Institution: University of Liverpool

Unit of Assessment: 10 Mathematical Sciences

a. Overview

The **Department of Mathematical Sciences** is part of the **School of Physical Sciences**. It initiates and supports research activities through **five research clusters**: **Pure Mathematics, Applied Mathematics, Theoretical Physics, Statistics and Probability, Financial and Actuarial Mathematics**. Focused research groups within these clusters are as follows:

- Pure Mathematics – *Dynamical Systems*, *Singularity Theory*, *Algebraic Geometry*;
- Applied Mathematics – *Waves and Solid Mechanics*, *Mathematical Biology*;
- Theoretical Physics – *String Phenomenology*, *Quantum Field Theory and Applications*.
- The cluster Statistics and Probability operates as one group, as does Financial and Actuarial Mathematics.

Research activities are enhanced through four interdisciplinary Research Centres: the Research Centre for Mathematical Imaging Techniques **(CMIT)**; the Research Centre in Mathematics and Modelling **(RCMM)**; the Environmental Radioactivity and Modelling Research Centre **(ERRC);** and the Institute for Financial and Actuarial Mathematics **(IFAM)**.

b. Research strategy

Key principles of the research strategy are: (i) to support and develop sustainable research clusters in order to maintain critical mass and carry out world-leading research; (ii) to empower staff to conduct outstanding research to fully engage in the Department's research activities and produce internationally competitive publications; (iii) to develop pathways to impact and enhance collaborative and interdisciplinary work through research centres; (iv) to connect to priority research themes of UK Research Councils (EPSRC, STFC, NERC, BBSRC) and to the strategic research plan of the University of Liverpool.

(i) Support and development of sustainable research clusters. The Department recognises its academics as its greatest resource; it strongly supports and seeks to develop newly appointed staff to ensure they realise their potential (an approach exemplified by the recent promotion of L. Rempe-Gillen, appointed as Lecturer in 2006, to a Personal Chair in 2012). A strong sense of community is created through seminar series and interaction between senior academics (e.g. Prof **Rees** FRS) and younger members of staff who often already have outstanding track records (e.g. **Rempe-Gillen**, and **Hall**, both winners of the Whitehead Prize from the London Mathematical Society). A new appointment in Singularity Theory (**Karpenkov**) is part of our plan to maintain a high international standing in this area, in which the Department has a long and distinguished history. A recently appointed lecturer in Algebraic Geometry, (**Pagani**), similarly brings new blood to a group already enjoying a strong international reputation. New appointments in Theoretical Physics (TP) and Applied Mathematics (AM) include **Gorbahn** (TP) and **Thompson** (AM). These staff support the areas of Quantum Field Theory and Mathematical Modelling of Wave Phenomena, where the Department has a strong international standing. Since RAE2008, the Department has invested significantly in Probability, Statistics and Financial Mathematics with 10 new appointments, including the creation of the new research cluster in Financial and Actuarial Mathematics, which has already been successful in attracting a four year EU FP7 project.

(ii) Empowering staff to conduct outstanding research. Our dedicated academic staff members are the Department's greatest asset. We are committed to providing a stimulating research environment and enabling them to progress successfully in their careers. We provide support, advice and mentoring to researchers at every career stage, while offering them the freedom to develop their own independent research directions. The **Departmental Research Committee** plays a central organising role by initiating, monitoring and supporting research initiatives and leading an internal review process for research grant applications. Each research cluster is represented on the committee, ensuring that there is a direct route by which staff, as stakeholders in our research activities, engage with and are consulted on new initiatives.

(iii) Enhancing collaborative and interdisciplinary activity. The Department endeavours to

encourage, support and foster the contacts required for interdisciplinary research and collaborations through our well-established research centres as listed above. For example, CMIT attracts external funding from the NHS to support the development of novel algorithms in medical imaging and more generally high quality interdisciplinary projects in the interface between Life Sciences, Medicine and Mathematics. Interdisciplinary collaboration at School level and beyond is also encouraged and coordinated by the School Research Committee, the Faculty Research Strategy Group and the University Research Strategy Group (where Rempe-Gillen has been a Faculty representative since 2009). An example of such activity is the involvement of the Financial and Actuarial Mathematics cluster in the University's Risk and Uncertainty Institute, which is a major initiative involving 45 academic staff from 10 academic departments around the University.

(iv) Connecting to priority research themes of UK Research Councils. We encourage the development of connections with other disciplines and to industry, as promoted by UK Research Councils, in order to establish transformative and cross disciplinary research. We develop new pathways to impact to ensure that the significance and relevance of the mathematical sciences is recognised. The departmental and school recruitment policies are also aligned with RCUK research priorities. We connect to the RCUK societal challenge themes of Energy, Digital Economy, Living with Environmental Change and Global Uncertainties, and participate in three of the University's seven cross-cutting interdisciplinary Research Themes**:** Living with Environmental Change, Materials for the Future and Personalised Health (for which **K. Chen** acts as Faculty Champion). Highlights include the well-established *Environmental Radioactivity and Modelling Research Centre,* which has a significant impact in the analysis of environmental pollution; modelling of multi-scale metamaterial systems (in the framework of RCMM activities), which are used in the design of a new generation of solar batteries; and development of a strong connection with SERCO and AMEC to model localisation of defects in welded junctions of cooling contours of nuclear power plants (again with support from RCMM). Three industrial workshops have been organised by RCMM and held at the Department of Mathematical Sciences in Liverpool, all with strong participation from SERCO (Dr Will Daniels and his colleagues).

Development since RAE2008 and future research strategy. Since RAE2008, the organisational structure for the research in the Department has been substantially changed. Previously the unit was organised in four divisions, but has now moved to research clusters that ensure a coherent approach across the Department. In terms of investment, the Department has maintained the size of the research clusters and the quality of research in Pure Mathematics, Applied Mathematics and Theoretical Physics. In accordance with the research strategy principles outlined above, substantial investment has been made in the area of Probability and Statistics, and Financial Mathematics. This re-organisation has led to considerable success in competition for external research funding and has attracted an excellent cohort of research students, as evidenced below in sections c and d. The research centres listed above have also substantially developed since 2008 in accordance with our strategy of enhancing collaborative and interdisciplinary activity.

For the future, we plan to maintain the strength of clusters in accordance with the first key strategic principle above. We have also identified the following opportunities for development, which will enable further progress in implementing our strategic principles (iii) and (iv):

- Applied Mathematics: we plan to identify and attract a senior research leader to strengthen the Mathematical Biology area;
- Pure Mathematics: we plan to enrich this cluster with high quality appointments in Analysis to facilitate enhanced interaction with Applied Mathematics in the area of partial differential equations and nonlinear analysis.
- Financial Mathematics: we plan to invest further in this area to strengthen our involvement in the *Institute for Risk and Uncertainty*, which is a major interdisciplinary initiative involving academic staff from many areas across the University.

c. People, including:

i. Staffing strategy and staff development

There are two elements to our staffing strategy: the first concerns how we attract and recruit outstanding academic staff, and the second addresses how we ensure that staff are able to develop their career and experience a supportive and creative environment.

Recruitment. Our recruitment policy is aimed at ensuring that each research cluster has a healthy mixture of outstanding researchers at every level; ranging from early career researchers to experienced senior staff who provide leadership and mentoring. This occasionally means recruiting at a senior level where the cluster has been affected by a retirement or departure. Examples include the appointment of **Gorbahn** as a senior lecturer in Particle Physics Phenomenology (2012), and our plans described above to recruit at a professorial level in Mathematical Biology. More often we invest in the future by appointing promising researchers at junior level who can then develop their careers within our support structure. A guiding principle is that we appoint the best researchers in their field, which means that positions are advertised over broad research areas consistent with our cluster structure, rather than over narrow topics. Examples include the appointments of **Karpenkov**, **Pagani, Sharkey, Thompson**, and **Zhang**. Occasionally, we target recruitment for a specific strategic need, such as the provision of a mathematical contribution to the University's interdisciplinary Institute for Risk and Uncertainty (**Constantinescu**, **Siska**, **Papaioannou**, **Pamen**). In addition, we appointed two STFC Advanced Research Fellows, **Teubner** and **Tatar**, to permanent academic positions after they confirmed their sustained research potential. During the REF period, 14 new academic appointments have been made to enhance critical mass in all key areas across the Department, including Financial and Actuarial Mathematics, Pure and Applied Mathematics, Probability and Statistics, and Theoretical Physics. The Department's strong international reputation helps attract high-calibre researchers from all over the world, with recent appointments including **Gorbahn** and **Teubner** (Germany), **Karpenkov** (Russia), **Constantinescu** and **Tatar** (Romania), **Pantelous** and **Papaioannou** (Greece) and **Y.Chen** (China). Another high-profile international research appointment (EU-funded) at a senior level is **McPhedran** (Sydney, Fellow of the Australian Academy of Sciences).

Support and Development. The second principle of our staffing strategy is to provide all our academic staff with the training and development opportunities they require to fulfil their potential:

- We closely follow the RCUK coordinated *Concordat to Support the Career Development of Researchers*. This includes principles of recruiting, selecting and retaining academic staff, recognition of their contribution, strong support of staff in a diverse and global research environment, engagement in their career development, promoting the principles of diversity and equality as outlined below, and regular review of academic progress of academic staff.
- Each researcher and academic member of staff participates in the University's Professional Development and Review (PDR) process. On an annual basis, the process provides an opportunity for a collegial discussion that reviews progress against agreed key objectives and plans. The process empowers staff members to set and discuss their own objectives, as well as identify obstacles to progress, and hence to share responsibility for their own development, in accordance with the Concordat.
- In view of our strategy of appointing promising researchers at an early stage of their research career, particular care is given to ensure that early-career researchers receive the necessary support in their career development. A system of research mentorship pairs all newly appointed staff with experienced researchers, and has proved to be helpful and efficient. New staff also receive a reduction in their teaching duties while they establish their research careers at Liverpool. Special attention is also devoted to personal and professional development opportunities, which are readily available via a central University programme. Especially useful are grant proposal writing workshops attended by all newly appointed academic staff, and the University's recently developed *research team leadership programme* (attended by **Rempe-Gillen** and **Guletskii**). Research Committee makes it a priority to support early career researchers in attending conferences or organising meetings and research workshops. Examples include sponsored research visits by **Constantinescu**, **Karpenkov**, **Pamen**, **Siska**, **Thompson**, and a departmental

contribution to the sponsorship of high quality research workshops and conferences, involving and/or organised by early career researchers, in financial mathematics (**Pamen**, **Siska**, **Constantinescu**), and singularity theory (**Karpenkov**).

- More experienced researchers must likewise be supported in their career development and lifelong learning. Our strategy of maintaining viable and sustainable research groups ensures that staff have opportunities for obtaining advice and guidance on topics such as research management, publication strategies, research student supervision, grant applications, and all other aspects of academic life. In addition, Departmental and School leaders support senior academics as they take on new leadership roles at an institutional level and within the wider academic community.
- All academic staff are eligible to apply for research leave of one semester after no fewer than five semesters of teaching (a recent example is research leave by **Woolf** approved for 2013/14). Recent externally funded research leaves include a one-year stay by **Hall** in Brazil (San Paolo), and a two-year research leave for Prof L. Rempe-Gillen beginning July 2013. These periods of leave in other research centres are of significant benefit in establishing new directions of research and collaborations.
- The Department also benefits from the enthusiastic contribution of **honorary research fellows** as well as retired staff. Recent appointments as honorary research professors include Profs **Giblin**, **Morton**, **Maz'ya**, **Newstead**, **Bowers**, **A.Chen**, **Michael**; all international leaders in their fields who remain actively involved in the Department's vibrant research environment through their participation in seminars, interdisciplinary research projects and supervision of research students.
- The **visiting researcher programme** is supported and developed through the infrastructure of the RCMM, which offers pump-priming support and stimulates applications for external funding. The RCMM provides high-quality office accommodation for research visitors, a dedicated research discussion room and full access to computing and library facilities. The Department hosted more than 70 research visitors during the REF period; the list of recent visitors in 2013 includes Mulholland, Dasgupta, Anulova, Nasell, Loenne, Piccolroaz, and Gei.
- The Department strongly supports the **principles and policies of equality and diversity**. In particular, women in mathematical sciences are well represented by **Bearon**, **Y.Chen, Constantinescu**, **N. Movchan**, **Piliposyan**, **Pratoussevitch**, **Rees**, and **Zychaluk**. During the REF period **Bearon** and **Zychaluk** had maternity leave, and were carefully supported by the Department to enable them to combine family commitments and their academic work. **Constantinescu** has been selected for the Aurora leadership programme for women in high education run by the UK Leadership Foundation. The University has Athena SWAN Bronze status, and the School of Physical Sciences will apply for the Bronze award in 2014. **Constantinescu** and **Zychaluk** are members of the School Athena SWAN working group, and **Constantinescu** represents the School at the University Athena SWAN group.

The **success of the measures** that we have described above is evidenced by the research successes of our members of staff. These successes are recognised and valued by the Department, School and University by highlighting them in the School newsletter and our websites, and through working with the University's press office in promoting our work in the media. Departmental promotions during the REF period include: **Clancy**, **N. Movchan**, **Rempe-Gillen** (Personal Chair); **Guletskii**, **Liu**, **Pantelous** (Reader); **Bearon**, **Mohaupt**, **Pratoussevitch**, **Rakow**, **Woolf** (Senior Lecturer). A further example of the success of our approach of recruiting early-career researchers is **Constantinescu** (IFAM cluster), who has been strongly supported by the Departmental research strategy and development programme and secured a large-scale EU-funded FP7 research grant within 18 months of her appointment (see also Section b above).

ii. Research students

42 doctoral students have completed their degrees since 2008. We currently have 64 registered PhD students. PhD scholarships are funded through external grants (RCUK and EU Commission), DTAs, University Studentships (through the scheme of postgraduate teaching assistants), charity funding (e.g. the prestigious Duncan Norman Memorial scholarship), as well as overseas government funding and self-funding (mainly for overseas students). The University studentship

scheme is a recent addition to the Department, providing a minimum of four PhD studentships each year. In recent years, the number of overseas research students has grown, and has now exceeded the number of UK/EU research students trained by the Department of Mathematical Sciences.

The Department is committed to providing **high-quality training** for its research students. The arrangements include the **EPSRC-sponsored MAGIC Network of advanced courses**, as well as advanced modules in Mathematical Sciences delivered within the Department, and research seminars. MAGIC is a consortium of twenty leading UK Universities, using Access Grid videoconferencing technology. The lectures are delivered by world-class experts, and the scheme has proved to be effective, as well as very popular with students. At times, members of staff organise international postgraduate workshops at Liverpool (such as the 2008 *Complex Dynamics Graduate School*) to further enhance the student experience.

In addition to the departmental training, research students join **The Graduate School Skills Programme** (GSSP), provided centrally by the University in the form of six weeks of developmental activity over a three year PhD lifecycle. The programme has been running since 1999 with a strong interdisciplinary approach to professional development, offering a choice of fifteen intensive three-day themed skills workshops to first year PhD students.

The **annual assessment of progress** made by PhD students is based on a rigorous and robust procedure, incorporating a seminar presentation, submission of a detailed report and a thorough interview conducted by an assessment panel. Student progress is documented by an online University system which records their formal training and interactions with the supervisor and facilitates reflection on their achievements and targets.

The **University Poster Day** for second year PhD students is an exciting event that stimulates excellent presentations of novel research work. It is also accompanied by a range of career skills activities covering enterprise and business awareness, career management, teaching skills and work experience. Poster presentations are assessed by academic staff, and an annual prize is awarded for the best poster presented by a second year PhD student. All PhD students receive departmental support for participating in the British Mathematics Colloquium and/or British Applied Mathematics Colloquium, as well as attendance at relevant international conferences and workshops.

There have been some outstanding departmental successes; we mention **Colquitt**, who has published five peer reviewed research papers during his PhD course, with *Making Waves Round a Structured Cloak* (doi:10.1098/rspa.2013.0218) published in the Proc. Royal Soc. A and registering more than 1200 downloads in the three months following publication; **Colquitt** has been awarded an **EPSRC Doctoral Prize** and will take up a research appointment at Imperial College London from January 2014. **Haslinger** has completed three peer reviewed research papers and a peer reviewed conference paper, and was the winner of the highly competitive Duncan Norman Memorial Fellowship; **Lertchoosakul** has published six papers and recently secured a postdoctoral position at IMPAN (Poland); **Mihaljevic-Brandt** received the Poster Prize at the 2008 *LMS Women in Mathematics Day* and published three key papers from her doctoral thesis in leading journals before joining *Zentralblatt Math* in Berlin in a strategic role after a time as Assistent in Kiel, Germany; **Vaughan** received a prestigious nine-month `Scholarship for Foreign Doctoral Students' from DAAD (Germany) to study with Cortes in Hamburg, and has now returned there as a postdoc.

d. Income, infrastructure and facilities

External funding of research. The Department of Mathematical Sciences has been consistently successful in attracting large-scale funding for projects, many interdisciplinary in nature, from a range of sources such as EPSRC, BBSRC, MRC, NERC, STFC, DEFRA, The Royal Society, the European Commission, industrial Partners and registered charities (LMS, IMA, Leverhulme Trust); overall research spend since 2008 exceeds £5M. Examples include

- European Commission grants secured by **N. Movchan**, **A. Movchan,** and by **Rakow** of

overall value exceeding £3M;
- A major grant (of £1.3M) awarded to **CMIT** through EPSRC's *Healthcare Through Maths* initiative, complemented by an EPSRC CASE award;
- A series of long-term STFC Consolidated Grants, totalling over £2.4M within the REF period, secured by the **Theoretical Physics** cluster;
- An EPSRC Advanced Fellowship (£337,962, 2007-2013) awarded to **Rempe-Gillen**;
- A large-scale EU FP7 grant (€783,000) secured by **Constantinescu.**

In accordance with our research strategy, special attention is devoted to taking advantage of opportunities for interdisciplinary research projects, incorporating expertise from Mathematics, Engineering, Physics and the Life Sciences. In addition to the above EU funding, **A. Movchan** held three EPSRC grants on asymptotic analysis of singular perturbation problems in elasticity and wave propagation, with application in physics and engineering, and in particular thermal striping phenomena relevant to fracture within cooling contours of nuclear power plants. Another example of high impact is **Sharkey**'s work on modelling of H5N1 avian influenza that received external funding from DEFRA, as well as research on the spread of viruses in the UK farmed fish population and a recent EPSRC grant (first grant award), supporting a postdoctoral fellow. Collaborative work between **Clancy**, **Żychaluk** and the School of Environmental Sciences has recently attracted NERC funding for fundamental work in ecology, on dynamics of community composition, together with researchers at the University of North Carolina at Chapel Hill, the Wildlife Conservation Society, DEFRA's Centre for Environment, Fisheries & Aquaculture Science (Cefas), and Applied Biomathematics (a US-based ecological software company).

Additional RCUK grants were held by **Bearon**, **Chen**, **Lewis**, **A.** and **N. Movchan**, **Guletskii**, **Nikulin**, **Faraggi** and **Rempe-Gillen**. Funding has also been provided for sabbatical leave, collaborative visits, conference travel and workshop organisation by the *Royal Society*, *London Mathematical Society* and the *Leverhulme Trust* (**Goryunov**, **Pratoussevitch**, **Woolf**, **Hall**, **Rempe-Gillen**, **Clancy**, **Piunovskiy**, **Liu** and **Zhang**). A further series of research grants sponsored by registered charities, industry and overseas academic institutions, were held by **Appleby**, **K.Chen**, **A.Movchan**, **Piliposyan**, and **Vasiev**. The Theoretical Physics cluster accesses EU support through **Vogt's** membership of the network *LHCPhenoNet*, coordinated in Durham. Externally supported activities include high-profile conferences and workshops held at the University of Liverpool (see Section e).

Mechanisms to support external funding applications. All staff members are encouraged to seek external funding for their research, and potential grant applications are a key part of the annual PDR discussions (see Section c.) To improve rates of success, applicants are supplied with samples of successful proposals within the relevant funding scheme, and receive additional help through cross-reading of proposals within research groups and a supportive internal review process organised through the Research Committee. The departmental research centres support interdisciplinary grant proposals by facilitating contact with research users and scientists in other disciplines; this strategy has contributed to the successful large-scale bids in modelling (RCMM), mathematical imaging (CMIT) and financial mathematics (IFAM) mentioned above. The *School of Physical Sciences*, which consists of the Departments of Mathematical Sciences, Physics, and Chemistry, became a financial unit upon its creation in 2009. This flat structure allows us to be flexible in demonstrating institutional commitment to grant proposals with an approach tailored to the need of the individual applicant, be it by providing pump-priming or matching capital funding, or by pledging additional funded studentships to strengthen the application. For successful applications, indirect costs from research grants contribute to the departmental research budget, administered by the Research Committee, and PIs receive a reduction in their administrative or teaching workload. Grant administration is supported by a dedicated University research support team.

Future plans on external funding. We plan to build on our success in attracting funding for interdisciplinary research by developing further mechanisms for aligning grant applications with the RCUK priority areas, many of which have a strong multidisciplinary flavour. In particular, our research strategy calls for expanding the role of research centres in coordinating and generating

applications for large-scale RCUK grants, as well as ERC and collaborative grants funded by the EU Commission. The Theoretical Physics group will continue to seek sustainable long-term funding via STFC, and have been informally notified of continued Consolidated Grant funding covering the 2014-17 period. We also plan to diversify our research income by increasing the stream of funding from consultancy-type research contracts, already established by the ERRC team (**Piliposyan** and **Appleby**). The newly-established Institute for Financial and Actuarial Mathematics will be well-placed to exploit these sources of funding in the business sector and indeed is already working with major finance companies to improve their operating practices. According to the key principle (i) of our research strategy (section (b)), members of staff will continue to seek individual PI-led research grants, coordinated through our sustainable research groups, and we are further developing our mechanisms for supporting and encouraging applications for external funding. In particular, we are planning to implement a workload reduction to assist in the preparation of major grant proposals, to complement our current workload policy for PIs on existing major grants. We will also continue our policy of using the RCMM to provide pump-priming grants, specifically targeted at collaborative visits for the purpose of producing grant proposals and at small workshops which can also bring together groups for the purpose of generating larger multi-institutional grant proposals.

Infrastructure and Facilities. The Department enjoys a high-quality infrastructure to support its research activities. This includes the state of the art Mathematical Sciences Building, with excellent research facilities, office accommodation for PhD students, as well as specialised space allocated to the research centres in Mathematical Imaging Techniques; Mathematics and Modelling; Institute for Financial and Actuarial Mathematics; and the Environmental Radioactivity Research Centre.
Within the building, there are well-equipped seminar and discussion rooms used on a regular basis by the Mathematical Sciences Colloquium and cluster research seminar series. A *"MAGIC Room"* is equipped with modern Access Grid videoconferencing technology; in addition to use for postgraduate courses via the MAGIC network, it is also available for research workshops and seminars. RCMM provides support for research visits of international scholars and for high quality research workshops, with an annual budget of £12K.

The Department has two modern clusters (Apple Pro and Linux based) for high-performance computing, and professional mathematical software (Fortran and C++ compilers and libraries, Mathematica, MAPLE, MATLAB, COMSOL) which are available to all research personnel, research students and academic staff. In addition to the departmental installations, the University of Liverpool provides high throughput computing centrally via the CONDOR Pool, serviced and updated by the Computing Services Department. To supplement the departmental and institutional facilities, academic staff access external High Performance Computing as appropriate (e.g., **Rakow** in Theoretical Particle Physics makes extensive use of the *HECTOR* server in Edinburgh). All members of academic staff are supplied with modern workstations, which are renewed on a four-year rotation.

Technical support is provided by the Computer Services Department, and two full-time technical support members (Mr S. Downing and Mr D. Muskett) maintain and install research equipment and software. Administrative support for research activities is provided by dedicated professional services staff, who are based in the Department (secretarial support), the School of Physical Sciences (finance team) and central administration (research support office).

Academic staff, postdoctoral researchers and research students share a departmental research library (the Fröhlich Library). Modern library facilities (Sydney Jones Library and Harold Cohen Library) are also provided centrally by the University, while a dedicated postgraduate study room has been created in the Harold Cohen Library. An extensive range of research software is maintained on the central University Computer server.

e. Collaboration and contribution to the discipline or research base

A key goal of our research strategy is to foster high-profile research collaborations, interdisciplinary research, research leadership and engagement with the wider research community. Examples include:

Research leadership and evidence of esteem are well represented across the unit of assessment.

Highlights during the REF period include **Rempe-Gillen** and **Maz'ya** being awarded the LMS Whitehead Prize and Senior Whitehead Prize, respectively. **Rempe-Gillen** also received a 2012 Philip Leverhulme Prize and the 2013 CMFT Young Researcher Award. **Pukhlikov** was elected *Fellow of the AMS*, as was **Wall**, who although retired is still active within the Pure Mathematics cluster. **A.Movchan** was awarded a *Docteur Honoris Causa* by Université Aix-Marseille in November 2012. The Department hosted high-profile international research meetings, including:

- *String Phenomenology and Dynamical Vacuum Selection* (2008, organised by **Tatar**)
- Industrial Workshop *Waves in Structured Media and Localisation* (2009, **A. Movchan**)
- *Modern Trends in Controlled Stochastic Jump Processes* (2010, **Piunovskiy**)
- *Image Processing Techniques and Applications* (2011, **K.Chen**)
- *An international workshop in Singularity Theory*, in honour of Bruce and Wall (2012,**Goryunov**)
- International Workshop *Elasticity Day* (2012, **A.Movchan**)
- Four workshops on *Actuarial & Financial Mathematics* (**Constantinescu**, **Pamen, Pantelous, Siska** 06/2012 – 06/2013).

Academic staff also made a significant contribution to organising major external professional events. We mention the 2011 *Newton Institute programme on Moduli Spaces*, of which **Newstead** was principle organiser, the Arnold-75 conference *Analysis and Singularities* (Moscow, 2012), where **Goryunov** was on the Programme Committee and the 2012 ICHEP (`Rochester') Conference in Melbourne, where **Vogt** was the theory convener of the *QCD, Jets, Parton Distributions* section. Recent invited plenary talks at major international conferences include a BMC 2013 *Morning Lecture* (Sheffield; Rempe-Gillen); the *Congress in Memory of Adrien Douady* (2008, France; **Rees)**; *Misiurewicz-60* (2008, Poland; **Hall, Rees**); *Summer School on Periodic Structures in Applied Mathematics* (2013, Göttingen, Germany; **N. Movchan**); *Shafarevich-90* (2013, Russia; **Nikulin, Pukhlikov**); *Khovanskii-65* (2012, Russia; **Pukhlikov**); *Computational Methods and Function Theory* (2013, China; **Rempe-Gillen**)*; Planck 2013* (Germany; **Jones**); *Lattice 2011* (USA; **Rakow**); *Loops & Legs 2012* (Germany; **Jones, Vogt**); *String Phenomenology 2009* (**Tatar, Faraggi**); *String Phenomenology 2010, 2011,* and *2012* (**Faraggi**); *Mathematical Models for Engineering Science* (MMES '10, Spain; **Piunovskiy**); and *ISI Workshop on Heavy-tailed Distribution and Extreme Value Theory* (2013, India; **Constantinescu**). In 2010 and 2012, two invited courses were delivered by **A.Movchan** at the CISM International Research Centre in Udine (Italy).

The Department hosts the *Mathematical Sciences Colloquium*, a lecture series that brings together staff from across the research clusters for presentations by leading researchers in mathematical sciences. We also host the prestigious *Barkla Lecture* in Theoretical Physics, which attracts interest from beyond the Department, due to the high profile nature of its speakers, such as Nobel Laureates Englert in 2008 and 't Hooft in 2009. Research groups additionally run regular *topical research seminars*.

Research Collaborations are at the core of our research activities, as evidenced by the many research papers published jointly by members of staff with colleagues elsewhere. These collaborations are facilitated through a well-developed research infrastructure. The *Research Centre for Mathematics and Modelling* (RCMM) supported 71 collaborative research visits of distinguished scholars to Liverpool during the REF period and provides pump-priming support for collaborative research proposals for external funding across the Department. The Departmental *Research Committee* funds collaborative visits of colleagues abroad. The *Centre for Mathematical Imaging Techniques* (CMIT) initiates and supports collaboration on the interface between Mathematics and Life Sciences through development and practical implementation of medical imaging applications, while the *Institute for Financial and Actuarial Mathematics* (IFAM) promotes world-wide collaboration with leading groups in financial and managerial science, including strategic partnerships with CREAR-ESSEC (Paris, France), HEC Lausanne (Switzerland) and the Indian Statistical Institute (Calcutta, India).

Some examples of particularly intensive and productive collaborative partnerships during the REF

period are as follows: **Bearon** & Thorn (Nottingham); **Faraggi** & Rizos (Ionannina, Greece) and Kounnas (Ecole Normale Superieure, Paris) – both co-authors visit Liverpool on a regular basis; **Gorbahn** & Brod (Munich, Germany); **Gracey** & Dudal, Verschelde (both Gent, Belgium) and Sorella (Rio de Janeiro, Brazil); **Guletskii** & Gorchinskiy (Moscow, Russia), with the work partly supported by Guletskii's EPSRC grant; **Hall** & de Carvalho (São Paulo, Brazil) – three research visits by de Carvalho to Liverpool and five visits to São Paulo by Hall, including a one year research fellowship (FAPESP Pesquisador Visitante); all visits externally funded by FAPESP; **Jones** & Hindmarsh (Sussex); **A.** and **N.Movchan** & Mishuris (Aberystwyth), McPhedran (Sydney, Australia, currently in Liverpool), Brun (Cagliari, Italy) and Jones (Liverpool LJMU); **Nair** & Hančl (Ostrava, Czech Republic), including roughly once-yearly invited funded visits to Ostrava; **Newstead** & Lange (Erlangen, Germany) – 15 papers published or submitted since 2008; **Piunovskiy** and **Zhang** & Dufour and Avrachenkov of INRIA, France, with regular research visits in both directions between Liverpool and INRIA; **Pratoussevitch** & Natanzon (Moscow, Russia) – partly supported by a Leverhulme Trust grant (2011-2014); **Rempe-Gillen** & Schleicher (Jacobs University Bremen, Germany) and van Strien (Imperial); **Tatar** & Watari (Tokyo, Japan) and Dasgupta (McGill, Toronto, Canadi); **Vogt** & Moch (DESY, Hamburg, Germany) and Vermaseren (NIKHEF, Amsterdam, Netherlands) – this collaboration involves frequent visits to NIKHEF by Vogt.

Engagement of staff in *large-scale collaborations* include the key role of **Rakow** in QCDSF (focusing on the structure of hadrons), UKQCD and European Twisted Mass (ETM); the work of **Vogt** as a member of the world-wide *Particle Data Group* (he is one of the authors responsible for Fragmentation Functions in the biennial *Report of Particle Properties*, the most-cited publication in high-energy physics); the large-scale EU grant on *Risk Analysis, Ruin and Extremes* (PI: **Constantinescu**), involving twelve leading research groups world-wide; and the large scale (£3.2M) BBSRC-SABR-funded *Dynamics and function of the NF-kappaB signalling system,* BBSRC BB/F005938/1 BB/F005938/2, where **Bearon**'s individual contribution was praised by Larson (National Cancer Institute) in the BBSRC Scientific Advisory Board's annual reports.

Interdisciplinary research is of a high priority for our unit of assessment, and for the institution as a whole. The University of Liverpool has identified seven cross-cutting **Research Themes** which span different departments and faculties, addressing significant global challenges where Liverpool has particular institutional strengths. Researchers in the Department, who can offer modelling and conceptual insights into these challenges, play an important role in cross-faculty work focused on three of these themes. **K. Chen,** the Director of CMIT, acts as Faculty Champion for the *Personalised Health* theme, while **A. Movchan** is part of the *Materials for the Future* theme, where he leads interdisciplinary conferences on waves in metamaterials. **Bearon** and **Sharkey** have organised a sequence of seminars for the theme *Living with Environmental Change.*

The **Waves and Solid Mechanics Group** led by **A. Movchan** has developed interdisciplinary work in mathematical imaging and modelling in materials science as well as modelling of fracture and interaction of waves with metamaterial structures (one of our impact case studies). This work has led to two industrial patents in the design of 'invisibility cloaks' (acousto-optical switches and elastic shielding systems). **RCMM**-funded activities include the 'Elasticity Day' research event, which brought together the relevant modelling communities from the UK and across Europe, and four successful interdisciplinary projects organised by **N. Movchan**. The **Mathematical Biology Group** is actively involved in the work of the interdisciplinary *Liverpool Institute of Integrative Biology*. **Bearon** collaborates with biologists and oceanographers in the area of biological fluid mechanics. **Sharkey** has developed interdisciplinary projects in Life Sciences, including his work on the spread of viruses in UK farmed fish populations (included as an impact case study) and joint work with Jonkers (Geophysics, Münster, Germany) and Westerhoff (Chemical Engineering, Manchester/Amsterdam). The group has attracted interdisciplinary funding from a number of external sponsors, as outlined in section (d). Interdisciplinary collaborations involving the **Statistics and Probability Group** include work of **Clancy, Bowers**, the Liverpool Veterinary School and the Veterinary Laboratories Agency (now AHVLA) on zoonoses in cattle and pigs that has attracted funding from DEFRA, BBSRC and the British Pig Executive. The **Financial and Actuarial Mathematics** group engages with other disciplines through IFAM, the interdisciplinary *Liverpool*

Institute for Risk and Uncertainty and the *N8 innovation forums.*

Connections with research users and development of pathways to impact are a key element of our research strategy. Examples include the work of **Piliposyan**, Director of the **Environmental Radioactivity Research Centre** (ERRC), who together with **Appleby** runs high impact projects in collaboration with colleagues from the Departments of Geography, Physics, and Earth and Ocean Sciences. The focus of their work (included in one of our impact case studies) is on the analysis of pollution records in sediments from lakes, with an immediate practical outcome; its international recognition is confirmed by a continuous stream of contracts from Europe, North America, and Armenia. **Movchan** organised three successful industrial workshops involving SERCO Assurance (Dr Daniels's group on non-destructive testing of welds in nuclear power plants). The April 2013 *Spring School on Financial and Actuarial Mathematics* organised by **Pamen** and **Siska** - sponsored by the LMS and the EPSRC – was attended, in particular, by representatives of the financial sector. The event also featured lectures by internationally acclaimed speakers including El Karoui (École Polytechnique, France) and Jeanblanc (Évry, France). The workshop *Perspectives on Actuarial Risks* (Jan. 2013, Ascona, Switzerland), organised by **Constantinescu**, attracted funding from the *Institute and Faculty of Actuaries*, among others, and featured keynote speakers from the *Swiss Reinsurance Company*. **K.Chen** works with the St Pauls' Eye Unit at the Royal Liverpool University Hospital (RLUH). This EPSRC-funded collaboration includes direct interaction with and contribution from NHS staff, and has led to a new and novel model for the analysis of retinal images from diabetic patients. Similarly, local and selective segmentation models are being developed at CMIT in collaboration with the RLUH and Clatterbridge Cancer Centre (CCC). In accordance with points (iii) and (iv) of our research strategy (Section a), contacts with research users help, in turn, to inform future research directions. This approach is exemplified by the work of the CMIT, where questions raised by collaborators in NHS hospitals directly lead to the identification of important areas for new research outputs and funding applications.

Beyond traditional pathways of disseminating research, **Pratoussevitch** contributed to the Clay Institute's 'Science Lives' oral history project by filming a scientific interview with Egbert Brieskorn in 2010, while in 2009 **Rempe-Gillen** organised a frontier science event at the 2009 BA Festival of Science and narrated the *BBC audio slideshow* The Art of Mathematics.

Further contributions to the research base. Academic staff contribute to the national and international research community through their leading roles in professional societies and editorial boards of international research journals. The latter include the *Bulletin/Journal/Proceedings of the LMS* **(Goryunov**, editorial advisor 2003-2012), LMS Mathematika, *Quarterly Journal of Mechanics and Applied Mathematics, SIAM Journal of Multi-Scale Modelling and Simulations* (**A.Movchan**), *Izvestiya:Mathematics* **(Nikulin)**. **Goryunov** is a coordinator of the British Singularity (Leeds-Liverpool-Warwick) network, while **Guletskii** is the Liverpool contact for the GLEN (Glasgow-Liverpool-Edinburgh-Newcastle) network, both LMS-supported**. Hall** is a coordinator of an IRSES grant involving 32 institutions in the EU and Brazil. **Jack** was chair of the 2008/09 Physics panel for the *IRCSET Postdoctoral Fellowships*. **A. Movchan** is member of the Steering Panel of the *ICMS* (Edinburgh), the *IUTAM UK Panel*, and of the *IMA's Research Committee.* **Rees** is chair of the *Royal Society Fellowships* panel, served on the *Dorothy Hodgkin Fellowship* panel and is starting a term on the Sectional Committee for election of new fellows. **Rempe-Gillen** has served on the *EPSRC Postdoctoral Fellowship selection panel*. **Tatar** is a current member of the *STFC Particle Physics Panel (Theory).* **Teubner** is a member of and convenor for the *International Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies*, and was part of a selection panel for the 2008 *DEISA Extreme Computing Initiative*, and **Vogt** served on the *STFC Particle Physics Panel (Theory)* from 2008-2010. **Woolf** serves on the *LMS Research Meetings Committee*. Major research monographs published since 2008 include *Geometry of Continued Fractions* (Springer) by **Karpenkov**, *Green's Kernels and Meso-Scale Approximations in Perforated Domains* (Springer) by **Maz'ya**, **Movchan** and Nieves, *Examples in Markov Decision Processes* (World Scientific) by **Piunovskiy, and** *Birationally rigid varieties* (AMS) by **Pukhlikov**.