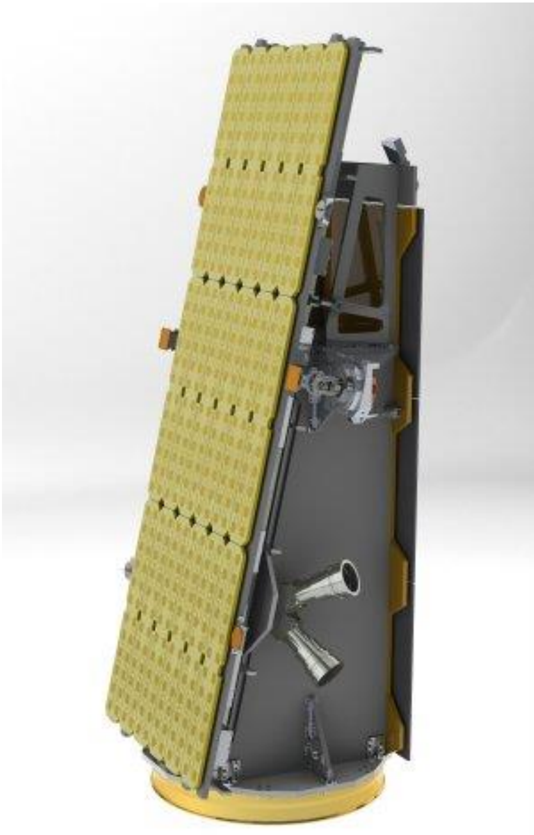


Figure 3.153 SSTL RapidEye satellite on SSTL-150 bus (left) and NovaSAR (right)

3.40.2 SSTL Clean Rooms

SSTL cleanrooms are located in its technical facility, the Kepler Building**,** adjacent to SSTL's headquarters, Tycho House. The 3,700m^2 facility has world-class clean test halls with 8T and 10T gantry cranes over reinforced floors, providing great flexibility for integration and testing of both small and larger spacecraft.

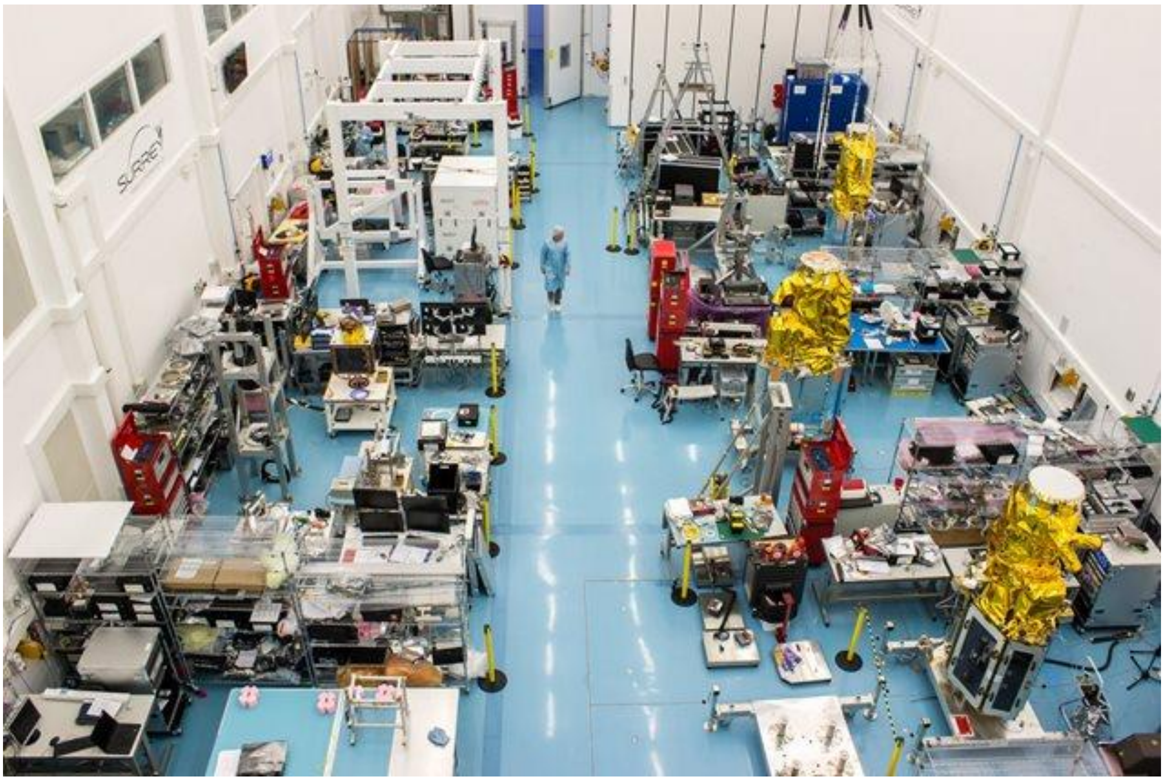


Figure 3.154 SSTL Integration & Test Hall with three DCM3 satellites

3.40.3 SSTL Environmental Test Facilities

SSTL has two large 125 m^3 walk-in thermal chambers which it uses for spacecraft thermal testing at ambient pressure. The company does all its spacecraft-level mechanical, thermal/vacuum, EMC and RF testing at external facilities.

3.40.4 SSTL View on Facilities

SSTL accepts that for the foreseeable future all its spacecraft-level environmental testing, with the possible exception of ambient thermal testing, will take place at external test facilities. As long as the testing can take place in the UK and is economically viable/competitive, SSTL is content with this arrangement. However, now that SSTL is producing larger spacecraft, in particular the GMP-series spacecraft (Geostationary Mini-satellite Platform) there is a requirement for physically larger test facilities than currently available in the UK. The need to travel to continental Europe to complete their spacecraft test programme causes a number of inefficiencies in relation to logistics, planning, project schedule and greater risks due to packing and unpacking. The logistics to access multiple facilities is a significant percentage of the overall schedule time that has to be allocated to the environmental test campaign. SSTL also cited that having to adapt to the working practices of multiple facilities, in particular those abroad, can be inefficient.

SSTL identified the lack of clean acoustic testing facilities in the UK as being another significant gap. Due to the increasing size of the spacecraft, requirements of the launch authority and in some cases the customer, SSTL needs to conduct spacecraft-level acoustic testing and the current test house they use was not designed with space cleanliness requirements in mind and it also has access issues in terms of door height and width, corners to negotiate and crane height.

It would be very beneficial to the upcoming SSTL GMP and remote sensing flight programmes if all the necessary spacecraft tests could be performed in the UK, ideally on a single site in order to minimise transportation and its associated increased risks, costs and logistical problems.

3.41 STAR-Dundee Ltd, Dundee

3.41.1 STAR-Dundee Company Background

STAR-Dundee, based in Dundee, is an aerospace engineering company formed in 2002 as a spin-out from the University of Dundee's Space Technology Centre, Section 3.48 below. Its primary focus is on spacecraft on-board data-handling and processing technology. The company delivers a comprehensive range of test and development equipment, chip designs and IP cores to the World's space agencies and international aerospace industry. STAR-Dundee is a world leader in SpaceWire and SpaceFibre technology and is active in designing advanced digital signal and image processing systems for space applications.

SpaceWire is a spacecraft on-board data-handling network which connects instruments to the mass-memory, data processors and control processors. SpaceWire is simple to implement and has some specific characteristics that help it support data-handling applications in space: high-speed, low-power, simplicity, relatively low implementation cost, and architectural flexibility making it ideal for many space missions. SpaceWire provides high-speed (2 Mbits/s to 200 Mbits/s), bi-directional, full-duplex data-links, which connect together SpaceWire-enabled equipment. Data-handling networks can be built to suit particular applications using point-to-point data-links and routing switches. SpaceWire is already in orbit or being designed into more than 100 spacecraft supporting Earth Observation, Science, Exploration, and Telecommunications missions. High-profile spacecraft using SpaceWire include: Gaia, ExoMars, Bepi-Colombo, Lunar Reconnaissance Orbiter, GOES-R, James Webb Space Telescope, and Astro-H.

Figure 3.155 STAR-Dundee SpaceWire Brick Mk3, a SpaceWire interface device

SpaceFibre is a new generation of SpaceWire technology which is able to support the very high data-rates required by sensors like Synthetic Aperture Radar (SAR) and multi-spectral imagers. SpaceFibre operates at multi-Gbits/s over electrical or fibre-optic cables. It complements the capabilities of the widely used SpaceWire on-board networking standard: improving the data rate by a factor of 10, reducing the cable mass by a factor of two and providing quality of service (QoS) and fault detection, isolation and recovery (FDIR) capabilities. Multi-laning improves the data-rate further to well over 20 Gbits/s. SpaceFibre is able to fulfil a wide range of spacecraft on-board communications applications because of its inbuilt quality of service (QoS) and fault detection, isolation and recovery (FDIR) capabilities.

Figure 3.156 Demonstrating SpaceFibre, the next generation of SpaceWire technology

3.41.2 STAR-Dundee Facilities

STAR-Dundee is based in a town house in the centre of Dundee which was built in 1817 and which has been renovated to provide an ideal environment for work on electronic system, chip and software design. STAR-Dundee also has a small research and development office in St Cugat, Barcelona.

STAR-Dundee has the equipment and software tools that it needs to design electronic equipment for spacecraft. These facilities include:

- Software development facilities
- Electronic test equipment
- Tools for FPGA, ASIC and PCB design
- SpaceWire test and development kit
- SpaceFibre test and development equipment
- SpaceWire and SpaceFibre IP cores
- General tools and soldering equipment

Figure 3.157 STAR-Dundee's offices in Dundee

3.41.3 STAR-Dundee View on Facilities

As explained above, STAR-Dundee has particular expertise in SpaceWire and SpaceFibre and its in-house facilities are dedicated to these technologies and to their further development. STAR-Dundee is happy to work with external customers under suitable commercial arrangements.

3.42 Swansea University

3.42.1 Swansea University Background

Swansea University is a research-led university that has been making a difference since its inception as the *University College of Swansea*, part of the University of Wales, in 1920. In 1966 it became the *University of Wales Swansea* before adopting the title of *Swansea University* in 2007. It has two campuses located on the north coast of Swansea Bay: Singleton Park Campus to the west of Swansea City centre; and Bay Campus to the east. It is the third largest university in Wales with around 18,000 students. It is ranked as a top-thirty research university, soaring up the 2014 Research Excellence Framework (REF 2014) league table to 26th in the UK. Swansea's approach to research builds on the aspirations of its founders, who in 1920 set out to respond to the requirements of industry. Their first five Chair appointments were in engineering, metallurgy, physics, mathematics, and chemistry – fields which remain prominent in the form of today's Science, Technology, Engineering and Mathematics (STEM) subjects. This underpins many of Swansea's most notable advances. Each of Swansea's five Colleges and two Schools houses research clusters that bring together research institutes, private companies, the public and voluntary and community organisations, and which build its capacity to lead in new and emerging areas.

3.42.2 Swansea Research Centres and Facilities

Swansea University has a number of world-leading research centres and facilities that are capable of supporting research and development activities in the space or space-related fields and applications:

- **Materials Advanced Characterisation Centre (MACH1)**: offers a wide range of material and measurement capabilities to deliver multi-sample, high-throughput testing of advanced materials to industry;
- **Advanced Sustainable Manufacturing Technologies (ASTUTE)**: the Swansea team has access to a wide range of expertise in Engineering such as the Materials Research Centre, the Civil and Computational Research Centre and the Welsh Centre for Printing and Coating;
- **Welsh Centre for Printing and Coating (WCPC)**: is one of the World's leading centres for research and development of printing and coating processes; and
- **Centre for Solar Energy Research (CSER)**: collaborates on renewable-energy R&D across Wales and has proven expertise and a world class reputation in researching novel photovoltaic materials and devices.

Swansea space research capabilities cover many aspects of space propulsion system design (described in the following section), earth observation and satellite applications expertise. Areas include: Satellite Design and System Engineering; Space Materials Expertise; Structural Modelling and Analysis; Low-shock Actuator Design; Computational Fluid Dynamics; Additive Manufacturing; Earth Observation (EO) for Climate and Weather Forecast; EO Application for Forest Resource Management; Sensor Simulation and Design; Photovoltaic Cell and Module Manufacture; and Materials Characterisation (including SEM with elemental analysis via EDAX, Optical microscopy, UV/visible/NIR optical spectroscopy (200-3300nm), Profilometer, Solar Simulator Class A with AM1.5 and AM0 calibration, four-point resistivity probe, Hall effect measurement, Bentham spectral response IQE and EQE, and Micro-Laser Beam Induced Current imaging).

The College of Engineering provides the Aerospace Engineering Space Stream programme to undergraduate students – BEng modules including Rocket and Space Technology; Satellite Systems; and Space Propulsion and Power Systems.

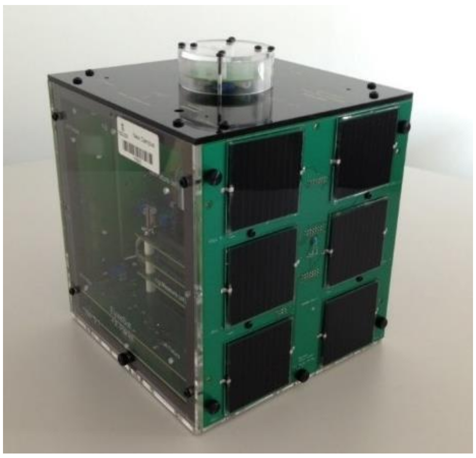


Figure 3.158 Nanosatellite used for classroom teaching

3.42.3 Swansea Chemical Propulsion Test Facilities

Chemical Propulsion: Swansea University has a mobile rocket test stand used in the demonstration of rocket propulsion principles for its space stream module 'Space Propulsion and Power Systems'. It is a demountable rig, currently fitted with the combustion chamber of a solid rocket motor. The current configuration can be used for solid rocket propellant characterisation (**Ba**llistics **Tes**t – measurements **BATES**), and test of solid rocket propellant grains or motors up to 130 mm diameter, length up to 2m. It can accommodate pressure and thrust (uniaxial) transducers, measuring pressures up to 300 bar, and thrust levels up to 180 kN (safety level is 350 kN). The test stand can also be adapted for testing of liquid (monopropellant and bipropellant) and hybrid rocket engines. It has been designed for easy dismantling and packing into a 1m x 1m x 4.5m box for easy transportation to external rocket test sites when required.

Figure 3.159 Swansea's Mobile Rocket Test Stand

3.42.4 Swansea University View on Facilities

Swansea University has long-standing and notable experience in collaboration with industry and research institutions in the UK and abroad. Its College of Engineering has excellent facilities to support space and space-related activities and is delighted to work/collaborate with potential external customers on a commercial basis subject to resource availability and terms. Large scale chemical propulsion tests can be realised in collaboration with several proving grounds in the UK.

3.43 Thales Alenia Space – UK, Harwell, Bristol and Belfast

3.43.1 TAS-UK Company Background

Thales Alenia Space (TAS) is a joint venture between Thales (67%) and Finmeccanica (33%). The world leader in telecommunication constellations, including Iridium and O3B, navigation, TAS can count the European Global Navigation Satellite Systems Agency as one of its major clients and is one of the key organisations in Galileo. A European leader in Earth observation, TAS has a major role in all generations of the Meteosat Programme. Being at the forefront of planetary and space exploration TAS is prime on the ExoMars 2018 mission with TAS UK providing the Reaction control System. TAS is an integral player in the construction of orbital infrastructures, contributing to half the pressurised volume of the ISS.

In 2014 TAS created a new subsidiary, Thales Alenia Space UK (TAS-UK) which, in addition to its propulsion activities co-located with its manufacturing partner Thales UK in Belfast, opened a new office in Harwell and acquired the space activities of Systems Engineering & Assessment Ltd (SEA). The acquisition of SEA reinforced its growth in systems engineering and research and technology. In 2014, building up from 10 people, it now employs almost 150 people. TAS-UK has a long heritage and expertise in electronics, mission subsystems, and propulsion subsystems, with a considerable client base including ESA and national Space Agencies across Europe and beyond. TAS-UK is keen to support the UK government's aims in growing its national space capabilities and global market share of the industry.

3.43.2 TAS-UK Clean Rooms

TAS-UK has a new 116m^2 ESD-safe Class 100,000 (ISO 8) clean room at its Bristol site with three Labcaire laminar flow cabinets, providing a Class 100 (ISO 5) cleanliness environment for manufacture. The TAS-UK clean room manufacturing facility in Belfast will be completed by third quarter 2016.

Figure 3.160 TAS-UK clean room in Bristol

Figure 3.161 TAS-UK clean room in Bristol

Figure 3.162 TAS-UK clean room manufacturing facility in Belfast will be completed in 2016

TAS-UK does not have any test facilities at its Harwell base but expects to make extensive use of the adjacent RAL Space environmental test facilities.

3.43.3 TAS-UK Chemical Propulsion Activities

TAS-UK's propulsion production facility is based within the Thales Belfast facility which was formerly Shorts Missile Systems, where it is the leader for short range weapon systems in the UK and within the Thales group and employs over 480 people. It is the centre-of-excellence for missile personnel where activities are broad ranging and serve to meet the requirements of customers seeking design, manufacture, assembly and test of complete integrated systems, products or components. The NEOSAT auxiliary chemical propulsion system will be integrated into these facilities.

3.43.4 TAS-UK Electric Propulsion Facilities

The main focus of TAS-UK EP current activities is the ESA NEOSAT programme and the UK TAS team at its new Harwell facilities is ramping up specifically to support this programme as well as additional propulsion activities related to ESA exploration missions. It is currently expected that NEOSAT propulsion modules will be integrated within the UK in Belfast where TAS and Thales UK are setting up 550m^2 of clean room space for propulsion (both chemical and electrical) integration inside the Thales UK facility. Thales UK is investing in the clean room mainly for civil work. TAS is investing in all hardware needed to equip the clean room for propulsion activities including an X-ray chamber, leak-testing and proof-testing capabilities. The clean room will be commissioned by the end of third 2016 quarter.

3.43.5 TAS-UK View on Facilities

All of Thales Alenia Space spacecraft-level AIT activities are currently carried out in continental Europe, mostly using the environmental test facilities of Intespace in Toulouse. However, TAS is one of the primes exploring investment in the UK through the expansion of AIV facilities within the Harwell Space Cluster, in particular for spacecraft up to 5 tonnes, although access to such a comprehensive suite of facilities is more extensive than those currently available within the UK. In addition to what is already in place or planned for the Harwell site, EMC and shock testing are the main additional facilities that would be needed and of course, all the AIV facilities would need to be competitively priced.

This expanded suite of facilities would essentially constitute a National Environmental Testing Facility and although such a National facility clearly has to be 'open', there will need to be some confidentiality during operations to protect new designs, since small differences in technology can make a big difference to business. A shared facility model would need to be developed which respects commercial sensitivity and protects IP.

In addition to the need for spacecraft-level test facilities as summarised above, there are some sub-system-level facilities missing that TAS-UK has identified as being needed:

- In order to implement electric propulsion systems on its GEO and MEO platforms TAS-UK has a need for a comprehensive integration and test facility dedicated to integrating complete EP propulsion modules - it is hoped that this gap can be filled by developing the facilities in Belfast.
- Another gap identified by TAS-UK is the lack of propellant storage facilities, especially for cryogenic propellants and some of the new alternative green propellants, which are often explosive.

3.44 TWI Technology Centre (Wales), Port Talbot

3.44.1 TWI Background

TWI has its headquarters in Abington, Cambridgeshire, and was formed in 1922 as the Institute of Welding Engineers. It went through a number of iterations before becoming The Welding Institute (TWI) in 1968. It is one of the world's foremost independent research and technology organisations, with 3500 Industrial members and expertise in materials joining and engineering processes as applied in industry. It has 5 regional centres in the UK, including the TWI Technology Centre in Wales, and numerous international branches all over the World.

TWI has been supporting the exploration of space through delivery of advanced technologies for more than three decades.

TWI has developed precision welding techniques and coating technologies that meet the extremely exacting demands of the sector, working to minute tolerances. The Company's technology has landed on the surface of Saturn's moon, Titan, sealed the external fuel tank of the Space Shuttle, provided the means by which the two halves of the Orion crew exploration vehicle are joined together and continues to support the sector and the new global space companies expanding the boundaries of space exploration.

Relevant technologies

Several of TWI's advanced technologies have already been exploited for space applications; many others hold further potential:

- Friction stir welding
- Linear and rotary friction welding
- Power beam welding (laser and electron beam)
- Coatings
- Additive manufacture
- Advanced non-destructive inspection

Standards

TWI is actively involved in committees for a number of standards with implications for the space sector:

- ECSS-Q-ST-70-15C – Space product assurance – NDE of space vehicles
- ECSS-Q-ST-70-39C – Space product assurance – Welding of metallic materials for flight hardware
- AWS D17.1 – Specification for fusion welding for aerospace applications
- AWS D17.3 – Specification for friction stir welding of aluminium alloys for aerospace applications.

3.44.2 TWI Technology Centre (Wales) Services and Facilities

TWI Technology Centre (Wales) is the leading centre in the UK for R&D into Advanced NDT techniques and specialises in the development and application of non-destructive testing (NDT) methods and in leading research for companies across the world.

The Centre provides real-world solutions to inspection challenges across multiple industries, such as aerospace, using specialised technologies. It houses a full complement of state-of-the-art NDT equipment and benefits from staff experienced and qualified in a wide range of NDT methods across all industrial sectors.

Services provided include inspection, application and equipment development, technology transfer, Level lll consultancy, training and validation of NDT applications. TWI offers services that add value to organisations engaged in manufacturing and construction around the globe and in 2017, the facility in Wales will grow from 1,400 m^2 to 2,500 m^2 with a new state-of-the-art extension.

Figure 3.163 TWI Technology Centre in Port Talbot

The overall capabilities of TWI Technology Centre (Wales) may be summarised as:

- Engineering and Technical Development Services
- Maintenance Repair and Overhaul
- Other Support Organisations
- Product and Material Testing
- Skill, Education and Training
- Support for management, productivity, accreditation and IT

Figure 3.164 TWI NDT Inspection Lab in Port Talbot

Figure 3.165 Robotic inspection of an aerospace component

3.44.3 TWI View on Facilities

The TWI Technology Centre in Wales offers truly World-class state-of-the-art facilities for research, development and application of NDT techniques which have direct application for the space sector. Similarly its advanced welding and coating technologies have been used for space applications for more than three decades for assemblies requiring extreme tolerances.

3.45 UK Astronomy Technology Centre (UK ATC), Edinburgh

3.45.1 STFC / UK ATC Background

The Science and Technology Facilities Council (STFC) is one of seven research councils in the UK. The research councils form part of UK government and report to the Department for Business, Innovation and Skills (BIS). STFC runs major science programmes using its own research capability and acts in support of the major UK physical science facilities, as a result of which it is able to offer access to world-class science expertise and facilities to UK industry and to other government agency customers. The major STFC sites are: Rutherford Appleton Laboratory, Oxfordshire (which includes RAL Space, Section 3.34 above); Daresbury Laboratory, Cheshire; Chilbolton Observatory, Hampshire; and UK Astronomy Technology Centre, Edinburgh.

The UK Astronomy Technology Centre, referred to hereinafter as UK ATC, is the national centre for astronomical technology. The Centre's principal activities are the design, build and verification of remote sensing instrumentation, from UV to THz, with a particular emphasis on IR. The primary target market is astronomy, with customers from the world's major telescopes - both ground and space-based. This also enables its scientists to carry out observational and theoretical research into fundamental questions such as the origins of planets and of galaxies. However, the UK ATC is increasingly becoming involved with Earth Observation space instrumentation and missions especially those based on small satellites and CubeSats.

3.45.2 UK ATC Clean Rooms

The UK ATC has two large Integration Halls, shown below, with a 10T crane, adjacent sub-assembly areas and a Control Room. There are also a number of other smaller integration areas including three clean rooms and dedicated detector development, optics and software development facilities, including test cryostats up to 1m x 1m x 0.8m and optical test equipment including interferometers and alignment telescopes.

Figure 3.166 ATC Integration Halls

3.45.3 Higgs Centre for Innovation

The Higgs Centre for Innovation is a new £11M industry-facing facility being built at the UK ATC to create new market opportunities whilst also inspiring the next generation of scientists and engineers. It will focus on big data and space technologies, two of the 'Eight Great Technologies of the Future'. It will supply business incubation and start-up business support, by exploiting UK ATC and academic instrumentation and big data capabilities for commercial use. Working in partnership with the University of Edinburgh, the Centre will house up to 12 small businesses, as well as academic and PhD posts, to provide PhD students the opportunity to gain entrepreneurial experience as they start their research careers. The final architect's design of the building is shown below. Construction started in January 2016 and the building will be complete in early 2017.

Figure 3.167 Higgs Centre for Innovation (picture credit jmarchitects)

The Higgs Centre is of particular relevance to this study since it will house a suite of dedicated micro/nano-satellite test and development facilities. These have been designed around units of <50cm per side and <50kg (approximately) - and will thus service the component, sub-system, CubeSat / nano-sat, and micro-sat markets. All facilities will be housed within cleanrooms - ranging from Class 10,000 to Class 100 - and all designed with the security/confidentiality requirements of industry in mind. Facilities will include as a minimum: vibration/shaker (including slip table); thermal-vacuum (supplementing the existing range of cryo-vac facilities); and functional-electronic test (including a ‘Nano-Bed CubeSat Mission Development Facility’).

3.45.4 UK ATC View on Facilities

The UK ATC already has excellent facilities for development and test of space instrumentation as evidenced by a number of advanced technology space programmes it has worked on including MIRI and SPIRE; and these facilities will be considerably enhanced by those planned for the Higgs Centre, especially the Nano-Sat test facilities, which are still being finalised, and will continue to be added to after opening. The UK ATC welcomes working with external organisations under suitable commercial arrangements.

3.46 Ulster University, Belfast and Jordanstown

3.46.1 Ulster University Background

Ulster University is Northern Ireland's largest university with over 23,500 students spread over four campuses. Ulster University has a strong track record in research and innovation and Ulster's ability to apply knowledge to solve real-world issues, and support investment and business growth, has garnered global respect and a reputation for world-leading research excellence.

Ulster University has been working with NASA since 2002 across a range of areas including Autonomic Computing, Apoptotic Computing and Autonomous Software Systems research and currently holds 16 joint patents and 100+ publications. The University's space interests are encompassed within the Faculty of Computing and Engineering through its Engineering Research Institute, Computer Science Research Institute, Engineering Composites Research Institute and joint partner's centre, the NI Advanced Composites and the Institute for Fire Safety Engineering Research and Technology Centre.

3.46.2 Faculty of Computing and Engineering

Computer Science Research Institute (CSRI): CSRI was established in 2004 within an institutional strategy to facilitate selectivity in research support. Specific strong capabilities are Intelligent Systems, Smart Environments, Artificial Intelligence and Applications Information and Communications Engineering.

Engineering Research Institute (ERI): ERI has a strong basic research portfolio coupled with applied and clinical related research and has been essential in developing strong capability within the following areas, Sensors and Connected Health, Nanotechnology, Composites and Aerospace Materials, Medical Engineering, Tissue Engineering, Clean Technology.

Engineering Composites Research Centre (ECRE) at Jordanstown: ECRE has been at the forefront of engineering excellence for textile weaving and composites and has attracted significant government and industrial funding for its work on the manufacture and modelling of 3D woven fabrics for structural composites. This work includes modelling and integration of sensing technologies and development of hybrid structures (metallic and thermoplastic yarns). Recent activities have focused on high performance thermoplastic composites, the development and understanding of new advanced preforming processes including 5-axis, Spatially Reinforced Composites (SpaRC) in collaboration with Bombardier and on the reuse of high value carbon fibre and thermoplastic waste streams. ECRE has extensive experience in the fibre preparation and weaving of tailored preforms using carbon, glass, basalt and polymeric fibres (including aramid, UHMWPE) and natural fibres including wool, flax and viscose rayon for the production of 3D woven textile reinforcements for the aerospace, automotive and construction sectors. In order to address the challenges faced by industry, ECRE has been working in a cross-disciplinary manner engaging expertise from textile, engineering and scientific backgrounds. This has allowed novel technologies and products to be developed and adapted to provide robust, cost effective and environmentally sustainable solutions such as addressing waste carbon fibre from the aerospace industry through the design and development of small scale prototypes.

ECRE has also developed significant expertise in the development and processing of high performance thermoplastic composites. This includes novel thermoplastic composite fibres for weaving and stitching and a new area of design and manufacture of high performance materials for additive manufacturing funded by EPSRC. Other interests include the development of smart/functional activity within composites and the integration of microvascular networks into complex composite reinforcements.

Northern Ireland Advanced Composites and Engineering Centre (NIACE) in Belfast: Ulster University (Composites Engineering and Advanced Metal Forming groups) is a joint partner with Queen's University Belfast in the Northern Ireland Advanced Composites and Engineering Centre (NIACE). This industry led, university hosted centre is a technology hub for the research and development of advanced engineering and advanced materials technologies, particularly in the area of advanced composites technologies, across a range of industrial sectors. The Ulster research team is currently working on a range of industry led projects in NIACE including joining of composites, reusable bagging materials, recycling of high performance thermoplastic and thermosetting materials, filament winding, integration of sensing configurations into composite structures and development of low cost tooling.

3.46.3 Ulster University Composites Engineering Facilities

Ulster has a wide range of facilities to support its composites engineering research some of which are outlined below:

Jacquard Controlled Weaving Looms
A series of looms are used to weave designs in both 2D and 3D fabric preforms for advanced composites. The yarns used for space applications could be carbon or ceramic. The looms use single-rapier weft insertion and have variable speed take up motion. This versatile set-up allows the machines to weave many complex designs in carbon fibre. The work completed so far has included the manufacture of net shaped preforms such as T-pieces and I-sections for structural applications. Complex, bespoke, reinforcements are designed and manufactured utilising specialist knowledge and equipment.

Figure 3.168 Jacquard controlled weaving looms

Polymer and Composite testing equipment

Manufacturer: TA Instruments
- Differential Scanning Calorimetry (DSC) DSC Q100
- Thermogravimetric Analysis (TGA/DSC) Q600
- Dynamic Mechanical Analysis (DMA) Q 800
- Dielectric Analysis (DEA) DEA 2970 Dielectric Analyser
- TA instruments AR2000 Rheometer
- DSC is used to measure temperature and heat flow associated with material transitions providing quantitative and qualitative data on endothermic and exothermic processes. Glass transitions, Melting points, Crystallisation, Rate of cure, Degree of cure, Purity, Thermal stability. DSC provides important information that can be used to characterise materials, selection of best materials for specific applications, provides ability to predict product performance, optimisation of processing conditions and to improve quality
- TGA used to characterise thermal decomposition behaviour. Provides information on fibre volume fraction of composites, thermal stability, temperature of on-set of degradation, oxidative degradation and composition of polymer blends
- DMA measures changes in the viscoelastic properties of materials resulting from changes in temperature, frequency, and time. It can be used for measuring glass transition and secondary

transition temperatures, understanding and optimising curing phenomena in thermosets, predicting physical ageing of amorphous materials and correlating impact stability and damping

- DEA Provides valuable information about molecular and rheological behaviour of materials. DEA can characterise molecular relaxations, monitor the flow and cure of resins, and calculate activation energies for molecular relaxations. It is an ultrasensitive technique making it possible to detect transitions which are not seen by other techniques.
- Rheology is the study of what happens to viscosity as measurement conditions change. Viscosity can change dramatically as a function of shear and shear history for polymer solutions. Rheological behaviours are exploited to give products desired characteristics

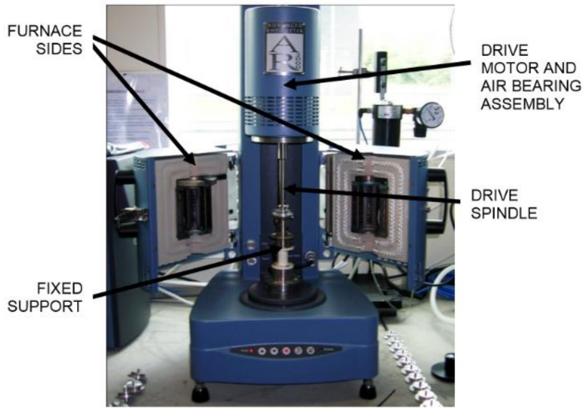


Figure 3.169 Polymer and composite characterisation equipment

Material Testing Equipment
Impact Testing Equipment

- Manufacturer: Instron
- Model Number: Dynatup® 9200 Series image

The Instron Dynatup impact testing machine is designed to measure energy absorption and related impact properties of polymers, metals, composites and resulting final components. It is ideally suited for use in aerospace, automotive, biomedical and specializing in finished product applications.

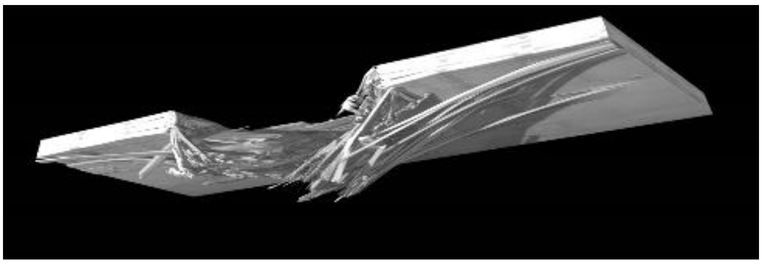


Figure 3.170 Impact testing equipment

Zwick Materials Testing Machine and fibre optic strain measurement
Type: Z100/TL3A with 3D ESPI Strain Measuring System

- Load range: 0 to 100kN

- Materials testing: state-of-the-art instrument with computer aided data acquisition and analysis
- High speed camera: Lake-IDT Y-3 High Speed Camera System, 1280x1024 pixels resolution at up to 2000fps
- Interfaces: USB2 & Gigabit interfaces, 8Gb memory and digital image correlation
- Strain mapping device: LaVision StrainMaster
- Strain measurement: embedded fibre optic strain measurement from Luna Innovations (Fibre Pro 2) and wireless strain sensors from Lord (V-link)

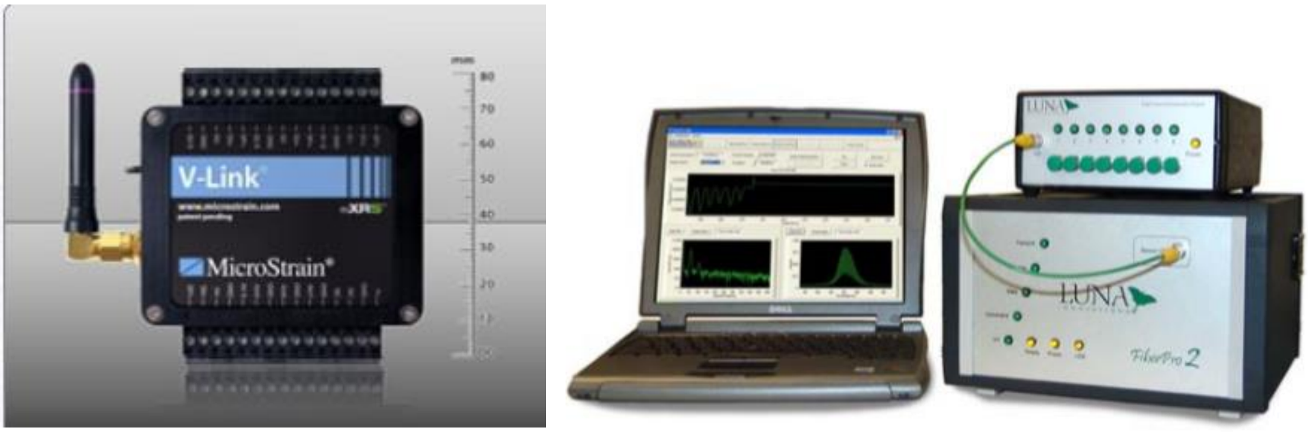


Figure 3.171 Strain mapping and fibre optic strain measurement

Twin Screw Extruder System

554-1148 Rheomex PTW16/25 XL Twin Screw Compounder,16 mm twin screw extruder with an L/D ratio of 25:1 L/D (extendable to 40:1 with the XL barrel extension)

Injection moulding machine

- HAAKE MiniJet injection moulding machine
- Injection pressure: 1,200 bar max
- Cylinder temperature: 400°C max
- Torque Rheometer mixer ThermoElectron Modular Chamber volume 120 cm3, Max. speed 250 min-1, Max. torque 160 Nm, Max. temperature 400 °C

Figure 3.172 Twin screw extruder and MiniJet injection moulding systems

Resin Transfer Moulding System

Composites Integration RTM system
The injection unit consists of a 10 Litre pressure-vessel with a control system and can deliver resins at 3 bar maximum pressure.

Figure 3.173 Resin transfer moulding system

FireSERT Institute for Fire Safety Engineering Research and Technology
FireSERT is a recognised international research centre in the Faculty of Art, Design and Built Environment. Its facilities include: a 600m^2 burn hall; a range of calorimeters including a 10 MW facility for full-scale research; large-scale combination wall and floor furnaces, together with intermediate/small scale furnaces. The Computational Fluid Dynamics (CFD) fire modelling suite complements the experimental facilities thus ensuring that the next generation of CFD models are based on sound scientifically-based experimental research. In addition, a 250m^2 fire dynamics laboratory provides the necessary links between small, intermediate and large-scale work.

Figure 3.174 FireSERT's 20MW 9m x 9m large burn hood and 100 bar water mist system

Single Burning item test: BSEN 13823, measures: flame spread, heat release smoke production and burning droplets

Single Flame source: BS EN ISO 11925-2, evaluates the ignitability and measures burning time and flaming droplets/particles

Figure 3.175 Single Burning Item Test and Single flame source

Cone calorimeters: measure ignition time, HRR and smoke analysis following the BS476 ISO 5660, ASTM E1354, ASTM E1474, ASTM E1740, ASTM F1550, ASTM D6113, CAN ULC 135,ISO 13927 – ISO DIS 17554

Figure 3.176 Cone Calorimeters

Material characterisation: TGA, FTIR, MDSC, GCMS, UNI-FLAME APPRATUS

- Oxygen Index ASTM D 2863, BS ISO 4589-2, NES 714
- Connect TGA or cone calorimeter or with FTIR ISO 19702, ISO 9705, CEN TS 75545-Toxicity test
- Oxygen Index ASTM D 2863, BS ISO 4589-2, NES 714
- Connect TGA or cone calorimeter or with FTIR ISO 19702, ISO 9705, CEN TS 75545-Toxicity test

Figure 3.177 Material Characterisation

Fire Resistance: Fire Resistance applies to individual elements of building construction:

Non-load-bearing and load- bearing: measures integrity, insulation and load-bearing capacity using BS476, EN 1364 and EN 1365

Figure 3.178 Fire Resistance Test

3.46.4 Ulster University View on Facilities

Ulster University offers excellent facilities and capabilities across advanced engineering, advanced materials technologies, composites, fire testing and material characterisation, and computer science. Ulster has considerable experience in working collaboratively with industry and delivering effective innovative solutions.

3.47 University College London, Mullard Space Science Laboratory (MSSL), Guildford

3.47.1 MSSL Background

UCL was one of the first universities in the world to become involved in making scientific observations in space. Since MSSL was established at Holmbury St Mary in 1966, the laboratory has participated in more than 35 satellite missions and over 200 rocket experiments. MSSL has a wide range of facilities on site to support the technology programme within MSSL; these facilities are also available for use by other university groups and commercial companies, either as part of a research collaboration or via a contractual arrangement. The facilities are generally designed to cater for small to medium-sized instruments and to meet ESA, NASA or other space agencies' standards and requirements. In addition to test facilities, MSSL also has cleanrooms providing environmentally controlled areas for space flight hardware assembly, integration and test.

3.47.2 MSSL Clean Rooms

SSL has three clean rooms for assembly, integration and test of flight instrumentation. The largest of these is an ISO Class 8 (Class 100,000) clean room with a high-bay area 10m x 10m x 7m high; and a low-bay area 12m x 15m x 3m high, shown below. The second room is ISO Class 6 (Class 1,000), 12m x 10m and contains most of the vacuum equipment; and the third is ISO Class 5 (Class 100), 15m x 8m, for precision assembly and optics work, also shown below.

Figure 3.179 MSSL ISO-8 high-bay/low-bay clean room (left) and ISO-5 super-clean room (right)

3.47.3 MSSL Vibration Facility

MSSL has a Ling Dynamics V726 vibration facility for flight hardware qualification and acceptance testing, installed in an ISO Class 8 clean room. Facility spec as follows:

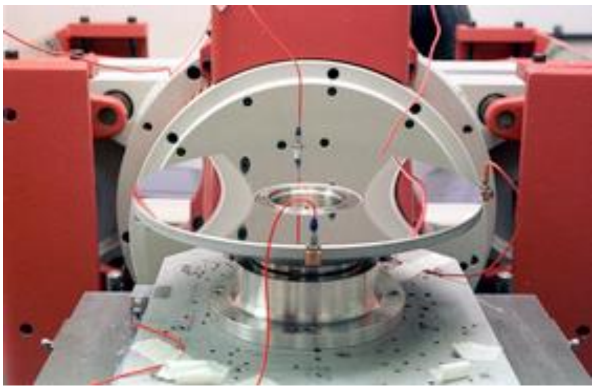


Figure 3.180 MSSL LD V726 vibration facility

- General information

- Max mass: 20 kg
- Max Thrust: 6.58 kN (acting on test specimen and adapter plate)
- Number of channels: 8
- Maximum displacement: 22 mm peak-to-peak
- Maximum velocity: 1.1 m/s
- Maximum acceleration: 90 g unloaded, 70 g for 1 kg test mass
- Controller: M&P VibPilot, capable of vector notching

- Sine Specifications
  - Frequency range: 5 Hz to 4 kHz
  - Sweep: Logarithmic or linear
  - Control modes: Single or multi-channel, average, extremal and notching
  - Max Thrust: 6.58 kN

- Random Specifications
  - Frequency range: 5Hz to 4kHz
  - Control modes: Single or multi-channel, average, extremal and notching
  - Max Thrust: 3.51 kN-rms

3.47.4 MSSL Thermal Vacuum Facilities

MSSL has a number of thermal-vacuum, vacuum-bakeout and cryogenic vacuum facilites used for qualification and acceptance testing of flight hardware, as follows:

Thermal Vacuum Test Facility The TVAC chamber can be configured either as a conventional thermal-vacuum chamber or as a low energy electron calibration chamber, the latter configuration being normally for sole use by MSSL.

The 1m Leybold TVAC chamber is pumped by a combination of a rotary pump, turbo-pump and a helium cryo-pump. The chamber houses a grounded mu-metal shroud, enclosed at both ends when being used as an electron calibration facility. This ensures that the residual magnetic field inside the chamber is less than one tenth of the Earth's magnetic field, producing an electron beam divergence of less than 1^{o} at 1keV. The mu-metal shroud is 0.7m long, 0.6m wide and 0.6m in height.

Figure 3.181 MSSL TVAC chamber

- Dimensions: 1m diameter by 1.1m long
- Electron beam diameter: 110 mm
- Electron beam energies: 30 eV to 20 keV
- Base vacuum pressure: 5 x 10^{-6} mBar
- Temperature range (shroud): -40^{o}C to +80^{o}C
- Temperature range (platen): -140^{o}C to +100^{o}C
- Temperature control: Closed loop PID control, +0.5^{o}C -0.5^{o}C
- Temperature measurement: 4 wire 1/10 DIN PT100 sensors, 8 sensors total
- Temperature/pressure logging: 8 channel plus pressure logging, user set logging interval
- Electrical feedthroughs: Various D-Sub connectors and high voltage connectors

20K cryostat The 20 Kelvin vacuum cryostat is a multi-shroud design, with 5 concentric shrouds, allowing efficient thermal de-coupling of the flight hardware from the external environment. The vacuum cryostat is 0.9m x 0.6m diameter.

- Dimensions: 1m diameter by 1.1m long
- Hardware mounting area: 0.4m diameter by 0.6m height
- Base vacuum pressure: 5×10^{-5} mBar
- Temperature range: 20K to 360K
- Temperature control: Closed loop PID control, ±0.2K
- Temp measurement: Eight Cernox sensors
- Temp/pressure logging: 8 channel plus pressure logging
- Electrical feedthroughs: Various micro-D

Figure 3.182 MSSL 20K vacuum cryostat

77K cryostat The 77K vacuum cryostat is mainly used for testing/ characterisation of flight CCDs. The cryostat consists of an outer stainless steel vacuum vessel with a stainless steel liquid nitrogen vessel mounted inside.

- Dimensions: 0.45m diameter by 0.8m (H).
- Hardware mounting area: 0.4m diameter by 0.6m height
- Base vacuum pressure: 5×10^{-5} mBar
- Temperature range: -150°C to +80°C
- Temperature control: Closed loop PID control, ±0.2°C
- Temperature measurement: 8 x 4 wire PT100 sensors
- Temp/pressure logging: 8 channel plus pressure logging
- Electrical feedthroughs: Various D-sub

Figure 3.183 MSSL 77K cryostat

Vacuum bakeout The bake-out facility comprises a stainless steel oil-free vacuum chamber with radiative and conductive heating elements to ensure even heating of hardware in the vacuum volume, instrumented with a residual gas anayser and TQCM monitor.

- Dimensions: 390 mm (Dia) x 750mm (H)
- Max temperature: 150°C
- Base Vacuum pressure: 5×10^{-7} mBar
- Temperature control accuracy: ± 2°C
- # of temperature sensors: 4 chamber + 2 shroud
- Temperature ramp rate: 0.10 to 5 °C per minute
- Temperature logging: 8 channel plus vacuum pressure
- Turbo pump: Seiko Seiki STP400 MagLev
- Backing pump: Scroll pump
- Vent gas: Zero Grade N2 (0.5 micron filtered)

Figure 3.184 MSSL vacuum bakeout chamber

3.47.5 MSSL View on Facilities

MSSL is generally content that its extensive environmental test and calibration facilities are adequate for its in-house programmes and that there is some spare capacity to support external customers under usual commercial arrangements. When larger test facilities are required for larger instruments it has good access to external facilities such as those at Airbus Portsmouth and at Harwell.

3.48 University of Dundee Space Technology Centre (STC)

3.48.1 University of Dundee and STC Background

The University was part of the University of St Andrews for 70 years before it became an independent institution, the University of Dundee in 1967. It comprises nine multi-disciplinary schools, the School of Computing being of particular interest to this study since it includes the **Space Technology Centre (STC)** in a purpose-designed laboratory and office accommodation which includes an electronic workshop. It has appropriate resources for the development of hardware and software for space applications as well as dedicated PC and Unix workstations and Unix-based servers. The Space Technology Centre conducts internationally leading research into several areas of space technology: spacecraft on-board data-handling, planetary lander technology and satellite data reception. In addition research is also done on system on chip and software development tools. It has had a major influence on the design of spacecraft on-board data-handling and processing systems. Specifically it led the development of the SpaceWire standard for ESA, which has now been widely adopted by the world's space agencies and is being used on many space missions. These SpaceWire developments led to the launch in 2002 of a spin-out company, **STAR-Dundee Ltd**, Section 3.41, to commercialise the group's world-leading SpaceWire technology and experience.

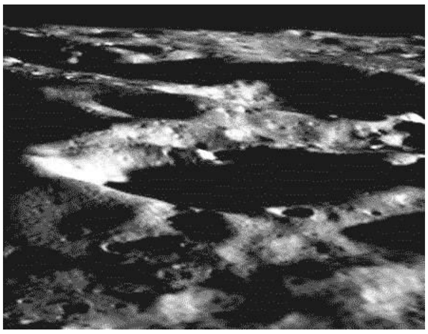
Although it recognises that it is not formally part of the current study, the University would like to point out that it has comprehensive vision-based spacecraft guidance and navigation control systems and an important satellite receiving station as summarised below.

3.48.2 PANGU

The Space Technology Centre at the University of Dundee, has designed and developed an important test facility for work on planetary landers, rovers, in-orbit rendezvous and other space applications where vision-based navigation is used at part of the spacecraft guidance and navigation control system. The result of over 15 years of research, the Planet and Asteroid Natural scene Generation Utility (PANGU) tool is now being used by ESA, European industry and other space agencies and space industry across the world to help test vision-based navigation systems.

PANGU is a tool for modelling the surfaces of planetary bodies such as Mars, the Moon, Mercury and asteroids using real and synthetic data. It is also able to model the form of spacecraft, rovers and other artificial devices. It has the ability to generate camera, LIDAR and RADAR images from any position and orientation to support off-line and closed-loop simulations of planetary landing, surface roving and in-orbit rendezvous operations. PANGU is designed to provide a high degree of realism while operating at near real-time speeds on modern desktop PCs with graphics cards that support OpenGL 2.0 and programmable GPU shaders. As an 'operational' tool, one that has a direct impact on the reliability of the spacecraft it is being used to help develop, PANGU is designed following ESA rules for software development and has undergone extensive verification and validation. The validation activities have involved internationally leading planetary scientist is assessing the terrain produced by the PANGU tool and the realism of the features incorporated in that terrain. PANGU is able to model the lunar surface with high fidelity, covering the complete descent and landing of a probe from 100's of kms away from the landing site to a few metres above before engine cut-out. PANGU is similarly able to model the approach to rotating asteroids. It can be used for surface operations including cooperating rovers and it can be used for in-orbit rendezvous of both cooperating targets and non-cooperating ones, the latter of particular interest for debris removal.

PANGU was developed by the University of Dundee for ESA and is now being used on many ESA studies and development projects aimed at producing precise and robust planetary lander guidance systems.



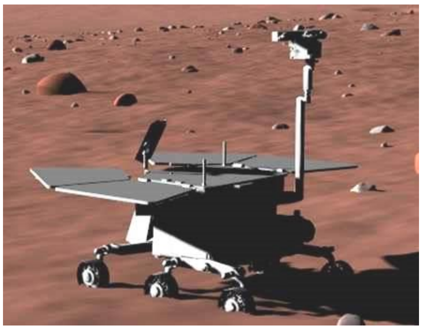
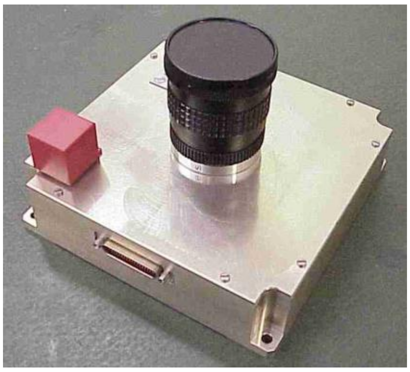


Figure 3.185 The Moon(left), a rover on Mars (middle), and asteroid 25143 Itokawa (right) using PANGU

3.48.3 Image Processing Chips

The STC also has the facilities and capabilities for the design and testing of image processing chips for vision-based navigation. This type of chip is used with a camera on a spacecraft looking at the body on which landing is to take place. The camera provides a stream of images to the image processing chip. The chip identifies notable features in the images and tracks there position in the image from one frame to the next. The movement of the features in the images is combined with information from the spacecraft inertial measurement unit (accelerometers and gyroscopes) to determine relative position of the spacecraft and the body on which it is to land. Dundee has provided image processing designs to ADS-F and –D, TAS-I, and to GMV in Spain as part of their work for ESA on vision-based navigation for planetary landers. The NPAL Camera (Navigation for Planetary Approach and Landing) is shown below.



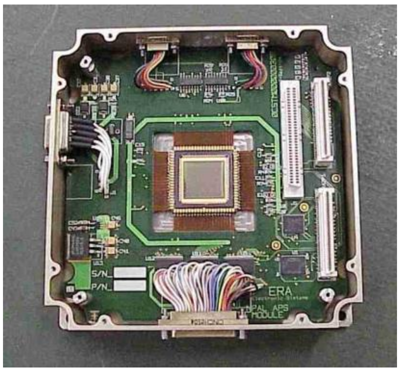


Figure 3.186 Navigation camera incorporating Dundee processing chip (images courtesy Airbus DS)

3.48.4 The Dundee Satellite Receiving Station (DSRS)

The satellite receiving station at the University of Dundee is one of the main stations in the UK receiving data from EO satellites for dissemination to the UK environmental science community. In addition to the core UK research users, other researchers, HEIs, colleges, schools, operational services and the general public around the world also make use of the services. Operational since 1975 and with an extensive archive of EO data collected during this period, DSRS forms part of the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS). Data are currently received from several direct broadcast polar orbiting satellites including the United States NOAA series and Suomi NPP, NASA’s Terra and Aqua, and the European MetOp series, which provide observations of Europe and the North Atlantic region. Geostationary satellite data are also received from Meteosat, GOES and MTSAT satellites, providing users with full global observations. The data are used in a range of applications including meteorology, marine, vegetation, snow/ice, volcano and earthquake related research and monitoring. Support for near-real time requirements is a key activity, e.g. for guidance of research cruise and aircraft field campaigns.

3.48.5 University of Dundee View on Facilities

The University’s Space Technology Centre has particular expertise and facilities to support research and development of on-board data-handling (OBDH) systems, planetary lander technology and EO satellite data reception. It is happy to work with external customers under suitable commercial arrangements.

3.49 University of Kingston

3.49.1 Kingston University Background

Kinston University was created in 1993 and now has around 20,000 students. Academic staff and teaching at the University are divided into five faculties with each faculty offering undergraduate and postgraduate courses, and undertaking research in related areas. The University's space interests are encompassed within the Faculty of Science, Engineering and Computing (SEC) which was formed in 2011 to bring together the interdisciplinary research from eight Schools, encouraging partnerships between academia and commerce.

3.49.2 Kingston Propulsion Facilities

The 'Rocket Lab' within the SEC has hybrid and bi-propellant rocket test facilities for research into rocket engine design and can provide a range of high quality evaluation and data analysis options. Research options include:

- green propellant compatibility testing;
- thermochemical modelling of combustion performance;
- mechanical engine design and finite element modelling;
- and data acquisition, safety analysis and risk assessment.

The facilities include a rocket engine test cell comprising a sound-insulated, blast-protected structure with air exchange ventilation and impact resistant viewports to monitor hot firing tests. A computer link allows for remote operation, data acquisition and automatically sequenced, controlled test firing. Other features include:

- Gaseous and liquefied gas propellant storage - plus cryogenic oxidisers (LOx)
- Electronic measurement of Thrust using FX1901 OEM compression load cell.
- Chamber Pressure measurement up to 400Bar
- Temperature / thermocouples on request, e.g. K-type
- Flow rate measurement using Venturi flow meter.

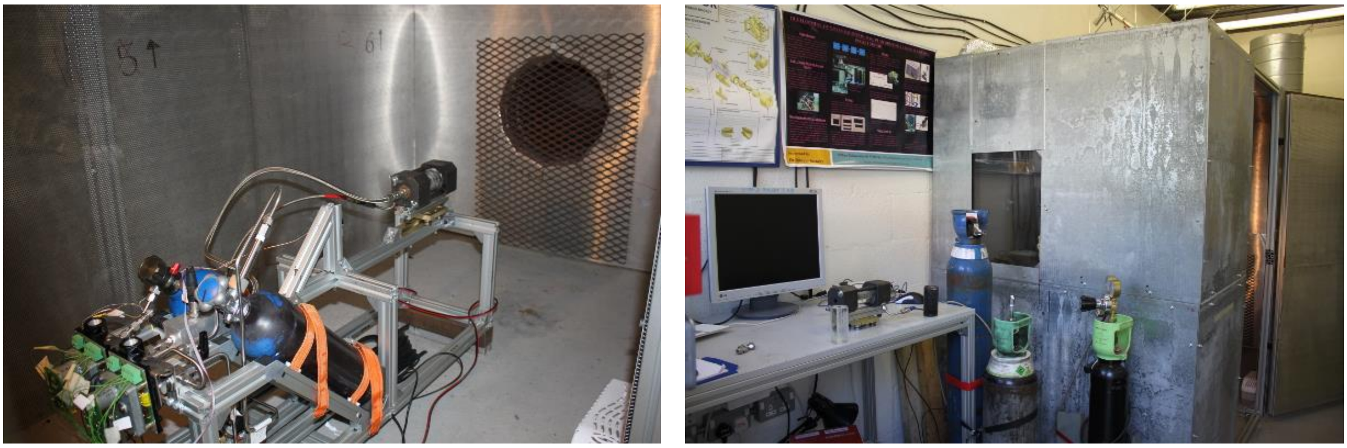


Figure 3.187 Bi-propellant rocket engine in Kingston's rocket test cell and external view of cell

Support facilities include a fully-equipped mechanical workshop, rapid-prototyping machinery, and a range of industry standard software for CAD and Finite Element modelling including Dassault Systems' Solid Works, ANSYS, + FLUENT and CFX. Chemical rocket engines are modelled using GDLPep, Isp and NASA CEA codes.

3.49.3 Kingston View on Facilities

Kingston University has excellent facilities for rocket engine research and is happy to work collaboratively with external academic and commercial users. The Group has well-established access to the Westcott facilities at Moog and Airborne when test requirements exceed the capabilities of its internal facilities.

3.50 University of Leicester Space Research Centre (SRC) and ASDEC

3.50.1 University of Leicester Background

Leicester University is a research-led university founded as Leicestershire and Rutland University College in 1921, when students were first admitted to the college. In 1927 it became University College, Leicester, awarding external degrees for the University of London, before being granted its Royal Charter in 1957, with the status of a full university and the right to award its own degrees. The University is organised into 4 Colleges, one of which, the College of Science and Engineering, includes the Department of Physics and Astronomy, within which most space-related research activities take place.

3.50.2 The Space Research Centre (SRC)

Research scientists at the University of Leicester (UL) have a long and distinguished record of discovery in space science. Every year since 1967 has seen a Leicester-built instrument operating in space. The Space Research Centre (SRC) and its parent Department (Physics and Astronomy) have held significant roles in many space missions for space agencies including NASA, ESA, UKSA, ISRO (India), JAXA (Japan) and CNES (France), covering astronomical, planetary and Earth Observation Science (EOS) missions. The SRC is housed in the Michael Atiyah Building (MAB), which opened in three phases, in 1998, 2003 and 2011. MAB comprises office space, laboratories, cleanrooms and workshops. The SRC has state-of-the-art cleanrooms, laboratories and workshops for integration, testing and qualifying flight and terrestrial instrumentation and a Planetary Laboratory for testing planetary analogue materials. The University is a partner in the EU-H2020-funded 'AHEAD' project ('Integrated Activities in the High Energy Astrophysics Domain', which includes provision of access by the UK scientific community (including SMEs) to test and calibration facilities at sites around Europe via the Leicester link.

3.50.3 SRC Clean Rooms

SRC has four cleanrooms: a large general-purpose 70m^2 ISO-6 (Class 1,000) cleanroom and 3 smaller specialist cleanrooms, each associated with a specific instrumentation-development theme, namely: EOS, planetary science, and X-ray optics.

Figure 3.188 UL large cleanroom, with JWST-MIRI hardware components

3.50.4 SRC Thermal Vacuum Chamber

SRC has a thermal vacuum chamber, dimensions ~600 mm diameter x ~1500 mm length. An inner shroud and cooling system allow for temperatures typically between -40 and +120 C; the temperature ranges depend on the coolant being used.

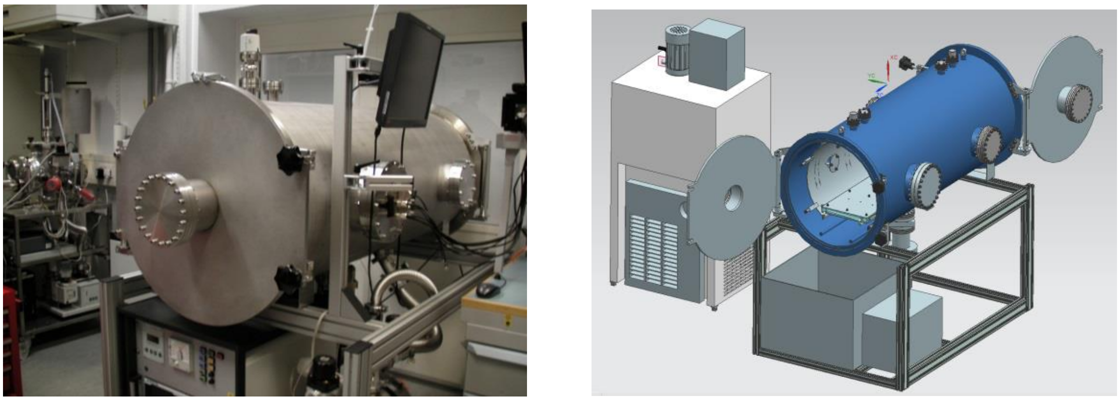


Figure 3.189 UL thermal vacuum chamber

3.50.5 SRC Vacuum Bakeout Chamber

Instrumentation (optics and sensors) and other equipment (mechanical parts, PCBs, mechanisms) to be placed in vacuum – either in on-ground test facilities or during flight in space - often require 'bakeout' prior to vacuum exposure in order to remove potential contaminants such as hydrocarbons and water which could adversely affect the instrument under test or the environment (vacuum test chamber, spacecraft platform). The UL Vacuum Bakeout Chamber (VBC) is sited within a clean (ISO 6), AIV area in the SRC, adjoining and with direct access to the large cleanroom, permitting appropriate handling of contamination-sensitive equipment. The chamber has a capacity of ~0.6 m^3 (0.8 m diam x 1.2 m length), and is equipped with two jacket heaters, a rotary-pump-backed turbo-molecular pump, a Faraday mass spectrometer for residual gas analysis (RGA), a Temperature-controlled Quartz Crystal Microbalance (TQCM), vacuum gauges, feedthroughs for temperature-control instrumentation and a gaseous nitrogen back-fill system for clean return to ambient pressure. The heater system can achieve a maximum chamber temperature of +125°C, and uses feedback from two PRTs to control the temperature of the baked items. A further 'watchdog' PRT is linked to a separate automatic heater shutdown to provide additional protection against exceeding temperature limits. The VBC has been used to date for bakeout to ESA/NASA standards, for several astrophysics and planetary space missions, including cases with sensitive optical surfaces, instances where the temperature limit had to be closely monitored and safeguarded, and contracted work for international partner organisations in Europe.

Figure 3.190 UL Vacuum Bakeout Chamber

3.50.6 Leicester Long Beam-line Test Facility, LLBTF

The Leicester Long Beam-line Test Facility (LLBTF) is a (nominally) 27.5m-length vacuum beam-line with an X-ray source enclosure at one end and an experimental chamber at the other. The experimental chamber opens into an ISO-6 (class 1,000) clean room to allow samples to be loaded and unloaded in a clean environment. The X-ray source chamber is pumped by a turbo-molecular pump and normally achieves pressures ~5×10^{-7} mbar. The source can be isolated from the beam-line so that either part can be vented independently. A number of different sources can be used: *(1)* low-voltage electron-bombardment source with Cu anode (various characteristic X-ray lines can be generated by coating the anode with other materials; maximum anode voltage approx 8kV); *(2)* 50kV 1mA sealed tubes with Mo target and Be window; *(3)* 100kV 3kW Philips tubes with Tungsten and Scandium anodes; *(4)* Deuterium lamp and monochromator. Included in the chamber is a filter wheel for provision of transmission filters and or collimating apertures. A range of standard filters is available for C-K, Cu-L, Al-K and Si-K. Other energies can be produced. The Philips tube can also be configured to bombard a target to produce fluorescence X-rays. The X-ray sources use thin-film transmission filters only; no X-ray monochromator is available. The use of the 50kV or 100kV tubes needs to give due consideration to radiation safety at the experiment and must be discussed with ULEIC staff.

The beam-line has an experimental chamber located at the mid-way point, with a high-precision linear drive station (Newport M-MTM200PE.1V6 200mm travel 0.1µm resolution). This equipment is not integrated with the system control software. Four other (non-instrumented) access ports are available between the centre point and the experimental chamber, for user-provided equipment. The experimental tank consists of a main chamber which is 1.25m in diameter and 1.5m long. In addition there is a permanently attached extension chamber which is approximately 0.76m diameter by 0.7m long. The tank utilises a cryogenic pump and roughed out using a roots/rotary pump combination. The tank base pressure is < 2×10^{-6} mbar. Mounting and connection of the cryo pump are configured so as to avoid transfer of vibration to the chamber. All adjustments can be made while the system is under vacuum and operational using UHV-compatible vacuum stepper motors. The system is designed to uniformly illuminate optics up to 210mm diameter. A PN diode beam monitor allows the spatial and spectral variability of the beam to be mapped. The turret assembly is a high precision rotation stage which allows the item under test to be rotated in ψ and ϕ. Nominal stability and repeatability of the rotation is better than 10 arc seconds. The system is also set up to rotate up to six samples into the beam one after the other by rotating a sample carrier about the X-ray beam (θ). The turret can be rotated through 180 degrees to allow easy loading of samples and can be used in the forward position or in the back position facing the detector. The nominal mounting area for items on the turret is 208mm (h) by 250mm (v), however it may be possible to accommodate larger items. The maximum mass that can be accommodated on the turret is about 5kg. The system includes a large active area, 90mm × 90mm, imaging MCP detector which is mounted on a three-axis movement. A set of IDL-based, image acquisition and control programs is used to adjust the position of the detector, turret and beam monitor and acquire image data from the detector. The system allows manual control but is also designed to automatically take multiple data sets under computer control. Image data from the MCP detector can be provided as either event lists or as linearised images. Normal control of the system is from a laboratory area outside the clean room. The test facility can acquire data 24 hours-a-day under computer control. All measurement sequences are set up from the laboratory area.

The long beam-line test facility is located in the basement of the Physics and Astronomy Building at the University of Leicester. The facility has been substantially refurbished over the last 10 years but has been in use since the mid-1970s and has been used to calibrate detectors and optics for numerous space missions, as well as supporting laboratory programmes in advanced X-ray optics.

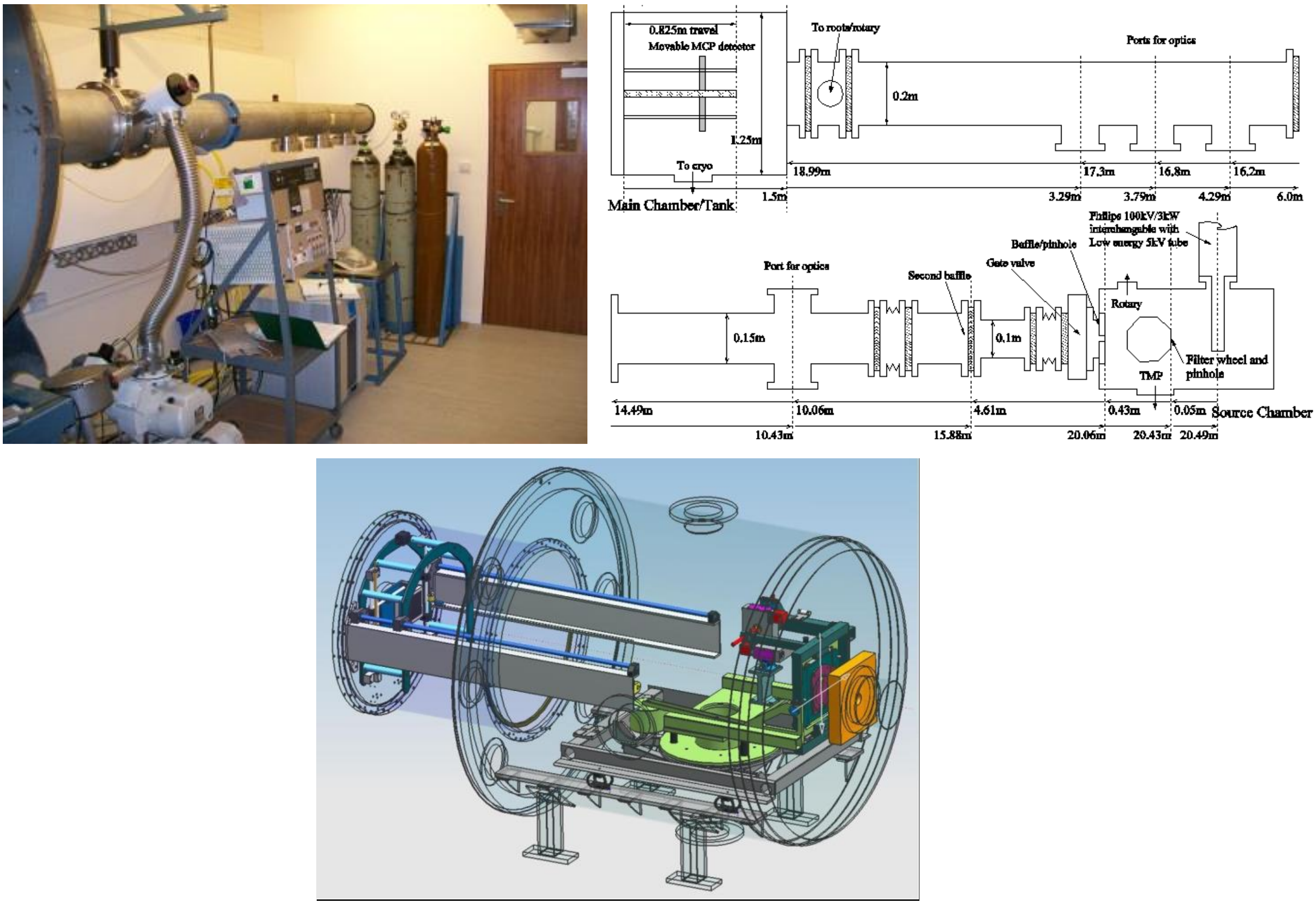


Figure 3.191 LLBTF showing (C-W from left) access points, schematic, and experimental chamber CAD model

3.50.7 Martian Environment Simulator

An ultra-clean thermal vacuum facility located within the SRC is used to support very cold testing of planetary instrumentation. The Mars Environmental Simulator, MES, originally developed for Beagle 2, is used for ultra-cold testing of flight parts. The MES is designed specifically for simulating the temperature and 6mBar atmospheric conditions of Mars but can be used to replicate other hostile environments. A Sterrad NX-100 H2O2 sterilisation chamber is available, along with DHMR and CO2 snow cleaning and supported with 3M PetriFilm swab verification and ATP surface monitoring. The MES dimensions are ~300 mm diameter x ~550 mm length.

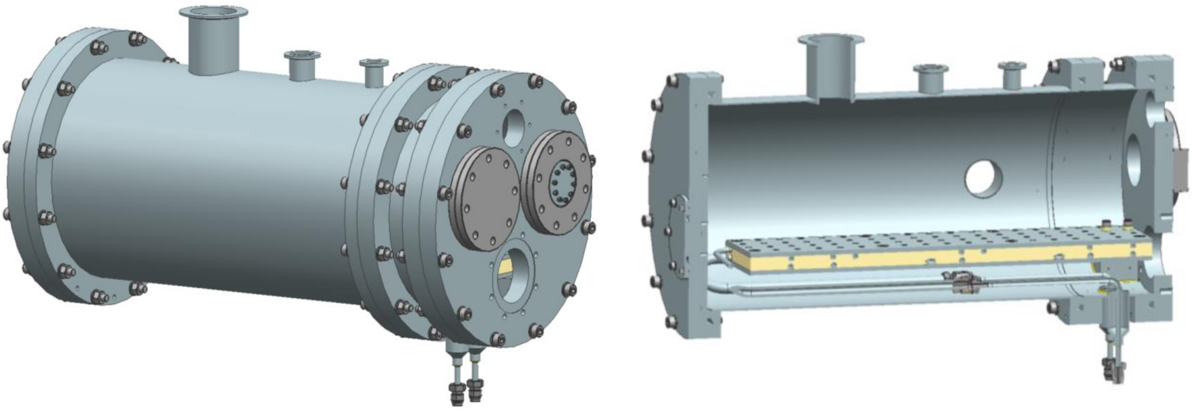


Figure 3.192 UL Martian Environment Simulator (MES)

3.50.8 Other Facilities

The University also has a variety of additional test and calibration facilities, including: vacuum X-ray test and calibration chambers and environmental test cabinets, and related CAD and mission-analysis software systems, as well as the new ASDEC facility described below.

3.50.9 ASDEC (Advanced Structural Dynamic Evaluation Centre)

The ASDEC (Advanced Structural Dynamic Evaluation Centre) facility was set up by the University of Leicester in 2014, with additional support provided by the EU and the Regional Growth Fund. It is situated at MIRA Technology Park in Nuneaton. It is the UK's first commercial 3D laser measurement to a new level. ASDEC uses the Polytec Robovib 3D scanning Laser Doppler Vibrometer acquisition system and Siemens LMS Test.Lab and Virtual.Lab advanced processing and analysis systems; and provides engineers with the first major shift in detailed dynamics understanding since multi-channel data acquisition systems became commonplace in the early 1990s. ASDEC's engineers can provide experimental modal analyses by measuring thousands of data points using its laser vibrometer system in the same time that traditional accelerometer-based methods can only measure in tens. In addition, the non-contact measurement technique removes any observer effect which in turn leads to better quality results giving significantly greater insight into designs. As a final step ASDEC correlates FE and CAE models using this highly accurate experimental data. These correlated models allow simulation teams to have greater confidence in their results which reduces development costs. ASDEC can bring its portable system to test sites across Europe and measurements can be made from a distance and through glass to be able to work on objects in clean room environments. Use in understanding space structures, instruments and dynamics of mechanisms are some of the areas ASDEC is targeting and is working closely with the Space Research Centre on such possible uses.

3.50.10 SRC View on Facilities

The SRC is generally content that its environmental test facilities are adequate for its in-house programmes, with the exception of EMC and space vibration test facilities. Its facilities have a transient loading and are in principle available for use by external customers - the University has demonstrated experience in accommodating external work, with appropriate planning. When larger test facilities are required for larger instruments, SRC has good access to external facilities such as those at Airbus and Harwell.

3.51 University of Oxford, Department of Physics

3.51.1 University of Oxford Background

The University of Oxford is a collegiate research university with evidence of teaching as far back as 1096, making it the oldest university in the English-speaking world. The university is made up of a variety of institutions, including 38 constituent colleges and a full range of academic departments. Its space activities, the subject of this report, are concentrated in the sub-Department of Atmospheric, Oceanic and Planetary Physics, which has been developing space instruments since the 1970s, with a broad spectrum of design and manufacturing skills including:

- Mechanical design including facilities for CAD and CAM
- Thermal design
- Focal plane and calibration target design and manufacture
- Product assurance
- Planetary protection requirements for planetary missions
- Flight electronics manufacture including flight flexible cabling based on etched circuits produced in the Department's Photo-fabrication Unit

The pre-flight calibration of multiple instruments has been carried out in chambers in the Department's clean areas which include facilities for thermal vacuum, vibration and shock testing.

3.51.2 University of Oxford's Clean Rooms

The Department has a clean assembly area that is routinely qualified to Class 1000 and utilises both horizontal and vertical air flows to maintain room cleanliness. One end of the cleanroom is given over to a wall-to-wall laminar flow bench qualified to Class 100. The room is swept by the air passing through the HEPA filters of the flow bench, while ceiling-mounted HEPA filter/fan units provide additional protection to test facilities located in the four equipment bays. The long laminar flow bench provides a large and convenient work area for the integration of space hardware and cable assemblies, with all movement of personnel occurring downstream from the work activity.

Figure 3.193 Oxford's Clean Assembly Area and Laminar Flow Bench

3.51.3 University of Oxford Vibration Facility

The Department's vibration facility comprises an integrated 16kN Ling Dynamics shaker and slip table housed in a Class 10,000 clean room. The shaker was used to qualify a number of HIRDLS subsystems and components such as the gyro electronics unit shown below and more recently: fibre assemblies for LISA-Pathfinder; the Compact Modular Sounder, CMS, for TDS-1; and numerous tests of the SEIS-SP development and flight models. While the facility can be operated under contract for the benefit of external users, the vibrator is generally viewed as an 'in-house' design and test tool.

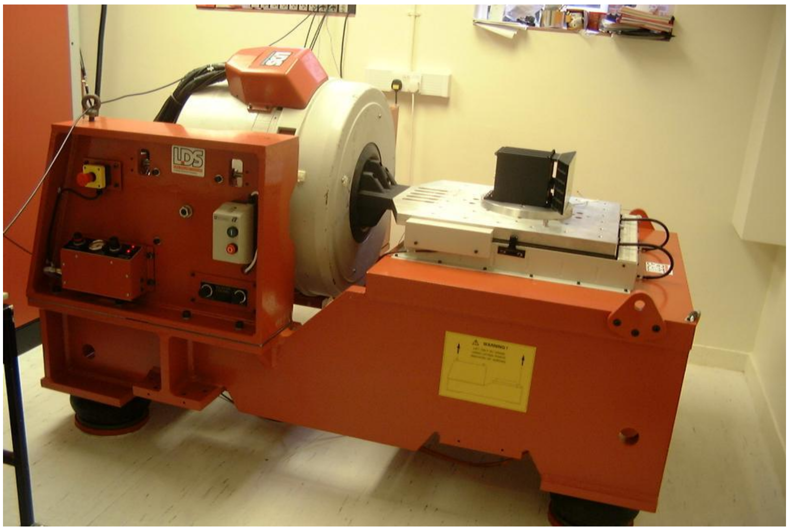


Figure 3.194 Oxford's 16kN LDS vibration facility

3.51.4 University of Oxford Thermal Vacuum Facilities

The Department has a number vacuum chambers in clean rooms which are available to external users subject to appropriate agreements and planning.

Cold Optics Chamber (COC): located in a Class 1,000 clean room, the COC comprises a cylindrical, 1m diameter stainless steel vacuum vessel orientated vertically (centreline along the g-vector) divided into two parts. The lower, smaller end-cap section is fixed to the chamber support frame whilst the upper cylindrical section may be raised or lowered using a mechanical hoist. The hoist has been designed to permit rotation about its centreline so that the top chamber section may be swung away from the centre-line of the lower section. This arrangement provides good access to the interior of the chamber whilst ensuring efficient use of the available working volume. Concentric tripods, comprising low thermal conductivity struts, support three concentric aluminium interface plates. The middle annular and the central circular interface plates are connected to the first and second stages of the cold head via flexible copper cooling straps. An outer annular interface plate completes the COC's 'optical bench assembly' with multiple tapped holes providing a convenient and versatile method of mounting test equipment to the 15 K (circular inner), 70 K (annular middle) and room temperature (annular outer) temperature zones of the assembly.

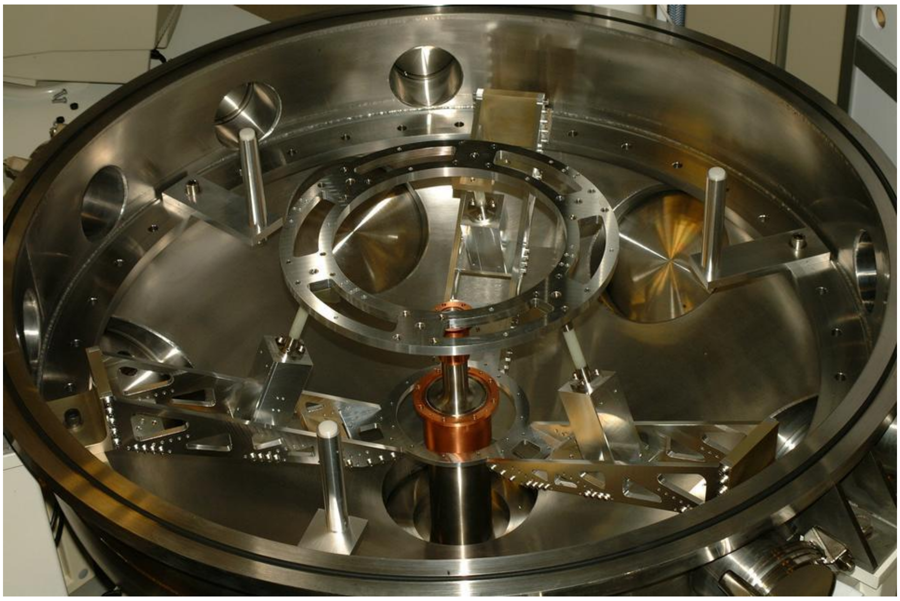


Figure 3.195 Oxford's Cold Optics Chamber

2.2m Calibration Facility: located in a Class 100 clean room, the 2.2m calibration facility was originally built for the test and calibration of the HIRDLS instrument, which required a low vibration environment, achieved by coupling the chamber's optical bench to a seismic mass under the chamber, isolated from the chamber body (i.e. similar to the RAL Space 5 m chamber, see section 3.35.6). The 2.2m chamber is shown below, with a schematic illustrating its vibration isolation.

Figure 3.196 Oxford's 2.2m low-vibration TVAC chamber

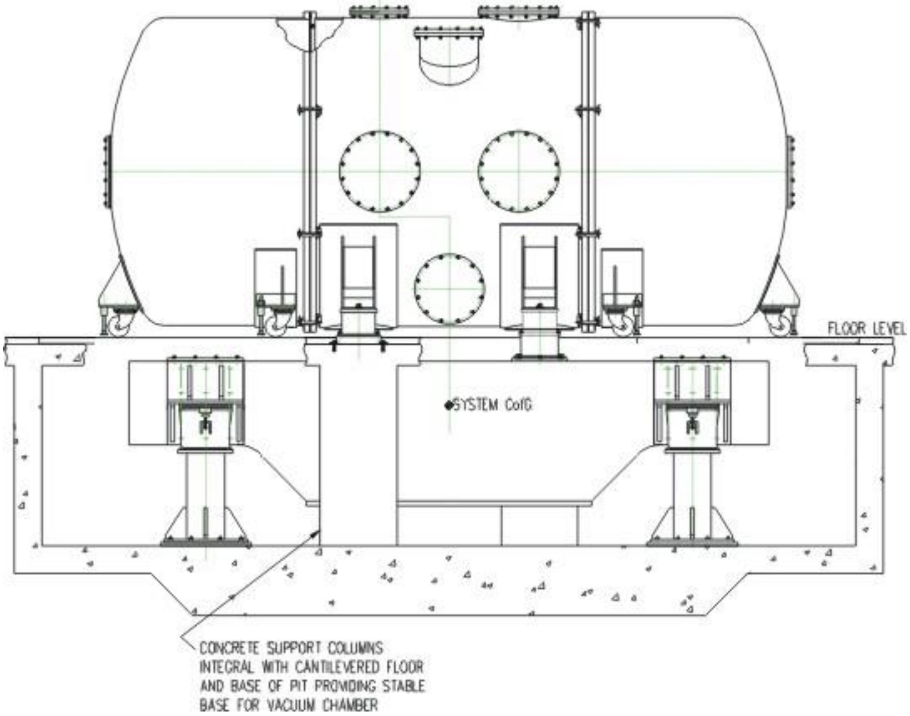


Figure 3.197 Schematic of 2.2m chamber showing vibration isolation

3.51.5 University of Oxford View on Facilities

The Department is generally content that its environmental test facilities are adequate for its in-house programmes. The facilities are available for use by external customers, subject to appropriate planning and commercial terms. When larger test facilities are required for larger instruments, the University has good access to external facilities such as those at Airbus and Harwell.

3.52 University of Southampton – Astronautics Group

3.52.1 University of Southampton Background

The University of Southampton began life in 1862 as the Hartley Institution, became a University College in 1902 with degrees awarded by the University of London and then was granted a Royal Charter to become the University of Southampton in 1952. It is now ranked among the top one per cent of universities in the World and is a founding member of the prestigious Russell Group, which brings together the knowledge and resources of 24 top UK universities who work together to protect and improve the quality of university teaching**,** support and facilitate innovative research projects**,** and build stronger links with business leaders and policy makers.

The University has around 24,000 students, of whom 8,000 are post-graduates, and comprises eight faculties, two of which are involved in space propulsion:

- the *Faculty of Engineering and the Environment (FEE)*, which incorporates the **Astronautics Group**, which has interests in space systems engineering and both electric and chemical propulsion; and
- the *Faculty of Physical Sciences and Engineering*, one of whose academic units is Electronics and Computer Science (ECS) which incorporates the **Plasma and Space Science Group**, with a strong interest in electric propulsion.

The Astronautics Group and the Plasma and Space Science Group are physically separated and do not work together and have their own interests, research areas and customer bases. Because of this they have requested that they should be treated as different organisations and have been given separate sections in this Report. This section concerns the Astronautics Group.

3.52.2 Astronautics Group Interests

The Astronautics Group's areas of research include: electric propulsion and plasma diagnostics; chemical propulsion; additive manufacturing; materials science and spacecraft systems engineering and design. The group also teaches the MEng Aeronautics and Astronautics degree programmes as well as a Space Systems Engineering Course for Industry. In order to support these activities, the Astronautics Group has a number of space environmental test facilities, including: the David Fearn Electric Propulsion Laboratory; the Thermal Vacuum Test Facility; the Graham Roberts Jet Propulsion Laboratory; the Engineering Manufacturing and Design Centre; and the ISVR acoustics group, which is described in Section 3.23 above.

3.52.3 Astronautics Group Electric Propulsion and Thermal Vacuum Facilities

The David Fearn Electric Propulsion Laboratory is a state-of-the-art electric propulsion and space systems testing laboratory and is used in the qualification of ESA EP projects. The thruster test facility consists of two chambers separated by a large pneumatic gate valve. This design allows the loading chamber to be accessed independently of the main chamber at high-vacuum, allowing for rapid fault finding and turnaround. The test chamber is also equipped with a tempered beam target and a heated shell comprising steel liner sheets. The loading chamber is equipped with a thermal shroud for thermal cycling and qualification. Three viewports are installed around the plant, one in the loading chamber and two in the test chamber.

Figure 3.198 Thermal Vacuum Facility within the David Fearn EP Laboratory

The vacuum chamber has the following characteristics:

- Dimensions: 2m x 4.5m main chamber and swing door with an isolatable (50cm gate valve) 0.75 x 1m loading chamber and swing door
- Two Coolpower 140T cryo compressors and two Coolpack 6000H 20K cold heads
- One Oerlikon Leybold MAG W 700 iP and two MAG W 2200 iP magnetically levitated turbopumps
- One Edwards XDS 35i and one Oerlikon Leybold LV140C roughing pump
- Interstage pumping between all main flanges and doors assure low leakage rates with double O-ring gasket system achieving ultimate vacuum of <$9x10^{-8}$mbar
- Graphite chevron closed loop water cooled target and 30kW chiller unit for high energy ion beams
- Tempering unit for (100°C) heating for accelerated outgassing of target
- Heated (8kW) stainless steel sacrificial liner for accelerated outgassing
- Transfer system to move a thruster from the loading chamber out into the main chamber and onto the centerline of the diagnostics arm
- 4 Pirani cold heads covering $5x10^{-9}$ mbar to 1000 mbar
- The loading chamber is equipped with a temperature controllable inner shell with LN2 and IR emitters for ESA qualification compliant thermal cycling and qualification

For diagnostics:

- Hemispherical beam probe arm and diagnostics set for plume measurements, beam characterization, ion energy and thrust vector analysis
- Pfeiffer Vacuum GmbH, model QMG 220 F2 residual gas analyzer and mass spectrometer with Quadera software
- Mettler Toledo high accuracy thrust balance for 0-500mN thrust measurement

Vacuum performance is as follows:

- Ultimate vacuum of <$9x10^{-8}$mbar with operation <$5.0x10^{-5}$ mbar with 28sccm xenon (~2.8mg/s) (full spectrum available on request)

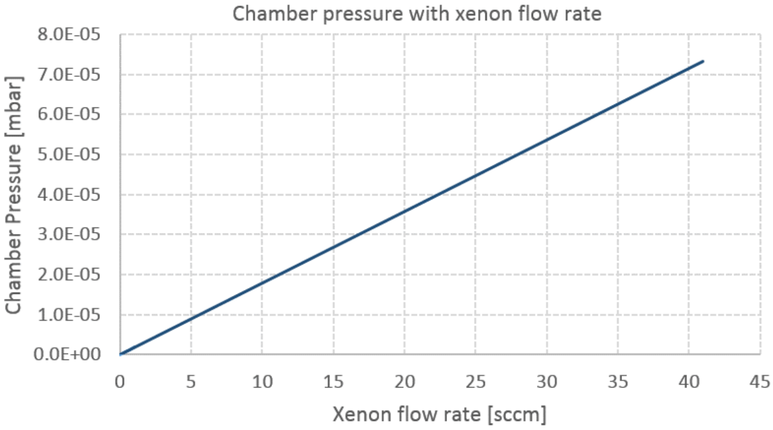


Figure 3.199 Chamber base pressure with active flow rate of xenon

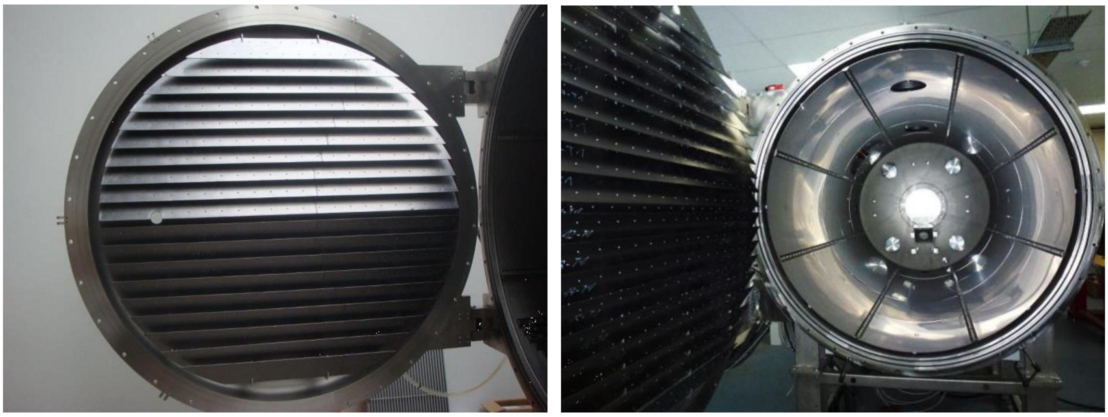


Figure 3.200 Graphite chevron target and swing door (left) and main 2m x 4.5m chamber (right)

Figure 3.201 Loading chamber with traversing carriage (left) and high power chiller (right)

3.52.4 Astronautics Group (FEE) Chemical Propulsion Facility

The Propulsion Group designs and builds chemical propulsion rocket engines, supersonic ramjet engines, and the Lab has a reinforced chemical propulsion test cell equipped with an propellant flow control systems and rocket exhaust system that can test motors up to ~100 N. Large blast windows are currently being installed along with advanced sound proofing.

Figure 3.202 One of 4 test cells in the Graham Roberts Jet Propulsion Lab

3.52.5 Astronautics Group Vibration Qualification Facility

The Astronautics Group Propulsion Lab has a vibration facility, shown below, for mechanical testing and qualifying its propulsion components and subsystems. The facility may be used by external users subject to availability and standard commercial terms.

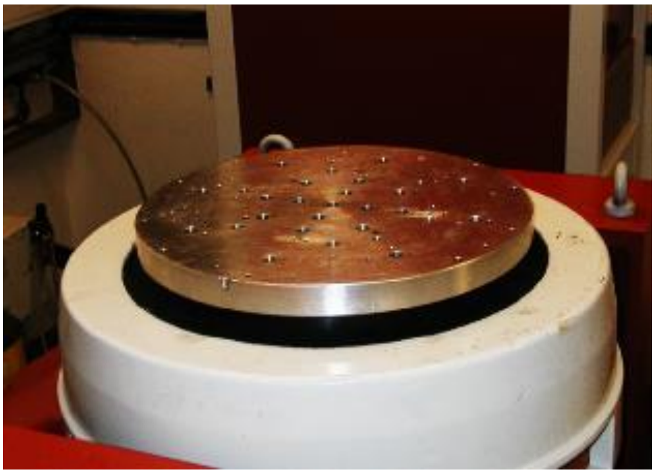


Figure 3.203 Vibration shaker in horizontal (left) and vertical configuration (right)

- Type: LDS Model 830-335T; max force sine and random 9800N, peak 29400N; max acceleration 60grms random and 75g sine peak; frequency range 0 – 3000Hz
- Controller: LaserUSB™ Laser Vibration Controller (swept sine, random, shock classic and SRS resonance search and dwell); 4 Analogue Input Channels each with ICP sensor power, 24-bit
- Data Acquisition System: 16-channel, 24-bit (2 cards: NI-4472BPCI, Vibration-Optimized DSA); Smart Office (m+p international) software; real-time (and post-) data processing; analyser DSA Pro + Smart Office Modal
- Analysis package: 8-channels NI 4472 Series, PCI-4474; 24-bit resolution, 110dB dynamic range, with LabVIEW software
- Combo Shaker and Slip-table: LDS Model LPT600-V830-335T Combo base slip-table magnesium slip plate with 600mm by 600mm working surface with grid of M8 inserts; max payload 500kg
- Power Amplifier: LDS Model SPA10K air-cooled class D 10KVA power amp including DC power supply for vibrator field and degauss coil

3.52.6 Astronautics Group Engineering Design and Manufacturing Centre (EDMC)

The EDMC services the Astronautics Group and contains a full suite of advanced manufacturing machine shop capabilities including 6-axis CNC, CMM, Electro-Discharge Machining (EDM) and Selective Laser Melting (SLM) machines.

3.52.7 Astronautics Group µ-VIS X-Ray Imaging Centre

The University of Southampton has invested over £3M in µ-VIS high resolution X-Ray computed tomography (CT) facilities. The facility, which was launched in 2011, offers state-of-the-art equipment and draws on the expertise of over 40 academic staff from across the University. The center specifically aims to provide a holistic approach to advanced 3D imaging, supporting all steps between original domain problem/query, through to verified, publishable conclusions.

In combination with the µ-Vis facility, the David Fearn EP Laboratory can also cater for non-destructive testing via high resolution X-ray computed tomography for advanced 3D imaging (up to 200nm resolution). This has been used for manufacturing analysis, assembly analysis, defect analysis, FE model generation. It can also cater for Scanning Electron Microscopes analysis for high resolution imaging and profilometery for surface roughness characterisation.

Figure 3.204 µ-VIS X-Ray Imaging Centre

3.52.8 Astronautics Group View on Facilities

The Astronautics Group has excellent facilities to support its space systems engineering activities and its in-house research interests and developments in both electric and chemical propulsion. The Group is happy to collaborate with external users subject to availability of resources and normal commercial arrangements.

3.53 University of Southampton – Plasma and Space Science Group

3.53.1 Plasma and Space Science Group Background and Interests

As explained in the previous section, the University has eight faculties, two of which are involved in space propulsion:

- the *Faculty of Physical Sciences and Engineering*, one of whose academic units is Electronics and Computer Science (ECS) incorporating the Electronics and Engineering Group with its Tony Davis High Voltage Lab, one of whose research groups is the **Plasma and Space Science Group**, with a strong interest in electric propulsion; and
- the *Faculty of Engineering and the Environment (FEE)*, which incorporates the **Astronautics Group** and which has interests in space systems engineering and both electric and chemical propulsion.

The Plasma and Space Science and Astronautics Groups are effectively independent organisations and have been given separate sections in this Report. This section concerns the Plasma and Space Science Group.

In the field of electric propulsion the Plasma and Space Science group has interests in:

- gridded ion engines, collaborating closely with QinetiQ, Section 3.33 above;
- PPTs (pulsed plasma thrusters), working with the University spin-off company Mars Space Ltd, Section 3.26 above;
- HCTs (hollow cathode thrusters) being developed under ESA funding;
- advanced 3-gridded ion engines (previously funded by an FP7 project, HiPER); and
- heaterless hollow cathodes.

3.53.2 Plasma and Space Science Group EP Facilities

The Plasma and Space Science group has a number of vacuum facilities for electric propulsion thruster testing, capable of producing the necessary high vacuum present in space. In addition, the group has two instruments used to evaluate PPT performance: a precision thrust balance to measure the impulse bit of pulsed thrusters and a sensitive mass balance which can be used to measure the mass bit. The Group's research is focussed on two sizes of PPTs, one for CubeSats and the other for NanoSats. For the CubeSat PPT, research is being conducted on how to optimise performance whilst still achieving the long lifetimes needed (more than one million pulses) with particular emphasis on the spark plugs needed for the discharge initiation. The HCT being developed under ESA funding has applications for large communications satellites for east/west station-keeping and for attitude control, leading to the so-called all-electric spacecraft. A model capable of predicting thrust from first principles is being developed in order to optimise the design and meet a specific set of requirements in terms of power, thrust and specific impulse. An optimised thruster will be designed, manufactured and tested. In order to measure the thrust directly, a new thrust balance is being designed and built. Research on the fundamental aspects of hollow cathodes and HCTs has been ongoing for some 20 years and is internationally recognised.

In order to support these developments, the Plasma and Space Science Group has 3 EP test facilities of varying sizes, as shown in the following photographs.

The smallest EP chamber is spherical and allows testing of hollow cathodes for fundamental investigations and advanced diagnostics including time and space resolved spectroscopy. The vertical chamber can be used for devices that do not require high mass flow rates such as PPTs or hollow cathodes and hollow cathode thrusters.

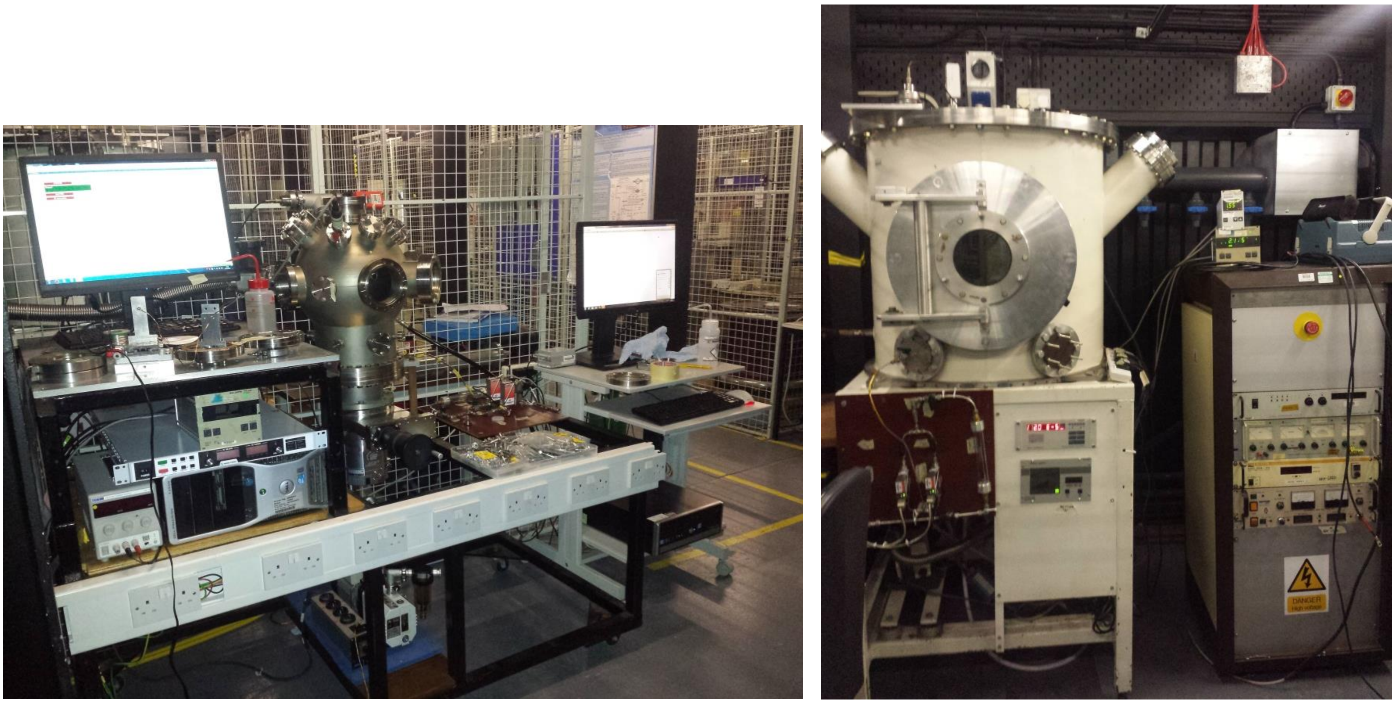


Figure 3.205 ECS spherical chamber for HC testing and vertical chamber for PPTs and HCTs

A larger chamber for the development of high power cathodes is shown during installation in the photos below. It is being upgraded by the addition of two 4500L/s maglev turbomolecular pumps, allowing high power, high current hollow cathodes to be tested(>50A) whilst maintaining low pressures of the order of 5 e-5 mbar. It will be used in a collaborative project for the development of high power cathodes with the Japanese Space Agency, JAXA.

Figure 3.206 ECS large chamber for high power cathode development

Another facility lies in the availability software called FFX (developed by Cody Farnell at Colorado State University) for the simulation of the erosion of the grids of GIEs. This type of software is state-of-the-art in that it allows 3-dimensional simulation which is essential for accurate lifetime predictions of GIEs.

3.53.3 Plasma and Space Science Group View on Facilities

The Plasma and Space Science Group has excellent facilities to support its in-house research interests and developments in electric propulsion. It is happy to collaborate with external users subject to availability of resources and normal commercial arrangements, as evidenced by its existing contracts with Mars Space, QinetiQ, ESA and the EU.

3.54 University of Strathclyde

3.54.1 University of Strathclyde Background

The University of Strathclyde in Glasgow was founded in 1796 as the Andersonian Institute, before receiving its Royal Charter in 1964 as the UK's first technological university. It is comprised of four main faculties, sub-divided into departments which deal with specific academic and research areas. The Department of Mechanical and Aerospace Engineering within the Faculty of Engineering and the Department of Physics (ranked UK's No 1 Physics Dept in REF 2014 [Research Excellence Framework]) within the Faculty of Science are the main departments engaged in space activities. Strength in space research and technology spans a broad range of programmes delivered through the **Strathclyde Space Institute** which is a multi-disciplinary venture addressing key challenges in space systems engineering, space robotics, satellite applications and access to space. The institute comprises: the Advanced Space Concepts Laboratory; the Centre for Future Air-Space Transport Technology; the Space Mechatronic Systems Technology Laboratory (SMeSTech); and the Centre for Space Science and Applications. Its space-related facilities include a Mission Laboratory, a Concurrent and Collaborative Design Studio, SMeSTech, and SCAPA, a multi-species radiation testing facility that is a potential game-changer for testing radiation detectors, components and subsystems in a realistic space radiation environment.

3.54.2 Strathclyde Concurrent and Collaborative Design Studio (CCDS)

The Advanced Space Concepts Lab includes a Concurrent and Collaborative Design Studio (CCDS) to develop rapid assessments and virtual prototyping of new space missions and concepts. Furthermore, the CCDS is a unique research facility to develop and experiment with new approaches and paradigms for the design and evaluation of complex engineering systems. The CCDS builds on the concurrent design approach currently used in the Concurrent Design Facility at ESA/ESTEC and at Harwell.

The CCDS implements a suite of computational toolboxes, databases and software, including a Space Systems Toolbox, an Optimisation Toolbox, and an Uncertainty Quantification Toolbox, all part of the larger collection known as the Strathclyde Mechanical and Aerospace Engineering Toolbox (SMART). This suite allows the designer to perform robust design optimisation, to design for reliability and to build resilience into complex systems. The development of these tools and methods is supported by the European Space Agency and the H2020 framework programme.

3.54.3 Strathclyde Mission Laboratory

The Advanced Space Concepts Lab is also home to one of the facilities sponsored by the Space Application Catapult: a Mission Laboratory with a Nano-bed CubeSat Mission Development Facility, enabling access to flight-like hardware for satellite technology providers, similar to the one on the Harwell site. This is the first Mission Lab to be implemented away from the Catapult site. It is the first step in the planned deployment of a national network of Mission Lab facilities planned by the Catapult. The Catapult is aiming to develop a small satellite supply chain in the UK and the Strathclyde Lab will provide easier geographic access to technology providers in the northern part of the UK. The Lab is expected to be used extensively by the Nano-bed manufacturer, ClydeSpace.

3.54.4 Strathclyde Space Mechatronic Systems Technology Laboratory (SMeSTech)

Although it is recognised that autonomous systems and robotics are not formally included in the current study, the Institute would like to summarise the capabilities of its Space Mechatronic Systems Technology Laboratory (SMeSTech). The Mechatronics Lab boasts three dextrous robotic arms for high-precision planning and execution of complex movements with sub-millimetre accuracy, a Gazebo simulator for simulated operations using ROS and a mobile robot with a 270 degree 2-D LIDAR scanner, accelerated stereo depth-mapped vision, GNSS tracking, WiFi communications, tactile and ultrasonic sensors, and fully steerable wheels actuated by closed-loop control of wheel hub motors. A robot arm mounted atop this robot for haptic environmental interaction is also available, and can be used for sensing or interaction purposes. (ROS and ROCK are available for control of this robot).

In addition, the Laboratory includes facilities for an array of uses including system design, modelling, simulation and prototyping. There are large libraries of embedded software functions for use on high-reliability microcontroller systems in robotic space hardware and mechanical fabrication tools for prototype and proof-of-concept development.

The Laboratory is currently working on a portfolio of research projects in the above research areas, worth over £2 million and aims to work with the wider space research community to advance the development of common technology to support sustainable and peaceful space exploitations, develop mutual understanding, explore opportunities and tackle challenges in such an endeavour by seeking joint research projects.

3.54.5 Strathclyde Radiation Testing Facility – SCAPA

The Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) research centre is a major initiative within the Scottish Universities Physics Alliance to use state-of-the-art laser laboratories, laser-driven plasma accelerators and radiation sources to conduct research focused on the development and application of next generation accelerator technology. It is accommodated within the University's John Anderson building and comprises 1200 m^2 of shielded area in three radiation bunkers with space for up to 7 programmable beamlines, laser labs, preparation labs and a control area. Its relevance to this study is that laser-plasma-accelerators (LPAs) can reproduce or mimic certain kinds of space radiation, for example the Van Allen belt radiation, with a much higher level of realism than current state-of-the-art techniques. A single LPA can be used to generate relativistic electron, proton, ion and photon beams in a wide parameter range either singly or all at the same time, with fully controllable energy and flux. For example, broadband electron energies up to many 100's of MeV are possible, which is a unique avenue towards reproduction of the broadband spectral flux to be encountered on Jovian missions in the JUICE (JUpiter ICy moons Explorer) context.

The high fluxes and the feasible exponential-energy, multi-component radiation make it possible to test a whole variety of components at the same time, and if required under different viewing angles, decreasing substantially the costs as well as the time consumption of these tests.

After some seed funding from ESA, SCAPA is currently engaging with the UK community, including major institutions such as NPL and RAL's CLF, aiming at bringing the plasma accelerator and space radiation community together. The vision is to establish, in collaboration with ESA and UKSA, an advanced, flexible testing environment for the UK and European space radiation testing community at the SCAPA beamlines.

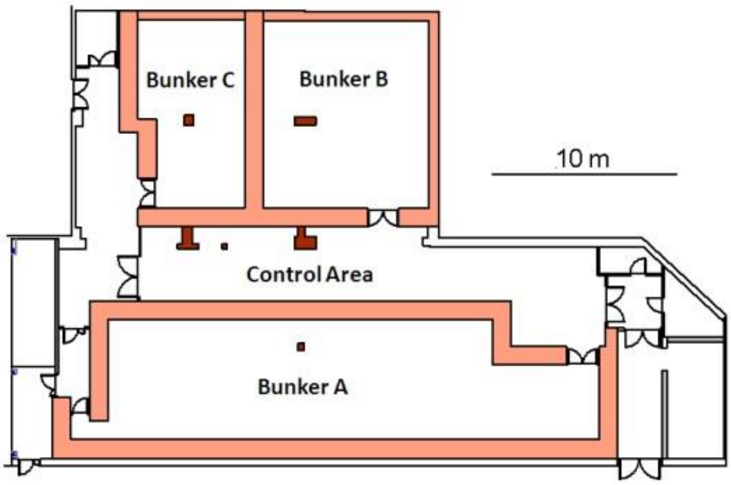


Figure 3.207 SCAPA Plan View and interior of Bunker A

3.54.6 Strathclyde View on Facilities

Strathclyde regards the four facilities summarised above as important contributors to the UK facilities landscape:

- Its **Mission Lab** containing the CubeSat flatsat enables the development of proof-of-concept payloads and satellite systems for future CubeSat missions. Additionally, it will provide ad-hoc and ongoing support for academic institutions, start-ups and SMEs to develop new payloads for CubeSats. This will mitigate the need for significant up-front investment that might otherwise be necessary to demonstrate new technology concepts.
- The **CDDS** will provide a unique multi-disciplinary environment for designing and optimising space missions and systems and develop new methods and approaches to improve performance, resilience and reliability of space systems and services. It will provide computational tools and expert support to Industry and Academia to demonstrate the feasibility of new missions, technologies and services and to improve the design of future space platforms.
- **Mechatronics** has been established as key technology in developing many intelligent systems and in particular for consumable products. There is much scope and many opportunities for its applications - in particular in space explorations
- The potential improvement in **radiation testing** space components, subsystems and detectors in a realistic multi-species space radiation environment using LPAs in the **SCAPA** facility promises to be a big step forward in the quality of radiation testing in the UK.

3.55 University of Surrey, Surrey Space Centre (SSC)

3.55.1 University of Surrey Background

The University of Surrey, located in Guildford, is a public research university specialising in science, engineering, medicine and business. It received its charter in 1966 having previously been located in Battersea as the Battersea College of Technology, before gaining university status. Its roots, however, go back to the Battersea Polytechnic Institute, founded in 1891 to provide further and higher education for London's poorer inhabitants. The university is particularly well known for its research on small satellites and mobile communications. It is organised into three faculties, with the Faculty of Engineering and Physical Sciences being the one in which the Surrey Space Centre is located.

3.55.2 Surrey Space Centre

The Surrey Space Centre, SSC, is a world leading Centre of Excellence in Space Engineering, formed in 1979 to pioneer microsatellite research and applications with emphasis on cost-effective technologies. Its strategy is to underpin the technical development of the space industry through its applied advanced research programmes. It remains the world's leading research centre for small, low cost space missions, generating leading research and bringing innovation to its spin-out company SSTL, see Section 3.40 above, and pushing the boundaries of cost effective satellite applications to develop next generation low cost small-satellite technologies.

SSC research capabilities cover many aspects of space vehicle design and satellite applications including: Planetary Environments, Science and EO Instrumentation and Remote Sensing Applications, Antennas and Radar (SAR); Space Weather, Radiation Environment and Effects; Signal Processing, Navigation and GNSS Reflectometry; Space Electronics, Embedded Systems, Data Handling and Communications; Spacecraft Power Systems and Energy Storage; Astrodynamics and Propulsion; Space Vehicle Control; RF Systems; Space Robotics, Rovers and In-Orbit Servicing; Autonomy, Artificial Intelligence and Biomimetics; Nano-Satellites, Aerobots, Spacecraft Structures and Mechanisms, and Innovative Space Missions. The SSC team brings decades of experience in providing academic courses on Space Engineering with bespoke educational activities and know-how technology transfers.

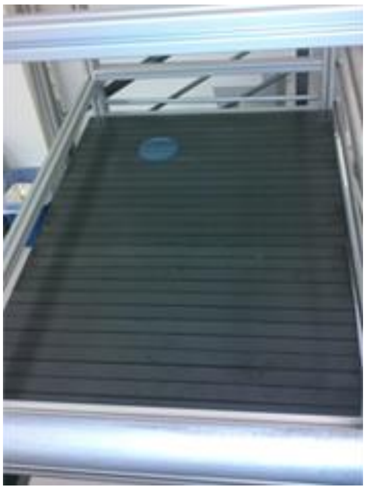
3.55.3 SSC Facilities

SSC has a range of facilities to support its space research and educational activities, including:

Cleanroom: Fully equipped ISO 7 (Class 10,000) cleanroom, with approximately 50m^2 floor space.

Air bearing systems: The SSC has a number of air-bearing test facilities to model the micro-gravity space environment for testing of spacecraft navigation and control systems (e.g. for simulating formation flying or proximity manoeuvres):

- **Micro-Porous Carbon Table**: 100cm x 150cm, 3DoF air-table (X-Y translation, Yaw); the MPC provides uniform airflow across surface, not subject to turbulent currents experienced by 'Air Hockey' type tables; supplied by in-house compressed air supply at range of pressures providing up to 70µm fly-height; it models CubeSat manoeuvring and docking using a spacecraft simulator mounted on passive puck.



.Figure 3.208 Micro-Porous Carbon Table

- **Granite Table**: 3 tonne granite to grade 00 standard; 200cm x 300cm; 3DoF air table (X-Y translation, Yaw); custom-made on-board flyer air-supply provides 15 minutes flight time after refilling; SSC has two sets of flyers, one representative of a CubeSat structure and one capable of supporting up to a 20kg simulator mass.

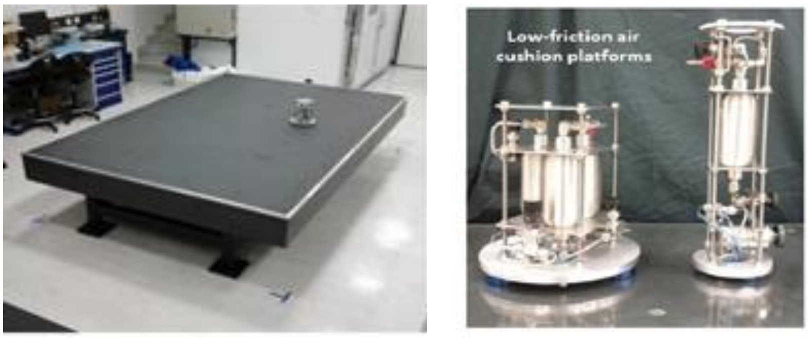


Figure 3.209 Granite table and flyers

- **Air-bearing NanoSat Simulator:** static 3DoF platform (Pitch, Roll, Yaw) using hemi-spherical air-bearing; with accommodation for flight-representative spacecraft systems, including CubeSat form factor; automatic balancing based on feedback control of translation masses; used to study effects of deployable structures and innovative attitude control systems embedded within these structures.

Figure 3.210 Air-bearing NanoSat Simulator

Radiation test facility: REEF (Realistic **Radiation Environment** Facility) to test the effect of space radiation environment and in particular electron-caused charging and dose-effects research.

Vacuum chambers: SSC has a number of vacuum chambers to test space equipment and in particular Electric Propulsion Systems, including: **Daedalus**, which has three distinct areas separated by gate valves, thereby enabling concurrent testing of thrusters, the main chamber being 2m x 3m and the other two chambers are 0.6m x 0.4m; and **Pegasus**, with a $1.5m^3$ volume, turbo-pumped to achieve 10^{-7} mbar in under 2 hours.

Electric propulsion: one of the electric propulsion technologies under development is the Quad Confinement Thruster (QCT), which is a high performance plasma propulsion system for spacecraft. The unique feature of this design is that the thrust produced by the device can be actively vectored by a unique configuration of electromagnets. QCTs have potential applications for large geostationary satellites because of potential cost savings due to the elimination of thruster gimbaling systems and are attractive because of their relatively high thrust performance at low levels of power.

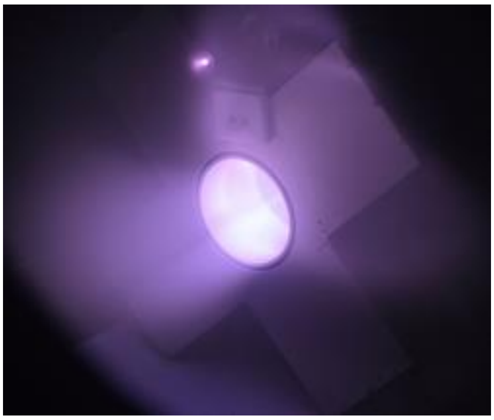


Figure 3.211 Quad Confinement Thruster

Hybrid rocket technology: SSC is active in other types of propulsion research including hybrid rockets, which have characteristics that are well suited to small spacecraft missions such as: environmental friendliness; unparalleled safety for a given level of performance; and the promise of highly reduced propulsion system cost make this technology a contender for the upcoming generation of highly maneuverable and cost effective small spacecraft.

Figure 3.212 Surrey hybrid rocket engine firing

Structural dynamics lab: equipped with a selection of **shakers,** controllers, a data acquisition system and a **shock table** to meet typical space equipment model validation and environment testing requirements.

Electronic Labs and mechanical workshops: including manufacturing facilities for electronics and mechanical systems.

Although it recognises that it is not part of the current study, SSC would like to point out that it has comprehensive ground station and robotics facilities including:

Groundstation: VHF/UHF 144MHz and 430MHz medium-gain and high-gain circular-polarised yagis and helical antennas both with rotator; LNA - 430-440MHz SP-7000 LNA preamp and 140MHz SP-2000 LNA; HPA - Discovery-2 VHF 400-1500W valve amplifier and Gemini-70 UHF 300W solid-state amplifier, Radios - ICOM 910H, Terminal Node Controllers, Paccomm Spirit-2, Symek TNC2H & Kantronics 9612+, Software Defined Radio Tools - Ettus USRP B210; Fun Cube Dongle (FCD), DVB dongles, Desktop Computers, Windows (Orbitron, SDR) and Linux (gnuradio, custom interfacing and data processing programs).

STAR Lab (Surrey Technology for Autonomous systems and Robotics)
Range of autonomous systems facilities for rover testing, including multiple rovers for autonomous multi-sensor navigation and rover-soil interaction testing.

Figure 3.213: Examples of STAR Lab rovers and wheel soil interaction test rigs

3.55.4 Univ of Surrey View on Facilities

The SSC has excellent facilities and has recently developed several bespoke testing systems with which to conduct its in-house research programmes, potentially available for external users. SSC has significant experience of collaboration with industry and research institutions in the UK and abroad, and is very happy to work with external customers subject to resource availability and standard commercial arrangements.

3.56 Vaeros Ltd, Harwell

3.56.1 Vaeros Company Background

Vaeros is the Aerospace Corporation's Civil and Commercial Operations division and it recently set up a UK subsidiary, Vaeros Ltd, at Harwell. The Aerospace Corporation is an independent, non-profit corporation operating a US-federally funded research and development centre, providing objective technical expertise, analysis, and assessments in multiple markets, including government, civil, and commercial customers requiring compelling solutions to complex technical problems. With more than five decades of experience, the Corporation provides leadership and support in all fields and disciplines of research, design, development, acquisition, operations, and programme management. Its unique depth of talent in a broad array of scientific and engineering disciplines and its freedom from conflict of interest allows it to provide leaders with the information they need to make the right decisions.

3.56.2 Vaeros Expertise and Services

Vaeros can make the following areas of expertise and services available to the UK space community:

Scientific and engineering expertise:

- Structural design and modelling
- Sensors and imaging
- Microelectronics
- Cyber security
- Computer and network architectures
- Software development and validation
- Telecommunications
- Astrodynamics
- Satellite design and orbital systems
- Satellite control and ground systems
- Guidance and control
- Propulsion
- Signal processing
- Advanced materials

Research, engineering, and technical support services:

- Systems engineering
- Laboratory evaluation
- Test and evaluation
- Mission planning
- Operations concepts
- Acquisition and programme management
- Launch and on-orbit failure analysis and anomaly resolution
- Prototype development
- Reliability analysis
- Independent readiness reviews
- Risk analysis and lifecycle cost modelling
- Non-Destructive Testing

3.56.3 Vaeros View on Facilities

Although Vaeros Ltd has no 'facilities' in the UK, it is able to offer the UK space community access to its full range of expertise and services available in the US. This includes access to its very extensive Physical Science Laboratories at Aerospace's Headquarters in El Segundo, California.

3.57 VIPER RF, Durham

3.57.1 VIPER RF Company Background

VIPER RF, established in 2008, is an independent ISO9001 certified microwave and RF design and product supply company based in Durham. It has expertise in the design and development of RF components and modules from 1-150GHz for aerospace, communications and defence markets. VIPER RF has worked with system integrators in the space domain and has experience of designing on European space qualified MMIC process technologies. VIPER RF is an approved design house for a number of world-leading GaAs and GaN wafer foundries.

3.57.2 VIPER RF Space Manufacturing and Test Facilities

Current capabilities and expertise include:

- **Custom design and supply:** monolithic Microwave Integrated Circuits (MMICs) and packaged die
- **Engineering test laboratory:** on-wafer probing; design and assembly of test jigs; DC to 40GHz/E/W-Band small signal and power measurements; linearity measurements

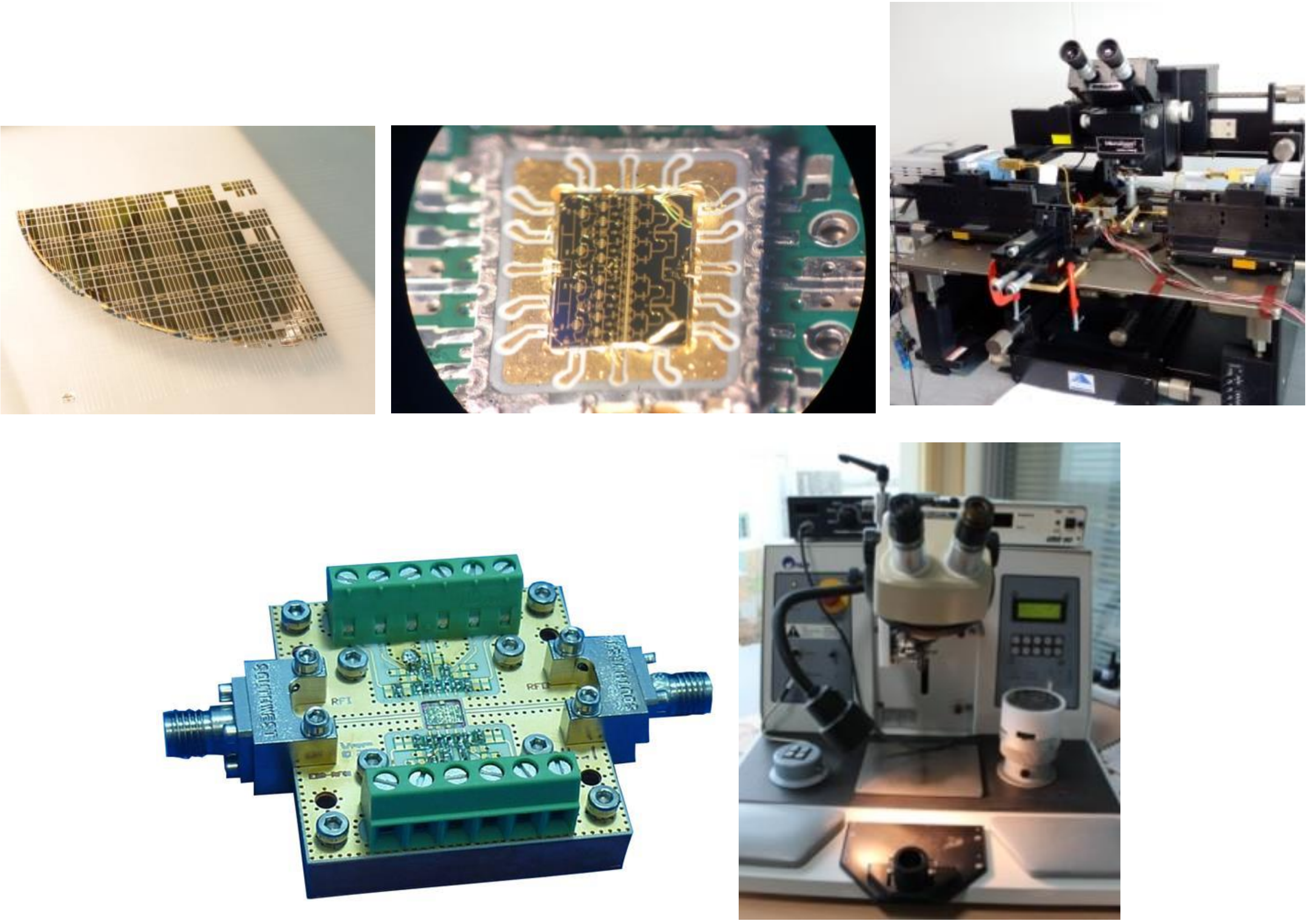


Figure 3.214 C-W from top left: GaN wafer, packaged MMIC, wafer-prober, wire-bonder, wafer test jig

3.57.3 VIPER RF View on Facilities

In terms of facilities, VIPER RF offers a custom MMIC design service using space-qualified wafer foundries, and component level engineering test service for MMICs.

4 ANALYSIS

4.1 Survey Summary

This 2017 Space Facilities Survey provides an extensive catalogue of space development and test facilities currently available in the UK from nearly 60 organisations, all of whom have identified what facilities they own and what additional facilities they think they will need in order to satisfy their future demands, illustrated as a capabilities and gaps matrix in Table 4.1 below.

	Clean rooms	Mass properties	Vibration	Shock	Pyro-shock	Acoustic	Thermal/vacuum	Planetary environment chambers	Thermal chambers	EMC	RF	Magnetic testing facilities	Radiation testing facilities	Instrument design & development	Instrument characterisation & calibration	Molecular spectroscopy	Subsystem supplier	Small spacecraft & instrument-level facilities	Large spacecraft-level facilities	Very large vacuum chambers	Specialist test facilities	Chemical propulsion design, development, test	High power chemical engine testing	Cold gas design, development, test	Electric propulsion design, development, test	Systems engineering & mission design	Mechanical design & development facilities	Space optics design & development	Space electronics design & development	Thermal design & development	No test facilities of own	External facilityuser	Possible future facility provider
ABSL / Enersys																					Y												
Airborne Engineering Ltd (Westcott)																						Y	F										
Airbus DS Portsmouth	Y		Y	Y			Y		Y	Y	Y			Y			Y	Y	Y	N	Y					Y	Y	Y	Y	Y		Y	
Airbus DS Stevenage	Y	Y	Y	Y			Y		Y	Y	Y			Y			Y	Y	Y	N	Y	Y				Y	Y	Y	Y	Y		Y	
Airbus Group Innovations																											Y						
AVS-UK	N		N	N			N		N	N				N			N	N			N				N	Y	Y				N	Y	F
3C Test Ltd										Y																							
Cardiff University	Y						Y		Y		Y			Y	Y						Y					Y	Y	Y	Y	Y			
Clyde Space	Y		N				N		Y	N	N						Y	Y			Y					Y	Y		Y			Y	
Cobham RAD Solutions													Y																				
COM DEV International (Honeywell)	Y		Y				Y		Y		Y			Y			Y				Y					Y	Y	Y	Y	Y		Y	
Cranfield University														Y				Y				Y				Y	Y					Y	
Cyth Systems					F																												F
Deimos UK	N	N	N	N			N			N	N							N								Y	N		N	N	Y	Y	
Element Materials Technology			Y	Y							Y																						
ESR Technology	Y						Y		Y												Y						Y						
European Astrotech Ltd																						Y											
Falcon Project Ltd																						Y	F				Y					Y	F
Glyndwr University																										Y	Y	Y					
Imperial College London	Y						Y					Y		Y	Y		Y	Y			Y						Y		Y			Y	
International Space Propulsion (ISP)																						Y											
Intertek, Leatherhead										Y																							
ISVR's Rayleigh Laboratories						Y																											
Lockheed Martin Space Systems Co UK	N	N	N	N			N			N	N						N	N	N	N						Y	N	N	N	N	Y	Y	
Magna Parva	Y													Y			Y				Y					Y	Y	Y		Y		Y	
Mars Space																	Y				Y				Y								
Moog UK (Westcott)																					Y	Y		Y									
National Physical Laboratory										Y	Y	Y	Y		Y																		
Neptec UK	N		N	N			N		N	N				N	N		N	N			N					Y	Y	Y	Y	Y	Y	Y	
Open University	Y							Y	Y					Y	Y			Y			Y					Y	Y	Y	Y	Y		Y	
Oxford Space Systems Ltd (OSS)	N		N	N			N		N	N	N			N			Y	N			N					Y	Y		Y		Y	Y	
Portus Aerospace Ltd, Portsmouth																	F								F				F				F
QinetiQ	Y																				Y				Y								
Queen's University Belfast	Y										Y										Y						Y		Y				
RAL Space	Y		Y				Y		Y					Y	Y	Y	Y	Y	Y		Y					Y	Y	Y	Y	Y		Y	F
RAL Space future possibilities	F	F	F	F		F	F		F	F	F								F	F													F
Reaction Engines Ltd									Y					Y			Y	Y			Y	Y	F			Y	Y		Y	Y		Y	F
Roxel (Safran-MBDA), Kidderminster																	Y				Y	Y	F	Y		Y	Y						F
Satellite Applications Catapult											F							Y															F
Spur Electron Ltd																					Y								Y				
SSTL – Surrey Satellite Technology Ltd	Y	N	N	N	N	N	N		Y	N	N	N	N				Y	Y	Y		Y	N		Y	N	Y	Y	Y	Y	Y		Y	F
STAR Dundee																													Y				
Swansea University																		Y			Y	Y				Y	Y						
Thales Alenia Space – UK	Y	N	N	N		N	N		N	N	N			Y			Y	Y	N	N	Y	Y			Y	Y	Y	Y	Y	Y		Y	F
TWI Technology Centre, Wales																					Y						Y						
UK ATC Edinburgh	Y		N	N			N		Y					Y	N			F			Y					F	Y	Y	Y			Y	F
Ulster University																					Y						Y						
University College London, MSSL	Y		Y				Y		Y					Y	Y		Y	Y			Y					Y	Y	Y	Y	Y		Y	
University of Dundee														Y															Y				
University of Kingston																						Y											
University of Leicester SRC	Y						Y		Y					Y	Y			Y			Y					Y	Y	Y	Y	Y		Y	F
University of Oxford, Dept. Physics	Y		Y				Y		Y					Y	Y			Y			Y					Y	Y	Y	Y	Y		Y	
University of Southampton- Astro			Y				Y										Y	Y				Y			Y	Y	Y					Y	
University of Southampton- Plasma							Y										Y	Y							Y							Y	
University of Strathclyde													F					Y			F					Y						Y	F
University of Surrey	Y								Y								Y	Y			Y					Y	Y	Y	Y	Y		Y	
Vaeros Ltd																										Y							F
VIPER RF																													Y				

Table 4.1 Current and Future Facilities vs Organisation (***Y*** = existing; ***N*** = needed, ***F*** = future planned)

In the table a green square (Y) shows that a facility exists within a particular entity; a pink square (N) shows a stated need or known facility gap for that entity; and a blue square (F) indicates that such a facility is hoped or expected to be provided in the future. However, it is not possible to indicate the scale, scope and characteristics of the facilities in a simple two-dimensional grid, so the survey details in Section 3 should be consulted for more information regarding each provider/user. There are some useful conclusions that can be drawn from the survey and these are analysed in the following sections.

4.2 UK Space Facility Locations

4.2.1 General Observations

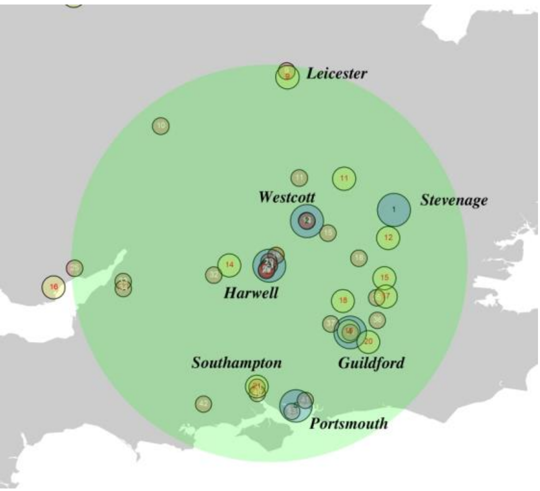
The locations of all organisations surveyed for the 2016 Report are shown in Figure 4.1.

Figure 4.1 Locations of all surveyed facilities/and or users in the UK

This shows where the various organisations are located with respect to one another, and gives a rough idea of the travel distances required to access facilities external to any organisation. Although there are space-active universities and companies located throughout the UK, it can be seen that the main testing facilities and the majority of potential users are concentrated in the Central South region of England, in fact within 75 miles of Harwell. It can also be seen that there are smaller clusters of facilities and potential users forming: in the South, around the Harwell locality, Westcott, Guildford, Southampton/ Portsmouth and London; in Scotland around Edinburgh and Glasgow; Belfast in Northern Ireland; and the 'Arc of Innovation' in Wales. These hubs or clusters of facilities are discussed in the subsections which follow.

4.2.2 The Harwell Hub

The majority of surveyed space organisations are located within a 75-mile radius circle centred on the Harwell campus, shown by the green circle on the plot below. The four largest space testing and assembly facilities in the UK are well within this circle and are approximately 60-70 miles from each other.



Key

Blue circles: large facilities (ADS Stevenage, ADS Portsmouth, SSTL, RAL Space, NPL, QinetiQ)

Small red circles: smaller facilities and users (ABSL, AVS-UK, 3C Test, Cobham RAD, COMDEV Aylesbury, Cyth, Deimos-UK, Element, Intertek, ISVR, Lockheed, Magna Parva, Neptek-UK, OSS, Sat Ap Catapult, TAS-UK, Spur Electron, Vaeros)

Medium yellow circles: Universities with space facilities (OU, Oxford, Leicester, Surrey, MSSL, Southampton, IC, Cranfield)

Figure 4.2 Facilities and organisations within a 75-mile radius of Harwell

Harwell appears to be acting as a 'hub' or centre of attraction for small entities and also for international organisations wishing to establish UK subsidiaries and it is likely that others, both national and international will follow. They will bring with them, or will have need of, testing facilities. The better and more competitively priced the facilities are on the site, the more likely it is that more organisations will come. Organisations outside the 75-mile radius are widely dispersed and face a significant amount of travelling to access any of the facilities at Harwell or at the Airbus main premises.

4.2.3 Chemical Propulsion Facilities

Performing a similar analysis for chemical propulsion, it can be seen in Figure 4.3 below that with the exception of Swansea University and TAS-UK in Belfast, all of the main players in chemical propulsion R&D in the UK reside within a 75-mile radius of Westcott (Magenta circle), and also within a 75-mile radius of Harwell (green circle as before). The Westcott site thus seems to be the *de facto* centre of a chemical propulsion hub, and is attracting organisations active in chemical propulsion for testing purposes, even where they do not have an on-site presence.

Key

Blue circles: large propulsion facilities (ADS Stevenage, QinetiQ)

Small red circles: smaller facilities and users (Airborne Engineering, European Astrotech, Falcon, ISP, Moog, Reaction Engines, Roxel, SSTL)

Medium yellow circles: Universities with propulsion interests (Cranfield Shrivenham, Kingston, Southampton Astronautics, Surrey)

Figure 4.3 Location of chemical propulsion facilities and potential facility users

4.2.4 Electric Propulsion Facilities

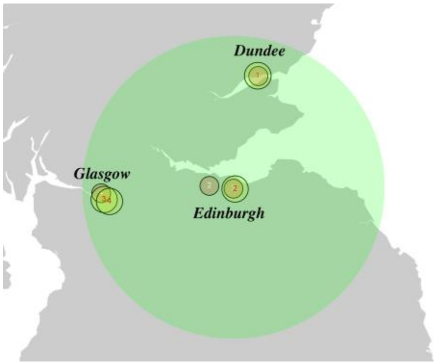
The situation for electric propulsion is less clear, with facilities currently established in Belfast (TAS-UK), Farnborough (QinetiQ), Harwell (TAS-UK), Southampton/Portsmouth (Mars Space, Portus, Southampton Astronautics, Southampton Plasma and Space Science), and Guildford (Univ of Surrey). There seems to be no logical centre of an EP hub, and perhaps there is there is no particular reason why one is needed.

4.2.5 The Northern Ireland Cluster

The focus of space activities in Northern Ireland is somewhat naturally Belfast, where space organisations include Queens University, Ulster University and TAS-UK.

4.2.6 The Scottish Cluster

In Scotland, there are several Universities, a number of small and large companies, and an STFC institute, all having significant space interests. These are all within a 50-mile radius circle centred on Edinburgh. Clyde Space (Glasgow), STAR Dundee (Dundee) and to a lesser extent ComDev (Edinburgh) have specialised test facilities of their own, but require access to additional third party AIV facilities, which are mostly south of the Border. Whilst STFC's UK-ATC (at ROE Edinburgh) currently has some environmental test facilities of its own, it is understood that the new Higgs Centre under development at their Royal Observatory site will have more extensive AIV facilities, and these could support the Scottish cluster. However, it is unlikely that all local testing needs can be met in the near future.



Key

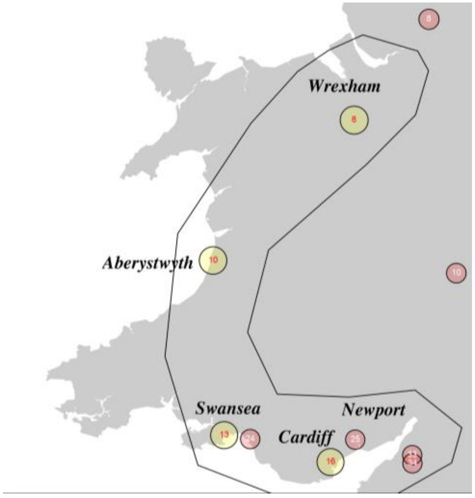
Small red circles: industry facilities and users (Star Dundee, Clyde Space, COMDEV Edinburgh, UK-ATC)

Medium yellow circles: Universities with space facilities (Dundee, Strathclyde)

Figure 4.4: Organisations within a 50-mile radius of Edinburgh

4.2.7 The Welsh Arc of Innovation

In Wales, most space organisations are not associated with an obvious central location, but rather they align with the 'Arc of Innovation' associated with the emerging Welsh space and high tech industries.



Key

Small red circles: industry facilities and users (Airbus Group Innovations, TWI Technology)

Medium yellow circles: Universities with space facilities (Cardiff, Glyndŵr, Swansea, Aberystwyth)

Figure 4.5 The Welsh 'Arc of Innovation'

The academic centres that responded to the survey (Cardiff, Swansea, and Glyndwr) and two that did not, (USW and Aberystwyth, to be included in next year's Report) are also members of the Wales Academic Space Partnership, itself part of the Arc of Innovation. This suggests that a federal 'virtual centre' model may be more appropriate than a centralised facility. This could be realised by enhancements to local facilities, which could then be shared within the Welsh space community.

It is worth noting that there is a concentration of activity in South Wales along the M4 'corridor', which makes the Harwell cluster reasonably accessible by road or rail, when facilities beyond those available locally are needed.

The universities all have on-site facilities such as clean rooms, vacuum chambers and laboratories, sized and equipped for their specialities rather than for general-purpose space use, but most are in principle available for third party use on a commercial basis.

There are also other locations in Wales which will be included in future issues of the report as and when the scope of the survey expands, including:

- the Pendine rocket range, operated by QinetiQ, which is primarily used for defence missile system testing, but the rocket sled track there has been used recently to test penetrator lander concepts for planetary exploration;
- the Aberporth firing range and UAV facility and associated controlled airspace, also operated by QinetiQ, which is a potential resource for proving of EO payloads on UAVs prior to spaceflight; and
- Llanbedr airfield, which is a potential site for a UK spaceport, and could host significant facilities in the future.

4.3 Entities Requiring Access to Space Test Facilities

There are a number of space organisations that are largely, or in some cases totally, dependent upon using external test facilities for testing their products at the subsystem or spacecraft levels. Some of these are SMEs and some are overseas organisations with a UK base at Harwell, and their future plans are contingent on availability of facilities, both in terms of future projects and of possibly implementing their own facilities. The organisations which have stated that they require access to external facilities include:

- SSTL – has large clean assembly areas and two walk-in thermal chambers, but needs access to large TVAC chambers, vibration facilities, acoustic test facilities, EMC chambers, RF and antenna test facilities
- Lockheed Martin Space Systems UK – if it is to fulfil its ambition to produce A2100-TR-class spacecraft in the UK, it needs access to a full complement of large-scale facilities including clean rooms, assembly areas, mass properties, TVAC, vibration, acoustic, EMC and NF antenna range
- TAS-UK – although it has small clean rooms and some subsystem test facilities in Bristol, if it is to produce Iridium-NEXT-class spacecraft in the UK, it needs the same facilities as Lockheed above
- Diemos UK – if it is to seriously consider the assembly and test of small spacecraft as it has done in Spain, Deimos needs access to a full suite of facilities as for Lockheed and TAS-UK, although perhaps on a physically smaller scale
- COMDEV – similarly to Deimos, COMDEV has built small satellites outside the UK and if it is to extend that capability to the UK, it needs access to a full suite of spacecraft-level facilities
- Neptek – is now building space subsystems and instruments in the UK and needs cost-effective access to a full suite of subsystem-level test facilities in all the disciplines listed above at the spacecraft-level
- OSS –needs access to a full suite of subsystem-level test facilities in all disciplines for its deployable booms and structures, with the addition of a gravity-off-loading facilities for deployment tests
- AVS – is hoping to build a variety of space subsystems in the UK, but this will only happen if it has good access to facilities as for Neptek and OSS.

It is also worth noting that even Airbus must use external facilities for some important test functions such as very large TVAC and vibration facilities; whilst most universities require specialist test services to complement their in-house facilities.

4.4 Commercial Issues

The existing large commercially-owned test facilities located at Airbus Defence and Space (Portsmouth and Stevenage) and at QinetiQ Farnborough were established to service their in-house needs. However, when not in use for in-house projects, these facilities are potentially available for use by third parties on a commercial basis. This raises some issues:

- Some of these facilities, such as the large EMC facilities at Portsmouth and Stevenage, are presently the only ones available in the UK for spacecraft-level testing. Potential users are reluctant in some cases to expose their intellectual property in another, potentially competing, commercial organisation's premises. Whilst it is possible to create private spaces using partitions and 'rooms-within-rooms' inside the large clean areas or test chambers, it is difficult to guarantee full confidentiality.
- Therefore those entities with the need to test large systems and/or spacecraft containing potentially valuable intellectual property would prefer do it in non-commercial premises, where equipment can be stored and moved with minimal exposure to commercially astute eyes.
- Commercial owners of large facilities are however focussed upon using them for their own programmes. Whilst the sale of unused capacity may be desirable for them, they seem to have difficulty putting resources into marketing and advertising the excess capacity.

4.5 Analysis Summary

For providers and users of space development and test facilities, the analysis may be summarised as follows:

- there are increasing numbers of small and large organisations requiring access to comprehensive space AIV/AIT facilities, which currently have few or no facilities of their own;
- some organisations are reluctant to use existing commercial facilities due to potential commercial exposure of their IP;
- those companies which do have significant facilities of their own often have a need for additional specialised facilities and they also point out that their in-house facilities are not fully utilised;
- organisations which do have spare capacity often find it challenging to spend significant resources on marketing their spare capacity;
- there is a concentration of small and large companies on or near the Harwell campus, and this is increasing; Harwell appears to act as a centre of gravity for SMEs and some overseas companies;
- it is anticipated that there will be a growing demand for medium-sized AIV facilities due to constellations of small spacecraft and Mega-Constellation initiatives;
- there is a concentration of space activity based around the Glasgow/Edinburgh axis in Scotland;
- there is a similar concentration of space interests around Belfast in Northern Ireland;
- space activity in Wales is based around the 'Arc of Innovation', which does not suggest an obvious location for a centralised facility; furthermore, the concentration of activity in South Wales has good, if somewhat distant, road and rail access to Harwell and nearby facilities.

For propulsion facilities the analysis indicates:

- there is a significant concentration of chemical propulsion organisations clustered at or near the Westcott site;
- the future growth of these companies depends upon their ability to access needed test facilities;
- there may be a case for an electric propulsion life-test facility that is currently not being met;
- there is no obvious centralised location for electric propulsion as there is for chemical propulsion.

Following on from these observations a summary of the survey findings can be found below.

5 CONCLUSIONS/SURVEY FINDINGS

There are a number of important conclusions that can be drawn from the survey and analysis, summarised in the following sections.

5.1 Relevance and Scope of the 2017 Space Facilities Survey

The scope of the 2017 Space Facilities Survey was restricted to three principle areas: system level environmental test and AIV facilities; chemical propulsion test facilities; and electric propulsion test facilities. It provides an extensive catalogue of space development and test facilities currently available in the UK from nearly 60 organisations, all of whom have identified what facilities they own and what additional facilities they think they will need in order to satisfy their future demands. Although it is recognised that it is not a complete survey since it was not possible to include all organisations with space interests within the study constraints, what is clear is that the UK already has a comprehensive suite of world-class space development and test facilities. It is important to ensure that their quality remains at the highest level and that any facility gaps identified during the survey are filled.

The 57 surveyed organisations represented all regions of the UK and included: large spacecraft primes; SMEs with interests in building small satellites and in providing space subsystems; environmental test houses; research organisations and many Universities. So although there are more in-scope organisations to be surveyed in the coming year, it is felt that the cross-section of organisations already surveyed is sufficiently broad for the conclusions to be valid.

5.2 A Central National Space Test Facility

In general terms survey respondents identified the need for a co-located suite of space test facilities to be established somewhere in the UK in order to avoid the expense, risk and schedule impact associated with moving a spacecraft around significantly during its final assembly, integration and test programme, particularly if some of the testing has to be carried out abroad. Harwell is becoming a centre of attraction for small and large space companies (both national and international), all of which need access to a complete spectrum of space test facilities. In addition, the majority of organisations active in space in the UK are based within a 75-mile radius of Harwell, so there seems to be an argument for establishing a national space assembly, integration and verification (AIV) facility on the Harwell campus. Other non-Harwell organisations with space testing facilities of their own which are available for third party use, could become 'spokes' to the Harwell hub.

There is a natural growth on the Harwell campus, which suggests that a comprehensive suite of AIV facilities located there could address many of the gaps identified in this study. In addition, foreign companies such as Neptek, Thales, Deimos, AVS and Lockheed Martin, all of which have few or no facilities of their own in the UK, would very likely expand their UK activities if they had access to local space test facilities at competitive market rates. Expanding the facilities on the Harwell site to be able to handle all of the common testing functions from payload-level testing, up to and including spacecraft-level testing is an option. In addition, there should be appropriately spacious adjacent facilities, permitting easy movement of payloads and spacecraft between test facilities, with ability to store and work on them in close proximity to the test facilities in a clean environment. Exactly what might constitute a national space test facility was discussed during the second workshop and there was general agreement that it should include: large cleanrooms, at least one of which should have gravity off-loading for boom and solar array deployment tests; a large TVAC chamber; mass properties; large vibration and acoustic test facilities; and a large EMC and near-field antenna test chamber. However, the Workshop did not attempt to define exactly what 'large' meant – only that whatever size it was, the test facilities should be designed to be future-proof as far as practicable.

It was noted that the Airbus space test facilities in Stevenage and Portsmouth are not fully utilised. It is possible therefore that their unused capacity could be developed to become 'spokes' of the Harwell hub, which could provide additional capacity for some testing tasks, and could also be commercially advantageous to Airbus. This model could perhaps also be used with other commercial facility providers, to mutual benefit.

If a National Space Test Facility were to be established, it is important that access to it should be established with a 'level playing field' with no preferential access for the facility operator or for the large spacecraft primes. SMEs and Universities should be guaranteed access on the same basis as the larger spacecraft providers. Any bid to build and host the Facility would be expected to address this in their proposal. Furthermore, the rates charged for using the National Facility must be competitive, otherwise potential users will be tempted to use other facilities even at the expensive of not exploiting the advantages of a 'one-stop-shop'. Again, this would be expected to be addressed in the Facility-bidder's proposal.

Protection of users' IP is another important factor for a National Space Test Facility. Several of the surveyed organisations indicated a reluctance to use existing commercial facilities, due to the risk of exposure of their IP to potential competitors. A National Facility would need to be sensitive to this need, and to provide facilities for commercial confidentiality, such as controlled access zones with screens, or rooms within rooms.

The needs of the CubeSat community are another special case. CubeSats potentially provide low cost access to space for a large academic and SME community, but this can only be achieved if there are low cost test facilities in which to conduct their final preparations for launch. This implies access to smaller, lower cost, test facilities with a lower cleanliness environment. There is no particular reason why such facilities need to be co-located with the main National Facility although it may be beneficial to tap into expertise associated with a larger facility.

It is not clear whether or not the testing requirements of 'mega-constellation' or 'convoy' missions are well suited to the National Facility concept. It is possible that the first few spacecraft models of a production-line build would benefit from the co-located test facility concept, but it is quite likely that the repeat builds from the production line would be subjected to a reduced-scope test regime requiring special-to-purpose facilities quite possibly on a different site.

In July 2017 it was announced that £99m of government funding was being provided for a National Satellite Testing Facility on the Harwell Campus in Oxfordshire.

5.3 A Central National Chemical Propulsion Hub

For chemical propulsion, the survey identifies the Westcott propulsion facility as a potential site for a national centre for chemical propulsion: a Propulsion Hub. The site is already well developed and is acting as a centre of attraction to SMEs and larger companies engaged in propulsion R&D. There is a similar geographical case due to the majority of the interested parties being within a similar 75-mile radius.

The Westcott site is already established as a national centre, providing services to a number of UK university groups and SMEs, but it is evident that further development is needed, and that it may be appropriate to focus public investment there. A clear gap in the UK is a facility to test medium-sized chemical engines at simulated altitude, which at present can only be done at facilities in Europe, such as at Lampoldshausen.

There is a general need for more test bays for moderate sized engine testing in the 1-2kN range, whilst there is another major gap for testing of larger engines of up to 100kN. Companies such as Moog, Falcon Project and AEL appear willing to develop facilities in the context of a national facility, either alone or in partnership with public funding, in order to support existing and planned new product lines.

Nearby propulsion organisations such as Roxel at Kidderminster could be identified as 'spokes' to the Westcott hub, as could also University groups such as those in Kingston and Southampton.

5.3 Electric Propulsion

While the gap analysis has identified the need for more EP test chambers and EP life-test facilities, there appears to be no logical central location as is the case with chemical propulsion.

In view of the long times needed for life testing of electric engines, it is likely that more capacity will be required if the UK is to support significant growth in the electric propulsion market. Some companies such as AVS have ambitions for development of new electric engine products, and will be unable to do this without a significant increase in availability of EP test facilities. A pragmatic approach could be to enhance the facilities in QinetiQ Farnborough as a 'hub' for example, as it is already a major centre, and is located reasonably close to potential users at Mars Space, the University of Southampton, Portus in Portsmouth, and SSTL. It is also within a short distance of the Harwell campus, and could thus support Lockheed, and smaller companies like AVS with specific need of EP testing facilities. Some small-scale testing can probably be accommodated at Southampton University as a 'spoke', but longer testing (particularly life testing) of bigger engines, would need the larger chambers such as at QinetiQ Farnborough or Thales-UK in Northern Ireland.

5.4 The Regional Centres

Scotland has a significant cluster of space R&D organisations in Glasgow, Edinburgh and Dundee. These organisations typically have some specialised in-house AIV facilities for their own projects, but do not appear to share each other's facilities. They all require some access to third party test facilities which are mainly located outside of Scotland.

COM DEV for example has comprehensive test facilities for most of its activities, but must use commercial test houses south of the border for EMC testing. Clyde Space has good facilities for testing its CubeSats at ambient temperature and pressure but needs access to third party AIV facilities for vacuum and vibration testing, which must be compatible with its low cost CubeSat approach. The UK-ATC has some instrument-level specialist test facilities, and is hoping to implement more comprehensive small-satellite AIV facilities as part of the new Higgs Centre, which could provide some local AIV resources for Scotland as a whole, as it is located within 50 miles of most organisations that may require access.

In Northern Ireland space activities and associated facilities are centred on Belfast, especially those of Thales-UK. However, for any organisations requiring access to test facilities not available locally, even visiting another UK test facility constitutes an 'overseas' trip, so having access to a National Test Facility on the UK mainland may not be much different from travelling to Continental Europe.

In Wales, space activity is distributed around the 'Arc of Innovation', and like Scotland, the local facilities belonging to the majority of organisations appear, to a first order at least, to meet immediate in-house requirements. However, as the industry evolves, more comprehensive and larger facilities in the Region could provide a stimulus to growth.

While there are space business incubation centres in Wales such as OpTIC in Glyndŵr University, and a multi-departmental downstream applications centre (ACSEM) in Aberystwyth, there appear to be no centralised general space AIV facilities available to the community, other than discretionary commercial access to the specialised facilities in the Universities. Most organisations will offer their facilities to third parties on a commercial basis, and where additional AIV facilities are needed, companies can travel to Harwell or elsewhere in the UK. While this may be acceptable occasionally, especially for those organisations close to the M4, enhancement of local facilities could be really useful in some sort of collaborative 'virtual centre' to stimulate what is already a vibrant upstream activity. A model based on the UK-ATC Higgs Centre may be worth exploring.

Annex A List of Abbreviations and Acronyms

Somewhat inevitably, the 'Space Business' is beset with abbreviations and acronyms, and this Report, since it presents a survey of nearly 60 organisations, uses many, many of them. Some of those that are highly specific to a particular technology have not been included in the following list, but most of the generic ones have been.

ABSL	AEA (Atomic Energy Authority) Battery Systems Ltd
ACS	Attitude Control System
ADS-P	Airbus Defence and Space, Portsmouth site
ADS-S	Airbus Defence and Space, Stevenage site
ADTM	Antenna Deployment and Trim Mechanism
AEL	Airborne Engineering Ltd
AIG	Astronomy Instrumentation Group (Cardiff Univ)
AIT	Assembly Integration & Test
AIV	Assembly Integration & Verification
ALM	Additive Layer Manufacturing (3D printing)
AMU	Atomic Mass Unit
ASDEC	Advanced Structural Dynamics Evaluation Centre (Leicester Univ)
ASIC	Application Specific Integrated Circuit
ATEX	ATmosphère EXplosibles (EU Directive for equipment in explosive atmospheres)
AVS-UK	Added Value Solutions (UK branch of Spanish company)
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CCD	Charge-Coupled Device (imaging detector)
CCDS	Concurrent and Collaborative Design Studio
CCSI	Centre for the Calibration of Space Instrumentation (RAL Space and NPL)
CDE	Centre for Defence Enterprise
CDF	Concurrent Design Facility
CEOI-ST	Centre for Earth Observation Instrumentation and Space Technology
CERN	Conseil Européen pour la Recherche Nucléaire
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Plastic
CISPR	Comité International Spécial des Perturbations Radioélectriques
CMM	Co-ordinate Measuring Machine
CNC	Computer Numerically Controlled (lathe or milling machine)
COMSAT	COMmunications SATellite
COSHH	Control Of Substances Hazardous to Health
COTS	Commercial Off The Shelf (parts or components)
CSO	Composante Spatiale Optique (French military reconnaissance satellite)
CT	Computer Tomography (3D X-ray imaging)
CTE	Coefficient of Thermal Expansion
CVT	Continuously Variable Thrust (rocket engine)
DAQ	Data AcQuisition
DCL	Declared Components List
DHMR	Dry Heat Microbial Reduction (to avoid contamination of parts for planetary protection)
DLA	Defence Logistics Agency (US radiation effects agency)
DLI	Dual Layer Insulation (thermal protection)
DoF	Degrees of Freedom
DPA	Destructive Parts Analysis
DSRS	Dundee Satellite Receiving Station
DUT	Device Under Test
EAL	European Astrotech Ltd
ECIT	Institute of Electronics, Communications and Information Technology (at QUB)
ECR	Electron Cyclotron Resonance (thruster)
ECSAT	European Centre for Space Applications and Telecommunications (Harwell)
EDM	Electrical Discharge Machining
EDS	Electron Dispersion Spectrometry
EEE	Electrical, Electronic and Electro-mechanical (parts or components)
EGSE	Electrical Ground Support Equipment
EM	Engineering Model (of a satellite subsystem or instrument)

EMC	Electro-Magnetic Compatibility
EO	Earth Observation
EOCF	Earth Observation Characterisation Facility (Imperial College)
EOS	Electro-Optic Sampling
EP	Electric Propulsion
ESA	European Space Agency
ESD	Electro-Static Discharge
ESR Technology	Engineering, Safety and Risks (originally of UKAEA) space tribology company
ESRF	European Synchrotron Radiation Facility (Grenoble)
ESS	Environmental Stress Screening
ESTEC	European Space Technology Centre
ESTL	European Space Tribology Laboratory (within ESR Technology Ltd)
ESQ	Early Stage Qualification
EU	European Union
EUT	Experiment Under Test
FDIR	Fault Detection, Isolation and Recovery
FEA	Finite Element Analysis
FIR	Far Infra-Red
FM	Flight Model (of a satellite subsystem or instrument)
FPGA	Field-Programmable Gate Array (microchip)
FSS	Frequency Selective Surface (tuneable antenna)
FTIR	Fourier Transfer Infra-Red (spectroscopy)
FWHM	Full Width Half Maximum
GEO	Geostationary Earth Orbit
GFRP	Glass-Fibre Reinforced Plastic
GMP	Geostationary Mini-satellite Platform (of SSTL)
GNSS	Global Navigation Satellite System
GSE	Ground Support Equipment
GSTP	General Support Technology Programme (of ESA)
GTRC	Gas Turbine Research Centre (Cardiff Univ)
HCT	Hollow Cathode Thruster (EP)
HDLT	Helicon Double Layer Thruster (EP)
HEPA	High Efficiency Particulate Air (filter for cleanrooms)
HPA	High Power Amplifier
HRAF	Harwell Robotics and Autonomy Facility
HPOC	High Pressure Optical Chamber
HSE	Health and Safety Executive
HTP	High-Test Peroxide (high concentration peroxide rocket fuel)
HTPB	Hydroxyl-Terminated Poly-Butadiene (rocket fuel)
IGS	Innovation and Growth Strategy
ILL	Institut Laue Langevin (neutron research in Grenoble)
IMDG	International Maritime Dangerous Goods (code)
IP	Intellectual Property
IR	Infra-Red
ISP	International Space Propulsion
ISVR	Institute of Sound and Vibration Research (Univ of Southampton)
ITAR	International Traffic in Arms Regulations
IUT	Item Under Test
JAXA	Japan Aerospace eXploration Agency
JUICE	JUpiter ICy moons Explorer (ESA mission)
JWST	James Webb Space Telescope
KERMA	Kinetic Energy Released per unit MAss (radiation dosimetry)
LDA	Large Deployable Antenna
LDA	Laser Doppler Anemometry
LEAF	Large European Acoustic Facility (ESTEC)
LEEP	Large European Electric Propulsion (chamber)
LEO	Low Earth Orbit
LIDAR	Light Imaging Detection And Ranging (distance measurements)
LMSCC	Lockheed Martin Space Systems Company
LN2	Liquid Nitrogen
LOX	Liquid OXygen
LPDA	Log Periodic Dipole Antenna

MAIT	Manufacture, Assembly, Integration and Test
MEMS	Micro-Electro-Mechanical Systems
MEO	Medium Eccentric Orbit
MGSE	Mechanical Ground Support Equipment
MLI	Multi-layer insulation
MMIC	Monolithic Microwave Integrated Circuit
MSF	Molecular Spectroscopy Facility (at RAL)
MSL	Mars Space Ltd (Southampton EP company)
MSSL	Mullard Space Science Laboratory (of UCL)
MWIR	Medium Wavelength InfraRed
NASA	National Aeronautics & Space Administration
NDT	Non-Destructive Testing
NF	Near Field (antenna)
NIACE	Northern Ireland Advanced Composites and Engineering Centre, Belfast
NOX	Nitric Oxides (various)
NPL	National Physical Laboratory
OBDH	On-Board Data Handling
OGSE	Optical Ground Support Equipment
OSS	Oxford Space Systems
OU	Open University
PCB	Printed Circuit Board
PDA	Phase Doppler Anemometry
PDF	Precision Development Facility (at RAL)
PEEK	Poly-Ether Ether Ketone
PIM	Passive Inter-Modulation (RF testing)
PIV	Phase-resolved particle Imaging Velocimetry
PMP	Parts, Materials and Process (management)
PPT	Pulsed Plasma Thruster
PRF	Pulse Repetition Frequency
PSD	Power Spectral Density
PVD	Physical Vapour Deposition
QAMEC	Queen's Advanced Micro-Engineering Centre (QUB)
QCM	Quartz Crystal Micro-balance (thruster measurement)
QCT	Quad-Confinement Thruster (EP)
QUB	Queen's University Belfast
RAL	Rutherford Appleton Laboratory
R&D	Research and Development
RAM	Resonant Acoustic Mixing (of solid rocket propellant)
RAM	RF Absorber Material
R&T	Research and Technology
REACH	Registration, Evaluation, Authorisation and restriction of CHemicals
REF 2014	2014 Research Excellence Framework (university research ranking)
REL	Reaction Engines Ltd
RF	Radio Frequency
RGA	Residual Gas Analyser
ROE	Royal Observatory Edinburgh
SABRE	Synergetic Air-Breathing Rocket Engine
SADM	Solar Array Drive Mechanism
SAR	Synthetic Aperture Radar
SCAPA	Scottish Centre for the Application of Plasma-based Accelerators
SEL	Single Event Latch-up
SEM	Scanning Electron Microscopy
SEU	Single Event Upset
SLM	Selective Laser Melting (manufacturing)
SME	Small & Medium Enterprise
SRC	Space Research Centre (Univ of Leicester)
SRS	Shock Response Spectrum
SSC	Surrey Space Centre (of Univ of Surrey)
SSD	Source to Surface Distance (radiation testing)
SSTL	Surrey Satellite Technology Ltd
STEM	Science, Technology, Engineering and Maths (teaching)
STFC	Science and Technology Facilities Council

TAS-UK	Thales Alenia Space – UK part
TDS	Time Domain Spectroscopy
TID	Total Ionising Dose (of radiation)
TQCM	Total Quantity of Condensable Material
TRL	Technology Readiness Level
TVAC	Thermal VACuum
TVC	Thrust Vector Control (of rocket engine)
TWI Technology	The Welding Institute Technology Centre (materials joining technology)
UAV	Unmanned Aerial Vehicle
UHF	Ultra-High Frequency
UKAS	UK Accreditation Service
UKSA	UK Space Agency
USW	University of South Wales (Newport)
UTIAS-SFL	University of Toronto Institute for Aerospace Studies – Space Flight Laboratory
VHF	Very High Frequency
VHM	Vector Helium Magnetometer
VLWIR	Very Long Wavelength Infra-Red
VNA	Vector Network Analyser
XRF	X-Ray Fluorescence