Roadmap Exercise in Raman and IR Spectroscopic Capability in the UK

The aim of this exercise was to produce a picture of the current vibrational spectroscopy landscape within the UK research sector both academically and industrially. This covered all levels of instrumentation capability from high end to hand held portable Raman and IR systems. The data was digested by a review panel and will be presented to the EPSRC as part of their road mapping exercise to better understand the future need for investment in cutting-edge and underpinning equipment to support world-leading physical science and engineering in the UK. More information on the roadmaps and some examples of previous ones and those in progress can be found here:
https://www.epsrc.ac.uk/research/ourportfolio/themes/researchinfrastructure/strategy/equipmentroadmaps/

Information was obtained via a survey comprising 54 respondents from across the UK. Whilst this is by no means exhaustive, it did allow certain conclusions to be drawn and we feel the response was adequate to provide a sample of the overall activity in the UK. The questions can be found in appendix 1.

The review panel for the survey outcomes and authors of this report consisted of:

Prof Duncan Graham	University of Strathclyde (Chair)
Prof Karen Faulds	University of Strathclyde
Prof Pavel Matousek	STFC Rutherford Appleton Laboratory
Prof Steve Meech	University of East Anglia
Dr Deb Roy	National Physical Laboratory
Prof Nick Stone	University of Exeter

1.0 Introduction

The UK has a very rich and vibrant Raman and IR research base allowing the widespread use of the two techniques, however, current state of the art research comes under increasing pressure from the ongoing and challenging funding situation. In the past, the UK researchers have played key roles in many critical developments underpinning the two fields. This includes the first observation of SERS effect (Fleischmann M., Hendra P. J., McQuillan A. J. *Chem. Phys. Lett.*, **1974** 26:163–166.), the discovery and first practical demonstration of Raman Optical Activity (ROA) (L. D. Barron, M. P. Bogaard and A. D. Buckingham *J. Am. Chem. Soc.*, **1973**, 95, 603-605), first demonstrations of macro ATR-FTIR imaging (Chan K. L. A., Kazarian S.G., *Applied Spectroscopy*, **2003**,_ 57, 381-389) to name a few. This also led to the early adoption of the techniques in applied research and by major UK industry (e.g. ICI, BP, GSK, AstraZeneca). This development and infrastructure also played a pivotal role in the formation of several world-leading UK companies and start ups in this area (e.g. Renishaw Spectroscopy Products Division, Renishaw Diagnostics Ltd, Teraview, Cobalt Light Systems) contributing to the UK economy in general (this is hard to quantify financially but we can point to >100 jobs in this sector from this sub-set of companies).

As a result of this strong heritage and existence of solid infrastructure (instrumentation, knowledge/people, world leading centres) the UK is nowadays a key world player in these fields in terms of both research volume and quality (see section 3.7 on citation analysis).

Currently, both IR and Raman spectroscopies form dynamic and prolific platforms on which the future growth of the UK economy in multiple sectors is reliant. Critical features of the effective translational process includes continuous investment in the instrumentation and knowledge base. This needs to be in both the fundamental research (an area spawning new techniques and concepts) and applied research (facilitating the ultimate translation into applications). The third commodity is the skill base of spectroscopic experts that are highly trained in these techniques and are vital to the continued sustainability of the UK's leading position on the global stage.

The UK is well poised to capitalise on the next wave of techniques and technological advances in the relevant fields dramatically influencing the direction of travel of the optical spectroscopy research community at present. Both IR and Raman are currently undergoing rapid developments in several areas stemming from the emergence of novel underpinning technologies and techniques e.g. portable Raman (due to recent advances in solid state lasers, dielectric filters, spectrograph and detector technologies), advent of non-invasive/through-barrier Raman concepts, development of advanced nonlinear Raman and nonlinear (fs) 2D-IR, advent of quantum cascade IR lasers, development of advanced SERS labelling techniques and recent developments in nano-IR and nano-Raman to name but a few.

It is also notable that both IR and Raman spectroscopies, as analytical techniques providing exceptional richness of chemical information in a fast and often non-invasive and non-destructive manner, also underpin many very distant scientific research and applied fields. This includes advanced industrial manufacture, materials and quality control as well as addressing major societal challenges (security, food, health and aging, environment, energy, etc).

2.0 Context

Vibrational spectroscopy (Raman and IR) is well established at a number of internationally leading centres across the UK (see section 3.7). This provides the essential foundation on which to develop and exploit the rapidly evolving technologies which underpin vibrational spectroscopy. Among these we identified recent progress in: solid state lasers, producing high power compact economical sources; new IR lasers; access to a broader frequency range through new optical materials; ultra-short pulse lasers for time domain spectroscopy; multidimensional spectroscopy; more sensitive detector technology. These provide rich opportunities for the further development of vibrational spectroscopy in the UK.

The UK is well placed to adapt these recent developments to generate new spectroscopic methods with a wide range of applications. There are a number of laboratories in the UK who already have an international reputation for advanced instrument development and fundamental spectroscopy leading to new cutting edge Raman and IR experiments and applications. Many of these groups have been successful in attracting significant funding from RCUK, EU and university sources, allowing them to establish and sustain high quality laboratories (our survey identified recent investment in excess of £10 million for sophisticated high end sources for vibrational spectroscopy). Recent examples include the establishment of centres for imaging, critical mass in bioanalytical and healthcare measurements, time domain Raman, terahertz spectroscopy and nonlinear-optical infra-red spectroscopy. In the majority of these centres the techniques developed are applied in a wide range of academic studies beyond fundamental spectroscopy (often in the fields of biophysics and materials science) thus generating broad academic impact. Importantly, most of these centres are closely integrated with groups who are able to pick-up the latest methodologies and adapt them to address important problems in a variety of 'real-world' applications. Recent examples include: Raman based analysis for improved healthcare diagnostics; food security; plasmonic imaging in cells; peptide sequencing and Raman explosives detections. There have been clear benefits to the UK economy which flowed from these developments (as mentioned in the previous section) with regard to industry presence and start-ups.

It is remarkable that many of these companies have developed products for analysis and sample characterisation. These products play a key role in supporting other areas of science in both academia and industry. For example, our survey revealed a spend of about £10 M on Raman and IR tools for imaging and analysis, much of it in University departments (as expected from the nature of the responders) but with significant numbers of users in industry and government laboratories. Applications include drug discovery and characterisation of drug formulations, analysing bone structure and polymer blend characterization. There is a clear and growing demand for all-optical (usually Raman based) analytical methods, which can be met by further infrastructure investment.

The strong and well established pipeline demonstrated in our survey, directly connecting fundamental vibrational spectroscopy through instrument development to real world applications, makes a compelling case for IR and Raman spectroscopy to be viewed as a key component of a science strategy which aims to promote world class science with impact. The current scene shows innovative sophisticated spectroscopy being applied across the science spectrum and rapidly translating into widely accessible and broadly applied analytical tools.

3.0 User landscape

In this section we attempt to visualise and interpret the data received from the survey. We have broken this down into a number of different key criteria which reflects the current activity in the UK landscape for Raman and infrared spectroscopy. We classified both Raman and infrared instrumentation into five different categories: high end systems, microscopes, multimodal based systems, benchtop instruments and portable systems.

3.1 Funding Source Relative to EPSRC and Other Types

We analysed the responses in terms of the funding source for the different categories of instrumentation. Figure 1 shows a bar chart relating to the two different areas in terms of the percentage of the systems funded by the EPSRC. The orange column displays the absolute number to give an indication of the scale. From this data we can say that the EPSRC tends to fund more sophisticated instrumentation such as the high end systems, microscopes and multimodal systems with other sources more prevalent with the bench top and portable systems. Other sources tended to include university, industry or alternative funding streams such as the EU. It is also iniformative to consider the absolute numbers of systems, it can be seen that Raman microscopes tend to dominate the Raman community with a reasonable distribution for bench top and portable instruments whereas the IR community have much more emphasis on bench top systems which probably reflects the characterisation power of IR for many types of chemical analysis. The application areas for Raman and IR are discussed in section 3.7.

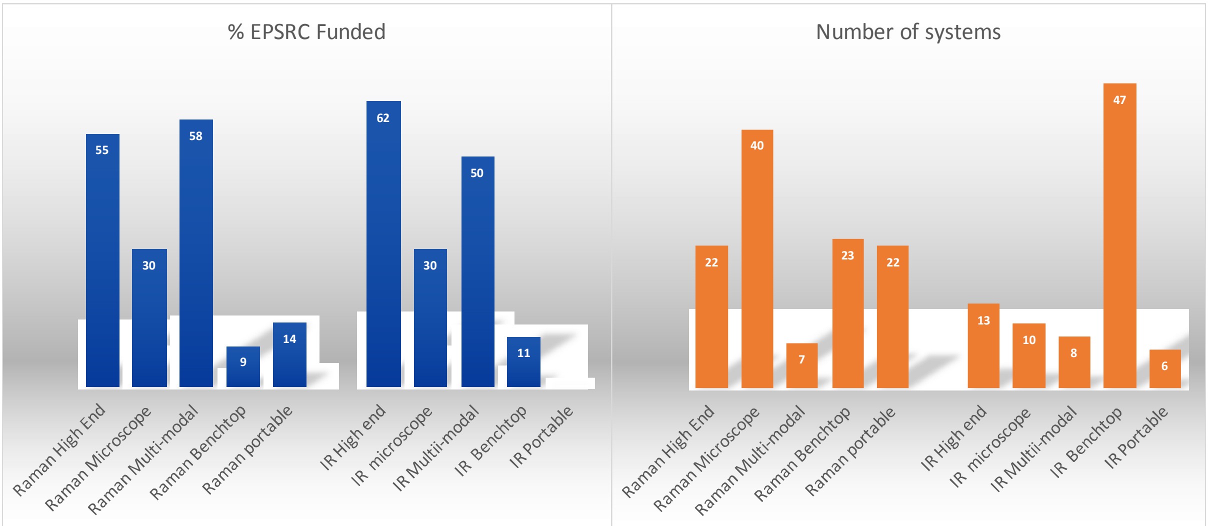


Figure 1 – Percentage of each category funded by EPSRC (blue) and then the absolute number (orange) for the different classes of Raman and IR systems.

3.2 Costs of Instrumentation

In this section we have analysed the approximate costs of the different categories of instrumentation for both Raman and infrared capability. The data is presented in box and whisker format which displays the upper and lower values in each category with the median and the second and third quartiles presented. There are some outliers in terms of the data as indicated by the crosses on the chart. The most immediate and obvious trend is that in both Raman and infrared instrumentation there is a decrease in the value of systems as we move from high end to handheld. Typically the median value for high end Raman and infrared instruments is about the same although there is a greater spread of values for the Raman instrumentation. There is very little variation in the costs of the handheld systems for both Raman and infrared reflecting the low cost nature of such systems. In addition, we observe a very tight grouping of costs for IR bench tops, which are the most popular category of instrumentation from this survey, and as such this is not a surprising result. Taken together with the percentage EPSRC funding data, we can suggest that the EPSRC has tended to fund higher end instrumentation at a reasonably high value indicating their emphasis on new research capability and supporting novel instrumentation development.

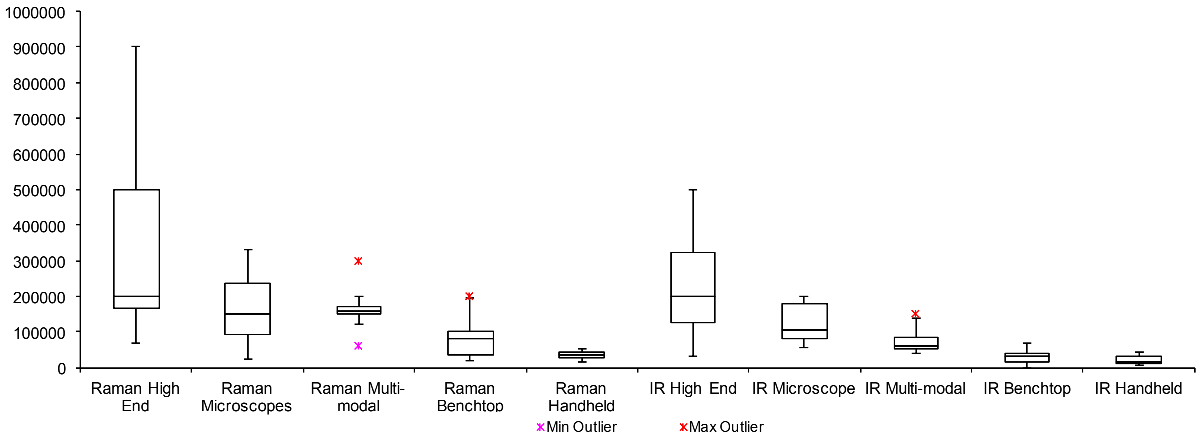


Figure 2 – Cost (£) distribution of the different categories of instruments for both Raman and IR. The box and whisper plots show the upper and lower values, the median and then the 2nd and 3rd quartiles.

3.3 Age

In this section we have considered the average age of the different types of systems and again presented this in a box and whisker format. There does appear to be a reasonable spread of ages and it is difficult to interpret this data with any degree of value beyond the fact that many systems are over 10 years old. The portable systems are perhaps not as new as we had anticipated with 5 plus years featuring in both Raman and IR capability and we observe that several systems in terms of the high end Raman and infrared are 2 to 3 years old. We suspect systems are often upgraded rather than replaced but have been unable to capture this in the survey however this indicates there has been very little recent activity in funding of high end Raman and infrared systems based on our survey return.

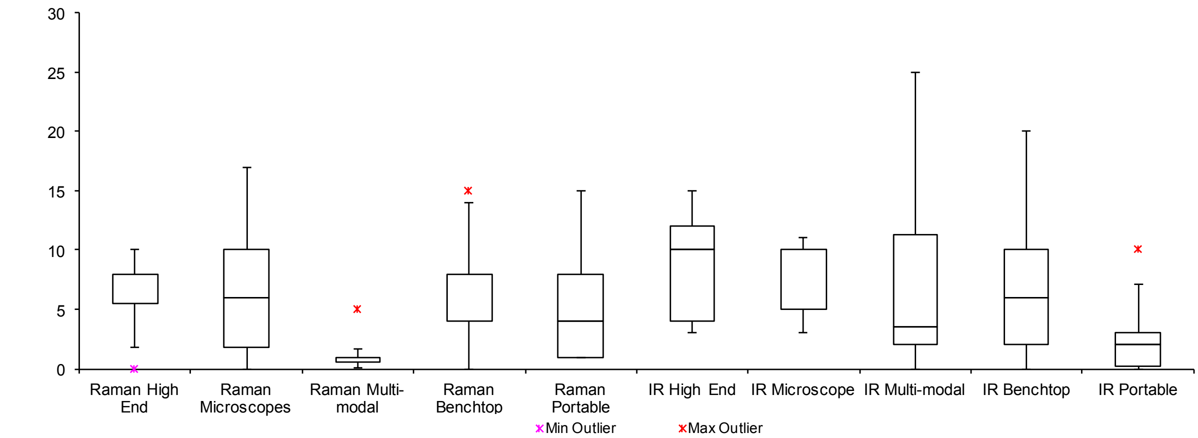


Figure 3 – Age (years) range for the different communities and systems.

3.4 Numbers of Users per System

This data indicates the number of users for the systems returned in our survey. From the survey we were able to calculate the number of users per specific system returned in the survey and report this in the plot in figure 4. In terms of Raman instrumentation, we can see that the Raman microscopes have the highest number of users which is probably not surprising as they are the most common type of Raman spectrometer. For infrared the bench tops have the highest number of users. The median for each type of system is reasonably consistent and ranges between 5-15 users.

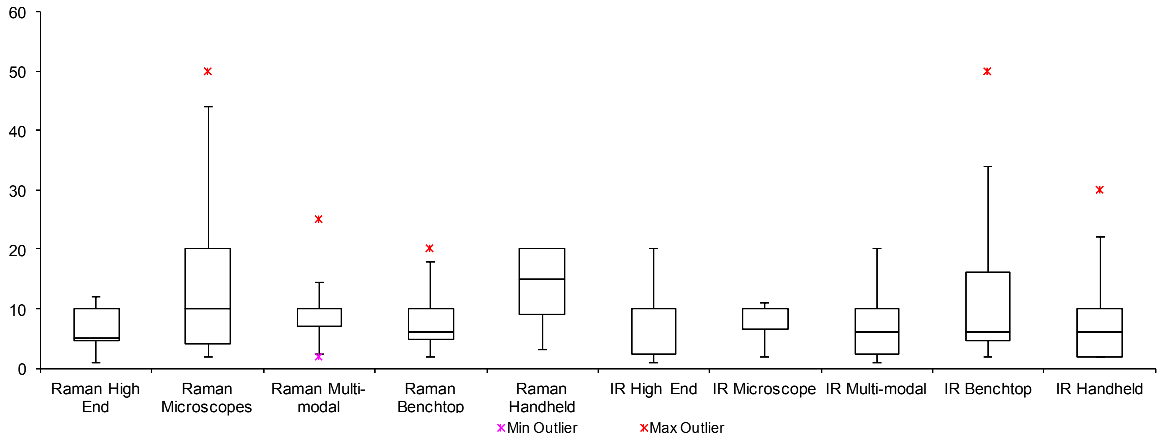
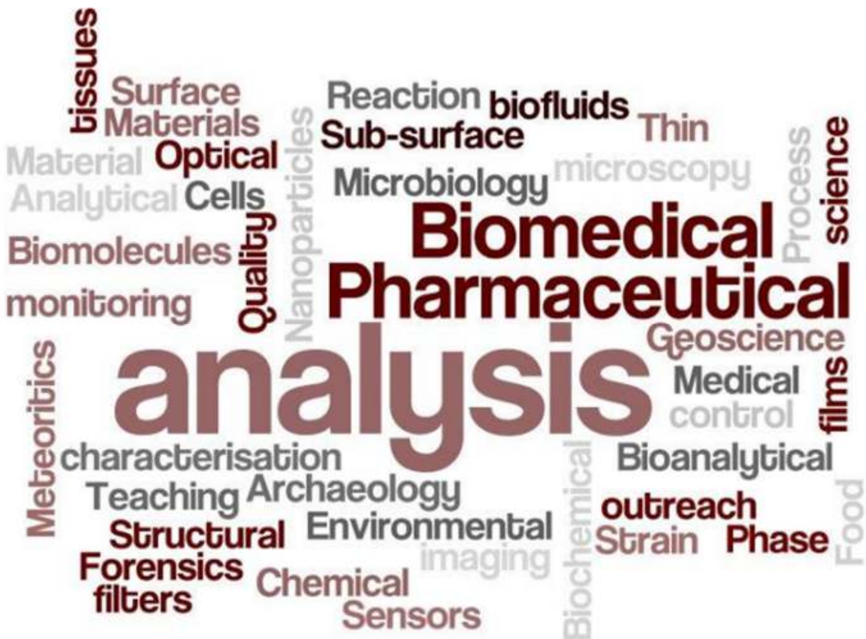


Figure 4 – Number of users for each category from each survey responder.

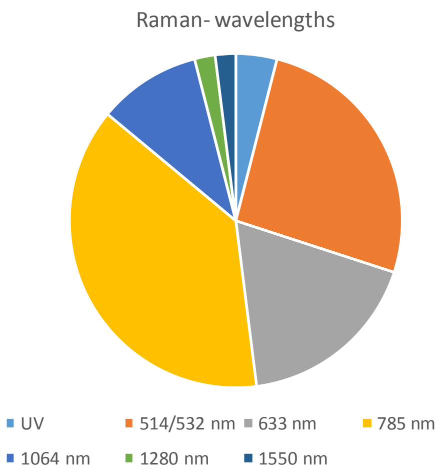
3.5 Types of Use

In this analysis we extracted the key words from the responses to the question on use and produced a wordall, which indicates the most frequently used words as larger text. From this simple graphic, we can see that analysis is the predominant term used by the responders, along with biomedical and pharmaceutical. Again this supports the observations in our narrative where we see the main uses of Raman and infrared in analysis moving into biomedical applications and with a strong basis in the pharmaceutical industry in the UK for characterisation.



3.6 Wavelength Capability

The different excitation wavelengths and wavelength regions for both Raman and infrared instrumentation that were preferred was also analysed. For the Raman returns we can see that the most popular wavelength is 785 nm which is to be expected due to the reduction in fluorescence and also easy availability of reliable diode lasers. The visible wavelengths, 514, 532 and 633 nm, are also reasonably common as well, with the alternative longer wavelengths and the UV making up the rest of this capability. Of course there will be some specific wavelengths not included in this pie chart which merely reflects the main wavelengths emerging from our survey. Based on laser sources this is exactly as one would expect. In terms of the infrared wavelengths, the mid IR clearly dominates with the near IR making up a sizeable component and the far IR a much smaller component.



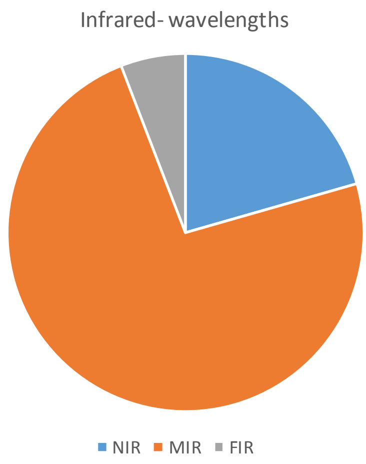


Figure 5 – Wavelength frequencies and regions for Raman and IR from the survey.

3.7 Publication and Citation Analysis

We also examined the publication data (Scopus) for the UK over the last five years using the search term 'Raman' in the title, topic, key words or abstract for Raman publications and then 'infrared spectroscopy or IR spectroscopy' in the same way. In the last five years this yielded 2910 papers for the Raman search and 3996 papers from IR. Figure 6 shows the numbers of papers per year from each of the Raman and infrared search terms.

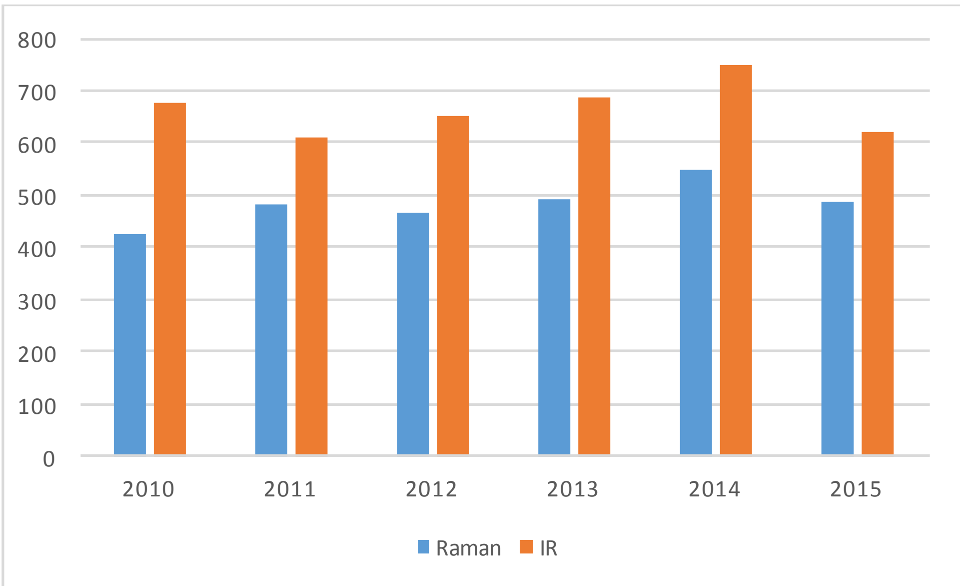


Figure 6 – Annual numbers of original research articles published with a UK address for Raman (blue) and IR (red).

These data shows that the Raman and infrared communities in the UK are reasonably stable in terms of their publications. There is a slight increase for both Raman and IR over the 5 year period.

These papers cover a range of different research areas but common to both Raman and infrared are that chemistry, materials science and physics and astronomy are the three publication classification areas that dominate these spectroscopic techniques. (Figure 7)

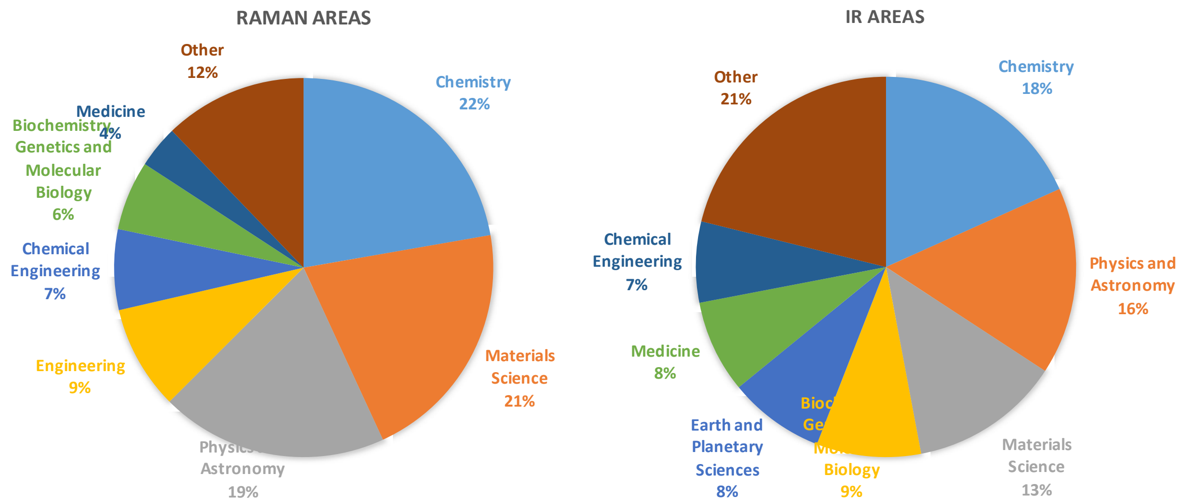


Figure 7 – Percentages of areas of classification for the Raman and IR papers.

In terms of the distribution around the UK, the heat map indicates the spread of geographical locations with an indication of intensity of publication from these areas.

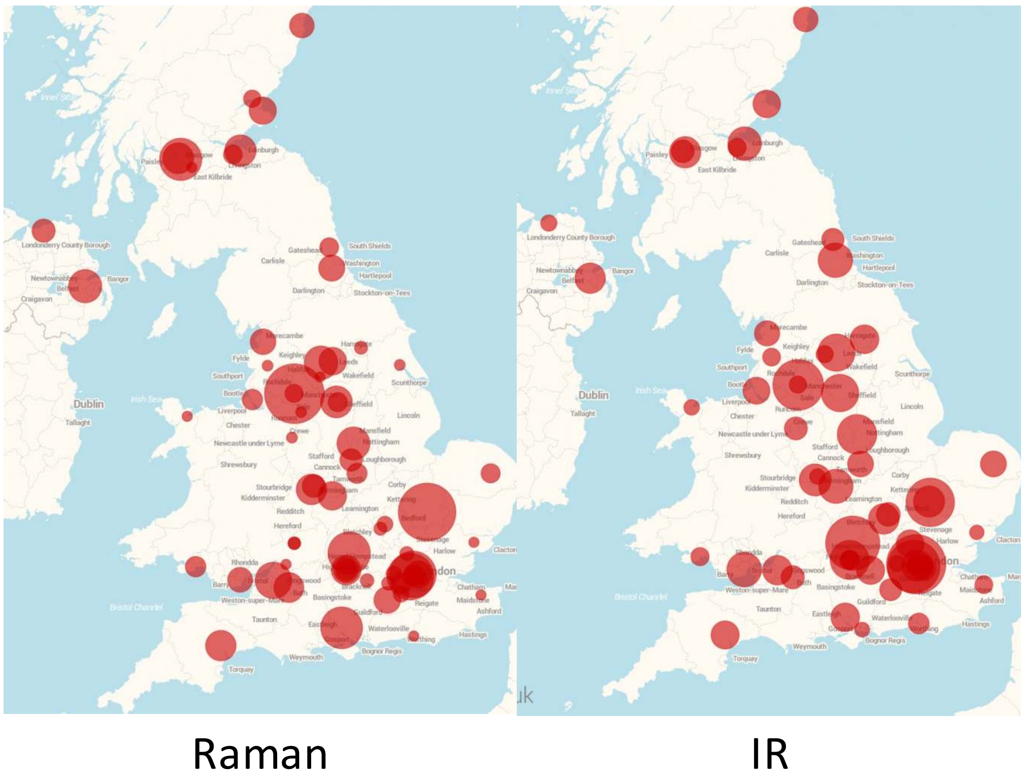


Figure 8 – Heat map showing the main areas of publication activity for Raman and IR papers in the UK over the last 5 years.

To assess the quality of the papers from the UK against other countries we used the benchmarking functionality available in Scival to compare the top 15 producers in both infrared and Raman research papers in terms of volume over the last 5 years. The quality was assessed by looking at the number of outputs in the top 10 percent of the world's publications in these fields. This data is shown in Figure 9 for Raman and Figure 10 for Raman.

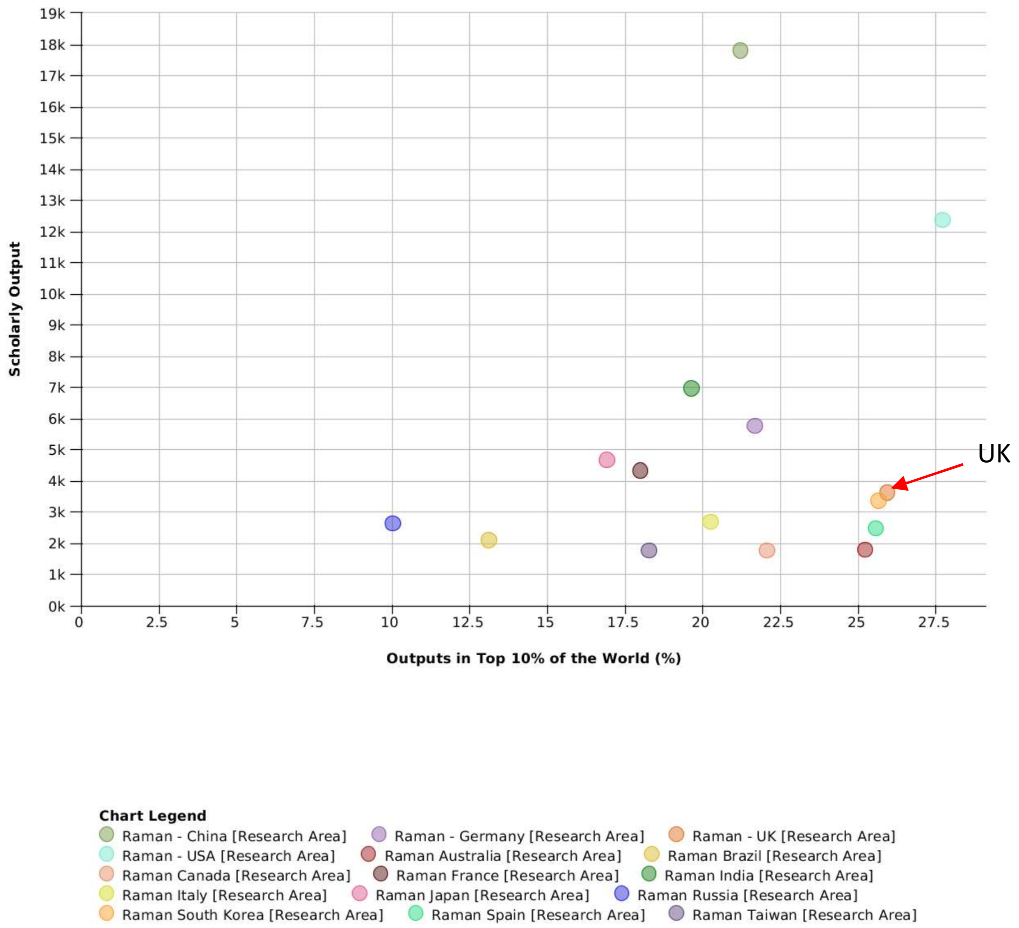


Figure 9 – Citation analysis for Raman outputs from top 15 international producing countries with % in top 10% of the world publications based on citation count. UK indicated by red arrow.

In terms of the Raman data, the highest volume is produced by China with the United States coming second at just under half of that volume. The UK produces just under 3000 papers as already stated. In terms of the quality of outputs, the percentage of outputs in the top 10 percent of the world is highest from the United States and very pleasingly we see that the UK comes in second place in the category of Raman publications. Grouped close to the UK are South Korea, Spain and Australia, indicating that these countries are comparable to the UK in terms of their Raman quality. South Korea produce a higher number of papers which is unsurprising due to the investment in their research community.

A word of caution for the Raman outputs needs to be made in terms of the yearly numbers as opposed to the 5-year average which shows a very healthy situation. Yearly averages show the UK topping percentage wise in 2013 then declining on a percentage basis to 2015. All other countries have an upwards trajectory. When considering the actual numbers rather than percentages the UK shows an increase which is encouraging and shows the increase in our top-10 percentile papers isn't as large as our overall growth in the Raman area. Of note, India is the country with the largest increase in absolute numbers of papers in the top-10 percentile.

When considering the infrared community, again the highest producer of publications is China by a significant amount, with the United States falling into second place. Again the highest quality outputs appear to come from the United States with the UK sitting in second place grouped with Italy, Germany, Canada and France. When considering the IR yearly totals we didn't see a dip as we did for the Raman percentages with all countries in the top 15 showing a slight yearly increase.

These are of course not exact metrics and should only be used as an indication, however it can be concluded that the quality of the research in the UK is very high for both the Raman and infrared fields over the last five years. Therefore, from these data we can state that direct investment into the research capability in terms of instrumentation, infrastructure and people has returned a high dividend and continued investment is crucial to maintain our world leading position and stop any slide in our ranking.

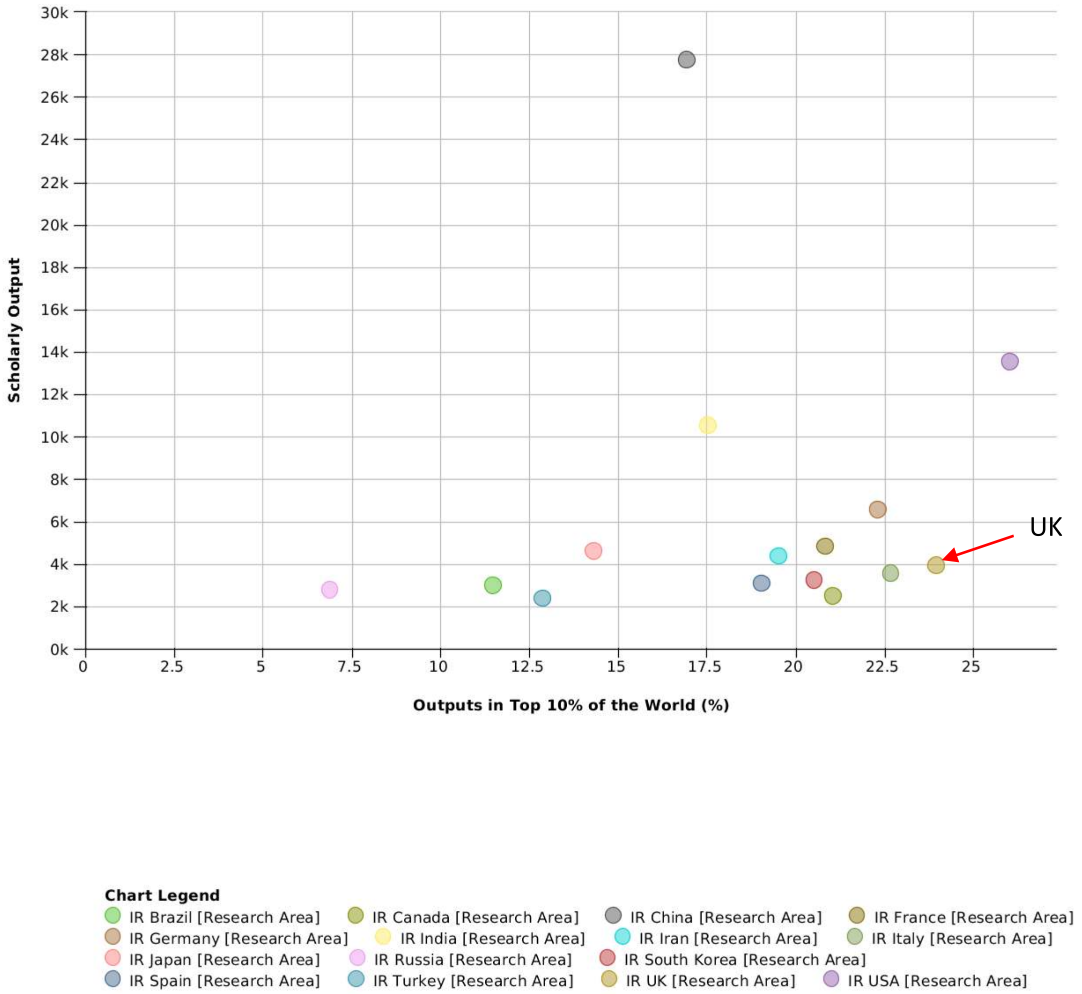


Figure 10 - Citation analysis for IR outputs from top 15 international producing countries with % in top 10% of the world publications based on citation count.

4.0 Sustainability

4.1 Finances and outputs

Since 2006 EPSRC has invested £4.6M, which is around 73% of the total investment, in Raman instrumentations in the UK. The corresponding investment for IR was £4.9M (56%).

From these investments and the scientific output data in 3.7, it is reasonable to assume that the funding from EPSRC boosts scientific research and publication in the UK. It is difficult to estimate how this investment spills over to create wealth, however, 27% by value of non-EPSRC investment on Raman and 44% on IR indicates a very good sustainable balance between RC and other investments internally within the UK.

4.2 Skilled researchers

The high percentage of quality publications from the UK in both Raman and IR clearly indicates the high skill set of researchers in the UK, especially in academia. Training of such highly skilled researchers has been taking place for many years and the sustained high level of quality publications is a result of the quality of the training and the training environment. To remain at the forefront internationally, such training activities need to continue especially on advanced Raman and IR techniques such as coherent Raman scattering (CRS), surface-enhanced Raman, 2D IR and tip-enhanced Raman/IR techniques.

4.3 Shared facilities

Most Raman and IR facilities are being used by research groups of 10-20 users, and in the range of 4-5 facilities are reported to be used by more than 20 users primarily within the university or other organisation. In this survey there is one mention of a national user-facility catering to the researchers in the UK (STFC). Establishing shared user-facilities, especially for the techniques that require highly skilled researchers such as coherent Raman, tip-enhanced Raman and ultra-fast IR, is valuable in expanding the use of the technique into new application areas, and fostering interdisciplinary activities.

4.5 Engagement and adoption of new technologies into vibrational spectroscopy

Progress on Raman and IR spectroscopy has been significantly influenced by developments in other technologies such as laser light sources, detector technologies, optical technologies and electronics. The driver for incorporating new technologies include high speed detection and imaging, investigating ultra-fast processes at the macro and nano-metre length scales in ambient conditions as well as in-vitro/in-vivo. It is expected that this trend will continue and some of the frontier developments on Raman and IR will very much depend on the progress of affordable ultra-short pulsed lasers (e.g. fibre lasers), near-infrared and IR sources (e.g. quantum cascade lasers), ultra-fast detectors for UV to IR wavelengths (e.g. fast readout detectors), combination of technologies such as AFM and Raman/IR.

4.6 Increasing and diversifying the user base

In the last 20 years, the user base has been rapidly expanding from the traditional areas of physics, chemistry and materials science to include less traditional areas of biology, clinical diagnosis, industrial quality control and online monitoring, forensic etc. Many new-users are interested in utilising the technique for solving problems in different areas of science. To support such expansion it is important that (a) Raman and IR data become easily interpretable to the new users, (b) data remains comparable within the research community, and (c) measurements are standardised through reference samples and reference methods. For example, currently there is no ISO standard for Raman spectroscopy techniques, and development of such standards should be integrated within future activities. These is also impact in accelerated translation of the techniques for wider social and commercial benefits and wealth creation, as mentioned in sections 1 and 2. Research activities from concept to commercialisation need to be supported throughout the technology-readiness levels (TRL). For example low TRL research can be supported by research councils and mid-TRL research can be supported jointly with other schemes (e.g. Innovate UK) to bridge the valley of death. This will also train new generations of Raman and IR spectroscopists to sustain the high level of activities in the UK.

5.0 Gaps and Opportunities

No specific major gaps have been identified at present. The UK academic research community is engaging with the emerging technologies and concepts at early stages and in a timely manner. Current funding pressures stemming from the ongoing challenging funding landscape are identified as an area of threat and in need of addressing and monitoring. It is crucial to maintain the lead and the effectiveness of the UK in capitalising on ongoing advances in these areas. This will put the UK in a strong position to capitalise on the next developments (including yet unforeseen) and indicates that the healthiness of the sector is dependent on the level and continuity of funding. We note the specific threat that cutting edge instruments for use in various application based research is limited, due to restrictions on instrument capital costs in grants.

Next emerging opportunities can only be exemplified and not fully defined. Emerging trends have been identified in

- Shorter wavelength quantum cascade lasers (IR)
- mid-IR supercontinuum light sources
- mid-IR up conversion technologies using non-linear optical approaches
- mid-IR fibres enabling flexible applications of mid-IR absorption spectroscopy and imaging

- other novel mid-IR optical components
- megapixel mid-IR focal plane array detectors
- the process of miniaturisation and increased robustness of Raman technologies – underpinning the emergence of portable devices and new application areas in often distant scientific disciplines.
- recent developments of nonlinear techniques (fs Stimulated Raman Spectroscopy (fs SRS), fs 2DIR, …)
- novel SERS labelling concepts
- emergence of spatially sub-diffraction limited IR and Raman concepts (nano-IR and nano-Raman)
- novel through barrier concepts in Raman (TRS, SORS, SESORS, …) driving novel applications across diverse disciplines

6.0 Risks to the UK

The vitality and continuity of the IR and Raman UK research and industrial communities have produced clear benefits to the UK. To benefit from current and future developments requires sustaining and increasing funding levels in these areas. Lack of support would lead to deterioration of both the research infrastructure (aging and obsolete systems) and the loss of the skill base – both crucial elements underpinning the current relative health of this sector. This would also lead to the rupture of the chain of translational research from basic to applied research. This shockwave would propagate across research and application disciplines into multiple sectors affecting both research and industry due to the widespread nature of these underpinning analytical techniques.

7.0 Key Findings and Recommendations

The survey data with the publication analysis indicates that the UK is in a strong position in terms of the high quality and range of instrumentation available, the number of users that are engaging in the community and the quality of the research outcomes. The age of the systems is a cause for concern and investment from the research councils into high end microscope and multimodal based systems for both Raman and infrared is a strong recommendation from this report. This will allow the research community to continue to develop new advances in the area, driving forward innovation and creating economic growth and sustainability in the UK sector.

Our key findings are that the UK is highly active and has a long history of research excellence and innovation in the Raman and infrared spectroscopic research communities. There is a wide range of instrumentation available in the UK supported by a number of different sources but the higher value instrumentation is predominantly EPSRC supported. We have not covered central facilities to any great extent in this road map and have relied on the information provided by a small subset of the overall UK community. Industry are early adopters of new technologies such as miniaturised portable Raman systems with appropriate methodologies and further analysis could be done in terms of industry involvement in terms of the research capabilities. The UK has produced a number of start-up and commercial entities based on the spectroscopic developments from the research base which again give sustainability to the field as well as creating employment for the highly skilled researchers produced as part of the training environments found across the UK. We have not focused on the training aspects of the Raman and infrared communities however it is safe to say that the number of publications indicate that there are a significant number of research active scientists capable of producing high quality outputs to continue to maintain and extend the UK's leading position in this field. Our recommendation is that the EPSRC continue to consider how to support this community with various initiatives to refresh and extend the research capability in both equipment, infrastructure and people as the evidence provided in this report indicates it is an area where the UK has strength that must continue to be supported.

The UK has a vibrant and successful Raman and IR research community supported predominantly by the EPSRC for high end instrumentation.   The quality of research is evidenced by the output analysis and we recommend the following actions:

1 – Increase the research base: To further support high end Raman and IR instrumentation to support future research developments and maintain the innovation emerging from the UK research base in this area.
2 – Increase the impact of the existing research base: To harness existing research breakthroughs and support maximum benefit to end users and other researchers through support for translational activities. Identify successes from the portfolio and support further development. This could be in partnership with other funders such as MRC, Innovate UK etc.
3 – Create new capability: To consider funding more hybrid systems with multi-functionality as genuinely new combined instruments rather than bolting two existing systems together.
4 – Build critical mass: To fund engagement of centres of excellence in Raman or IR across the UK to provide critical mass beyond the one centre through more collaborative research, greater research training opportunities and global engagement.
5 – Support the well found laboratory: To fund a refresh in the general area of Raman and IR where most systems are ageing but provide research capability to a large number of researchers in the UK.