

<p><b>Institution:</b> University of Bristol</p>
<p><b>Unit of Assessment:</b> 10 – Mathematical Sciences</p>
<p><b>a. Context</b></p> <p>The Unit of Assessment (UoA) is the School of Mathematics, comprising 87 staff (83.5 FTEs) whose research interests span mathematical science in its broad sense. The staff can be loosely grouped by research interests, and groups that have delivered impact on non-academic beneficiaries range across the whole UoA. They include Number Theory &amp; Combinatorics (16 researchers), Fluids &amp; Materials (8), Mathematical Physics (11), Quantum Information (6), Statistics (17), and Probability (12). We have extensive collaborations with researchers in other academic disciplines spanning science, engineering, social science and arts, with numerous publications co-authored with non-mathematicians. Several members of the UoA are associated with, and play central roles in leading, a number of interdisciplinary research centres in the University; these facilitate research activity outside traditional mathematical areas.</p> <p>The non-academic beneficiaries of our research are drawn from industry, the public sector, including governmental agencies and policy forming bodies, and the wider general public. Impact derives from our overriding policy to pursue excellence in research, to develop and maintain expertise across a range of new and emerging areas in mathematics and its applications and to interact with end-users. It is delivered through strategic initiatives and support mechanisms. Our most notable collaboration is with the Government Communications Headquarters (GCHQ) through the Heilbronn Institute, facilitating work on issues of national security. It has been a major strategic initiative within the UoA with several appointments of academic and research staff and has delivered results that are employed operationally. Other areas in which we have engaged include the energy sector, meteorology, banking and manufacturing, wireless networks, epidemiology, natural hazards, the environment and climate change. The delivery of impact from research has arisen through the strategic appointment of academic staff, the creation and maintenance of a research environment that allows opportunistic interactions and strategic partnerships with end-users, and the development of systems for supporting staff in their work outside of traditional academic realms. In particular, we have three members of staff to support impact-related activities: Directors of Impact (<i>Hogg</i>), Public Engagement (<i>Browning</i>) and Employer and Alumni Relations (<i>Porter</i>). (Here, and throughout, italics denote staff returned in UoA 10.)</p>
<p><b>b. Approach to impact</b></p> <p><i>[Introduction]</i> Our strategy for delivering impact from research during 2008-13 has been dual-stranded, featuring both directed strategic initiatives and the support of staff in taking advantage of opportunities that arise. Our researchers engage widely with experts and the general public to disseminate their results and have impact upon a diverse range of end-users from commerce, industry and government. This diversity is illustrated through our case studies, which include the application of wavelet methodologies in banking and manufacturing, nonlinear dynamical models of aircraft manoeuvrability at Airbus and the statistical assessment of environmental risk and climate change scenarios at the Met Office (UK).</p> <p><i>[Strategic initiative: Heilbronn]</i> The most significant strategic engagement with beneficiaries is the Heilbronn Institute for Mathematical Research (HIMR). We established the Institute in 2005 (renewed in 2008 and 2011), and it is a unique association between a university and GCHQ. It is a key component of GCHQ's strategy for providing national security. It has a major influence on mathematics in Bristol, and researchers have been able to achieve impact in the vital area of national security, as evidenced through two of our submitted case studies. HIMR supports fundamental research in number theory, algebra, combinatorics, algebraic geometry, quantum information, probability and statistics. The Institute appoints Heilbronn Research Fellows (currently there are 23) who are employed by the UoA to pursue their own research programme and to perform classified research in association with GCHQ. In these settings, research results have a direct impact on problems that are identified by GCHQ (see, for example, the case studies). The HIMR environment is strengthened by secondments of staff from other universities and numerous long term visitors. The employment model has also benefitted GCHQ in that several of the Heilbronn Fellows have moved to work there after completing their fellowships. Further engagement is derived from the four international workshops per year that HIMR sponsors, with both academic and non-academic attendees. As part of the UoA's ongoing commitment to expand</p>

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the engagement with GCHQ, three senior appointments have been made since RAE 2008 to support this research initiative (*Dokchitser, Toth, Wolf*). The UoA funds 8 regular seminar series associated with HIMR, and a distinguished lecture series, providing dedicated administrative support, the annual hiring of fellows, the roles of Associate (*Johnson*) & Strategic (*Wooley*) Directors, who are returned in this UoA, and an Institute Administrator.

*[Strategic initiative: statistics]* The Probability and Statistics groups have expanded significantly during the assessment period through new appointments of faculty and post-doctoral fellows. The expansion was supported by the SuSTaln initiative (Statistics underpinning Science, Technology and Industry, 2006-15), and this has spawned many projects with non-academic users. As reported in our case studies, modern statistical methodologies have been introduced in banking and manufacturing (*Nason*) and the assessment of uncertainty in environmental predictions (*Rougier*). Additionally, there are several emerging statistical research projects that are not yet sufficiently mature to be “formal” case studies in this submission. These have arisen through our strategy of supporting opportunistic research initiatives: *Leslie* proved consistency of Thompson sampling, a strategy to solve the exploration-exploitation dilemma in decision theory. The method is currently used by Microsoft, Google and LinkedIn to drive their selection of adverts to display to users every time a search is carried out. It is also at the core of Google Experiments, a module which allows website designers to experiment to optimise their websites, and in which the theoretical guarantees provided by this work deliver an important reassurance to users. *Didelez* developed an approach to model the dependence structure of multivariate point processes, arising, for example, when tracking a patient’s health over time. The research underpinned an investigation of testing by the Norwegian cancer screening programme and led to the removal a particular test from the programme. *Andrieu* formulated a novel statistical methodology for estimating parameters in dynamical models, which is suited to statistical inference from time series. This work is beginning to find application in banking, especially at the Banks of England and Belgium.

*[Strategic initiative: environmental research]* The UoA is a sponsoring department for the Cabot Institute ([www.bris.ac.uk/cabot](http://www.bris.ac.uk/cabot)). This is an interdisciplinary, cross-Faculty research institute at Bristol with a focus on risk and uncertainty in a changing environment. The Institute stimulates linkages with industry and government, developing partnerships, enhancing knowledge exchange across the sectors and building groups of shared interdisciplinary expertise. Cabot fosters impact by frequent internal, stakeholder and public events, as well as funding new activities and collaborations. *Rougier’s* statistical methods for the assessment of uncertainty in climate and other environmental models, as reported in a case study, are an example of a key research project within this realm. Closely allied to this interdisciplinary axis is research in modelling environmental flows. *Hogg* has formulated new models of the atmospheric dispersion of volcanic ash, the results of which are being used in the assessment of the safety of airspace for aircraft flight by Meteorological Offices in Iceland, UK, Australia, New Zealand and Japan. *Hogg* is also developing new models of lahars, as part of a UK consortium (STREVA) to strengthen resilience to volcanic hazards, which is engaged with end-users in Ecuador, Colombia and Montserrat. The School has further enhanced activity by the appointment of Huppert, who is widely engaged in the evaluation of scientific solutions to societal problems such as the sequestration of carbon.

*[Strategic initiative: life sciences]* As a part of our strategy, we look outwards towards non-traditional areas of mathematics with high impact outside academia, such as population genetics and systems biology. The School has made a number of senior appointments in such research areas, in particular *Beaumont*, who has worked in conservation and has collaborations in genetic epidemiology, and *Bowsher*, whose work in system biology has relevance to disease and to drug discovery. *Linden* has collaborated with experimentalists, leading to a paper in *Science* and a patent application in the area of protein design. *Didelez’s* research into statistical methods for causal analysis is central to the new Integrative Epidemiology Unit, partly funded by the Medical Research Council (£23M, 2013), with results to be applied to health services.

*[PG Training]* The UoA has a well-established strong track record for training high quality postgraduate students and delivers a programme that combines specialist and broad technical training with professional development. Our postgraduates are in high demand in industry, and

they have recently taken up positions in industry and governmental research agencies including Lloyds, Qinetiq, GCHQ, Institute of Cancer Research, BAE Systems Detica, Sungard, UK Met Office, Airbus, Tessella, HR Wallingford, SmartOdds, Toshiba and Last.FM. To ensure our students remain well informed about end users and beneficiaries of mathematical research, we launched in 2011 a postgraduate seminar series whose speakers are drawn from industry. The UoA has been a central player in the establishment of EPSRC-funded Doctoral Training Centres (DTCs) that have links across academic disciplines and outside of academia, both in the formulation and identification of the scientific challenges to be undertaken, and in the subsequent steering and governance. The primary focus of these initiatives is in training graduate students to tackle research problems at the boundaries between traditional academic subjects, and to provide cohorts of postgraduates well equipped to tackle emergent research problems and interact directly with beneficiaries. In particular, the Communications DTC (established 2010, renewed 2013) has strong industrial links, with several projects funded by industry (e.g. GCHQ, BAE, Thales). Through this centre, *Johnson* is supervising PhD students in the analysis of wireless systems (with NEC) and the efficient management of the broadcast spectrum (with Ofcom; an Industrial CASE award), and *Ganesh* is supervising a PhD student on spectrum access algorithms (with Toshiba). The DTC in Complexity Science (2007; renewed 2011) has led to publications in bio-informatics, neuroscience and epidemiology, and seeded longer-term collaborations. We have strategically supported these initiatives by appointment of staff (*Ganesh & Wiesner*) and have committed our own resources to supplement the available funds for postgraduate students.

*[Knowledge Transfer]* We have been involved with Knowledge Transfer Secondment Schemes to facilitate direct interaction with industrialists. For example, *Dettmann* received funds to support two projects with Toshiba, to analyse the boundary effects of connectivity in wireless mesh networks with randomly located nodes. This work was exploited by Toshiba Corporation in key negotiations between Japanese industry and the Japanese Ministry of Economy, Trade and Industry, and led to the ratification of Toshiba's proposal to standardise smart meter communication networks in Japan.

*[Public Engagement]* The UoA recognises the importance of public engagement and supports a focussed programme to communicate research results outside academia. Many permanent academic staff (approximately one third) have participated in such initiatives through press releases, public lectures, television documentaries and postings to online forums and blogs. Our aims are to raise the public's interest in mathematics, their awareness of the varied realms that mathematics can impact and its centrality within scientific research, and to inspire the next generation. In recent years, the members of the UoA collectively participated in a series of films, *Mathematical Ethnographies*, based on their mathematical research, and have staffed an exhibition at the Royal Society Summer Exhibition, as reported in a case study. The films document the creative process in research mathematics; they were shown at the Arnolfini Arts Centre, Bristol to a sold out general audience, and the Changing Perspectives exhibition (Bristol Gallery, April 2011). They have been available on-line, attracting several thousand viewers, and were sold on DVD.

Our work regularly attracts attention in the popular scientific press, and we facilitate this via press releases (6 in 2013). For example, work by the quantum information group has attracted particular attention, being taken up by popular science journals such as Scientific American and New Scientist as well as web sites such as Science and Science News for Kids. The UoA has been successfully involved with engagement activities with local schools through the Bristol Maths Sessions and the Undergraduate Ambassador Scheme, which allow aspects of the frontiers of research to be communicated to school students, eliciting positive feedback on their inspirational impact on the pupils. In collaboration with the Graduate School of Education, we have launched a series of "Teachers' circle" events. Their aim is to bring local mathematics teachers into contact with exciting and current research, through accessible lectures and problem solving sessions.

Communication of research and engagement with the public is recognised by the UoA as part of our core activities, not just as an extra to academic life. Engagement activities are actively encouraged and accounted for in the balancing of workloads. Our initiatives are supported by a Director of Public Engagement (*Browning*), an in-school role, who provides mathematical expertise on engagement activities. He is also supported by the University's Centre for Public Engagement

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and the Press Office. We anticipate our activities in this realm growing during the next few years.

*[Industrial Funding]* During the assessment period, several members of staff have received research council funding with substantial industrial contributions and there have been several direct industrial awards. Some examples include the use of multiscale methods of signal extraction on networks (GCHQ: £1.3M); the application of novel ideas from dynamical systems to transport and mixing in geophysical flows (US Office of Naval Research \$875k); and the development of new methods for forecasting energy demands (EDF, Shell, Vattenfall and GL Garrad Hassan, £700k). The impact from these and other industrially funded grants arises from the published research output, the transfer of methodologies from university-based research to an operational setting and the training of students, post-doctoral assistants and industrial collaborators, who have, in many cases, moved into full-time employment with the sponsoring company.

*[Government Advisory Roles]* Several members of the School have taken up national advisory roles, which impact significantly on governmental policy and operation. In addition to four members of the UoA who advise GCHQ, *Rougier* acted as an external expert to the UK Met Office (2007-9) and as a member of the Cabinet Office Expert Advisory Group for effusive volcanic eruptions (2013); *Huppert* chaired the European Scientific Academies Committee on carbon capture and storage (2013) and has acted as a Home Office consultant; and *MacCallum* (2012), former Director of HIMR, reported to Parliament on mathematics in security and intelligence.

*[Support]* The UoA appoints a Director of Impact (*Hogg*), formerly Enterprise Leader 2004-8, to support and provide in-house advice on how to respond to impact opportunities and how to pursue new research initiatives. The Director of Impact provides mathematics-focussed advice on funding applications, interactions with non-academic partners and other strategic initiatives, takes a lead in promoting 'impact' within the UoA and provides a link to the professional services offered by the University. Impact is now a standard item on the School Assembly agenda. The UoA has run training and awareness-raising sessions with all staff, facilitated by the University's Research Enterprise and Development team (RED), to ensure awareness of their opportunities to engage with non-academic beneficiaries.

The University has provided support for individuals to achieve impact through the services offered by RED. They supplied expert advice on contracts between researchers in the UoA and industrial companies and other non-research council bodies, in particular negotiating and resolving issues of intellectual property. UoA members (*Porter, Leslie, Linden, Wiggins*) initiated patent applications and have received detailed legal and scientific advice. Members of the UoA have accessed funds held by RED for Knowledge Transfer Schemes and Developing Impact. For example, *Hogg* received an award from the Enterprise and Impact Development Fund, to employ a software engineer to produce a web-based tool for calculating the rise of volcanic plumes. This software has already been used by 6 of the 9 global Volcanic Ash Advisory Centres.

### c. Strategy and plans

*[Overview]* We believe that significant and long-term impact derives from outstanding research. The UoA is outward looking, and many members of staff have ongoing collaborations with other academic disciplines, industries and government agencies. Intra-disciplinary collaboration linking diverse areas within mathematics is also a strength of the UoA (see above). Building on this strong research base, we will facilitate impact in the following ways: (i) support for researchers engaging with beneficiaries; (ii) strengthen links with GCHQ through the HIMR; (iii) develop new strategic initiatives; (iv) expand our activities in public engagement. These are described in what follows.

*[School Policy]* The UoA recognises the importance of achieving the full impact of its research and that generating impact, in its broadest sense, is part of an academic's duties. Impact-related activities, such as developing new non-academic contacts, embedding research outputs or participating in public engagement activities, are explicitly reflected in the balance of workloads between members of the school. Impact, and other contributions beyond traditional academic collaboration, is explicitly considered for promotion and progression.

*[School support]* The UoA will continue to have a Director of Impact (*Hogg*) to oversee and advise

on activities, to audit regularly its engagement with beneficiaries and will develop in-house mentoring schemes for industrial collaboration and consultancy. The UoA has appointed a Director of Employer & Alumni Relations (*Porter*) to facilitate liaison with companies and government agencies, especially in the southwest, and to maintain links with alumni. An Industrial Advisory Board will be formed to provide input on the curriculum and other matters. We will continue to fund the Mathematics in Business and Industry postgraduate seminar series (launched in 2011). These mechanisms foster engagement between researchers and end-users in industry and government, and maintain an environment conducive to the development of new non-academic collaborations.

*[University support]* Expert advice on enterprise, commercialisation and research development is available from RED to support the development of links with partners from industry, ranging from initial contact to long term, strategic partnerships. Members of the UoA have immediate access to this team, who provide detailed advice on contracts, intellectual property, technology transfer and commercialisation. We envisage working closely with these professionals and being closely advised by them as the impact agenda continues to evolve during the next years.

*[Heilbronn]* The Heilbronn Institute established in partnership with GCHQ with a remit to conduct fundamental research and to address directly issues of national security, has proven so successful that GCHQ made it permanent during the review period. It will remain a strategic priority for the UoA to strengthen research in discrete mathematics and probability, following the recent senior appointments. The UoA plans to expand the number and broaden the range of Heilbronn fellows, and to introduce a new scheme of enhanced five-year fellowships. Further commitment through secondment of staff to the Institute and support for seminars and conferences will continue.

*[Strategic initiatives]* One strand of the UoA's strategy is to build up research programmes that naturally lend themselves to impact. This approach led to strategic initiatives in the UoA, notably in Statistics and in Environmental Research. These areas will continue to be supported through future appointments (e.g. environmental risk), with beneficiaries that include government, public health, the software industry and finance. Other areas of anticipated expansion include quantum information, building on current strengths in experimental and theoretical work, and mathematical biology. Research in these areas does not automatically generate impact, so we will focus the mechanisms described above to ensure maximum engagement with potential beneficiaries, both those with whom we already have links and others with whom such links need to be developed.

*[Public engagement]* The UoA engages with the public through the media, public lectures and interactions with schools. We have appointed a Director of Public Engagement (*Browning*) to oversee these activities and develop new initiatives. Training and support is delivered by the University Centre for Public Engagement and courses delivered through the Staff Development programme. The UoA uses press releases, social media, as well as its own web pages, to publicise notable academic research as well as its non-academic impacts. Future plans include the creation of a 'press gang' drawn from postgraduate students, and tasked with writing up research outcomes in popular language for posting on the School website. We also plan a public lecture series dedicated to fundamental problems in mathematics and our own recent discoveries. The first of these will be given under the umbrella of 'Twilight Talks', a series of discussions for the general public run by the Centre for Public Engagement. Finally, we will continue and expand our outreach activities with local schools to inspire the next generation of students.

**d. Relationship to case studies**

Our case studies illustrate the broad range of mathematical research in Bristol. Some are associated with advances in a particular methodology, which have then been widely applied (e.g. Multilevel Statistical Modelling and Reversible Jump Markov Chains Monte Carlo), whereas others feature a more focussed piece of research that has directly engaged beneficiaries (e.g. avalanche interactions with barriers and the analysis of aircraft manoeuvrability). The majority of the submitted cases arose due to the research strength and agility of staff to exploit opportunities with end-users, allied with appropriate support from UoA and University; their genesis was before the 'formalised' impact agenda became firmly established. However, others, such as the two cases reporting impact on national security, have arisen through strategic initiatives and these are exemplars of what might be delivered in the future.