2023

Radiation Detectors for Health, Safety and Security Programme (RADDESS, 2018–2022): Evaluation Report

Research Council of Finland

Contents

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Foreword

The research programme Radiation Detectors for Health, Safety and Security (RADDESS) of the Research Council of Finland (formerly Academy of Finland) focused on novel device-driven and functional radiation detection systems in the areas of health, security and safety. The topic was intrinsically interdisciplinary and covered significant efforts in areas that range from quantum information to the optical imaging of biological tissues. The detection of photons is at the core of all these key applications and constitutes the basis upon which new devices and techniques can be developed. In this context, the programme supported the creation of new technology that combines information from multiple sources.

RADDESS was an “Academy Programme” that provided funding to projects studying novel device-driven and functional radiation detection systems in areas related to health and safety. The Research Council of Finland’s funding budget for the 18 projects selected to the programme was 12 million euros.

The new detector technology developed within the RADDESS projects combines data from multiple sources. In the context of pharmaceutical and industrial process control, for instance, the technology could increase safety and help prevent exposure to dangerous gases. The projects also generated new knowledge on, for instance, the development of surveillance cameras and the detection of concealed objects. They also developed more accurate forms of cancer therapy and created light emitters and sensors with a fundamentally different operating principle than those used in present technologies.

The main objective of this evaluation report is to examine the results produced within the RADDESS programme. The evaluation also includes recommendations for the future as well as ideas for a possible new programme.

The objectives of the evaluation were defined by the programme’s steering group, and the evaluation was carried out by an international group of experts in the field. The evaluation was carried out as part of the development of the programme activities of the Research Council of Finland, with a view to providing information to researchers, the Research Council of Finland and relevant stakeholders.

Executive summary

The Research Council of Finland tasked a five-member international panel to evaluate the Radiation Detectors for Health, Safety and Security (RADDESS) programme, highlight three success stories and suggest possible areas for improvement.

The panel unanimously agreed that the RADDESS programme was a remarkable use of a funding instrument to boost excellent research in Finland, thanks to its transversal target and the good match with the know-how present within the country. The outcome of the programme is, on average, very good, and the overall quality of the research conducted is impressive.

The panel makes several recommendations aimed, for example, at improving the structure of the funding scheme and the way the partners interact with each other and plan collaborations beyond the programme timeframe. One crucial aspect that requires some deeper actions is the involvement of industry in the projects and in supporting the outcomes that have a clear potential for development.

1 Introduction

1.1 Details about the RADDESS Programme

This report is the culmination of an evaluation of the Research Council of Finland's Radiation Detectors for Health, Safety and Security programme (RADDESS), which ran between 2018 and 2022. The programme was funded and coordinated by the Research Council of Finland, the major research funding agency in Finland. It consisted of 13 research projects funded through the main call for applications, plus five projects funded through a second call, as summarised in Table 1.

In keeping with other focused research programmes of the Research Council of Finland, RADDESS was funded for a fixed period. This evaluation therefore assesses the success of the completed programme and uses the findings to make future recommendations for the Research Council of Finland to be considered.

Table 1. Calls of the RADDESS programme 2018–2022, call timeframes, budgets and number of funded projects.

Call	Timeframe of projects	Budget	Funded projects
Main call 2017	2018 to 2021	€10.0m	13
Second call 2019	2020 to 2022	€2.0m	5

The key research objective for the RADDESS programme was to strengthen basic research on radiation detection technologies and facilitate the development of new device-driven and functional radiation detection systems. The main call for applications was designed around the following three key themes (applications were only required to align with one of them, but many were aligned with more than one):

- generate new and innovative scientific knowledge about new radiation detection technologies and their applications especially in the health, safety and security fields
- steer research towards the development of device-driven and functional radiation detection systems in areas of application that are significant for the future
- develop knowledge and expertise in basic research so that physical phenomena can be better understood and used in developing more sensitive and more accurate radiation detectors.

The other objectives of the programme were as follows:

- facilitate the creation of new multidisciplinary research teams and national and international collaboration networks
- promote the mobility of researchers and doctoral candidates
- improve the international competitiveness of research and industry
- create societal impact.

The Research Council of Finland began preparing materials for the evaluation and initiated the evaluation process in April 2023. An independent panel of five international experts and a scientific secretary were appointed to provide a critical evaluation of the performance of the programme and to provide conclusions and recommendations for consideration in a future radiation detection programme.

1.2 Terms of reference

The members of the evaluation panel are presented in Table 2. All members acted as individual experts and did not represent their employers. The report covers the RADDESS programme as a whole and is not an evaluation of each project individually. The principal focus of the evaluation is on the programme's performance with respect to projects in the main and second calls for applications.

Table 2. RADDESS evaluation panel and members' affiliations.

Member	Affiliation
Prof. Daniele Brida (Chair)	Full Professor in Experimental Condensed Matter Physics, University of Luxembourg
Prof. Daniel Elson	Professor of Surgical Imaging and Biophotonics, Imperial College London
Prof. Andrea Neto	Head of THz Sensing Group, Technical University of Delft
Prof. Małgorzata Kujawińska	Full Professor in Photonics Engineering, Warsaw University of Technology
Dr Marek Šmíd	Director of Laboratory of Fundamental Metrology, Czech Metrology Institute
MSc Alba Viejo Rodríguez (scientific secretary)	Doctoral Researcher, Department of Physics and Materials Science, University of Luxembourg

The panel was asked to evaluate how successful the RADDESS programme had been against the following criteria:

- scientific quality of the programme
- establishment of multidisciplinary research groups
- creation of new national and international research collaboration networks
- increasing the mobility of researchers
- scientific and societal impact of the research
- added value of working as a part of the programme

- need for future research/research programmes in the field
- projects' cooperation with industry.

The panel was also asked to highlight strengths and weaknesses of the programme, draw clear conclusions and make specific recommendations, provide a fair and honest evaluation and include success stories in the report.

This report will be made public and circulated directly to the relevant stakeholders of the RADDESS programme.

1.3 Evaluation process

The Research Council of Finland provided the panel with background programme information, including the programme memorandum and a report on the activities. An extensive range of data sources and analyses from the projects selected in the programme calls was also provided, covering the programme memorandum, final project reports, project presentation videos, researcher survey responses, a summary of programme activities and the public abstracts of each project application. These materials together set the boundaries for the panel's evaluation.

The panel grouped the criteria listed in Section 1.2 into five areas:

1. **Quality**: scientific quality of the programme
2. **Interdisciplinarity and multidisciplinarity**: distinctive properties of the programme with respect to disciplines and final project outcomes
3. **Collaboration and mobility**: creation of new national and international research collaboration networks, taking into account the social context
4. **Connections with industry**: involvement of the projects with industry
5. **Future**: follow-up recommendations for future research projects in the field.

These five areas formed the basis of the aggregate evaluation of the 18 individual projects selected in the main and second calls (Table 1). Short public abstracts for all these 18 projects are included in Appendix 2.

The panel conducted all business remotely. A pre-meeting was held on 26 April 2023 to agree on the evaluation process. All panellists were paired for the assessment of the last four areas above. This resulted in every area and project having two panellists, one as a main responsible examiner and a second one for cross-checking, ensuring a robust and self-calibrating evaluation. The first area, quality, was assigned to the chair member. These contributions formed the starting point for discussions at the evaluation meeting held on 10 May 2023, where the panel discussed their evaluations across the areas.

A foundational recommendation of the panel on 10 May 2023 was that that a programme targeting radiation detectors for health, safety and security should be supported within the portfolio of the Research Council of Finland or elsewhere within Finland's research support mechanisms. On that basis, the panel drafted a report with specific recommendations and agreed unanimously on its content and conclusions.

The remainder of the report is structured as follows. Section 2 presents the detailed evaluation and corresponding recommendations. It has two subsections: the first a summary of the aggregate strengths and weaknesses, the second a presentation of specific findings. Section 3 provides a brief conclusion and lists for convenience all the specific recommendations.

2 Evaluation and recommendations

Having reviewed all the material provided, the panel unanimously concluded that the RADDESS programme was overall a successful programme with some aspects that could be improved in the perspective of maintaining such a funding scheme.

2.1 Aggregate strengths and weaknesses

With 18 projects funded in the RADDESS programme across a wide range of topics and application areas, generalisations of aggregate strengths and weaknesses are not easy to make. However, with that caveat in mind, what follows is a summary that the panel felt was noteworthy and indicative of issues that may need to be considered in a future programme around the same topic.

2.1.1 Strengths

Quality

- The programme targeted a topic that combines specificity in its goals while being intrinsically broad in application and interdisciplinarity.
- On average, the programme yielded excellent results, as exemplified by the three success stories highlighted in this report (see Appendix 1).

Multidisciplinarity and Interdisciplinarity

- A high level of multidisciplinarity was achieved in many of the projects, which increased the quality and interest of the research. Some of the projects positioned themselves at the forefront of the emerging multi-, inter-, and transdisciplinary trends in imaging, measurement and sensing applications.
- Some project teams were able to coordinate a great number of researchers and collaborating institutions with complementary expertise to achieve ambitious outputs.

Connections with industry

- In projects targeting life sciences, the usefulness of the developed solutions for the stakeholders was in many cases self-evident.
- In projects targeting technology/components development, the involvement of and connection to VTT Technical Research Centre of Finland Ltd was the strongest indication of the worldwide usefulness of the research.

Future

- For a significant number of projects, the scientific research continues to be extended and further developed in many European research projects and offers huge opportunities for future investigation.

2.1.2 Weaknesses

Some weaknesses are evident in the aggregate of the programme itself and are reported below. The individual and project-specific weaknesses are not reported here since they were not the object of this evaluation.

Quality

- The level of funding and the duration of the projects were inconsistent between the two calls. (Recommendation on consistency)
- An evaluation of the impact of the projects on the career of early-career researchers is missing in the reporting or underplayed. (Recommendation on early-career scientists)

Multidisciplinarity and interdisciplinarity

- Some projects were apparently highly interdisciplinary and had a great number of researchers (e.g. more than 50) contributing to the workplan. However, from the documentation it was not always clear what the roles of these scientists were, and more clarity in the report would have been useful.
- Some projects were not inherently multidisciplinary or interdisciplinary, and this was not a drawback. However, if they did involve a specific target application and an advancement in technological readiness levels, it would be beneficial to test the technology in the final setting. In such projects, this is the only true way to determine if the findings are a success.

Collaboration and mobility

- The significant reduction and changes in the mobility plans (due to the international situation) influenced in many cases the efficiency in cross-fertilisation of ideas and expertise between collaborating groups, and it slowed down the career advancement of early-career researchers.
- In general, there was a lack of reported collaboration between the project teams participating in the programme, even where there was an evident correlation or complementarity between the research topics.
- Most of the reports did not indicate which collaborations (international and national) were new ones and which were continuations. It was therefore impossible to fully evaluate the influence of the RADDESS programme on the enhancement of the partners’ collaboration and mobility.

Connections with industry

- In general, considering the applied nature of radiation detection and the rapidly increasing demands for imaging, sensing and measurements, the programme could have done more with preparation of technology demonstrators followed by an active industrial engagement or clinical evaluation.

- The involvement of industrial partners in the programme was somewhat limited. A participation of industry in advisory boards could be stimulating in steering projects towards successful uptakes or the creation of spin-offs.

Future

- Some projects did not clearly report the potential uptake of the project results in the final reports, which may negatively impact their prospects for future opportunities to secure funding.

2.2 Specific findings

2.2.1 Quality

The research carried out in the framework of the RADDESS programme targeted the development of advanced detectors (or evolution of detection techniques) for a range of different applications that are at the forefront of global research efforts.

Overall, the programme produced outputs that can be recognised to be of a high standard in the international landscape. In particular, some of the research projects led to truly remarkable results. The activities in the 18 funded projects were well balanced across the different targets of the programme, with projects dealing with bioimaging for health applications and other targeting sensing and detection at frequencies relevant for security. Some projects include a full development from the concept to the demonstration of a detector device while others deal with the optimisation of a technique or the improvement of a specific scenario of application.

In this context, the panel notices that the scope of the research was clearly commensurate with the amount of funding, since the projects with a higher level of support could have a more complete development while the projects with a lower level of funding were more specific and specialised. The projects funded in the second call, being shorter and with a lower level of average funding, were, while generally still successful, narrower in scope.

Recommendation on consistency:

> **The panel suggests keeping, within the constraints of the Research Council of Finland's financial situation, the structure of the project funding as consistent as possible and maintaining a uniform project duration.**

While the quality of research is obviously not just about papers and citations, they are the main indicator we have within our scope. Remarkably, the RADDESS programme resulted in a good quantitative and qualitative publication record with a large number of papers, some of which in prestigious journals.

A second parameter used by the panel for the evaluation was the ability to attract additional funding or plan future proposals for doing so, and some projects were successful in this criterion as well. Of course, the overall level of success is somewhat variable, but this is within the expectations for this kind of funding scheme. It is however important to remark that the panel did not find any specific project to be particularly problematic.

The panel notes that the success of early-career researchers involved in the activities is also an important parameter in order to evaluate the success of a project. Of course, this information might be limited in the timeframe of the evaluation but still relevant and, at the time of writing, has not been provided to the panel.

Recommendation on early-career scientists:

> **Projects should pay particular attention to the career development of early-career researchers (obtaining fellowships, permanent positions, becoming professors or research leaders, etc.). The applications and the final reports should include some information about this aspect.**

The main observation that can be drawn based on the outcomes of the different projects is that the development of advanced detector or related techniques is a strong highlight within Finland’s R&D activities. One particularly remarkable aspect is the fact that such a funding scheme can be rather targeted, while at the same time benefit several different scientific communities ranging from health and biology to nanofabrication and condensed-matter physics in a naturally interdisciplinary context.

2.2.2 Interdisciplinarity and multidisciplinarity

As stated in the RADDESS programme memorandum, one of the objectives of the programme was to “facilitate the creation of new multidisciplinary research teams and national and international collaboration networks”. The panel has reviewed the final reports, output publications, summary presentations and questionnaire results to evaluate whether the programme was successful in this aim and to make recommendations for the future.

The self-reported questionnaire results report that 79% of the projects met their multidisciplinary research collaboration goals (“well” or “very well”), with 97% reporting that new joint research ideas were formed and 69% claiming an intention to apply for joint funding with the partners. The interdisciplinary goals of the projects would not have been fulfilled without the RADDESS programme (59%). There was an increase in collaboration companies and researchers during the programme, many of which involved multiple disciplines or final applications. Only 11 out of 29 respondents reported industry involvement in the project or steering group.

These numbers are consistent with the panel’s evaluation of the research projects, noting that some projects had a relatively small element of multidisciplinary research.

The projects involved a suitable level of multidisciplinarity and interdisciplinarity that matched the aims of the programme call well. Such a programme is anticipated to cover fundamental research on detector technologies, as well as more specific implementations of concepts at a higher technological readiness level than in an existing application. The funded projects provided a good cross-section of technologies, including biomedical, chemical, security and many other disciplines.

The panel noted that some projects did not require multidisciplinary work to achieve their objectives. For instance, MilliRAD produced GRIN lens arrays integrated with MMIC detector chips to produce millimetre-wave radiometers. This included modelling, fabrication and testing, but with no final application, and the work could be completed by a relatively small team. Another example would be LAMARS, which developed graphene THz detectors integrated with CMOS devices. Even though the work was not multidisciplinary, it has reached a wide audience thanks to the number and quality of published outputs.

Many of the projects developed detectors for specific end-uses in mind, and this type of applied science is typically multidisciplinary, requiring fundamental device development and evaluation in the relevant application domain. In such cases, even if it is arguable whether the fundamental development work is multidisciplinary, the interaction with the end-user and industry adds a distinct multidisciplinary emphasis to the work.

The panel also found that some of the projects were highly multidisciplinary – typically those that involved clinical work. For instance, MINMOTION aimed to develop a motion compensation approach for PET/CT using ECG and IMUs to correct for respiratory, cardiac and head motions, allowing better imaging and potentially more accurate radiotherapy. This involved researchers in computing (ML and image reconstruction), molecular imaging (Stanford), physics, hardware development and clinical expertise. HyperStokes developed microscope and macroscope hyperspectral polarisation imaging systems that could detect diseases based on histology but also in human subjects being assessed for diabetes-induced skin lesions. Such projects require large teams and close collaboration between the clinical and technical sides, and in general the outputs from the work appear across a range of journals and conferences. This level of multidisciplinarity did increase the risk to the project, particularly due to the restrictions imposed by the Covid-19 pandemic. As a result, some projects were not able to progress to the important in vivo test phase, leaving an important knowledge gap and requiring more funding.

Overall, it is clear that many of the projects were very successful at delivering multidisciplinary and interdisciplinary research involving large teams of researchers. Other projects did not need this level of interaction but nevertheless were successful in a single discipline. However, there were a few projects working in specific application domains that developed devices, but they have not been tested in the final application domain. There may be good reason for this, including the disruption caused by the pandemic, but it may also be due to the lack of end-users or specific expertise.

Recommendation on advisory boards:

> **Projects proposing an applied technology should have a co-investigator or an advisory board that includes expertise to ensure that the project reaches a final application.**

Recommendation on cross-project interaction:

Multidisciplinary work across projects could be improved by providing further interaction opportunities during regular programme meetings.

2.2.3 Collaboration and mobility

As regards collaboration and mobility, the RADDESS programme aimed to facilitate national and international collaboration networks and promote the mobility of researchers and doctoral candidates. However, the panel recognised that the programme was partly executed in exceptional conditions (pandemic 2020–2022, international situation as of February 2022), which influenced the international collaboration and especially the execution of the mobility plans of the programme participants. The panel took into account these circumstances while evaluating the programme's success in this aim.

The self-reported questionnaire results showed that 40% of projects managed to increase researcher mobility. In the reported mobility, approximately 70% (33 visits) were from a RADDESS partner to a foreign organisation. The results indicate an increase in collaboration with national (58%) and international (55%) companies and researchers during the programme.

These numbers are consistent with the panel's evaluation of the research projects, noting that some projects had no mobility at all.

Taking into account the exceptional conditions during the execution of the RADDESS programme, the panel judged that the international collaboration aspects of the programme were good and that they satisfied the relevant objectives described in the programme memorandum.

However, the international mobility was weaker than originally expected in the programme and planned in the applications. Several mobility plans were strongly reduced, totally cancelled or changed from international into internal ones. This is most evident in the projects from the second RADDESS call (three-year projects 2020–2022), such as FLEXRAD, HydroGer and Paraoanu, which reported no short- or long-term mobility.

In the projects originating from the first RADDESS call (2018–2021 with extension to 2022), most of the mobility took place in 2018–2019 and late 2022 only. In these periods, many examples of exchanges and visits were noted, with eight projects reporting 0–3 mobility periods and five projects reporting 4–8 periods. Of these, approximately 62% were short-term visits. The long-term visits were usually of a duration of one month.

The panel recognised that in most cases the mobility goals were well defined and supported the projects' advancement and the career enhancement and personal development opportunities for early-career researchers. Also, in some cases the mobility resulted in joint publications in highly recognised journals and in EU project proposals.

International collaboration was strong overall (e.g. HyperStokes collaborated with seven countries, Paraoanu with seven, LIGHTER with six, LAMARS with six, MBMIB with four, HyPSI with four and Flexrad with three). However, it was not possible to indicate which collaborations were new and which were continuations of existing collaboration. In most cases, the RADDESS partners, which had good international collaboration, also had vivid interaction with national companies and research institutions. In many cases, the international collaboration was, due to the pandemic, based on remote contacts, exchange of samples or even remote access to unique equipment on the international partner's site, which replaced the planned mobility periods.

Despite the unfavourable conditions, the RADDESS programme resulted in several joint publications with international partners, and several EU collaborative projects (granted or submitted) originated from the programme (e.g. from HyperStokes, LIGHTER, HydroGer, LAMARS, Paraoanu and Oksanen).

The panel observed that having projects with a different duration (4 + 1 years in first call, 3 years in second call) in the same programme provided different conditions for organising collaboration and mobility. Most probably, the projects from the second call relied mainly on their previous international contacts.

The final observation refers to missing collaboration opportunities. Firstly, it seems that some of the RADDESS projects operated in similar application areas, and the platform for collaboration between these projects should have been created already during the programme execution (the joint seminars did not work well in this respect). Secondly, none of the projects reported utilising the technological or collaborative opportunities created by the EU, including the European Technology Platforms in Photonics or the support of such projects as ACTPHAST 4R and PhotonHub Europe.

Recommendation on mobility:

> **The impact of early-career researcher's mobility and international cooperation on their career enhancement should be monitored after the programme.**

Recommendation on future funding opportunities:

> **The influence of the RADDESS programme on increased Finnish participation in EU and international projects and standardisation activities should be monitored.**

2.2.4 Connections with industry

The projects funded under the RADDESS programme were clearly divided in two categories. A significant portion of the projects, in the following indicated as "medical systems", mostly targeted medical or biological applications while another portion, in the following indicated as "technology components", were aimed at improving the state-of-the-art of non-destructive testing.

The fact that these two types of projects were clustered in the same programme is original and poses some challenges for connections with industry.

The "medical systems" projects employed mostly both doctors and physicists and were of a larger multidisciplinary nature. In most instances, the projects had an ambition to develop entire systems that would lead to useful applications in relatively short times, with experiments on animals and even humans. The timelines, the need of specific development and the originality of the work could be and was appreciated by specialists in the field. However, the ambition of these projects can be appreciated also by non-specialists.

In absence of contribution to the projects from very large industries acting as final integrators of medical systems, the actual usefulness of the proof-of-concepts cannot be easily assessed. Since Finland does not host such world-level industries, it is difficult to achieve a confidence that the best projects were chosen.

The “technology components” projects, for the most part employed some physicists and engineers. Finland is certainly hypertrophic in the technology of radiation imaging, considering its small size (possibly thanks to the exploits of Nokia in the 1990s).

Most of the “technology components” projects were concerned with **components**, rather than systems. In these projects, it is relatively simpler to identify the specific originality in the development and also to assess the evolution of the technological readiness level over the project period. Here, the difficulty is that the utility of the projects to society is much more difficult to assess. In comparable technology programmes running in Europe, the industry involvement is typically significantly higher. The industry, being able to choose the technology from the best providers also in other European countries, can decide to connect to the national technology leaders only in the specific subfields where the country can play a leading role.

In the RADDESS programme, the main indication of the worldwide usefulness of the research dedicated to “technology” was the connection to VTT Technical Research Centre of Finland Ltd. Since the strength of the Finnish researchers was already visible at the start of the programme, it appears that the scope of the programme was to maintain the high level of university education in the field of radiation technology. The panel did not get the impression that this programme particularly facilitated the achieving of a Nokia-like industrial breakthrough.

The clustering of two type of projects (“medical systems” vs “technology components”) in the same programme will probably not lead to synergies with industries, since the typical guidelines for deciding which projects to fund are necessarily very different in the Finnish landscape.

An effort to solidify the industrial or research panorama by joining efforts with other Nordic countries would probably benefit the Finnish academic environment very much and other countries, too (Sweden, the Netherlands, Denmark and Norway).

Recommendation:

> **“Medical systems” and “technology components” could well be two smaller subprogrammes, responding to different stakeholders and application drivers.**

Recommendation on advisory boards 2:

Projects progressing towards a device should include an advisory board with a suitable industrial expert. If the expertise is not available within Finland, also consider international contributions.

2.2.5 Future

While Finland belongs to the mid-sized countries in a European context and to the smaller countries globally, it is a global leader in the development of optical radiation detection and imaging systems. Helping boost Finnish international competitiveness in the sector of electromagnetic detectors development and prepare the sector for future needs is important for the country.

The RADDESS programme succeeded in taking up a rather pioneering initiative for supporting the development of new radiation detection technologies, facilitating a broad range of measurement of specific properties of organisms, materials or processes. The panel sees the creation of new sustainable multidisciplinary research teams, national and international collaboration networks and support for the interdisciplinary approach to the provided research as a unique and substantial benefit of the programme and evaluates it as a great basis for future research and development projects at both a national and international level.

Although some of the funded projects could not demonstrate straight experimental validation of the developed research during the project lifetime, probably requiring further funds to achieve desired targets, a majority of the funded research clearly exhibited not only the potential of developed facilities and techniques but validated also a first concrete uptake. A particular example is the project ‘Universal electromagnetic radiation detector’ (UNIDET), where researchers developed, optimised and characterised a unique broadband photoacoustic detector system leading to room-temperature-based precise sensing in the infrared and THz spectral range in the first part of the project. In the second part of the project, the researchers tested several applications of that detection system, including spectrometric detection of radioactive molecular gas species, criteria air pollutants and black carbon in the atmosphere.

Recommendation:

The project proposals and reports should consistently include a description of the potential uptake of the results in future research and applications.

Many projects achieved excellent results in developing device-driven and functional radiation detection systems and in establishing new measurement methodologies or validating of the applicability of new physical phenomena. However, very often the projects documented either weak or missing interdisciplinary collaboration with potentially interested industrial partners, which at the same time is understandable while considering the early stage of research. Yet, more intense collaboration with industrial partners would have a strong potential to embrace the dissemination of excellent project results.

3 Conclusions and final recommendation

The evaluation panel found that the Research Council of Finland's RADDESS programme was, overall, quite successful in funding excellent consortia and in producing results that are qualitatively excellent even when compared to the global stage.

The list of detailed recommendations presented in the previous sections must be understood as a series of suggestions that could improve the planning of the funding scheme, the streamlining of proposals and reporting, and the organisation of the projects themselves.

One particularly critical area is the involvement of industry and the transition to higher technological readiness levels for the ideas proposed in the framework of RADDESS. Indeed, this is an aspect that could be improved partially by optimising the programme, as recommended, and partially with synergistic actions with other stakeholders in Finland, thus promoting the continuation of projects in even more applied directions or even creating spin-offs and start-ups.

However, the panel stresses that the quality of the research achieved within the RADDESS programme is absolutely remarkable. Identifying success stories to highlight was quite challenging given the abundance of possible choices. For this reason, **the main recommendation of the panel is that the RADDESS programme should be continued or reproposed with a similar target**, since the topic of developing radiation detectors covers transversally the top-notch expertise present in Finland. It has the potential to highlight and boost excellent research in several areas of fundamental, technological and medical development.

Appendix 1: Success stories

Success story: SICSURFIS

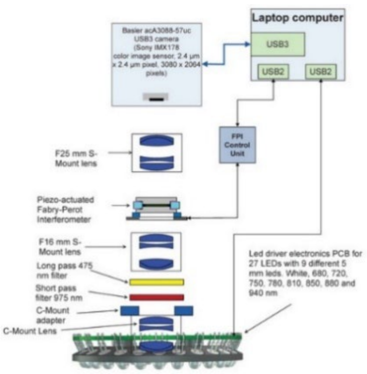
During this project, a new type of detector has been built that incorporates a Fabry-Perot interferometer (FPI) into a hand-held imaging device. The control of the illumination LEDs and the FPI allows reflection images and photometric stereo to be captured at different wavelengths. This concept has been packaged into a small and lightweight clinical device, with analysis and processing methods developed at the University of Jyväskylä. The imaged tissue could also be digitally reconstructed into a 3D model. Training and testing using pixel-by-pixel machine learning (e.g. CNN) on the spectral intensity information produced images that display a particular target pathology.

In one of the output studies on 42 lesions, the team achieved a sensitivity of 87% and a specificity of 93% for distinguishing between melanoma and pigmented nevi, and between melanoma and normal skin, respectively. The host institutes were well placed to complete this project, being equipped with optical laboratories with characterisation and fabrication facilities. The clinical setting allowed medical data to be acquired and analysed against the gold standard. The IP that has been protected will also allow for further commercial activity, which may prove important in allowing larger clinical trials and future adoption.

Achievements:

- Minimising spectral imager developing mems-Fabry-Pérot interferometers capable of covering a wide spectral range with one component (450–850 nm) (VTT)
- Extending the spectral range of the imager to 400–1700 nm (VTT)
- Optimised manufacturing process of MEMS-FPI (VTT)
- Method to calculate surface structures (JYU)
- Method to retrieve skin optical parameters using machine-learning models (JYU)
- AI method for skin cancer classification (JYU)
- Patient test to classify skin cancer (HUS/VTT/JYU)

VTT = VTT Technical Research Centre of Finland Ltd, JYU = University of Jyväskylä, HUS = Helsinki University Hospital



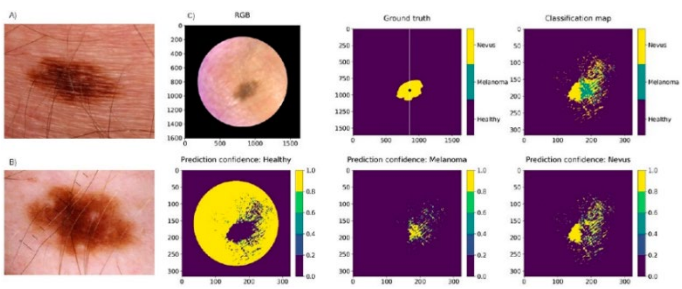


Figure 1. Left: Block diagram of the SICSURFIS spectral imager [1]. Right: Clinical (A) and dermoscopy images (B) and a classification map (C) of a dysplastic nevus classified as a melanoma. The test data (right half of the image) included pixels classified as both melanoma and nevus. However, according to the majority voting analysis, there were more melanoma pixels. Light reflection caused probable artefacts in the surrounding area of the lesion. [2]

Literature:

[1] Raita-Hakola AM, Annala L, Lindholm V, Trops R, Näsilä A, Saari H, Ranki A, Pölönen I. FPI Based Hyperspectral Imager for the Complex Surfaces-Calibration, Illumination and Applications. Sensors (Basel). 2022 Apr 29;22(9):3420. doi: 10.3390/s22093420.

[2] Lindholm V, Raita-Hakola AM, Annala L, Salmivuori M, Jeskanen L, Saari H, Koskenmies S, Pitkänen S, Pölönen I, Isoherranen K, Ranki A. Differentiating Malignant from Benign Pigmented or Non-Pigmented Skin Tumours-A Pilot Study on 3D Hyperspectral Imaging of Complex Skin Surfaces and Convolutional Neural Networks. J Clin Med. 2022 Mar 30;11(7):1914. doi: 10.3390/jcm11071914.

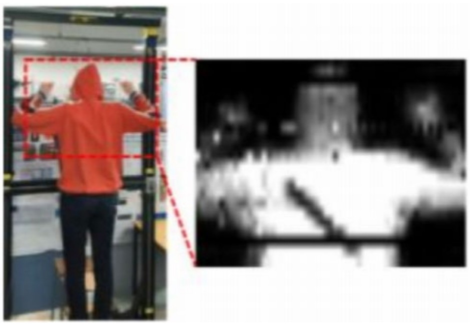
Success story: BOLOSE

The Bolose project developed three different cryogenically cooled detectors for high-sensitivity power detection and imaging in the THz range. The project significantly strengthened the already significant know-how base in this domain in Finland.

Achievements:

- achieving a significant breakthrough in imaging for security; the team is now the world leader in concealed weapon detection at stand-off distances
- facilitating international synergies with complementary groups in the Netherlands and the US
- contributing to many high-impact publications [1–3] as highlights
- delivering two master theses and two PhD theses

Existing systems in the THz regime employ only up to a few hundred detectors together with opto-mechanical scanning to cover an adequate field-of-view, achieving scanning speeds not nearly sufficient to be practical. In contrast to this, the Bolose project demonstrated, for the first time, a fully staring 2D detector array video camera, operating at 9 Hz. The imaging system is built around the detector technology of kinetic inductance bolometers, allowing the operation in the intermediate temperature range >5 K and the scale-up of the detector count into multi-kilo-pixel arrays.



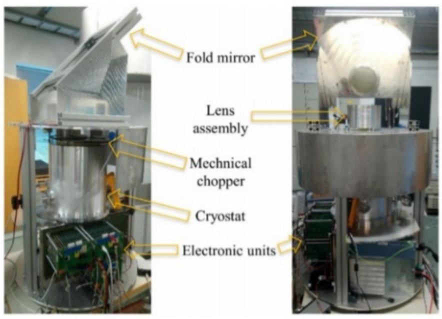


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Figure 2. (a) Snapshots from THz video imagery taken with the imaging system developed in the project and compared against optical imagery acquired with a mobile phone camera. Rod-shaped Plastic Rod of 30 mm diameters are concealed under the clothing of the test person. (b) Imaging system developed in the project, shown from the side (left panel) and from the imaging direction (right panel), with some of its subsystems indicated [1]

Literature:

[1] J. Luomahaara et al., "A Passive, Fully Staring THz Video Camera Based on Kinetic Inductance Bolometer Arrays," in IEEE Transactions on Terahertz Science and Technology, vol. 11, no. 1, pp. 101-108, Jan. 2021, doi: 10.1109/TTHZ.2020.3029949.

[2] Yan, C., Hassel, J., Vesterinen, V. et al. A low-noise on-chip coherent microwave source. Nature Electronics 4, 885 (2021). https://doi.org/10.1038/s41928-021-00680-z.

[3] Juuso Manninen, Mohammad Tasnimul Haque, David Vitali, and Pertti Hakonen “Enhancement of the optomechanical coupling and Kerr nonlinearity using the Josephson capacitance of a Cooper-pair box” Phys. Rev. B 105, 144508 – Published 25 April 2022.

Success story: LAMARS

The LAMARS (Layered 2D Materials Based THZ Spectroscopy and Imaging) project focused on various THz devices based on graphene, other layered 2D materials and their heterostructures. More specifically, the project focused on 2D nanomaterial fabrication, optimisation of plasma-wave and field effect transistor-based mixer-type detectors and related components to facilitate low-cost coherent detection. New physics related to graphene and other layered 2D-material-based, optically pumped THz emitters were investigated

Achievements:

- precise control of twist angle for large-scale 2D homostructure fabrication
- first direct visualisation of THz plasma waves and understanding of the THz detection mechanisms in graphene filed-effect transistor
- world’s smallest spectrometer with a tunable van der Waals junction
- ultrasensitive Mid-Infrared gas and bio-sensing with graphene Plasmons

The results can be used to design new types of sensitive THz detectors and spectrometers.

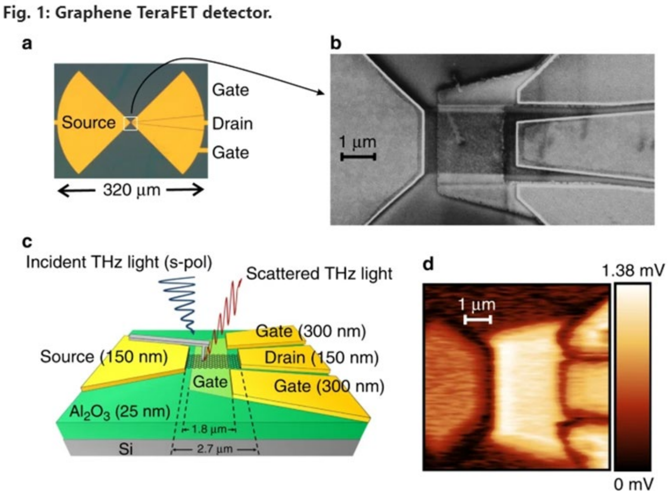

Figure 3. (a) a photograph of a GFET device monolithically integrated with a bow-tie antenna, (b) displays its scanning electron mirograph, (c) a schematic representation of the channel region of the TeraFET device and (d) displays a near-field image of the gate region for the device illuminated by radiation at 2 THz.

The project had support from a strong international collaboration network, covering THz laboratories in Europe, Asia and North America. The mobility of the researchers also contributed to their development (e.g. postdoctoral project funded by Research Council of Finland, project funded with ERC Advanced Grant).

Examples of project outputs:

Patent application: “Miniaturized spectrometers”, FIPT202300000005266 (2022)

More than 60 papers published, highlights:

[1] H. Yoon, et al., Science 20 Oct 2022, DOI: 10.1126/science.add8544F.
[2] Xi et al., Nanotechnology, 33, 085207 (2021) DOI: 10.1088/1361-6528/ac3948
[3]Soltani et al. Light: Science & Applications 9:97, https://doi.org/10.1038/s41377-020-0321-0

Appendix 2: Public descriptions of the funded projects

AGRUM (three-year funding)

Assessment of the Graft Rejection Using Millimeter Waves (Zachary Taylor)

Corneal-tissue water content is critical parameter in diagnosis of cornea-related conditions and diseases. Currently, the methods to evaluate water content are very limited, may be invasive, and are often based on subjective evaluation by the physician. AGRUM aims at developing millimetre- and submillimetre-wave imaging technology for corneal diagnosis. The new technology will be integrated with the existing corneal diagnosis methods so as to yield combined information across vast spectral range. Also, AGRUM aims at developing new electromagnetic models for cornea that are more detailed and allow accurate inversing of the medically relevant parameters.

BOLOSE

Ultrasensitive bolometers for security applications (Kirsi Tappura, Pertti Hakonen, Mikko Möttönen)

The project consortium develops sensing technologies for electromagnetic radiation in the frequency band of 0.3–1 THz. The band is particularly useful in security applications, thanks to the radiation penetration through materials used in clothes. This can be utilized in the detection of concealed objects. In addition, compared to, e.g., radio waves or microwaves, comparably short wavelength enables realization of high-resolution imaging systems. The project develops different detection approaches. Concrete objectives include the detection of room temperature object with maximal contrast, i.e., as limited by the natural background noise. We also aim to demonstrate the detection of single quanta of light at THz frequencies. This is a significant milestone in the development of extremely sensitive radiation detectors.

Digi-photon-Det

Single-photon detector array for simultaneous label-free Raman and fluorescence lifetime spectroscopy (Ilkka Nissinen, Anssi Mäkynen, Marjo Yliperttula)

Raman and fluorescence lifetime spectroscopies are commonly used methods to resolve the chemical content of material. Raman signal provides spectral fingerprint based on the low frequency vibrational modes of a molecule, and fluorescence lifetime originates from the relaxation time of excited electrons of a molecule. Combining fluorescence lifetime and Raman spectra offers more powerful method for material analysis than either of them alone. In this project a single photon avalanche diode array with time-to-digital converter array will be developed to measure both the fluorescence free Raman and fluorescence lifetime spectra of high fluorescent biological samples simultaneously with a pulsed laser. The detector measures accurate time domain photon distributions from which both spectra can be derived. This detector can be used for a remote multipoint spectrometer for label free pharmaceutical and industrial process control to increase safety issues, especially in toxic processes.

FLEXRAD (three-year funding)

Flexible, high-sensitivity UV and X-ray radiation detectors enabled by high-resolution-printing of metal oxide phototransistors (Jaakko Leppäniemi)

Printed electronics can offer new applications in radiation sensing and imaging (for example X-ray, UV radiation), where the flexibility, low-cost and large-area of the detectors can be of benefit and expand the opportunities of such detectors in non-destructive testing (NDT) and inline process control. The project develops the technology for the fabrication of such flexible X-ray detectors. The focus of the project is on materials and inks for the utilization of novel high-resolution printing technique and it aims to optimize the sensitivity of radiation detector elements using various approaches. The project is a collaboration between VTT Technical Research Centre of Finland and the National Institute of Advanced Industrial Science and Technology (AIST) in Japan.

GlowTrack (three-year funding, continuing)

In-vivo imaging device based on biophotonic implants (Mika Lastusaari, Laeticia Petit, Jonathan Massera)

Implants can find multiple different applications in medicine, from in bone reconstruction to treatment of teeth sensitivity. One important problem is their imaging post-operation as they are invisible in X-ray imaging. Recently, a new optical imaging technique was developed using persistent luminescence (PeL) nanoparticles. However, this technique presents major limitations: the nanoparticles need to be charged before injection and these particles are not biocompatible. The proposing team showed the potential of merging glass with PeL particles. We plan to develop clinically relevant implants which not only are bioactive but also emit PeL from Red to NIR. The novel implants, based on novel PeL particles, could be then charged through the skin to be imaged in-vivo allowing one to monitor in-vivo and over time the implant resorption without the use of X-Ray. This research will have a major impact not only in bio-imaging and but also in all light-based materials for photonics.

HydroGer (three-year funding)

Superior IR imaging via hydrogenated germanium nanostructures (Hele Savin)

In this project we will develop highly sensitive IR-sensors for germanium substrates. We will explore how specific nanostructuring as well as hydrogenation treatments developed originally for silicon technology can be exploited in germanium technology.

HyperStokes

Hyperspectral Stokes polarization imaging for detection of biotissues abnormalities (Aliaksandr Bykau)

The project is devoted to the development of a new disruptive imaging technology for non-invasive, rapid and accurate assessment of biotissues with the particular emphasis on cancer detection. Specifically, we aim to determine whether our technology accurately and sensitively detects the pathological conditions of a tissue in real-time, which could potentially obviate the need for time-consuming and laborious histopathological processing of biopsy samples. With cancer treatment costing EU 124 bn (Finland – 0.7 bn) per year, not including the costs of reduced lifespan and ability to work, the potential for significant spillover benefits to the population from our new technology may be extremely huge. In addition, the developed detection approach can have a significant impact in various relevant strategically important areas including food quality control, label-free biosensing, pharmacy and health care.

HyPSi

Hyperpolarised MRI of Porous Silicon nanoparticles for low-field intracranial imaging (Mikko Kettunen, Joakim Riikonen)

Low-field magnetic resonance imaging (MRI) of hyperpolarised compounds have the potential to revolutionise medical MRI by allowing development of low-cost portable MRI devices. The approach could enable earlier diagnosis, which would have life-changing consequences especially for patients with cerebrovascular diseases. In this project, we develop methods for MRI imaging using hyperpolarized porous silicon particles as contrast agents in neurological models at high and low magnetic fields. The aim of the project is to establish the experimental basis for further development of hyperpolarized low-field MRI.

LAMARS

Layered 2D Materials Based THZ Spectroscopy and Imaging (Sanna Arpiainen, Zhipei Sun)

The LAMARS project will focus on various THz devices based on graphene, other layered 2D materials and their heterostructures to introduce a paradigm shift in the THz spectroscopy and imaging applications. More specifically, the project will focus on the optimization of the plasma-wave and field effect transistor based mixer-type detectors and related components to facilitate low-cost coherent detection. The feasibility in direct (non-coherent) detection for passive radiometric imaging of room temperature targets are also examined. New physics related to the graphene and other layered 2D material based optically and electrically pumped THz emitters will be investigated with the final aim to develop a new generation of THz spectroscopy and imaging systems.

The project has strong international collaboration network, covering THz laboratories in Europe, Asia and North America.

LIGHTER

Nanotheranostics based on light (Tanja Tarvainen, Vesa-Pekka Lehto)

In order to minimise the risks of cancer treatments related to open surgery and ionising radiation, novel more efficient therapy forms are actively being developed. One of the challenges related to these treatments is an accurate targeting of the treatment effects to the cancer cells. The efficacy of the treatments is typically monitored as a separate imaging procedure. Therefore, it would be desired, especially for the needs for personised therapy, to be able to link the therapy and treatments, preferably in such a way that these could be implemented using a same device. The proposed project approaches this problem by taking the first steps towards the development of a photothermal therapy system integrated with tomographic imaging based solely on light.

MBMIB

Multispectral photon-counting for medical imaging and beam characterization (Panja-Riina Luukka, Teemu Siiskonen, Simo Särkkä, Tuure Tuuva)

The aim of this project is to develop a next-generation medical imaging detecting system, capable of multispectral imaging. Such a detector system will fundamentally change the way how imaging is done in medical and industrial applications. Our approach is to employ a direct detection system based on photon counting, which would open possibilities for new diagnostic procedures due to the superior efficiency, contrast, image quality and lower patient dose.

MilliRAD

Compact Millimeter-wave Radiometers (Pekka Pursula, Kari Halonen)

The project main goal is to develop a prototype of wafer-level integrated radiometric array at 250 – 300 GHz, and demonstrate the feasibility of compact radiometers for security and health applications. Subgoals include extending MMIC radiometer functionality above 250 GHz using SiGe HBT process, and development of planar, wafer-level integration system for the radiometers.

MMIC chips include antennas on membrane for low loss characteristics, Dicke switch, low-noise-amplifier (LNA) and diode detector. The planned radiometer will be the highest frequency radiometer demonstrated at SiGe process.

For the fabrication of large radiometric detector arrays, we propose integration based on planar lens matrix structures on Silicon. The successful development of the integration system will enable compact radiometers and millimetre wave systems for number of applications, such as security and health imaging, space and telecom.

MINMOTION

MEMS-based Intrafraction Motion Tracking for PET/CT and Radiotherapy (Eero Lehtonen)

In this project, we will develop a new method for motion compensation and gating in PET/CT imaging and radiotherapy. Our approach is based on measuring motions from multiple locations in the upper body using several highly sensitive MEMS-based inertial measurement units (IMUs), and on fusing this information with that obtained from PET/CT scanners. The considered motion estimation approach is inexpensive and does not require large or fixed hardware. We believe that by processing information from multiple motion sensors allows estimating organ movements and quiescent phases more accurately than is possible with the currently used methods.

Oksanen

Thin-film optoelectronics for sensors and surveillance (Jani Oksanen)

Optoelectronic components play a key role in multiple sensor, monitoring and surveillance applications ranging from security cameras and gas sensors to automotive sensors and first person view controlled or autonomous vehicles. This project aims at demonstrating and developing new semiconductor based sensing solutions and more efficient infrared lighting methods to enable new and improved sensor, surveillance and monitoring systems. The expected advances are based on combining state-of-the-art compound semiconductor material growth abilities with the novel diffusion driven charge transport (DDCT) mechanisms we have recently demonstrated. This will provide the possibility to develop light emitters and sensors with a fundamentally different operating principle than used in present technologies, constituting new openings with substantial societal, scientific and technological potential.

Paraoanu (three-year funding)

Quantum-Enhanced Detection (Gheorghe-Sorin Paraoanu)

During this project we will demonstrate new, disruptive concepts for detection, based on the principles of quantum physics. By using a processing scheme which is based on machine learning algorithms, we will show how ultrasensitive detection of magnetic field can be achieved with a device consisting of a superconducting circuit. Furthermore, we will realize detection of time-dependent electromagnetic fields, including that of microwave radiation at the level of a single photon. Our results have applications in magnetic bran imaging and in high-energy physics (axion detection).

SICSURFIS

Spectral Imaging of Complex Surface Tomographies (Ilkka Pölönen, Jarmo Alander, Annamari Ranki, Heikki Saari)

SICSURFIS is creating a cost efficient hardware and software solution with miniaturized spectral sensors and illumination devices for the spectral imaging of surfaces with complex tomography. Miniaturisation is based on metal mirror mems-fabry-perot interferometers. Utilization of FPGA, will make system energy efficient. For these devices, we will further develop novel software tools to analyse and model the data applied to the detection of e.g. skin cancer and caries.

Project is joint collaboration of University of Jyväskylä, VTT Technical Research Centre of Finland, University of Vaasa and Helsinki University Central Hospital.

THERAD

Novel measurement and sensing technologies for thermal radiation of unwanted fires (Simo Hostikka, Tapio Ala-Nissilä, Simo-Pekka Hannula, Andrey Mityakov)

THERAD research aims at creating a new fire detection paradigm and measurement technology by combining gradient heat flux sensors with novel spectrally selective coatings into robust, low-weight and low-cost thermal radiation sensors. First we will design the coating systems by computational techniques. We will investigate the suitability of two manufacturing techniques for manufacturing the micro- and nanoparticle inclusions in thin coating layers to implement infrared bandpass filters. Coated sensors will be optimized and calibrated for the use in flame detection and measurement problems, and validated using experimental and computational methods.

UNIDET

Universal electromagnetic radiation detector (Markku Vainio, Erkki Ikonen)

UNIDET project focuses on the development of a universal electromagnetic radiation detector. The new detector technology is based on the photoacoustic effect. It can be used to measure radiation power with high precision over a large dynamic range, with unprecedented operating range that extends from visible to the far-infrared and THz regions of the electromagnetic spectrum. UNIDET detector makes possible new scientific experiments and improves measurement capabilities in health, safety and security applications, such as in the detection and analysis of explosives and toxic gas compounds.

