Institution: Aberystwyth University

Unit of Assessment: 10 Mathematical Sciences

a. Overview

The Department of Mathematics and Physics (DMAP) at Aberystwyth University (AU) has a research environment that strongly encourages inter-disciplinarity, and active cross-fertilization between mathematics and physics is straightforward. The department's staff have been awarded over 5 million pounds in research funding and have published over 400 peer-reviewed journal papers during the census period. Each of the two mathematics research groups contains staff with distinct disciplinary backgrounds, leading to a vibrant and unique research culture:

The **Mathematical modelling of Structures, Solids and Fluids** group (MMSSF) includes Cox, Davies (ECR), Flikkema, Greenall (ECR), Mishuris, Mughal (ECR), Vellender (ECR), Wrobel (ECR), and two Marie Curie Professors (Rogosin, Slepyan). Their interests cover diverse problems in solid and fluid mechanics, including (i) elasticity, biomechanics, plasticity and viscoplasticity, with Aberystwyth becoming a centre for the Wiener-Hopf method, and (ii) the structure and rheology of complex fluids, including foams and granular materials and polymer self-assembly. Approaches include modelling, accurate mathematical analysis, numerical simulation, and experiment. DMAP staff undertaking **mathematical modelling of solar phenomena** are submitted to Physics (UoA 9). Several staff have membership of other research groups in AU, particularly Materials Physics (MP). Flikkema, who works with Cox and Mughal on numerical optimisation, is returned with the MP group to UoA 9. Mishuris works with the MP group on ceramics, Cox and Davies work with AU computer scientists on visual computing, and Mughal works with AU biologists on cereal grains.

The Aberystwyth **Quantum Structures, Information and Control** group (AQStIC) includes three permanent staff – Burgarth, Gohm, Gough. They work in the area of quantum systems in interaction with their environment, and in particular the emergent field of quantum control engineering. This is a highly interdisciplinary field incorporating ideas from information theory, (non-commutative) stochastic analysis, mathematical physics for open quantum systems, and modern control theory. The group has an expertise in functional analysis and operator theory which it applies to practical quantum models. Gough and Burgarth are also members of the Materials Physics research group, and Burgarth is returned to Physics (UoA 9), emphasizing the link between the mathematics of quantum systems and their realization.

All mathematics staff are engaged in international collaborative research. The Wales Institute of Mathematical and Computational Sciences (WIMCS), initially funded by HEFCW, has provided an umbrella for mathematics research in Wales during the census period, and staff have engaged with its aims, organised and participated in its cluster activities, and served on its various steering committees.

b. Research strategy

DMAP's aims are to grow and strengthen both mathematics research groups by

Aim 1: producing and publishing high-quality research and growing research income streams;
Aim 2: recruiting and training junior researchers;
Aim 3: offering staff the time and money to exploit the interdisciplinary environment;
Aim 4: expanding international collaboration and organising and international conferences.

Aim 1. Mathematics staff have published over 150 peer-reviewed papers in international journals during the census period. All research-active staff are expected to seek relevant external funding to support their work. **Annual research spend** in mathematics has now increased dramatically to as much as half a million pounds per annum; funding from RCUK awards, for example Gohm's EPSRC grant on Operator Theory (£245k) and Cox's EPSRC Advanced Fellowship (£450k), has been supplemented by European FP7 awards. For example, Mishuris has exceeded his £400k target as a professorial WIMCS appointment: he is now core-funded by AU with a **research funding portfolio** that includes collaborative FP7 projects with industry on hydraulic fracture (total €1.5M), parametric resonance (total €2.4M), and the design of ceramics (total €1.8M), and individual Marie Curie fellowships, coordinating Argatov's project on modelling arthritis and

Piccolroaz's project on fracture mechanics (€200k each). He is PI on two further FP7 projects (one ITN and one IRSES) starting in 2014. Our other WIMCS appointment, Mughal, has received Science Foundation Ireland funding for an international conference in Dublin.

We plan to further **increase research income** using our increasing experience with European funding schemes and with large collaborative research projects that include industry and SMEs. We will target Marie Sklodowska-Curie actions in Horizon 2020, seek opportunities for commercialisation and industrial secondments, and increase internal (AU) collaborations, not only with physics (quantum control and numerical optimization) and computer science (visualisation of scientific data), but with biological sciences (modelling of granular materials), health sciences, and physical geography (carbon sequestration) for example.

Aim 2. In DMAP we aim to recruit and train **junior researchers** both through the replacement of retiring staff and partly through external funding. The 8.3FTEs returned in 2008 has now increased to 10.75. We have used funding from the Coleg Cymraeg Cenedlaethol and WIMCS to help support full-time members of staff, and used money from EU FP7 projects and RCUK sources for teaching buy-out to allow our top researchers to concentrate on research projects. Our training programme includes help in developing research proposals and on good practice in the management of research grants, as described in part **c** below.

Aim 3. DMAP runs a **research leave** scheme, described below in part **c**. Internal funding for research and research travel comes from the AU conference fund and the AU research fund (which both prioritize ECRs). In addition, DMAP makes available a travel fund (which prioritizes new collaborations), summer fellowships for distinguished visitors, and PhD studentship funds.

From August 2013, DMAP will work more closely with the Department of Computer Science (DCS) in a new Institute (IMPACS) that will enable yet further active cross-fertilization between the three areas of mathematics, physics and computer science.

Aim 4. More than half of the mathematics we publish is achieved through **international collaboration** with colleagues in Europe, the US, and Australia. This will be continued through targeted use of the DMAP travel fund and the research leave scheme. Mathematics conferences and workshops in Aberystwyth, described in part **e**, have attracted leading mathematicians from all over the world. DMAP staff have also organised many meetings in the UK and Europe, including at the Isaac Newton Institute for Mathematical Sciences in Cambridge, the ICMS in Edinburgh, and Oberwolfach in Germany.

These four aims are described in a DMAP strategy document which is updated biennially with the aim of assisting the department and the research groups to develop research capacity and research of world-leading quality, to integrate the activities of mathematics and physics for mutual benefit, and to address the strategic priorities of the Research Councils and other funding bodies, by appropriately emphasising academic, social and economic impacts of the research. This process is coordinated by the **department's Research Committee** (RC), which consists of research group leaders and the Head of Department, with frequent co-opting of other staff, ensuring an easy route to the proposal of strategic interdisciplinary projects.

The delivery of the research strategy is monitored by the RC through data collected in the University's Current Research Information System (PURE) and bi-annual monitoring meetings between individual staff and the Head of Department and DMAP Director of Research. In these meetings we identify and refine key indicators to monitor the performance of individuals and groups, including research outputs, grant income and research student supervision, paying particular attention to both the quantity and quality of such indicators. The RC regularly refines the policy on research grant application and management, which helps to improve our profile of grant application successes. This information feeds into regular departmental monitoring meetings with the University Research Committee.

The University's Research Office has received further investment during the census period to

provide an improved support service to researchers, including (particularly interdisciplinary) grant development and application, improved research finance processes, large research-intensive project management, and coordination of REF and Research Monitoring. In July 2013 the Research Office merged with the University's Enterprise Office to create the Department of Research, Business & Innovation (DRBI). With a combined staff of fifty, the department delivers integrated and proactive research and enterprise development services.

Strategic objectives for Mathematics, progress in the current census period, and future directions are summarised as follows:

The **AQStIC** group's research on **Classical and Quantum Stochastic Optimal Control** has been successful in the areas of quantum networks, in which a PhD student graduated during the census period, and quantum coherent feedback control, gaining recognition in the quantum physics community. The group benefited from Burgarth's appointment, widening the scope of the group by adding various aspects of quantum computation, in particular **system identification and controllability**. The group's combined skills in mathematics with applications in physics are a key strength, and are considered a key area for future growth. In addition, links with computer scientists in AU will be forged, for example in areas such as quantum computation.

The group seeks now to characterise **controllability in noisy quantum systems**, i.e. quantum dynamical semigroups. The mathematical background to this work is related to research in **operator algebras and mathematical physics,** typified by Gohm's EPSRC grant. Working with a PDRA, Gohm developed applications of braid group representations via non-commutative de Finetti theorems. Further work on operator algebras has been undertaken with higher rank graphs and associated C*-algebras. The group is continuing to organise regular international workshops in Aberystwyth, attracting many distinguished participants (see part **e**).

The **mathematical modelling** (MMSSF) group has been active in both **solid and fluid mechanics**, with some overlap**,** for example Cox and Mishuris' work on mean curvature flows**.**

Two PhDs have graduated in the area of **nonlinear analysis** and optimization. Mishuris and Wrobel (Marie Curie Fellow and research lecturer), with funding from the FP7 project HYDROFRAC, are using analysis of crack propagation and fracture to provide **efficient numerical solvers** for the oil industry. Related work on PDEs, singular integral equations, **Wiener-Hopf Theory**, and **multi-scale asymptotic methods** was boosted by two Marie Curie staff, hosted by Mishuris: Piccolroaz (Italy) worked on crack propagation in heterogeneous materials and Argatov (Finland) on biomechanics and osteo-arthritis. Mishuris continues to work with both of them on extensions to these projects. Vellender gained his PhD on the asymptotic analysis of PDEs in irregular domains and is now a Research Lecturer**,** extending this work to **imperfect interfaces**. Slepyan, who previously visited in 2010 and 2012, is developing models of vibrating machines and lattice-type structures, in collaboration with engineers in industry.

In research on **complex fluids**, Cox has shown that quasi-static models of foam flow accurately reproduce slow experiments and now seeks to develop models of **dissipative systems** and the dynamics of fast flows. Davies, who has been appointed to a five year lectureship, has explained how objects falling through a foam interact, and this work is now being extended to non-spherical **three-dimensional** objects. They are collaborating with computer scientists on visualisations of foam rheology, through the pan-Wales RIVIC project in visual computing. Two PhD students graduated in this area during the census period, and the group's simulations have been used in collaborative work published with biophysicists, chemical engineers, and pure mathematicians. The recent addition of Greenall to the group, brings expertise in mean-field modelling of complex fluids.

Mughal, employed initially by WIMCS and now fully-funded by AU, has used analysis and numerical experiments with hard-spheres packed in cylindrical channels to reveal a hierarchy of **densely packed arrangements**, and he is now exploring the role of topological defects in complex fluid rheology. His work has recently attracted funding from plant scientists, interested in the packing and settling of grains, opening the door to further research collaboration in the biological

sciences. Working with AU physicist Flikkema, Cox and Mughal have developed numerical conjectures about the optimal (least perimeter) arrangement of two-dimensional bubbles in the plane and are beginning a **combinatorial enumeration** of candidates.

c. People, including:

i. Staffing strategy and staff development

DMAP's staffing strategy is to retain, develop and reward staff and to further recruit researchers in the research groups with a commitment to undertaking high quality research. We aim to make appointments that can transcend disciplinary boundaries, particularly between mathematics, physics and computer science. Since RAE2008 the number of staff is almost unchanged, and a recruitment round is currently underway that includes two posts in Mathematics.

New appointments since 2008 are Burgarth (open-ended contract), Davies (5 year contract as a Welsh-Medium Mathematics Lecturer, part-funded by the CCC, the Welsh Federal College), Greenall (2 year lectureship), Mughal (open-ended contract as a lecturer in mathematical modelling, initially part-funded by WIMCS), Vellender (4 year contract as a research lecturer, based on teaching buy-out for Mishuris), and Wrobel (Marie Curie Fellow, with a 2.5 year follow-on research lectureship). In addition, Slepyan and Rogosin joined DMAP in 2013 as research professors in Marie Curie positions. Cox was promoted to a personal chair in 2011.

DMAP hosts two retired but research-policy-active Fellows of the Royal Society, Profs Houghton and Walters. The larger unit formed by the merger of Mathematics and Physics benefits from their advice and guidance on national and international initiatives, and on grant applications. Other emeritus staff include Mavron and McDonough, both active in algebraic combinatorics.

We have recruited international staff from Italy, Poland, Russia, Israel and Belarus since 2008. Two staff submitted to RAE2008 have returned to their countries of origin (Sweden, Portugal; both were WIMCS fellows with 2-year appointments) and another moved to a permanent lectureship in Kent. PDRAs have come from the UK, Russia, and the United States, and those that have left have been appointed to a PDRA position in France, and to lectureships in the UK and Ireland.

DMAP mathematicians have initiated strong links with Poland (Rzeszow University of Technology and the SME EuroTech, Wrobel's previous employer) and Italy (Trento University and the SME Enginsoft), with frequent exchanges of staff (five staff outgoing, four staff incoming) and research students of up to a month each. The department has also hosted Marie-Curie fellows from Italy (24 months) and Finland (24 months).

All staff are expected to complete three days of personal **staff development and training** each year, including courses run locally (by AU's DRBI and Centre for the Development of Staff and Academic Practice) or elsewhere. Early- and mid-career researchers are encouraged to lead research projects and to take on leadership positions within the department, acquiring experience and expertise that will consolidate the sustainability of the research environment. Staff development is supported by regular research planning and monitoring meetings and peer advice on research proposals.

The DRBI run a compulsory course on financial management of research grants. ECRs are each assigned a mentor from among the senior staff in their research group, who advise on grant application processes, university procedures, etc. during the probationary period of 3 years. Applications for promotion are encouraged, and we now use a new University mentoring scheme for candidates for promotion to senior lecturer and reader.

Strategies for identifying research opportunities, developing applications, and generating grant income involve support at both a departmental level, using the expertise of senior staff and research groups for compulsory peer-review to help younger colleagues to target project ideas for funding, and at a University level, through the DRBI. The latter offers resources including an internal library of successful grant applications, and facilitation of strategic bids for large research grants.

DMAP operates a **research leave** scheme for all academic staff, for one semester in eight, subject to an appropriate research plan for the leave period, enabling intense periods of research, the development of research grant applications, and writing of major pieces of work. The research leave policy also provides for buy-outs funded by external grant income. Successful use of research leave is monitored and informs future decisions on leave allocation.

DMAP is committed to implementing the Concordat to Support the Career Development of Researchers, and the university received HR excellence in research awards in 2010 and 2012. Research staff are assigned mentors within their research group, complete a probation agreement with targets for publications and conference presentations, and are encouraged to engage in internal and external professional development courses. Burgarth was selected for the 2013 round of the Welsh Crucible, a competitive HEFCW-funded initiative leadership development programme.

Standards of research quality and integrity are articulated in the Aberystwyth University Policy on Safeguarding Good Research Practice. All staff receive equal opportunities training before serving on interview panels, and the University is currently applying for Athena Swan status.

ii. Research students

To enrich the Department research community and culture, we actively seek to increase the number of PGR students. We acknowledge that there are limited funding opportunities for PGR students and the Department therefore offers postgraduate scholarships to attract outstanding international and home students, in addition to the full Doctoral Career Development Scholarships jointly offered by the University and the Department. Additional funding has also come from both RCUK and FP7 sources.

Research students are selected on the basis of an application form and research proposal, and are expected to have achieved a 2:1 degree or equivalent. All PhD students are given office space and a desktop computer. They are assigned both a main and a second supervisor, the latter often from a complementary discipline. Academic training is provided through regular research seminars given by internal and prominent external speakers, at regular research group meetings, and through giving research presentations to all students and staff at an annual event. Further research training and skills development is provided by the University, in a compulsory first year 20-credit generic postgraduate skills module, which includes courses on LaTeX and Linux, reading, writing and presentation skills for research, and also careers advice.

Research students are offered the opportunity to contribute to teaching, for example by delivering problem classes and a help-desk. They gain experience in conference organisation by assisting with the meetings that we organise (see part e), and in public engagement activities by making short presentations during school visits and university open days. Three of our current PhD students have been seconded to industry, and opportunities for longer secondments both to industry and to overseas universities now exist.

Progress is monitored annually, and satisfactory progress after 1 year is a necessary pre-requisite to move from the MPhil to the PhD programme. The monitoring takes the form of reports from the student, both supervisors, and the Head of Department, confirming that progress is being made and that the future direction of the project is clear and understood by the student. This is assessed by a board of academic staff from DMAP, who interview all students annually, and is then ratified at university-level. Destinations of PhD students include PDRA positions, teaching posts in schools and universities, and jobs in software engineering. During this census period, the submission rate was 100%.

d. Income, infrastructure and facilities

Research **income** has risen from the £85k reported for RAE2008 to £1.7m, mainly from FP7 and RCUK sources.

This income is supplemented by **consultancy** services with a range of companies. The research expertise of staff is available on university webpages, including AU's directory of expertise, leading to (i) formal links, with non-disclosure agreements, such as with BTG International on medical uses

of foams; (ii) collaborative academia-industry grants, such as with SINTEF on hydraulic fracture and with Procter and Gamble on sudsing; (iii) informal links that have arisen through public presentations and private communications, such as the characterisation of paints and oils (Honeywell) and advice on broadcasting (e.g. for the BBC). Another aspect of our provision is open source, bespoke software (e.g. for the prediction of hydraulic fracture).

Specialist infrastructure and facilities: DMAP hosts a 128-node Beowulf high-performance computing cluster, accessible to all staff and students for modelling and simulation, paralleling the provision by HPC Wales. Further **investment** has centred around improved backup and storage facilities in 2013. This is complemented by desktop PCs in all offices, which are replaced on a rolling basis, ten 3D stereo desktop PCs distributed between offices and a dedicated computer lab in DMAP, and a 3D stereo "wall" with infiniband connection to the compute cluster. The computer facilities are overseen by members of IMPACS technical staff.

A £0.5M upgrade to IMPACS' shared mechanical workshop facilities, funded by AU and HEFCW and announced in 2012, will co-locate all technical and research facilities for mathematics, physics and computer science within the Physical Sciences building, improving support for experimental activities in complex fluids, foams and granular materials upon completion.

The Physical Sciences building, in which all DMAP staff and laboratories are based, contains a branch of the university library dedicated to Mathematics, Physics and Computer Science, with both books and periodicals. All important journals are available there, with online access to an even wider set of journals. Further journals are available in the National Library of Wales, a legal deposit library adjacent to the campus. In addition, the department hosts the Scott Blair Collection of books and papers on rheology, on behalf of the British Society of Rheology.

Experimental research on complex fluids, granular materials and foams is based in the rheology laboratory. Facilities include three rotational rheometers, a capillary rheometer, and a Vision Research Phantom V7.3 colour high speed camera. These facilities are supported by a mechanical workshop employing two staff, and an electronic workshop employing two staff.

e. Collaboration or contribution to the discipline or research base

Our **collaborative** projects are truly international: Mishuris has joint grants with companies and academics in the US, Norway, Italy, Israel, Poland and several countries in the Former Soviet Union, including a programme of research secondments both to and from Aberystwyth; Cox published a research monograph with colleagues in France in 2013; Gough has strong links with Australia (James, Nurdin), with reciprocal visits funded by LMS and EPSRC. In a UK context, Cox's involvement in an EPSRC P&G strategic partnership also involved groups in Manchester and Imperial, Mishuris' FP7 grant PARM-2 includes groups in Loughborough and Liverpool. More than two-thirds of our publications during the census period include a collaborator outside AU.

Senior (professorial) visiting scholars have been funded by the Royal Society, the LMS, EU FP7 projects and by DMAP itself. Examples include D. Bigoni (Trento, Italy, 2008, 2010), M. James (Australian National University, 2012), J.D. Key (Clemson, Cape Town and AU honorary professor; annually), B. Kümmerer (Darmstadt, 2012), V. Kushch (National Academy of Sciences of Ukraine, 2013), H. Maassen (Radboud University, 2012), R. McPhedran (Sydney University, 2012), E. Radi (Reggio Emilia, 2012), W.R. Rossen (Delft, 2012), M. Schürmann (Universitaet Greifswald, 2012), I. Sevostianov (New Mexico, 2013), M. Shikrande (Central Michigan, 2010), F. Stachowicz (Rzeszow, 2012), D.L. Weaire FRS (Trinity College Dublin, 2008, 2011, 2013).

Mathematics staff have played, and continue to play, a leading role in WIMCS, with colleagues in Bangor, Cardiff, Swansea, and Glamorgan (South Wales). This includes the organisation of meetings and workshops, and serving on the cluster steering committees and research committee. DMAP is supporting this initiative through staff salaries and funding for travel. Mathematicians also collaborate with computer scientists throughout Wales in another initiative, the Research Institute for Visual Computing (RIVIC).

Several DMAP staff have served on EPSRC **grant-awarding panels** during the census period. In

addition, Mishuris was on grant-awarding panels for the Slovak Research and Development Agency (2008-09), the Israel Science Foundation (2010, 2012), FP7 ERC (2011), the Einstein Foundation Berlin (2012), and the New Eurasia Foundation, Government of the Russian Federation (2012).

Cox is Honorary Secretary of the British Society of Rheology (since 2011) and a council member (since 2009). Mishuris is a member of the Steering Committee of the Health Modelling Centre Cymru (hmc²) and the WIMCS Research Committee, and Cox and Mishuris are both on the Steering Committee of the Computational Modelling Cluster of WIMCS. Walters, a Distinguished Research Fellow in DMAP, is a member of the Science Advisory Council for Wales. During the census period, Cox was elected a Fellow of the IMA (2010) and of the Learned Society of Wales (2013), and Mishuris was elected a member of the International Society for the Interaction of Mechanics and Mathematics (2011).

Staff have been **principal organisers of conferences** in the UK, including a Royal Society discussion meeting on Principles and Applications of Quantum Control Engineering (2012). At ICMS, Mishuris led a "Research in Groups" project on singular problems in mathematical elasticity and Cox organised a meeting on isoperimetric problems (2012), while Gohm undertook "Research in Pairs" at Oberwolfach (2008). Two workshops at the Isaac Newton Institute, on Quantum Control Engineering and Foams and Minimal Surfaces, will be organised in 2014. Elsewhere in Europe, staff have organised CECAM-funded meetings on the rheology (Dublin, 2012) and coarsening (Paris, 2013) of foams, an SFI-funded meeting on Packing Problems (Dublin, 2012) and an FP7-funded workshop on Recent advances in numerical simulation of hydraulic fracture (St Petersburg, 2013). Burgarth has embraced social media, and his Q+ hangouts at quantiki.org have 2600 followers on Google+.

In a Welsh context, partly through our involvement in WIMCS we have organised many international joint **workshops and conferences** in Aberystwyth, many with LMS funding, on subjects including the Wiener-Hopf Method (2010, 2012), Stochastic Processes at the Quantum Level (2009), Representations of Braid and Symmetric Groups (2011), Quantum Probabilistic Symmetries (2012, including an LMS regional meeting with guest speaker Voiculescu), the first Summer School on Quantum Information, Computing and Control (2012, co-sponsored by the Imperial CDT), and Classifying Structures for Operator Algebras and Dynamical Systems (2013). Aberystwyth has played a full part in the annual Gregynog Wales Mathematics Colloquium, organising in 2008 and 2012, the WIMCS Annual Meeting was hosted in 2008, and we will co-organise the 2014 BAMC in Cardiff.

DMAP staff have **attended** over one hundred conferences and workshops since 2008. **Invited keynote and plenary lectures** by mathematicians include: Eufoam (Netherlands, 2008), Mechanics of time-dependent materials (Slovenia, 2010), ICM-Satellite Conference on Quantum Probability (Bangalore, 2010), The Armourers and Brasiers Cambridge Forum (Cambridge, 2011), IUTAM Symposium on Mechanics of Liquid and Solid Foams (Texas, 2011), Analytical Methods of Analysis and Differential Equations (Minsk, 2012).

Mathematics staff are on the **editorial boards** of Functional Analysis and Other Mathematics (Gough, DATES), ISRN Applied Mathematics (Mishuris, since 2010), Journal of Mathematics and Applications (Mishuris, since 2007), and Journal of Engineering Mathematics (Cox, since 2011).

In 2011, recognising his many contributions to mathematics, Mishuris was awarded a Belvedere professorship by the President of Poland. A personal **Research Fellowship** was awarded to Cox (EPSRC Advanced Fellowship, 2006-2011). Mishuris has honorary positions in Liverpool and Burgarth at Imperial. Two Marie Curie individual **fellowships** (Argatov, Piccolroaz) were hosted from 2010-2012, and Greenall came from an individual Marie Curie fellowship in Strasbourg (2010-2013). In addition, long term **fellowships** are associated with FP7 Marie Curie IAPP grants: HYDROFRAC (Experienced: Wrobel; More Experienced: Rogosin), INTERCER (Experienced: Zagnetko) and PARM-2 (More Experienced: Slepyan), as well as short-term visiting fellowships paid jointly by FP7 project-partners and AU.