UK SPACE AGENCY

Impact Evaluation Report: Herschel SPIRE Instrument

March 2017

The Herschel satellite being prepared for an acoustic test at ESA's space technology centre, ESTEC.

Credit: ESA.

Contents

Acronym list

AIG - Astronomy Instrumentation Group (Cardiff University)

HIFI - Heterodyne Instrument for the Far-Infra-red

HOC - Herschel Oversight Committee

HOG - Herschel Outreach Group

INTEGRAL - INTErnational Gamma-Ray Astrophysics Laboratory JWST - James Webb Space Telescope

ISO - Infra-red Space Observatory

MIRI - Mid Infra-Red Instrument

NAO - National Audit Office

PACS - Photoconductor Array Camera and Spectrometer

PI - Principal Investigator

PPARC - Particle Physics and Astronomy Resource Council

RAL - Rutherford Appleton Laboratory

REF - Research Excellence Framework

SPIRE - Spectral and Photometric Imaging REceiver

STEM - Science Technology Engineering Mathematics

STFC - Science and Technology Facilities Council

UCL-MSSL - University College London-Mullard Space Science Laboratory

UK ATC - UK Astronomy Technology Centre

VFM - Value for money

Executive summary

The Herschel SPIRE instrument delivered remarkable scientific results for UK academia, demonstrated UK excellence in space science technology, and represented exceptional value for money for the UK taxpayer.

The SPIRE (Spectral and Photometric Imaging REceiver) instrument flew on board Herschel, a European Space Agency (ESA) science observatory mission, and was built by an international consortium comprising more than 18 institutes from eight countries, led by Principal Investigator Professor Matt Griffin (Cardiff University). It was one of three Herschel scientific instruments, the other two being PACS (German-led) and HIFI (led by the Netherlands).

Herschel was launched in May 2009 with a total cost of approximately €1bn and carried the largest astronomical telescope yet flown. The mission operated until April 2013 when its liquid helium coolant was exhausted as planned. SPIRE Post-Operations concluded in June 2016, and now the Herschel Science Archive is to be maintained in perpetuity by ESA.

UK public investment of £16.5M supported the design, development, operations and post-operations of SPIRE from 1998 to 2016. This evaluation aims to analyse how the UK public investment in the Herschel SPIRE project has been delivered in practice and whether its objectives were met. Programmatic considerations were included in an assessment of how well the project was implemented, in terms of why it did (or did not) deliver as expected, together with an overall assessment of the impact of the SPIRE project on UK academia, industry and broader society and whether it represented value for money.

The report has been prepared by collating evidence and information from a wide range of internal and external sources, and has been presented to a review board for finalisation and ratification. The board comprised independent external experts from the Agency's UK Herschel Oversight Committee (HOC) and included stakeholders from the relevant science user community, as well as SPIRE project team members.

The report sets out the policy context of original funding approval, and the top level funding objectives at that time:

- support the Herschel mission's capabilities in addressing fundamental scientific questions, especially concerning galaxy formation and life cycles of stars;
- ensure the UK was instrument PI (Principal Investigator) in order to secure strong, long term UK influence over the technical and scientific development of the mission, to shape design and optimise the science around UK interests and strengths;
- exploit the high level of UK technical expertise built up through work on previous infrared and submillimetre astronomy missions, and maintain the outstanding international position of the UK in these areas.

The SPIRE instrument was successfully delivered to the Herschel spacecraft, meeting eventual schedule, and operated with a high degree of performance and reliability throughout the mission lifetime. SPIRE baseline instrument performance specifications were met or exceeded, resulting in a factor of more than 10 increase in data returned compared to what was originally guaranteed. The breadth of UK roles complementing the PI role, and further evidence obtained through this evaluation, suggest that UK influence was strong, both in the development of the SPIRE instrument, and the Herschel mission as a whole.

Led by the PI, 6 UK institutes had core roles in the design, construction and operation of the Herschel SPIRE instrument. Complementing the UK PI leadership and hardware provision roles with significant investment in the SPIRE ground segment operations and instrument data processing added value by allowing UK groups to design and shape, and be very conversant with, the whole data chain, from initial capture to processing and exploitation. Involvement in SPIRE also inevitably contributed to building reputation for all participating UK institutes, helping them position for future roles in space science missions.

The UK's international position in infrared and submillimetre astronomy is also measured in terms of UK science return and the report finds strong representation by UK scientists in Herschel publications, as summarised below, with particularly intensive use of SPIRE. As of 29 April 2016:

- 1691 refereed papers had been published using Herschel data. This publication rate is the highest of any major ESA observatory (as of March 2017 this figure is 1932)
- Of 1031 SPIRE papers, 682 (66%) had UK authors and 260 (21%) were UK-led.
- Of the 30 most highly cited Herschel science papers, 20 had used SPIRE data (5 SPIRE-only, and 17 SPIRE + PACS); seven of the 30 were UK-led and all of those seven used SPIRE data.
- 21 Herschel papers had been published in Nature or Science, 13 of which used SPIRE data, 13 had UK authors, and four were UK-led (all of which used SPIRE data).

In terms of economic impact, the report highlights that SPIRE was initiated by PPARC (Particle Physics and Astronomy Research Council) in 1998 as a solely scientific and research driven project, with no requirement for direct industrial engagement. The core investment objectives and overall drivers for UK participation in the Herschel mission were largely unquantifiable benefits, arising from the intrinsic value of enhanced scientific knowledge. Many of the scientific impact benefits are difficult to quantify in economic terms and it will be many years before the value of the scientific advances will be fully understood.

Despite this, publically funded SPIRE institutes in the UK awarded contracts to industry worth approximately £1.25M for various instrument hardware components, and SPIRE played a key role in the development of Cardiff University spin out company QMCI Ltd. The company existed before SPIRE but, building on the research and development activities and facilities untaken for the instrument, capabilities in highly sensitive, ultra cold terahertz (THz) detectors have been commercialised and brought to the global market. The detection systems developed with the resources funded through participation in Herschel SPIRE are now used in the fields of bio-medical imaging and bio-molecular spectroscopy for health science, plasma fusion diagnostics for sustainable energy, remote atmospheric sensing, synchrotron and free-electron laser diagnostics, and artwork analysis and curation.

15 months before the Herschel launch, in the beginning of 2008, the UK Herschel Outreach Group (HOG), chaired by Prof Griffin, was formed to coordinate a national outreach and PR programme. Measuring the precise impact towards public understanding of space and student STEM uptake as a result of these initiatives would require detailed longitudinal analysis which is beyond the scope of this review, however the scale of the HOG programme and its reach should at the very least provide

an indication that it has stimulated engagement with space science. A schools programme was developed and implemented by the HOG with the assistance of teaching professionals the total reach of these sessions is over 20,000 pupils per year. Eleven major public events have been organised by the UK Herschel team and supported by Cardiff staff. Media coverage has publicised the technical and scientific work of the Cardiff team, with articles in UK and foreign newspapers, and Herschel was designated number 7 in Time Magazine's Inventions of the Year in 2009.

Management and delivery context is detailed, concluding that the UK project was well managed and had effective oversight, both at the project and programme director level. SPIRE, Herschel, and the Planck mission (with which it shared launch) suffered several challenges, largely a result of interdependencies from the scale of international collaboration, and technical issues associated with developing cutting edge space technology. Launch delays were deemed as deferring science return, but not impacting on science quality or meeting overall science objectives.

The evaluation finds that in terms of Economy (minimising costs of resource input), Efficiency (the relationship between the output and the resources to produce them) and Effectiveness (the relationship between the intended and actual results of public spending), the investment has delivered value for money.

Through the evidence collected the report finds that all three top level objectives can be seen to have been met, but does note that methodological constraints were brought about by the fact that regular formalised outcome monitoring and impact evaluation was not built in to the function of the project's oversight bodies from the outset. Evidence for the evaluation was collected retrospectively, and during the 18 year project duration other relevant information may have been lost or not recorded, limiting the degree to which all outputs, outcomes and impact can be reliably linked and attributed to Herschel SPIRE.

Recognising these constraints, the report concludes with recommendations for future similar exercises:

- Setting clear, measurable, objectives from the outset of the project – to more robustly evaluate whether they have been achieved.
- Regularly collecting impact information and monitoring outcomes from the outset of the project – to ensure all relevant outcomes are reported and not lost in long duration projects.
- Holding interim impact evaluations, planned into project schedules as key development phases are completed – this is particularly important for long duration projects, and would contribute to understanding of whether future expected benefits are likely to be realised, and whether any interventions are required to make sure they are.

In this respect this impact evaluation and its findings should also be regarded as an interim review, since the impact and science exploitation of Herschel SPIRE data, and long term economic benefit from the project, will continue for several decades. This will be monitored in partnership with STFC, which provides research funding for science exploitation of Herschel SPIRE data.

1. Herschel and SPIRE overview

1.1 Herschel was an ESA Science Programme cornerstone observatory mission, launched in May 2009 with a total cost of approximately €1bn. It carried the largest astronomical telescope yet flown (3.5m diameter). Three scientific instruments (HIFI, PACS, SPIRE) performed sensitive imaging and spectroscopy and were provided by nationally-funded consortia led by the Netherlands, Germany, and the UK, respectively.

1.2 The SPIRE (Spectral and Photometric Imaging REceiver) instrument was built by an international consortium comprising more than 18 institutes from eight countries, led by Principal Investigator Professor Matt Griffin (Cardiff University). Herschel operated until April 2013 when its liquid helium coolant was exhausted as planned. A three-year Post-Operations phase was supported by the UK Space Agency in the UK with the objectives of finalising and documenting the calibration, data processing software, and generating the legacy data products. SPIRE Post-Operations concluded in June 2016, after which the Herschel Science Archive will be maintained in perpetuity by ESA.

2. Aims of the Evaluation

2.1 This evaluation aims to analyse how the UK public investment in the Herschel SPIRE project has been delivered in practice and whether its objectives were met, including what impact those objectives had. The main focus of the review has been to understand the impact the investment has had on UK academia, industry and broader society. Programmatic considerations will be included in an assessment of how well the project was implemented, in terms of why it did (or did not) deliver as expected, however the key purpose of the review is an evaluation of the overall impact of the SPIRE project and whether it represents value for money.

2.2 In line with the HM Treasury Magenta book[1] and the UK Space Agency Evaluation Strategy[2] the evaluation is primarily concerned with the following two key objectives:

2.2.3 How was the SPIRE project delivered? Identifying the **process** associated with delivering the UK roles, the extent to which it was successfully handled, and what the key outputs were.

- What were the stated objectives of the project?
- Establish what outputs were delivered as a direct result of the project (i.e. delivery of the SPIRE instrument)
- What contextual (delivery environment) factors may have influenced the ability of the project to achieve its outputs and objectives; e.g. budgetary, political, resource or technical constraints?
- Explore the success of the programme in relation to meeting budget, schedule and technical performance

2.2.4 What difference did the project make? This is both an identification of the key outcomes and an analysis of whether the observed outcomes would have happened anyway.

[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/220542/magenta_book_combined.pdf

[2] https://www.gov.uk/government/publications/evaluation-strategy-uk-space-agency

- Did the project achieve its anticipated outcomes?
- Who were the key beneficiaries?
- What would have happened to the beneficiaries without the UK role on Herschel?
- Scientific publications stemming from the programme and any other scientific gains resulting from the UK participation in the mission.
- Did the benefits justify the costs? And any value for money consideration.
- The nature and extent of the direct benefits accrued to the grant holders. Identification of economic benefits stemming from the SPIRE role, such as directly attributable additional contracts won or any spin-out companies.
- Any other lessons learnt from the project that could help future UK roles on ESA Science programme missions.

3. Methodology

3.1 Methodological constraints on the evaluation arise from the fact that regular formalised outcome monitoring and impact evaluation were not built in to the function of the project's oversight bodies from the outset, and were not explicit considerations at the time of funding approval. Public funding for Herschel SPIRE was first approved and implemented in 1998, and has spanned 18 years and three successive funding bodies; PPARC, STFC and UK Space Agency. This long timescale, and the lack of ongoing outcome and impact monitoring, limits the evaluation to a largely retrospective review and therefore limits the degree to which all outputs, outcomes and impact can be reliably linked and attributed to Herschel SPIRE.

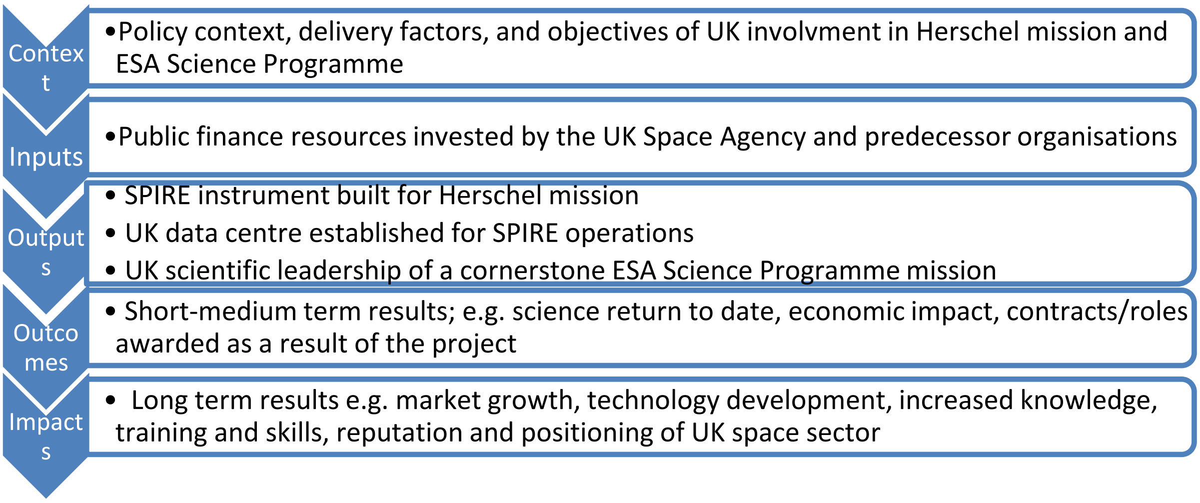
3.2 Based on the Agency's Evaluation Strategy, the project could be considered as requiring a Level 2 (externally commissioned) evaluation because of the medium-high level of overall public investment. However there is very low uncertainty around outcomes since these have been well documented, and very low ongoing financial risk to the Agency since the UK SPIRE project is now complete, therefore a Level 1, internally-led, evaluation has been adopted.

3.3 In order to meet the objectives of the impact evaluation, this report has been prepared by collating evidence and information from:

- UK Herschel Oversight Committee reports;
- REF (Research Excellence Framework) cases submitted by the project's Principal Investigator (PI);
- an externally commissioned case study carried out by London Economics;
- legacy reviews and reports from the Agency's predecessor funding organisations PPARC and STFC;
- the final draft of 'Programmatics, Management and Reviews' chapter of an upcoming ESA Herschel Lessons Learned report;
- several interviews with, and further reports and email correspondence from, Prof Griffin and UK SPIRE team;
- further additional inputs from the project outreach officer and associated spin-out company QMCi Ltd.

3.4 The evaluation report has been presented to a review board for finalisation and ratification. The board comprised independent external experts from the Agency's UK Herschel Oversight Committee (HOC) and included stakeholders from the relevant science user community, as well as SPIRE project team members.

3.5 The impact evaluation uses the framework of the following logic model:



4. Policy Context

4.1 Herschel was an ESA space science mission, delivered through its Science Programme. The UK is a founder member of ESA, and membership of ESA allows it to take part in its mandatory activities, including participation in the Science Programme.

4.2 Supplementing the ESA programme, the UK manages a national funding programme to enable UK scientists to participate in the missions through the provision of scientific instrumentation and data processing software and systems. The UK-led SPIRE instrument (one of three instruments on board the Herschel spacecraft) was supported and funded through this national programme. The national programme recognises the intrinsic value of this as a national endeavour, and its capacity to deliver tangible benefits through scientific and technological innovation, growth, training and inspiring the next generation of researchers and engineers.

4.3 Funding for UK involvement in SPIRE had originally been approved in 1998 by the Particle Physics and Astronomy Research Council (PPARC – later subsumed into STFC). The current UK Space Agency national science programme is derived from the programme previously delivered by PPARC and STFC; the Agency inherited responsibility for space science instrumentation and operations on ESA missions from the Research Councils upon its formation in 2010.

4.4 The PPARC and STFC funding policy context, in which the majority of Herschel SPIRE funding was approved, was heavily weighted towards science excellence; industrial engagement and public engagement were not explicit requirements. By contrast the Agency programme has a much increased focus on industrial engagement and direct economic impact.

4.5 Through a PPARC-led peer review process it was determined conclusively that the SPIRE project was the most effective route for the UK to secure major involvement in the Herschel mission. PPARC decided to concentrate resource to ensure UK leadership on the SPIRE instrument rather than fund a parallel role on the Dutch-led HIFI instrument. It was also decided that the UK should invest strongly in data processing as well as SPIRE instrument hardware, to ensure scientific success and maximise return to the UK through scientific exploitation. Successive funding packages from PPARC and STFC supported the development and build of the SPIRE instrument and operations from 1998 to 2010. Upon its formation, the UK Space Agency inherited responsibility from STFC for the continued operations and post-operations support of Herschel SPIRE in 2010, and funding support was provided via further Agency programmatic reviews through to the end of the SPIRE post-operations phase in June 2016.

PPARC - STFC investment (1998-2010): **£12m**

- Funding from Particle Physics and Astronomy Research Council and Science and Technology Facilities Council for the design and manufacture of the SPIRE instrument in the UK, and establishment of the SPIRE operations centre.

UK Space Agency investment (2010-2016): **£4.5m**

- Funding from UK Space Agency for post-launch support (commissioning, in-orbit technical support and data processing and optimisation) and post-operational data processing, calibration and archiving activities to put the data into usable legacy catalogues with supporting documentation and handbooks

Total UK public Herschel SPIRE public investment: **£16.5m**

5. Funding objectives of the Herschel SPIRE Programme

5.1 The original SPIRE proposal was subject to review by PPARC to ensure programmatic, technical and financial feasibility, however the investment justification and objectives were centred on scientific merit. As an academic research-focused funding body, industrial engagement was not an explicit PPARC requirement. The required technical expertise to develop the SPIRE instrument was also already contained within the proposed institute consortium, without direct industrial participation. Although industrial benefit from UK involvement in ESA Science missions was expected via the geo-return mechanism, this was taken to operate at the programme, as opposed to instrument, level.

5.2 The complete scientific goals of SPIRE were very wide-ranging and covered most areas of current astrophysics, as appropriate for an instrument on board an ESA observatory mission, but the top level objectives and scientific design drivers of SPIRE were to address fundamental scientific questions around galaxy formation and the formation and life cycle of stars.

5.3 Investment in UK leadership of the SPIRE instrumentation and leadership of the SPIRE Instrument Control Centre (ICC) was aimed at exploiting the high level of UK technical expertise built up through work on previous infrared and submillimetre astronomy space missions and ground-based observatories, and maintaining the outstanding international position of the UK in these areas. Herschel and SPIRE also addressed important areas of astrophysics in which the UK community has strong research interests and world-leading status.

5.4 Investment in SPIRE to ensure the UK was instrument PI (Principal Investigator) was aimed at securing strong and sustained UK influence over the technical and scientific development of the mission, to shape the design and optimise the science around UK interests and strengths, and to ensure that the UK community would be well-placed to scientifically exploit the data returned.

6. Outputs

6.1 The direct outputs of the funding:

- Grants provided to UK institutes, led by Cardiff University, for the design, construction and operation of Herschel SPIRE instrument:
  - Cardiff University – PI role, filters, internal calibrators, thermal system, instrument test support
  - Imperial College – software contribution, instrument test support
  - UCL-MSSL, Surrey – Instrument enclosure, thermal system
  - Rutherford Appleton Laboratory – instrument assembly and testing; project management and system engineering; main institute for the Instrument Control Centre (ICC)
  - UK Astronomy Technology Centre - beam steering mirror
  - University of Sussex - software contribution

- SPIRE instrument delivered to ESA, meeting eventual launch schedule, and meeting or exceeding all technical specification and science requirements – see ‘SPIRE Instrument Performance’ below
- UK influence and involvement in overall Herschel mission design
- SPIRE PI-ship bought UK observatory time on all Herschel instruments, maximising UK science return and allowing the UK community to optimise science on mission.
- High quality SPIRE data legacy archive, shaped around UK research interests and strengths

6.2 *SPIRE instrument performance*

6.2.1 Instrument performance, as proposed at the start of the project, was exceeded; essentially leading to over 10 times more scientific data obtained than the baseline specification. Key technical performance improvements were in the following areas:

6.2.2 Camera/Photometer and spectrometer:

- Field of view: enlargement by a factor of two (from 4 x 4 arcminutes to 4 x 8 arcminutes)
- Sensitivity: overall improvement by a factor of (2.2, 2.8, 2.5) at (250, 350, 500 μm)
- The combination of these gives factors of improvement in observing speed of (10, 16, 12) at (250, 350, 500 μm) – more than an order of magnitude
- Extension of guaranteed wavelength range from 200 – 400 μm to 194 – 670 μm (a factor of 2.4 greater wavelength coverage);
- Improvement of sensitivity by a factor of 5 – 10 (depending on wavelength), corresponding to a factor of 25 – 100 in observing speed depending on wavelength

6.2.3 The amount of scientific data that the satellite could obtain in a given amount of observing time was proportional to the observing speed. The instrument optimisation detailed above represents a major enhancement of scientific performance and productivity; more than an order of magnitude increase in observing speed and effectively over 10 times more scientific data than would have been possible with just the originally guaranteed performance. This improvement was made possible by continual effort to maximise performance and a very constructive attitude on the part of the ESA Project Team to enable the UK SPIRE team to do so. The fact that significantly more science data was collected in the course of the mission's limited lifetime represents an increase in value for money, and is underscored by the high scientific productivity in terms of refereed papers.

7. Contextual factors, programme delivery success

7.1 The following sections describe the historical context of the project and its impact on Herschel SPIRE delivery success. As detailed in 'Methodology' the information is drawn from interviews with, and report material from, the SPIRE PI and project team, archive UK oversight reports and the final draft of the 'Programmatics, Management and Reviews' chapter of an upcoming ESA Herschel Lessons Learned report.

7.2 Herschel and Planck co-implementation

7.2.3 As identified in the ESA commissioned Herschel Lessons Learned 'Programmatics, Management and Reviews' chapter final draft, the most significant factor influencing the early stages of Herschel development was the ESA Executive's decision in 1996/7 to combine Herschel and Planck (Cornerstone and Medium class missions) for implementation as a single project with an ESA budget equivalent to 90% of that of one Cornerstone mission, in order to accommodate Mars Express and Cluster-2 in the wider ESA Science programme budget envelope. Implementing the two projects together placed great strains on ESA, on the National Agencies, and on the scientific institutes building the instruments. Many of the same institutes across Europe were involved in both missions simultaneously, and whilst this provided a large consortium from which to draw expertise, it led to significant funding and resource pressures.

7.3 Funding and resources pressures

7.3.1 Herschel and Planck co-implementation brought about significant pressures on funding and resource allocation throughout the European consortium. This was eventually addressed by ESA, which provided some extra funding to all five instrument consortia. This enabled the projects to be pushed forward without scientific descope.

7.3.2 The SPIRE project was a large UK-led international collaboration of more than 150 scientists, engineers and managers from eight countries (Canada, China, France, Italy, Spain, Sweden, UK, USA). In the UK, the SPIRE System Engineering function was under-resourced, which led to challenges in effective management of the international SPIRE consortium, resulting in technical problems and delays.

7.4 Management Challenges

7.4.1 At the ESA level, the complexity and challenges of the mission meant that close involvement of national funding agencies was essential, but in the early stages of Herschel and Planck development there was no steering committee body established at the international level. ESA reporting processes were slow and information and decisions were quickly out of date. The lack of a European level steering committee meant national funding agencies did always have adequate visibility of external events which may have affected their funded national contributions. The need for change was recognised, with the UK SPIRE team at the forefront in pushing for improvement, and the ESA Herschel Project Manager organised programmatic meetings involving all key stakeholders to improve the sense of common purpose and address immediate issues in a communal and practical way. These quarterly meetings (consisting of ESA Project Management, instrument PIs and Project Management, and national funding Agency representatives) were essential in ensuring that all parties had a common and up-to-date understanding of what the problems and challenges were, and could understand everyone's role in addressing them. The meetings went on to act as the model for all future mission level international ESA steering committees.

7.4.2 In terms of UK programme oversight, an independent programme director was appointed by the original funding organisation PPARC to manage both Herschel and Planck. The programme director reported to the oversight committee and provided detailed and in-depth scrutiny. The programme director managed the overall budget and addressed emerging schedule pressures. The Herschel SPIRE team deemed the position very beneficial to the overall programme, recognising that independent technical and programmatic oversight is important and valuable for very complex programmes such as Herschel. Progress was managed in much more detail and frequency than funding body oversight committee meetings alone would have provided, and the independence of the programme director also allowed for demonstrably unbiased reporting to the UK funding agency.

7.5 Technical Challenges and Delays

7.5.1 Both Herschel and Planck experienced numerous technical challenges and associated delays, with the Dutch-led HIFI Herschel instrument causing significant ESA level launch slippage towards the end of the programme. The Planck cryo-coolers were the most pressing UK problem, causing significant slippage and requiring several major funding uplifts. The Planck telescope, Herschel telescope and Herschel solar panels all also experienced major delays.

7.5.2 Final launch date was May 2009, compared with an originally foreseen target (in 1999) of 2007. These overall delays allowed the SPIRE instrument to recover lost schedule, but did introduce cost increases as the schedule stretched. These factors, though delaying the core outcomes (i.e. exploitation of scientific data returned from the mission), are not deemed to have affected the SPIRE project in meeting its overall objectives. Conversely, the delays were taken advantage of by the project team and can be regarded as having contributed to increasing the performance and scientific exploitation of the mission.

7.6 Unforeseen Benefits

7.6.1 The delays provided more time for instrument hardware testing and ground segment data analysis software preparation. They also brought in extra resource for UK scientific exploitation as the community had more time to prepare – this was of importance for Herschel as it was a lifetime-limited mission (because of the reliance on the finite on-board helium coolant supply).

7.6.2 The delays also provided time for a significant level of additional end to end testing at spacecraft level, leading to overall confidence that all systems were robust and functioning as expected before launch. This was at additional cost both to ESA and Member States, providing funding for staff retention and continuity of critical mission knowledge, and de-risking cutting edge technology.

8. Did the project achieve its anticipated objectives?

8.1 The project's objectives were built around strong UK instrument leadership and influence of the mission and instrument design, leading to strong UK science return. The 'Key Outcomes' observed below suggest that a very good rate of exploitation has been achieved. As described in 'Funding Objectives', the top level objectives of the UK SPIRE project can be categorised as:

8.2 ***Support the Herschel mission's capabilities in addressing fundamental scientific questions around galaxy formation and life cycles of stars***

8.2.1 The SPIRE Instrument was successfully delivered to Herschel spacecraft, meeting eventual schedule, and operated with a high degree of performance and reliability throughout the mission lifetime. SPIRE baseline specifications were met or exceeded (detailed in '6.1 SPIRE instrument performance'), resulting in a factor of over 10 increase in data returned than originally aimed.

8.3 ***Ensure the UK was instrument PI in order to secure strong, long term UK influence over the technical and scientific development of the mission, to shape design and optimise the science around UK interests and strengths***

8.3.1 UK funding secured the UK Principal Investigator role on SPIRE. Metrics for the extent of UK influence were not built in to the programme from the outset, however the breadth of UK roles complimenting the PI role, and further evidence obtained through this evaluation, suggest UK influence was strong, both in the development of the SPIRE instrument, and the Herschel mission as a whole.

8.3.2 The UK-led SPIRE team actively lobbied ESA for spacecraft performance enhancements, particularly to the stray light properties of the Herschel telescope, contributing to the increase in data return detailed above (and indeed to improved science from the other Herschel instruments). The SPIRE team also ensured that their role allowed UK community observing time on all Herschel instruments, not only SPIRE.

8.3.3 Led by the PI, 6 UK institutes (detailed in Outputs) had core roles in the design, construction and operation of the Herschel SPIRE instrument. Complementing the UK PI leadership role with significant investment in SPIRE ground segment operations and instrument data processing added value by allowing UK groups to design and shape the whole data chain, from initial capture to processing and exploitation. These roles allowed the UK teams to scope the format of data in line with their requirements and areas of expertise by leading the process that develops the data analysis pipelines and calibrations.

8.3.4 Data from all publically funded ESA science missions is eventually released as open access; however the lead roles for the Herschel mission and the SPIRE instrument enabled the UK university groups a head start during the nominal one-year proprietary period. Further advantage was gained by being able to apply their intimate instrument knowledge to aid the interpretation and subsequent long term scientific exploitation of the data.

8.4 ***Exploit the high level of UK technical expertise built up through work on previous infrared and submillimetre astronomy missions, and maintain the outstanding international position of the UK in these areas***

8.4.1 As previously mentioned, metrics to determine the extent to which this objective was achieved were not built into the SPIRE programme from the outset. Despite this, it is clear that infrared and submillimetre heritage from across the many participating UK universities was harnessed to develop the SPIRE instrument hardware and supporting software, utilising significant prior public investment in these groups.

8.4.2 As detailed further below, UK ATC went on to take the lead role on the mid-infrared instrument MIRI on board the James Webb Space Telescope (JWST), the major NASA 'Hubble successor' mission due for launch in late 2018. Although this success should not be fully attributed to Herschel SPIRE, UK ATC participation in SPIRE was very helpful in securing this leadership.

8.4.3 Involvement in SPIRE inevitably contributed to building reputation for all participating UK institutes, helping them position themselves for future roles in space science missions. The UK's international position in infrared and submillimetre astronomy may also be measured in terms of UK science return and therefore exploitation and publications (see Outcomes below).

9. Who were the key beneficiaries?

9.1 The key direct beneficiaries were the UK institutes (listed in Outputs) which were funded to participate in the Herschel SPIRE project.

9.2 As an observatory-class mission with a broad, active astronomical community underpinning it, a core requirement on the Herschel mission consortium (ESA and the instrument teams), beyond the delivery of a functioning spacecraft and its raw data, was to offer this community the means and support to carry out research.

9.3 The SPIRE team was instrumental in supporting this mission-wide goal, and provided significant observing opportunities, data products, software and support documentation for the exploitation of its data by the wider research community.

9.4 Herschel has successfully performed ~37,000 science observations representing ~23,400 hours of allocated observing time. All of these, together with an additional ~6,600 science calibration observations representing ~2,600 hours of observing, are publicly available to the worldwide astronomical community through the Herschel Science Archive, maintained in perpetuity by ESA.

10. Key outcomes:

10.1 A summary of key outcomes is provided below. These outcomes are described in more detail in the following sections 'Science Return and leadership', 'Economic Impact', 'Outreach'.

- As a UK-led development, scientific optimisation of the SPIRE instrument design was strongly influenced by the UK participating institutes and the broader UK scientific community, so that its design drivers were well-matched to the strengths and interests of the UK scientific community.
- High visibility of SPIRE and Herschel amongst the UK community in the run-up to the mission, ensuring strong participation in Herschel observing programmes. This has been manifested in the strong representation by UK scientists in Herschel publications, as summarised below (see Science Return), with particularly intensive use of SPIRE.
- Training and skills – numerous scientists and engineers who have worked on SPIRE and been trained in the advanced technologies and techniques that this entailed, have moved on to highly-skilled jobs in industry, finance, and secondary education.
- Prominence in terms of recognition by ESA and the international scientific community of the UK's status as a major partner in ESA and in international space science. SPIRE was built by 18 institutes in eight countries, working effectively together under UK leadership.
- Involvement of the UK ATC in SPIRE, through building one of its cryogenic mechanisms, constituted its first major space project, and provided experience and a track record in space instrumentation which paved the way for UKATC to be the PI institute for the MIRI instrument for the James Webb Space Telescope, the major NASA 'Hubble successor' mission.
- While there was no direct industrial participation in the SPIRE project, UK SPIRE institutes working on instrument hardware placed a significant number of contracts with industry for the manufacture and delivery of both flight hardware and test equipment. QMCI Instruments Ltd., a spin-out company associated with Cardiff University, also won substantial contracts to provide flight hardware components both to ESA and to one of the other Herschel instruments.
- Leadership of SPIRE was the basis of an organised and sustained public and schools outreach programme in the UK.

10.2 Negative outcomes

All impact evaluations should consider negative outcomes resulting from investment. Other proposed projects were obviously not funded as a consequence of the decision to fund Herschel SPIRE. These would by definition have had a lower scientific priority than SPIRE for PPARC and STFC during the funding approval process, so the decision to fund SPIRE should not been seen as a negative outcome from the perspective of UK priorities and science return.

10.3 Science Return and UK leadership

10.3.1 UK leadership of SPIRE resulted in the scientific optimisation of the instrument design being strongly influenced by the UK participating institutes and the broader UK scientific community, so that its design drivers were well-matched to UK strengths and interests. From 2001, in parallel with the Cardiff-led manufacture of the instrument, Cardiff academics were prominent in defining and then carrying out Herschel's science programmes. Prof Griffin coordinated the SPIRE Science Team (over 300 members), responsible for the consortium's science programme, and other Cardiff staff lead several of the large Herschel Key Projects.

10.3.2 The high visibility of SPIRE and Herschel amongst the UK community in the run-up to the mission ensured its strong participation in Herschel observing programmes. This has been manifested in the strong representation by UK scientists in Herschel publications, as summarised below, with particularly intensive use of SPIRE.

10.3.2.1 Herschel publications as of 19 April 2016:

- 1661 refereed papers have been published using Herschel data. This publication rate is the highest of any major ESA observatory.
- Most Herschel papers have been published in major astrophysics journals: Astronomy & Astrophysics (50%); The Astrophysical Journal (25%); Monthly Notices of the Royal Astronomical Society (15%); others (10%).
- 906 (54%) of Herschel papers have UK authors, and 260 (15%) are UK-led.
- (309, 1134, 1031) papers have used (HIFI, PACS, SPIRE) data.
- Of the 1031 SPIRE papers, 682 (66%) have UK authors and 260 (21%) are UK-led.
- Of the 30 most highly cited Herschel science papers, 20 use SPIRE data (5 SPIRE-only, and 17 SPIRE + PACS); seven of the 30 are UK-led and all of those seven use SPIRE data.
- 21 Herschel papers have been published in Nature or Science, 13 of which use SPIRE data, 13 have UK authors, and four are UK-led (all of which use SPIRE data).

10.3.2.2 Four examples of the impact of these publications are provided below:

1. Star Formation in the Milky Way and Nearby Galaxies Kennicutt et al.
Annual Review of Astronomy and Astrophysics, vol. 50, p.531-608
625 citations
Review of state of the art in star formation in galaxies with assessment of Herschel's major impact on the field. UK lead author

2. From filamentary clouds to prestellar cores to the stellar IMF:
Initial highlights from the Herschel Gould Belt Survey Andre et al.
Astronomy and Astrophysics, Volume 518, L102
551 citations
Initial paper describing Herschel's discovery of the ubiquity and importance of filamentary structure in the interstellar medium and its impact on star formation, and of the clear link between the stellar initial mass function and the pre-stellar core mass function - both major science results.
Major UK involvement

3. The Detection of a Population of Submillimeter-Bright, Strongly Lensed Galaxies Negrello et al. Science, Volume 330, Issue 6005, 800
First paper describing use of Herschel-SPIRE survey data to identify strongly gravitationally lensed high-redshift galaxies, allowing them to be studied spectroscopically to reveal how galaxies formed their stars in the early Universe.
202 citations
UK lead author

4. The Herschel Multi-tiered Extragalactic Survey: HerMES
Oliver et al.
Monthly Notices of the Royal Astronomical Society, 424, 1614, 2012
Overview of the hugely successful (UK-led) HerMES extragalactic survey, detecting and characterising ~100,000 galaxies and enabling a huge range of new science
287 citations
UK lead author

10.3.3 In 2014 ESA adopted Key Performance Indicators to measure impact of its science missions. The ESA Science Programme generated an approach to measure this impact relatively: "The number of times a mission is cited in the literature is often used as a measure of the "impact" of a paper. This is unavoidably an imperfect indicator, however it is one that is most often used in the academic community to assess the impact of the work of individual scientists or of teams. To quantify it in a "relative" sense, the indicator often used in assessing the impact of an individual researcher, or of a research group, is the "impact factor", i.e., the average number of citations per paper (computed over a given period). For the purpose of defining a Key Performance Indicator, an impact factor over the two previous years has been defined, so that the impact factor for the ensemble of ESA-led missions for 2015 is defined as"[3]:

$$\frac{Number\ of\ citations\ in\ 2015\ to\ the\ refereed\ publications\ from\ ESA-led\ missions\ in\ 2013\ and\ 2014}{Number\ of\ refereed\ publications\ from\ ESA-led\ missions\ in\ 2013\ and\ 2014}$$

Publication statistics for selected ESA-led missions:

	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
ESA-led Missions	Launch	End of Operations	Refereed Publications			(7) Member State/Total (First Authors)	Citations		No. of Unique Names		Impact Factor	
			Total	2014	2015		Evaluated in 2015	Evaluated in 2016	Evaluated in 2015	Evaluated in 2016	2014	2015
COS-B	1975	1982	176	0	2	81%	4,800	4,900	240	260	-	-
IUE	1978	1996	3,283	11	19	42%	-	94,040	-	4,940	-	-
Exosat	1983	1986	737	3	2	77%	23,950	24,400	1,060	1,100	-	-
Giotto	1985	1992	269	0	1	72%	-	12,150	-	520	-	-
Hipparcos	1989	1993	2,400	58	62	49%	75,650	83,140	4,840	5,140	4.5	4.4
Ulysses	1990	2009	1,766	34	32	41%	-	41,040	-	2,620	-	4.8
ISO	1995	1998	1,831	58	35	67%	70,250	78,200	3,400	4,720	3.2	5.6
SOHO	1995	-	5,070	213	216	38%	120,300	143,880	5,840	6,440	3.8	3.9
Huygens	1997	2005	214	5	0	60%	4,550	5,080	780	800	-	-
XMM-Newton	1999	-	4,496	332	329	61%	110,250	130,920	9,880	10,980	5.4	6.2
Cluster	2000	-	2,257	157	175	48%	29,000	32,240	3,020	3,280	3.4	3.2
INTEGRAL	2002	-	919	49	61	73%	25,400	27,920	2,420	2,620	3.5	3.9
SMART-1	2003	2006	81	7	1	65%	650	720	400	360	1.6	-
Mars Express	2003	-	891	73	47	62%	16,700	21,440	1,980	2,140	2.6	3.3
Rosetta	2004	-	602	53	153	75%	3,750	6,220	1,820	2,700	2.2	2.9
Venus Express	2005	2014	503	40	62	62%	4,250	5,740	1,240	1,400	1.7	2.4
Herschel	2009	2013	1,661	336	301	67%	31,450	41,780	5,900	6,760	8.9	6.9
Planck	2009	2013	940	328	325	50%	20,000	28,500	3,540	4,520	6.7	17.0
PROBA-2	2009	-	59	13	10	59%	350	480	240	280	3.4	2.9
Gaia	2013	-	85	31	37	76%	160	420	220	520	-	4.1

[3] ESA/SPC(2016)13, Programme's Performance in 2015 and Science Key Programme Indicators (KPI's)

10.3.4 The table above shows that Herschel had the highest impact factor of any comparable ESA Science mission in 2014, and second highest in 2015. Although this impact cannot be attributed to UK funding for the Herschel SPIRE project alone, taken with the SPIRE specific publication data, it clearly illustrates the success of the UK roles in delivering high quality science.

10.3.5 Herschel SPIRE was recognised in the STFC 2013 Programmatic Review report as a "hugely successful far-IR mission with strong UK leadership roles" (http://www.stfc.ac.uk/files/programmatic-review-report-2013/). The STFC Astronomy Advisory Panel Report (October 2012) directly attributes the UK's world-leading positions in sub-mm astronomy to Herschel-SPIRE. (https://www.stfc.ac.uk/stfc/includes/themes/MuraSTFC/assets/legacy/aap_prreport_submitted_nov22.pdf)

10.4 Economic Impact

10.4.1 Cardiff University Astronomy Instrumentation Group (AIG) and QMCI Ltd.: The Cardiff University AIG led the design and manufacture of the SPIRE flight hardware. AIG spin out company QMCI Ltd existed before Herschel, but building on the Research and Development activity untaken for SPIRE, and using the same research-funded development skills and facilities, AIG capabilities in highly sensitive, ultra cold terahertz (THz) detectors have been commercialised and brought to the global market through QMCI Ltd.

10.4.2 QMCI is co-located with the Cardiff AIG and is an established market leader in many aspects of THz instrumentation, offering customised THz systems for many applications. Its close collaboration with the AIG ensures that technology is adapted swiftly and appropriately for commercial, civil and governmental users, and that knowledge transfer and exchange between academia and industry is rapid.

10.4.3 As a result of this, AIG THz detection systems developed with the resources funded through participation in Herschel SPIRE are now used in the fields of bio-medical imaging and bio-molecular spectroscopy for health science, plasma fusion diagnostics for sustainable energy, remote atmospheric sensing, synchrotron and free-electron laser diagnostics and artwork analysis and curation. These instruments all incorporate the enabling technologies originally developed for astronomy by the AIG: detectors and cryogenic systems, band selection filters and quasi-optical components.

10.4.4 According to QMCI Managing Director, Dr Richard Wylde, since 2008 the aggregate business volume transacted by QMCI is in excess of £4 million, of which more than 80% depends directly on contributions made by the AIG"(Cardiff University REF2014 case study: http://impact.ref.ac.uk/casestudies2/refservice.svc/GetCaseStudyPDF/3466). More than 90% of the activity is exported (30% Europe; 30% US; 30% Far East). The company employs five highly skilled technical staff in Cardiff, makes use of AIG academic consultants and utilises experienced local representatives in Japan, China, and Korea.

10.5 Commercial Economic Analysis

10.5.1 London Economics Ltd. was externally commissioned to carry out an independent case study analysis of Herschel SPIRE. This analysis focuses largely on easily quantifiable commercial benefits, which should be taken as one part of the overall picture of economic impact. As touched on elsewhere in this report, Herschel SPIRE was initiated by PPARC in 1998 as a solely scientific and research driven project with no requirement for direct industrial engagement.

COST	Public investment (1998-2016): **£16.5m**	Funding from, PPARC, Science and Technology Facilities Council and UK Space Agency
COST	Private investment: **£2m**	Salaries to academic staff involved in SPIRE across The Rutherford Appleton Laboratory; Cardiff University; The Mullard Space Science Laboratory; The UK Astronomy Technology Centre; Imperial College London; and The University of Sussex. Assuming 30% of FTE for six academics for ten years
BENEFIT	Direct benefits: **£5.6m**[3] contribution to GVA	■ STFC funding to analyse Herschel data: **£3m** (45 Post Doc Researcher Years) ■ FP7, HELP: €2.5m, of which **£891k** to Sussex, Cardiff and Cambridge ■ FP7, VIALACTEA: €2m, of which **£285k** to Cardiff and Leeds ■ FP7, DustPedia: €2m, of which **£427k** to Cardiff ■ Horizon 2020, CosmicDust: €1.8m, all of which to Cardiff University, **£1.3m** ■ FP7, SPACEKIDS: €2m, of which **£285k** to Cardiff University ■ GVA share assumed to be **90%** due to labour-intensive nature of projects.
BENEFIT	Spillover benefit: **£4.05m** GVA	■ QMCi's sales: **£0.4m** (2008-2015: 100% SPIRE related) ■ Space Manufacturing average GVA:turnover ratio (Case for Space2015): **34%**

http://londoneconomics.co.uk/wp-content/uploads/2015/11/LE-UKSA-Return-from-Public-Space-Investments-FINAL-PUBLIC.pdf

[3] Using prevailing exchange rate on 27 July 2015 from http://ww.xe.com; 0.71243 £/€

		■ Feasibility contract for Chinese weather satellite: **£250k** ■ Feasibility contract for Airbus Defence and Space EO satellite: **£250k** ■ Follow-on contract from Airbus Defence and Space: **£4m**[4] ■ GVA share assumed to be **90%** due to labour-intensive nature of projects.
	Other wider benefits:	■ **200-300** undergraduate students in research-led teaching programmes and a **2,000-3,000** students in lecture-teaching programmes drawing on SPIRE ■ Around **35** Postgraduates directly involved in SPIRE and **50** relying on its data ■ UK ATC, proving flight heritage with SPIRE, which helped them win European leadership on the MIRI instrument for the James Webb Space Telescope ■ SPIRE science and technology injection of skilled and educated people into the workforce and thus contributed to UK productivity ■ Inspiration of young people to study STEM subjects ■ Greater understanding amongst the public of how the Universe works ■ 782 papers using SPIRE data (72% have UK authors; 24% are UK-led) [Feb 15]
	Additional information:	■ Deadweight: **Low** (little or none) ■ Displacement: **30% at most** (share of SPIRE team that was permanent staff) ■ Leakage: **Very low** (industrial), **medium** (benefits, e.g. non-UK papers- 28%) ■ Lag: **10 years** (from agreement to first outreach programmes) ■ Duration: **50+** years (due to STEM outreach and continuous benefits thereof)
RoR	Aggregate	■ Rate of return – Public return **to date**: **-0.54** ■ Rate of return – Direct benefits **to date**: **1.8** ■ Rate of return – Spillover benefits **to date**: **1.03**

10.5.2 Estimated value of contracts awarded by UK SPIRE institutes to UK industry:

- Cardiff ~ £50k on external machining of focal plane cryogenic components and cryoharnesses
- MSSL ~ £200k on external procurement of the instrument cold boxes and thermal-mechanical supports
- RAL ~ £1M on the test facility cryostat and cryoharnesses
- Total: Approximately £1.25M

10.5.3 It should be noted that the analysis and aggregate rate of return presented above focuses on directly quantifiable commercial economic benefits to date. The core investment objectives and overall drivers for UK participation in Herschel SPIRE were largely unquantifiable benefits, arising from enhanced scientific knowledge. These lead to a stronger UK research base that maintains international competitiveness, as well as the intrinsically valuable improved knowledge of infrared and submillimetre fields of astronomy.

[4]Both feasibility studies and follow-on contract awarded to consortium of Cardiff University, QMCi and Thomas Keating Ltd

10.5.4 The economic analysis presented here should therefore be regarded as interim only; many of the scientific impact benefits are difficult to quantify in economic terms and it will be many years before the value of the scientific advances will be fully understood.

10.6 Outreach

10.6.1 Herschel funded research and the accompanying PR and outreach programme have given the public valuable and exciting insights into science and technology. Importantly, this extends to enhancing educational learning and stimulating engagement with STEM subjects in schools. With many more scientific discoveries to come from Herschel's database of observations, the outreach programme will be sustained, and contacts with educators and the media will be continued.

10.6.2 At the beginning of 2008 (15 months before the Herschel launch) the UK Herschel Outreach Group (HOG), chaired by Prof Griffin, was formed to coordinate a national outreach and PR programme. It included members from all UK SPIRE institutes (Cardiff, Imperial College, UCL-MSSL, UK ATC, STFC-RAL, Sussex) and several other UK institutes involved in Herschel science. A national network of scientists and engineers from Cardiff and other UK Herschel institutes was also established to assist with events (schools visits, public talks, exhibitions, etc.).

10.6.3 A schools programme was developed and implemented by the HOG with the assistance of teaching professionals. It consisted of interactive lesson plans, talks, and demonstrations using Herschel to illustrate several subject areas: multi-wavelength astronomy, spacecraft engineering, space dust, cosmology, and the solar system. A series in 2010 across Wales reached 130 teachers, and sessions at the National Space Centre and Science Learning Centre, Leicester, have reached 90 teachers. With each secondary school teacher reaching ~100 new pupils each year the total reach of these sessions is over 20,000 pupils per year.

10.6.4 Up to the end of 2013, eleven major public events were organised by the UK Herschel team and supported by Cardiff staff. Including the Royal Society Summer Exhibition in both 2009 and 2012 (with visitors of 5,000 in 2009, and 14,000 in 2012) and Big Bang Fair in four successive years (2010-2013), leading to personal invitations to return each year. Each Big Bang Fair was attended by around 35,000 people, mostly secondary school pupils.

10.6.5 Media coverage has publicised the technical and scientific work of the Cardiff team, including articles in UK and foreign newspapers including The Independent, The Sunday Times, The Daily Telegraph, The Calgary Herald, Asian News International, The Qatar News Agency, and many more. Herschel was designated number 7 in Time Magazine's Inventions of the Year in 2009. (http://www.time.com/time/specials/packages/completelist/0,29569,1934027,00.html)

10.6.6 Herschel SPIRE outreach activities were the subject of a 2014 REF (Research Excellence Framework) impact case study, which was rated 4*, the highest possible rating, via an independent expert panel assessment. (http://impact.ref.ac.uk/CaseStudies/CaseStudy.aspx?Id=3467)

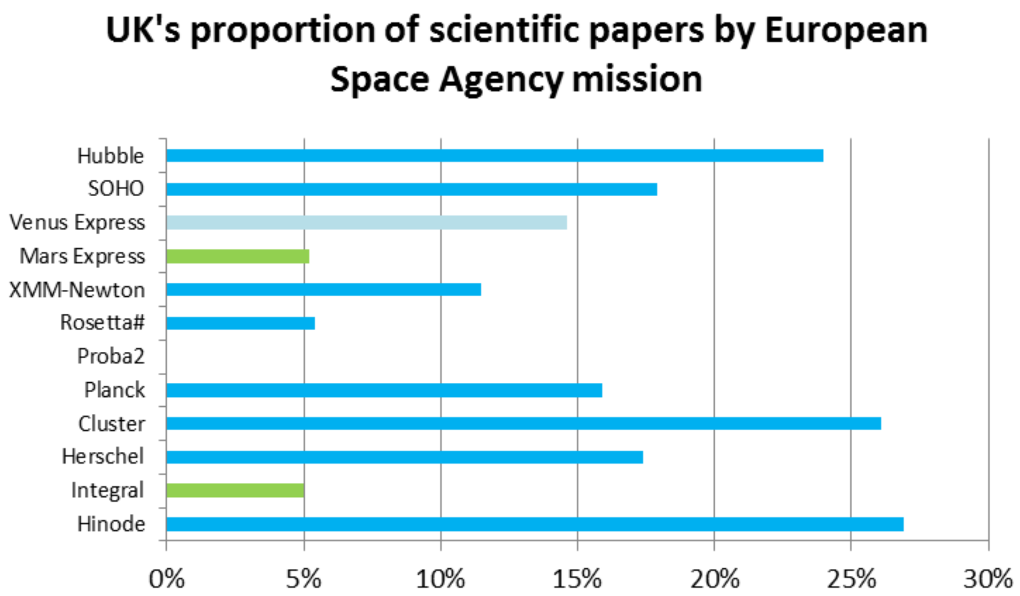
10.6.7 The Herschel-SPIRE team received the 2013 Royal Astronomical Society Group Achievement Award, and also received Arthur C Clarke awards at the UK Space Conference in 2010, Individual Achievement award to Prof Griffin, and 2013, Team Achievement award. In 2011 Prof Griffin was awarded the Royal Astronomical Society Jackson-Gwilt medal - awarded for outstanding invention, improvement, or development of astronomical instrumentation or techniques. The internal

Herschel/Planck team was awarded the French Association for Aeronautics and Astronautics Grand Prix in 2010.

11. What would have happened to the beneficiaries without the UK role on Herschel?

11.1 Establishing a full counterfactual scenario for the SPIRE project is unfeasible due to its duration, scale and complexity. However, the following observations can be made regarding the role the project had in several of the observed outcomes:

11.2 Recent publication statistics from ESA clearly demonstrate that UK science return from ESA Science missions is significantly higher with Principal Investigator roles. We can reliably estimate from this that having no UK role in Herschel would have significantly reduced the science return stemming from the mission for UK academia. Core roles on science missions allow academics privileged access to data during initial proprietary access periods, and intimate instrument knowledge gained from being centrally involved in their design and build, also helps in the interpretation of data. The blue bars in the missions below indicate ESA science missions on which the UK had PI roles, the green bars without.



Source: ESA

11.3 Using the baseline of the Mars Express or INTEGRAL missions, we could expect the proportion of UK-led Herschel scientific papers to reduce from 17% to 5% in a counterfactual scenario whereby there was no PI role on SPIRE or Herschel.

11.4 UK ATC involvement in SPIRE was very important in enabling the UK to take the lead on MIRI instrument for the major NASA mission JWST. Aside from a very low-level previous involvement in one of the instruments on ISO, SPIRE was UK ATC's first significant space project (UK ATC was responsible for the beam steering mechanism for SPIRE). That experience helped UK ATC in convincing ESA, European and US partners that they had the necessary track record in space technology. UK ATC's and MIRI PI Prof Gillian Wright's background in ground-based infrared spectroscopic instrumentation and astronomy was also key to this, however SPIRE was a critical step on the way to MIRI.

11.5 The filter technology developed for SPIRE was made available to the PACS instrument on a commercial basis via QMC IL, and through the resulting connections with ESA they were able to secure a major contract for the Local Oscillator windows for Herschel-HIFI.

11.6 Herschel also paved the way for Cardiff and Thomas Keating Ltd. involvement in the MWS meteorological instrument under a commercial contract to Airbus Ltd, and the potential for a future contract for a similar instrument on a Chinese satellite as noted in the London Economics economic analysis in section 10.5.

12. CONCLUSIONS

12.1 In assessing the impact of the investment in Herschel SPIRE this review has considered impact in terms of science return and outreach (which are part of the remit of the original funding body PPARC, and later of STFC) as well as economic impact (which was not).

12.2 Value for money

12.2.1 An objective of the impact evaluation has been to assess the overall value for money (VFM) of the public investment in Herschel SPIRE. The National Audit Office (NAO) VFM criteria[5] have been adopted as a simple framework, consisting of Economy (minimising costs of resource input), Efficiency (the relationship between the output and the resources to produce them) and Effectiveness (the relationship between the intended and actual results of public spending (outcomes)). Taking these three criteria together, the UK public investment in Herschel SPIRE can be seen as providing value for money:

[5] https://www.nao.org.uk/successful-commissioning/general-principles/value-for-money/assessing-value-for-money/

12.2.2 Economy: Cost and effort allocation was rationalised through PPARC, STFC and UK Space Agency competitive and peer review processes. The UK SPIRE roles were approved for funding based on capability to deliver the top level funding objectives of UK involvement in Herschel in the most cost effective approach. Through the regular UK oversight mechanisms and funding agency approval processes, costs and resource allocations continued to be scrutinised and rationalised as the project developed.

12.2.3 Efficiency: As a scientific research driven mission the SPIRE investment compares favourably to other similar investments. The outcomes reported through sections 10 and 11, particularly those measuring science return and impact against comparable space science activities, demonstrate SPIRE delivered UK science leadership and significant UK science return – both core investment objectives.

12.2.4 Effectiveness: The SPIRE instrument was delivered to its eventual schedule and significantly exceeded its agreed performance specifications with over 10 times more scientific data returned, an enhancement of scientific return and productivity. As reported from section 8 onwards, the three top level objectives of the UK SPIRE project were met.

12.3 Recommendations for future impact evaluations

12.3.1 As stated in section 3 'Methodology', constraints were brought about in conducting this impact evaluation due to the fact that outcome monitoring and impact evaluation were not built in to the function of the Herschel SPIRE oversight bodies from the outset, and were not explicit considerations at the time of original funding approval. Conducting this impact evaluation retrospectively has served to illustrate three key points to be noted for future similar activities;

12.3.2 The importance of setting clear, measurable, objectives from the outset of the project: the top level funding objectives used in this impact evaluation were obtained from legacy PPARC reviews. Beyond the base objective of delivering the SPIRE instrument to specification, cost and schedule, the broader funding objectives of ensuring UK scientific leadership and science return are clearly sensible, but it is difficult to robustly evaluate whether they have been achieved without clear metrics to measure success, designed in from the outset.

12.3.3 The necessity of regularly collecting impact information and monitoring outcomes from the outset of the project: this evaluation has gathered a range of evidence from the 18 years since original funding approval. During this long timescale other relevant information may have been lost or not recorded, limiting the degree to which all outputs, outcomes and impact can be reliably linked and attributed to Herschel SPIRE. Throughout the lifecycle of a project, outcomes should be reported and collected. This could be built in to the function of management and oversight bodies, and would contribute to overall project progress monitoring. As an ongoing practice it would also help both the Agency and the project team understand whether expected benefits are likely to be realised and whether any interventions are required to make sure they are.

12.3.4 Recognising the long duration of many space science projects, interim impact evaluations should be planned into project review schedules, potentially coinciding with transitions from one development phase to another. As above, this would help with benefit realisation, and contribute to groundwork for future exercises.

12.4 Summary conclusions

12.4.1 The Herschel-SPIRE project achieved its top level objectives as defined at the time of funding approval. In terms of measurable objectives, all science performance objectives specified for the SPIRE instrument were met or significantly exceeded. There are additional benefits that have been measured retrospectively. SPIRE fundamentally contributed to addressing all the science questions of the Herschel mission, has achieved a strong science return for the UK, and the breadth of UK involvement has cemented the UK leadership role in infrared and submillimetre astronomy and led to significant roles for contributing institutes in follow on missions such as UK ATC's lead role on the MIRI instrument on board the Hubble successor JWST (James Webb Space Telescope). Herschel SPIRE has demonstrated the UK's ability to deliver a major role on a large ESA science mission and support it through its entire life-cycle, allowing the maximum scientific benefits to be reaped of such a long term investment.

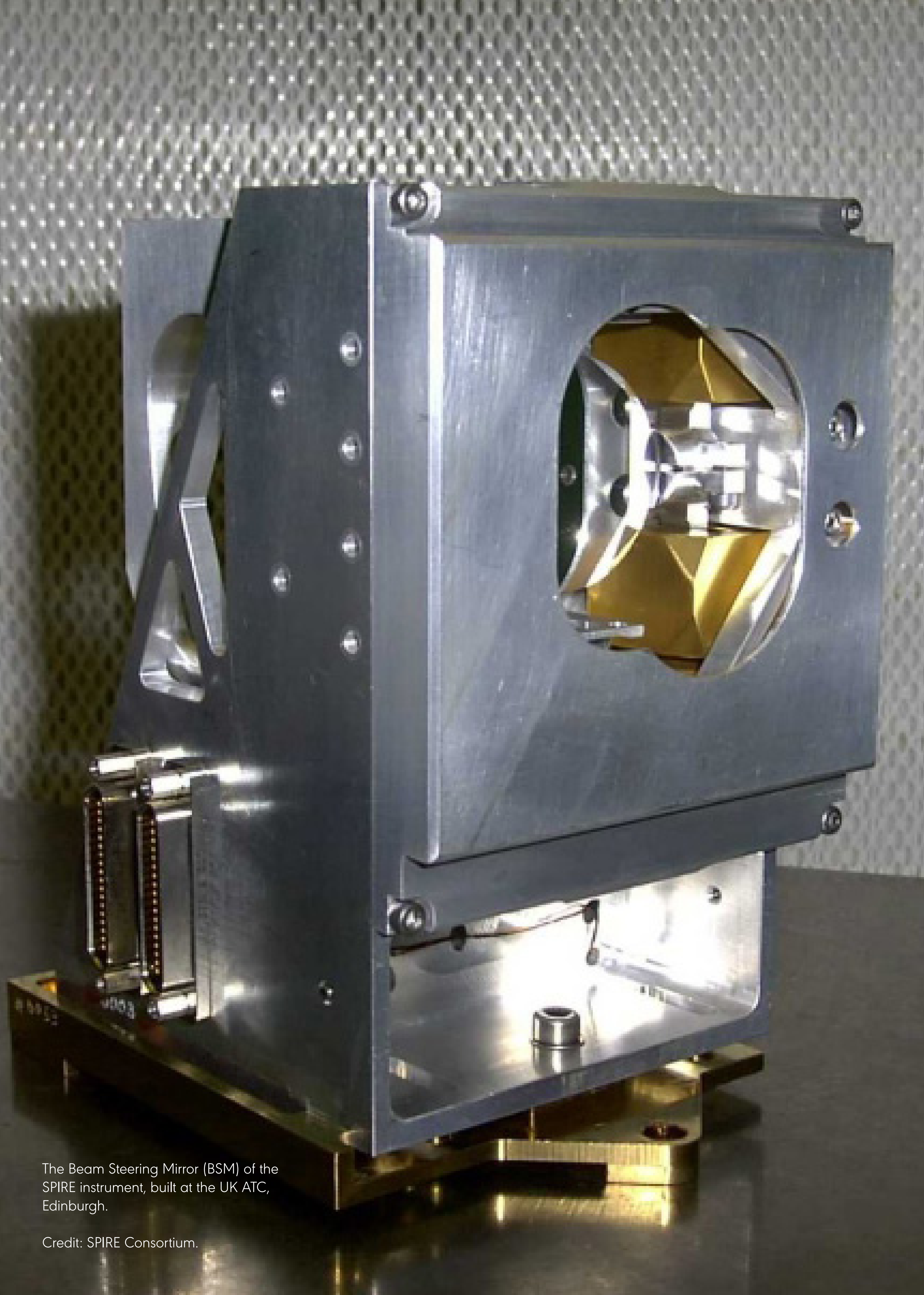
12.4.2 The UK contribution to Herschel generated a critical mass for build-up of expertise in this area of scientific R&D in the UK. The project is now embedded as a key part of the UK academic 'ecosystem' and without it there would be a much less influential far-infrared and sub-millimetre space science and engineering community in the UK. As detailed in '7. Contextual factors, programme delivery success', the management improvements during Herschel and SPIRE have been implemented by ESA as a model for its future missions, and many Herschel staff are now working on the next generation of Science Programme missions.

12.4.3 On assessing economic impact it is important to note that most quantifiable analysis in this evaluation focuses on direct commercial and contractual outcomes. The core investment drivers for Herschel SPIRE were largely unquantifiable benefits, arising from enhanced scientific knowledge, which has its own intrinsic value, of which we are not yet in the position to know the long term economic return. Overall commercial and contractual economic impact may have been larger had this been a key consideration or requirement at the time of PPARC funding approval in 1998. Direct industrial participation or engagement in the SPIRE consortium was not a requirement, however there were several unplanned but very positive economic spill-over benefits observed, as detailed in 'Economic Impact'.

12.4.4 Through the UK Herschel Outreach Group (HOG), chaired by the PI Prof Griffin, the project has contributed public engagement with science and to STEM learning in schools. Measuring the precise impact towards public understanding of space and student STEM uptake as a result of these initiatives would require detailed longitudinal analysis which is beyond the scope of this review; however the scale of the HOG programme and its reach should at the very least provide an indication that it has stimulated engagement with space science.

12.4.5 These direct and indirect benefits in terms of science return and UK leadership, development of the research community, economic impact and outreach would not have been derived in the absence of the investment by PPARC, STFC and UK Space Agency.

12.4.6 Furthermore, the review and its findings should in effect be regarded as an interim review, since the impact and science exploitation of Herschel SPIRE data, and long term economic benefit from this, will continue for several decades. This will be monitored in partnership with STFC, which provides research funding for science exploitation of Herschel SPIRE data.



The Beam Steering Mirror (BSM) of the SPIRE instrument, built at the UK ATC, Edinburgh.

Credit: SPIRE Consortium.

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