# Radio Astronomy Strategic Review: Panel Report

## 1 Introduction

### 1.1 Basis for the Review

The UK has a long and world-leading role in radio astronomy, having led many of the innovations in the science and technology in this area. It is critically important to maintain this leadership role into the future as the SKA will provide an opportunity for transformational science. It could easily be argued that without the UK's leadership role in radio astronomy we might not have the SKA at all and certainly not the SKA Headquarters located at Jodrell Bank. Building on this leadership, it is essential that the UK maximises not only the scientific opportunities that SKA provides, but also ensures that UK industry plays a significant part in the construction, and additionally, benefits from a legacy of technological spin-off.

This UK Radio Astronomy Strategic Review (RASR) resulted from STFC's Balance of Programmes Review in 2016. This concluded that with the future investment in the SKA then: '*In the case of radio astronomy, it can be argued that the total cost to STFC is now high relative to the overall volume of activity and UK interest in the area*'. Recommendation 5 from the Review then stated: '*We recommend an immediate review of UK involvement in all on-going, and planned, radio facilities and experiments (including UK leadership of MeerKAT and ASKAP radio surveys - neither of which are UK-supported) to create a strategic roadmap for radio astronomy towards the SKA era. This review, in consultation with the radio community, should assess and tension the range of facilities available to UK astronomers and determine the key SKA 'pathfinders' (surveys and telescopes) in preparation for the main UK-led SKA science'*.

As a result, the Science Programmes Office set up an ad-hoc panel in May 2017 with a remit to report to Science Board in December 2017. The terms of reference and membership of the Panel are given in Appendix 1 and 2 respectively. It should be noted that in referring to radio astronomy, we specifically denote wavelengths in the cm and longer wavelength domains. Therefore, the near mm and submm are excluded from this Review and hence ALMA and the JCMT are not discussed. The specific facilities under discussion are principally e-MERLIN, LOFAR, MeerKAT and ASKAP along with the use of VLBI as a technique, which brings in the EVN (European VLBI Network) and JIVE (the Joint Institute for VLBI in Europe). Where we refer to the SKA in this report, we specifically mean SKA1.

### 1.2 Process

The RASR Panel met on four occasions with a community questionnaire being agreed at the first meeting in June. This was subsequently issued to the UK astronomy and solar physics/MIST communities and this is discussed further in section 3.4. The second meeting (September 8$^{th}$) received presentations from e-MERLIN, EVN/JIVE and LOFAR. Some members of the Panel also attended the UK SKA Science Meeting held at the Royal Observatory Edinburgh on September 7$^{th}$. At this meeting, the Chair of the RASR gave a short presentation about the Review, which was followed by a general discussion about the needs of the community in leading up to the SKA. The Chair attended the two-day ‘e-MERLIN and EVN in the SKA era Workshop II’, held at Jodrell Bank on September 11th/12th, and gave a presentation that was followed by an extended and lively discussion session. The third and fourth meetings were held on October 24th and November 23rd. The recommendations from this review are presented in section 6.2 on page 15.

# 2 The role of Radio Astronomy in the STFC Science Challenges

The UK’s astronomy community has been at the forefront of research in radio astronomy for more than six decades. Most recently researchers have pioneered the development and exploitation of cutting-edge radio facilities to address the key issues captured in the STFC Science Challenges. These UK-led activities relate to all four of the main challenges, with a particular current emphasis on: *“How did the Universe begin and how is it evolving?”* and *“How can we explore and understand the extremes of the Universe?”* and in the future also: *“How do stars and planetary systems develop and is life unique to our planet?”*

The key benefit of the radio waveband for astronomy research is its use as a tracer of physical processes across a huge range of energies and scales. Hence, radio observations can probe the formation of the agglomeration of material as planets form around stars, provide insights into the processes occurring on small-scales around the supermassive black hole in the centre of the Milky Way and other nearby galaxies, and trace the interplay between gas cooling, star formation, the feedback from accretion in active galactic nuclei and the growth of structure on the largest scales in the Universe. The two main SKA-pathfinder facilities used for these endeavors and which are currently supported by the UK, (thereby providing the foundation for our wider leadership in the field) are e-MERLIN and the UK’s contribution to the International LOFAR Telescope. It should also be noted that many UK astronomers make significant use of other major international radio facilities such as the JVLA (Jansky Very Large Array), GMRT (Giant Metrewave Radio Telescope) etc.

# 3 The Radio Astronomy Community and planning for the SKA

### 3.1 Involvement in the SKA design

This Review does not discuss the current UK involvement in SKA design and construction but suffice to say that there is major involvement in a number of workpackages with leadership roles in the SKA Data Pipeline and Signal and Data Transport areas. Indeed, the UK leads two of the SKA Project pre-construction design Work Packages; Signal and Data Transport (SaDT) and Science Data Processor (SDP) − the network and high performance computing core of the Observatory. The UK also leads key elements within several other work packages/design consortia. UK Universities and STFC National laboratories are leading in providing the resources to deliver these work-package designs for the telescope. Table 1 highlights the breadth of areas where the UK has involvement.

The STFC has invested £36M in the design phase to date, with £7M for the UK teams in FY17/18 and £7M allocated for FY18/19. The project’s Critical Design Review (CDR) dates

| Work package | Cambridge | Manchester | Oxford | UCL | STFC Labs |
|---|---|---|---|---|---|
| Science Data Processor* | x | x | x | x | x |
| Signal and Data Transport* | | x | | | x |
| Low-Frequency Aperture Array | x | | x | | x |
| Mid-Frequency Aperture Array | x | x | | | |
| Telescope Manager | | | | | x |
| Dish | | | x | | x |
| Central Signal Processor (inc Pulsar search) | | x | x | | x |
| Phased Array Feed | | x | | | |

*UK consortium lead

Table 1 UK involvement in SKA design workpackages

were pushed back in 2017 after the conclusion of the Cost Control Programme, which started in November 2016 and concluded in July 2017. This provided a comprehensive assessment of the construction costs and identified over £100M savings as well as a recognised 'deployment baseline' to match the contributions available when the project moves to the construction phase. The construction phase costs have been capped at €674M but this figure could be increased if more members join the project, with a subsequent increase in capability,

As the project moves toward the various element CDRs and the crucial system CDR at the end of 2018, the design consortia will be delivering effort for these CDRs. After the CDRs are closed out, the project will enter a pre-construction phase where testing work will take place before 'full' construction begins in 2020.

### 3.2 Anticipated use of the SKA

In late 2016 the UK community was polled by the UK Square Kilometre Array Science Committee (UKSKASC) about expected use of the SKA, specifically asking how many FTEs were currently invested, how many were planned to be deployed in the future, and in which scientific disciplines. The results suggested that the SKA is viewed as a major community activity, even in a pre-operational stage, with just over 55 FTEs predicted to be deployed by 2021. This confirms the very high interest in the SKA. Furthermore, the response was far from being confined to what might be thought of as the traditional cm-based radio astronomy community and was spread across 30 research institutes. This reinforced the experience from ALMA that with user-friendly proposal processes and science-ready data products, the lack of interferometry experience is not a deterrent to proposing programmes (see Section 3.4 for further discussion). The resulting distribution of disciplines of expected SKA interest is shown in Figure. 1.

### 3.3 Programmes on the SKA

The SKA Board has agreed that in the first call for proposals Key Science Projects will be undertaken for the first five years of operation. While this has not yet been finalised, the working

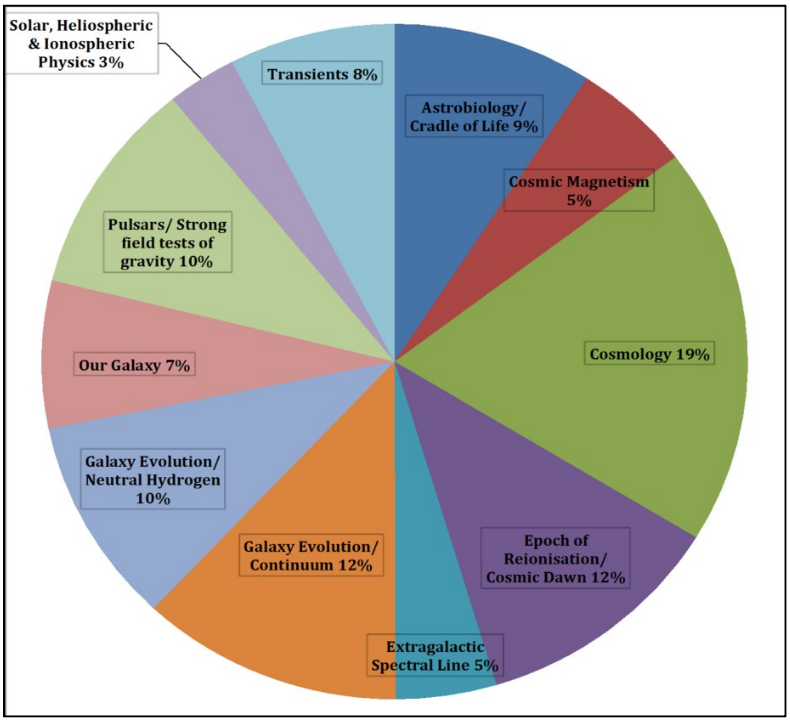


Figure 1. Distribution of research activity for the SKA showing the wide range of science anticipated

assumption by the SKA Office is that this will be at the level of 70% of observing time. These are mostly anticipated to be extremely large, challenging and world-leading surveys that will involve a considerable number of individuals from the partner countries. While it is not yet determined what themes the KSPs will cover or how the KSPs will be formed and agreed, it is clear that the UK needs to be as deeply involved as possible and that leadership of KSPs is a key strategic goal. Fortunately, the UK is currently well-placed to satisfy both of these requirements, with a high proportion of members of the current SKA Science Working Groups and with leadership roles in a number. The current position is shown in Table 2. It should be noted that the Chairs/co-Chairs rotate and so this is a snapshot of the current position, which may or may not be reflected in KSPs without further work and support from STFC. Nevertheless, it is strongly expected that with this support the UK is in an excellent position to capitalise on these leadership roles. This is discussed in later sections.

### 3.4 Results from the community questionnaire

A questionnaire was issued to the astronomical/solar-system/MIST communities over the summer. The questionnaire asked: '*Please tell us how STFC could best support your research and development in preparation for early SKA science. Where relevant, please discuss which precursor/pathfinder facilities you currently use and/or intend to use*'.

| SWG Membership | UK Number | Chair/co-Chair |
|---|---|---|
| Cosmology | 26 | |
| Cradle of Life | 8 | co-Chair |
| EoR | 7 | |
| Exgal continuum | 16 | co-Chair |
| Exgal spectral line | 10 | co-Chair |
| HI Galaxy | 5 | |
| Magnetism | 9 | |
| Our Galaxy | 9 | co-Chair |
| Pulsars | 10 | |
| Solar helio and iono | 21 | co-Chair |
| Transients | 10 | |

Table 2. Current snapshot of UK representation on SKA Science Working Groups

There were 92 respondents covering most of the UK universities and including a number of overseas institutions, especially JIVE in the Netherlands. Most of the overseas respondents were interested in the use of e-MERLIN as part of the EVN and VLBI networks. Appendix 3 lists the major responses in terms of institution, while Figures 2 and 3 show the breakdown by career stage and research area of the respondents.

The questionnaire demonstrated strong ongoing involvement and support for LOFAR and e-MERLIN, both for their own scientific contributions and their value as SKA pathfinder instruments. It is important to emphasise that for both facilities this support spans a wide range of UK institutions and science areas.

A common thread in questionnaire responses was that gaining early experience with SKA-like proposals, observations and analysis was going to be particularly important, and would give those individuals a head start in the competition for access to the SKA. It was also noted that some of the SKA partners, in particular South Africa and Australia, were investing in SKA Fellowship schemes and there was concern that the lack of such avenues in the UK could put us at a disadvantage. While PhD studentships were seen to be valuable, it is the lack of early career researchers that was seen to be the problem. In addition, many postdocs, having been trained within the UK, subsequently leave to go abroad to our competitors. This brain-drain in key talents was seen as a real problem and potentially strategically damaging. The issue of a likely reduction in available postdoctoral effort if access to EU funding is reduced/removed was also raised as a particular concern.

It should also be noted that the importance of investment in early-career researchers was the primary feedback from both the RASR presentation and the discussions at the e-MERLIN meeting in September *(Recommendation 1)*.

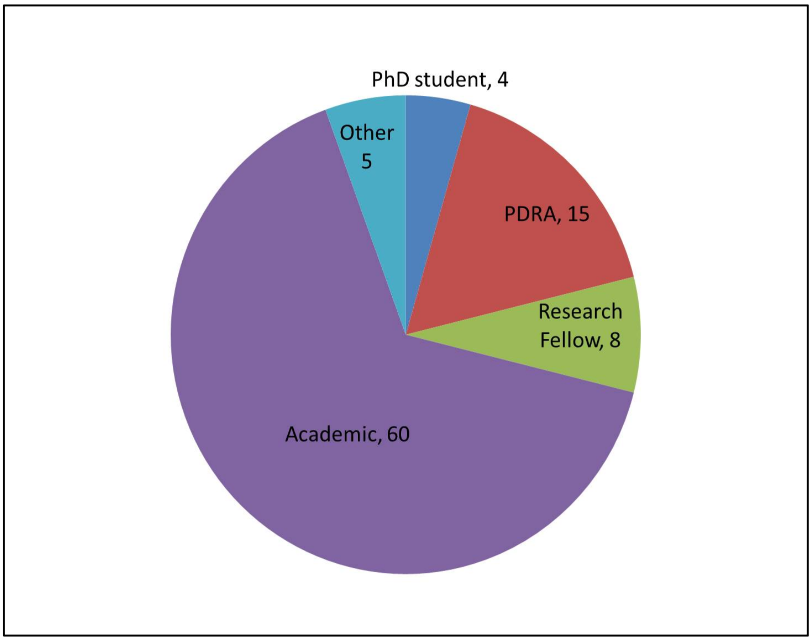


Figure 2. Questionnaire response breakdown by career stage

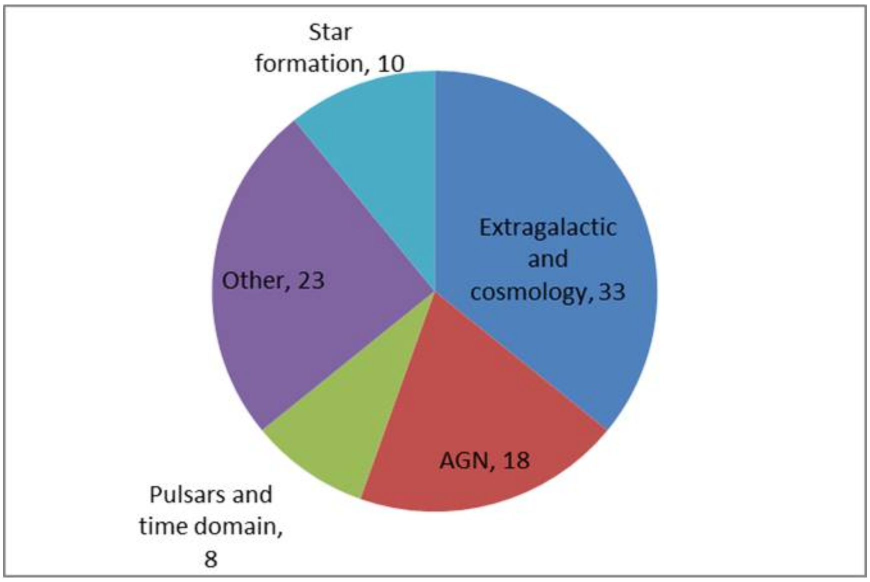


Figure 3. Questionnaire response breakdown by anticipated research activity, which maps well with the SKA interests shown in Figure 1.

This comment that people may be as important as facilities was also reflected in the uncertainty expressed in just how science-ready the SKA pipelines will be. SDP will deliver a range of data products including images and spectral cubes, but the scope of these products is unclear and some key science areas may require higher quality or specialised data reduction not provided by SDP. One example is Epoch of Reionization (EoR) science, which requires direct access to visibilities, where algorithms and pipelines are being developed by the community rather than the SKA project.

Finally, while many respondents stressed the need to maintain leadership and maximise return on the UK's investment in the SKA, a number of comments also emphasised the community value and strategic importance of maintaining a broad radio astronomy programme rather than valuing only activities directly linked to preparation for the SKA, particularly given the uncertainty of SKA timescales.

### 3.5 Input from the STFC's Steering Committee for the e-MERLIN/VLBI National Facility

This committee has an oversight role in the operation of the e-MERLIN/VLBI National Facility and wrote to the Panel on November 10$^{th}$ urging full support for the e-MERLIN grant proposal. They point out the benefits of the National Facility and that, if fully upgraded, it would provide science 'on a par' with SKA1. They also point out the advantages of common software (see section 4.3) and the ability to 'try out' proposals on e-MERLIN prior to SKA submission. Their letter is found at Appendix 4.

# 4 The timeline and roadmap to the SKA

### 4.1 Overview and current timeline

The highly complex commissioning process and operation of next-generation radio interferometers, compounded by the current uncertainty in the SKA construction schedule (which has changed during the course of this Review), means that determining a timeline with specific dates is difficult. However, decision points are easier to define. In addressing the question of timelines we have assumed that the actual construction of the SKA (currently the 'deployed' option) will commence in mid-2020. The current projected dates from the SKA Office are:

- science commissioning to start in Q1 of 2022
- science verification observations to start in Q3 of 2024
- shared risk proposals due in Q3 of 2025
- shared risk observations to start in Q1 of 2026
- PI and KSP proposals due in Q2/Q3 of 2026
- PI science observations to start in Q4 of 2026
- KSP observations to start in Q4 of 2027

From this it is seen that routine science from the SKA is still some way into the future. While the majority of KSP observations may require fully matured operation of the SKA, it is inevitable that close engagement during the Science Verification and Shared Risks phases will be a requirement for groups intending to form KSPs. This should provide access to important early science and it will be important to support this involvement through the early phases, with more emphasis on instrument commissioning to ensure scientific leadership later on. However, this latest schedule has clear implications for the ongoing support for the current facilities, especially e-MERLIN.

Construction of the SKA is only the start of SKA science; to maximise the benefit, as was seen from the previous section, science users will be key. The UK needs to set aside funding for a Regional Data Centre, whose European location has yet to be decided, and also, user support. The ALMA Regional Data Centre could serve as a model and there are obvious synergies that would enable an ALMA and SKA UK user support group to be a single entity. Therefore, STFC needs to plan for the funding of these critical areas for the science exploitation of the SKA *(Recommendation 9)*.

In the following subsections we address the capabilities, funding levels and future plans of the facilities indicated in our terms of reference and tension these by highlighting their respective merits.

### 4.2 LOFAR

LOFAR, the LOw Frequency ARray, consists of 51 simple, antenna stations operating at metre wavelengths. These are situated mainly in the Netherlands with 13 in other countries including the UK, which hosts one of these stations at STFC Chilbolton. The annual UK contribution is currently £230k. LOFAR is substantially more sensitive than any other instrument currently operating at wavelengths of a few metres, with unmatched spatial resolution (of a few arcseconds) and image quality for this wavelength regime, and a powerful survey capability due to its wide field-of-view. After a slow start in 2014 it is now delivering world-beating science with over 130 papers published. This ramp-up in publications reflects the extreme difficulty of data analysis, working with very large data volumes and solving problems relating to wide-field data calibration and ionospheric effects. Indeed, because of this, LOFAR is the key pathfinder for SKA-LOW. Many lessons being learnt are also relevant for SKA-MID, with imaging software developed for LOFAR recently used to successfully deliver “first-light” images from MeerKAT, which is the core of SKA-MID. In this sense, ramping-up the SKA should be much faster given all the lessons learned with LOFAR, as long as these are fully incorporated

The UK already has a very strong involvement with LOFAR. While the UK investment represents around 2% of the total, the science return is around 15% as measured by the involvement as PI/Co-I/Members of the LOFAR Key Science Projects, and 13% of published papers have UK-based first authors (from 7 institutions). Currently 24 institutions are involved, albeit some more heavily than others; the highly active core component is probably around 10 universities. Overall, LOFAR serves as an excellent example of what the UK should be seeking for the SKA, especially in terms of scientific leadership. Science involvement, algorithmic development, pipeline tools and big-data analysis are all hugely valuable learning tools for involvement with the SKA.

LOFAR is seeking to develop a greater capability with LOFAR 2.0, which will be funded mostly by the Netherlands and other European partners, but would require a UK one-off injection equivalent to an annual contribution. LOFAR 2.0 is an upgrade of the correlator to allow multiple science programmes to be operated simultaneously using the same data-streams but differing reduction pipelines. This is also a key requirement for the SKA. LOFAR 2.0 also incorporates an electronics upgrade to dramatically improve sensitivity and observing efficiency. While LOFAR continues to expand with stations in other countries (Ireland, Italy, Latvia) it is not envisaged that there will be a need for any further stations to be constructed in the UK.

The next funding request to STFC for LOFAR is due in 2018 and will include operating contribution plus the one-off support for the LOFAR 2.0 upgrade. LOFAR offers a powerful stepping-stone to the SKA, giving users hands-on experience of data from a next-generation facility, strengthening their position with key science programmes and providing valuable experience of solving many of the SKA data analysis challenges. The Panel is unanimous in agreeing that involvement in LOFAR represents extremely good value for money and should be fully supported at the highest priority, along with exploitation and funding for LOFAR 2.0. *(Recommendation 2).*

## 4.3 e-MERLIN

### *4.3.1 Overview*

e-MERLIN is a world-leading facility and occupies a particular unique niche in its combination of wavelength coverage (from approximately 1 to 30cm), high sensitivity, and an angular resolution matching, or even exceeding that of the Hubble Space Telescope. As well as delivering high-calibre science, e-MERLIN provides a centre of excellence for technology development for cm-wave radio astronomy and VLBI research. Some impressive first results of the high-profile e-MERLIN Legacy programmes are now beginning to emerge.

However, there has been concern in the UK community that the promise of e-MERLIN has not yet been fully realised due to the slow delivery of data from these programmes. There have been a number of reasons for the delay; one example is the difficulty of removing radio frequency interference (RFI), especially low-level and variable components that currently have to be undertaken manually. This presents a huge overhead in terms of staff effort, both from Jodrell as well as the observing teams and has led to some disenchantment in the community. The anticipated launch of a new automatic data pipeline with RFI noise removal will provide a major benefit to users and increase the productivity and output of e-MERLIN significantly. Successful completion and roll-out of this pipeline should be a short-term, highest priority for e-MERLIN.

### *4.3.2 e-MERLIN Operations*

Given the uncertainty in the SKA construction and operational timescales noted above, it is crucial that e-MERLIN receives continued support at this time to complete the already funded Legacy Science Programmes and to continue to deliver on a wide-range of high-quality science. It is vitally important that e-MERLIN receives funding commensurate with its delivery goals; attempting to try and do everything with an under-resource of budget would put future funding at risk. The Panel is unanimous in supporting e-MERLIN operations for the next five years. As a matter of principle we defer to PPRP for the prioritisation and level of support for the aspects of the operational programme, but note that PPRP/Science Board needs to be very clear what e-MERLIN is expected to deliver and what it should not focus on *(Recommendation 3)*. The requested e-MERLIN operational budget is £2.7M per year for the next five years.

The Panel also strongly believes that now is not the time to assess the long-term future of e-MERLIN. The next e-MERLIN operations grant application will be in 2023. Therefore, the Panel recommends a further review, specifically addressing the role of e-MERLIN in the era of the SKA, to be held in early 2022 *(Recommendation 5)*. This time-frame should provide a better ability to tension the science and technology benefits from a continued e-MERLIN operation against the progress of the SKA.

Before concluding this section on e-MERLIN operations we note that there are two components of the operations funding request that could be considered as upgrades (see 4.3.3), albeit at a different level of funding. One of these is the inclusion of the Lovell telescope in the e-MERLIN array for 120 days per year. This gives increased sensitivity (by a factor of two) albeit with reduced field-of-view and is important for a number of science programmes. This increase in sensitivity offers good value for money and we support this. However, we defer to PPRP to recommend the number of extra nights depending on the science case. (*Recommendation 4*).

The second 'upgrade' is the inclusion of two telescopes at the Goonhilly Earth Station in Cornwall. This capital phase is funded by a consortium of universities (CUGA), led by the University of Leeds. This project is nearing completion and while there are no development costs requested by e-MERLIN, operational aspects will require additional resource. The addition of Goonhilly will substantially improve image quality by roughly doubling the spatial resolution for e-MERLIN and by improving the uv coverage for southerly sources -- important for particular Galactic science targets, extragalactic survey work in specific fields and for overlap with ALMA and other southern hemisphere facilities.

### *4.3.3 e-MERLIN Upgrades*

As for most facilities, remaining competitive requires continuous development, and e-MERLIN has proposed a natural and logical pathway to achieve this. Their plan provides increases in sensitivity, better frequency coverage and a pathway and training ground for UK SKA astronomers, while also potentially benefitting SKA technology developments. The Panel paid particular attention to the details of this plan, bearing in mind their intrinsic science value and also their contribution to the UK involvement in the SKA and the potential for industrial return. It is assumed that the specific science cases will be peer-reviewed and ranked through the PPRP process.

In general terms, part of the case is that an upgraded e-MERLIN will enable some of the 'low hanging fruit' to be garnered by UK astronomers before the SKA comes into full operation. This is because a fully upgraded e-MERLIN has almost 30% of the collecting area of SKA-MID, provides a wide frequency range (1-25 GHz) with a large instantaneous bandwidth (8 GHz), a wider field-of-view at the lower frequencies and excellent sensitivity (microJansky) with sub-arcsecond resolution. This would be a powerful instrument on the world-stage, accessible to the UK community, would position e-MERLIN as a uniquely capable facility for high spatial resolution SKA follow-up observations and has the potential to provide a training ground for UK use of the SKA.

Nevertheless, it is unclear to the Panel that all the upgrades are necessary on the strategic path to the SKA. At this point we note that we are not commenting specifically on the affordability, but more the strategic balance that might be gained for the UK. Some of the upgrades are particularly beneficial to certain science programmes, and again, we defer to the PPRP for the detailed assessment and prioritisation of these. It should also be pointed out that a key benefit of the upgrades programme is the retention of a level of technology capability. The UK needs to retain this so that it can capitalise on the expected work from the SKA Development Programme, and therefore there is a level of strategic benefit to an e-MERLIN upgrades programme beyond its direct science outcomes and value for SKA scientific preparation.

Workpackage 2.0 (WP2.0 - software development) of the e-MERLIN upgrades funding proposal stands out in that it would appear to have a particular strategic benefit leading up to the SKA. This workpackage is very closely linked to the software development for the SKA, involving mostly the same people, and would be implemented on e-MERLIN immediately after the SDP software delivery to the SKA. In addition to increasing the throughput of e-MERLIN (benefitting virtually all of the astronomical programmes), it would provide the UK user community with an SKA-like instrument. This would enable the community to gain experience and confidence with SKA data analysis software tools, would provide continued software development that would put the UK in the best position for industrial contracts, and would enable future software developments for the SKA to be continued with the same UK team *(Recommendation 4)*.

In principle a second upgrade offers another close synergy with the SKA and this is WP6, Digital Upgrades. This offers an increase in performance in the proposed S-band but its real advantage is at X-band, and for this to be fully achieved requires additional investment in WP4 and WP7. This full upgrade would make e-MERLIN very competitive with SKA1-MID but at a significant cost and with the benefits limited to only a part of the user community. If the future of e-MERLIN was certain beyond 2023, these upgrades would be an attractive option; however, given the uncertainty and funding levels, this currently represents a high-gain, high-risk option.

### 4.4 VLBI including EVN and JIVE

VLBI presents a unique capability for extremely high spatial resolution astronomical studies. The UK participates in the European VLBI Network (EVN) through an annual contribution (~€200k) to JIVE, the Joint Institute for VLBI ERIC (European Research Infrastructure Consortium) located in the Netherlands. Although the UK VLBI community is small, the science return is good for the funding invested and the role of e-MERLIN in the EVN is seen to be critical in terms of collecting power and baselines. An exciting future development is the possibility of ‘wide-field’ VLBI, something that could readily see a notable increase in the community. Although a niche area, given the modest funding level, VLBI and JIVE continue to provide value for money for the UK *(Recommendation 7)*.

It should also be noted that VLBI has been a very attractive area for use of Newton funding for the Development of Radio astronomy in Africa (DARA) and for EC funding via ‘Jumping JIVE’. The UK, South Africa, and wider-African countries have been engaged in this very successful pan-national programme that has run alongside their own national programmes. This has seen the repurposing of communications dishes as elements of an African Very Long Baseline Interferometry Network (AVN). There have been various other ODA programmes (both Newton and the Global Challenges Research Fund) in astronomy, including radio astronomy, in Latin America and Southeast Asia.

### 4.5 Additional SKA precursors

International effort towards the SKA is recognised in what are termed SKA precursors (defined as being located on the SKA sites in South Africa and Australia) and SKA pathfinders (other international radio telescopes). UK involvement in many of these facilities comes at the level of individual researchers, but can be significant.

***MeerKAT*** consists of 64x14m dishes that will ultimately be incorporated into SKA-MID. MeerKAT produced its first science images in 2017 and has a well-defined science programme dominated by ten large survey projects (>1000hrs telescope time over 5 years) that directly anticipate SKA surveys. UK researchers co-lead 4 of the 10 top priority MeerKAT surveys with significant involvement in the others. Maintaining this leadership will provide a direct route into leadership of SKA-MID surveys. Current STFC support for UK MeerKAT involvement is via the exploitation grants line.

***The Australian SKA Precursor (ASKAP)*** is designed as a mid-frequency survey instrument with 36x12m dishes using phased array feeds. ASKAP began science operations in 2017 with 75% of observing time during the first five years dedicated to ten large surveys. Although the UK participates in the surveys, leadership is overwhelmingly Australian, with limited Canadian and US involvement.

***The Hydrogen Epoch of Reionization Array (HERA*)** is a unique Epoch of Reionization (EoR) experiment at the South African SKA site. It is funded by the NSF for the deployment of 330x 14m fixed dishes in a close packed hexagonal layout. HERA is a focused experiment targeting the 21cm power spectrum from the Epoch of Reionisation with limited imaging performance and reliant on redundant baselines for instrumental calibration. HERA seems likely to rapidly become the most sensitive international EoR experiment, providing the first significant 21 cm science. Cambridge is a full partner in HERA, having provided receiver development and in-kind contributions. We note that HERA requested support from STFC via its Science Board in 2016 but this was not awarded.

***The Murchison Widefield Array (MWA****)* is the low-frequency precursor on the Australian SKA site and is building relevant infrastructure for testing SKA-LOW deployment. MWA was upgraded in 2016-17 to Phase 2, doubling the collecting area to 256 tiles (each of 16 dipoles) and significantly improving uv coverage. Phase 2 will test redundant calibration and with improved electronics will significantly improve MWA's EoR capability. Low frequency sky catalogs from MWA, such as GLEAM, are likely to provide the initial sky model for calibration of SKA-LOW. The MWA is primarily an Australian experiment with significant involvement from US and Japanese partners. Current UK involvement is at the level of a few individuals.

In summary, MeerKAT and ASKAP will explore similar mid-frequency science to SKA-MID. LOFAR and MWA most directly parallel SKA-LOW in technology terms, but HERA is likely to provide more EoR science prior to SKA. All precursors will explore transient science, although MWA is limited in its capacity for pulsar science. Along with LOFAR and e-MERLIN, experience with these instruments, especially MeerKAT and ASKAP is vital for building expertise ahead of the SKA. Involvement in MWA would be desirable for building familiarity with Australian infrastructure and preparing for SKA-LOW commissioning *(Recommendation 6)*.

### 4.6 Technology and future levels of support

As seen earlier, the UK has been particularly successful in contributing to the design phase of the SKA and holds leadership roles in a number of areas. In strategic terms maintaining this is seen to be extremely important, and one area stands out: that of data processing. Leadership of the SDP is a key aspect for the SKA, but in the UK context the experience of working with massive datasets and the need for HPCs is far from unique and represents an opportunity for STFC to take a leadership role with government for a UK central programme of this type, encompassing the widest possible range of scientific disciplines. Therefore, continued support for this area through e-MERLIN upgrade WP2.0 (see above) has a distinct strategic advantage for STFC and the UK as a whole.

The Panel recommends that STFC senior management takes the above on-board as a general strategic theme, capitalises on the SKA work being undertaken, and works with the UK government in their programme of 'Big Data' *(Recommendation 8)*.

As well as this example there are other technology areas that the UK should support in retaining valuable expertise for the era of the SKA that would otherwise be lost. These are held at a small number of institutions (Manchester, Oxford, Cambridge). Decisions on how or whether to support these will need to be taken in the next 3 years as the SKA design funding comes to an end, and will also depend on the level of support provided for particular e-MERLIN upgrades.

### 4.7 Protection of the Radio Spectrum

In passing, the Panel noted that a significant proportion of STFC's radio astronomy budget is assigned to covering spectrum protection costs, which at present is paid for partly by BEIS. A risk is that STFC cannot guarantee that BEIS will continue to pay its part indefinitely. In addition, there is a move by government to release more of the public sector spectrum over the coming years. While much of this is expected to come from current military allocations, where defence and scientific use have co-existed, it is understood that some of the high priority bands include, or are immediately adjacent to, important radio astronomy bands. While relinquishing bandwidth may save money in the short term, once it has been given up it cannot be re-purchased at a later date. Radio astronomy spectrum access is only one part of the UK science requirement, with further allocations used by space science, NERC, the Met Office etc. It is important that any changes to our requirements or to our ability to access and protect the necessary wavebands are considered in the wider context via our links with Ofcom. Maintaining spectrum protection across a range of frequencies is essential for radio astronomy and as such, the Panel recommends that any request to relinquish bandwidths should be considered by a specifically convened panel to assess and tension between these bandwidths *(Recommendation 10)*.

# 5 The European scene for Radio Astronomy

This has been well documented in a 2015 report for the EC coordination networks ASTRONET and Radionet by the European Radio Telescope Review Committee. This report was commissioned in part to address the European situation leading up to the SKA. The report painted a positive picture of European radio astronomy and in particular highlighted the critical value of human capital, not only in the traditional area of radio astronomy technology but in the rapidly developing areas of data analysis, software and supercomputing. The report also pointed out that, like other branches of astronomy, radio astronomy is now no longer the sole province of specialists, but has been opened up to the more general astronomical community through, for example, new (and highly simplified) tools for observing proposals, pipeline data analysis packages and data archives themselves. Like this Review, the report did not consider near-mm and submm facilities.

Europe has a large number of single dish radio facilities; mostly working in the cm regime and mostly working without a high degree of international collaboration. A notable difference is the EVN/JIVE (including e-MERLIN), which is regarded as extremely successful. LOFAR was seen as an up-and-coming facility and a key pathfinder to the SKA. The continuation of support for many of these single dish telescopes is provided not only in terms of the scientific return to the individual nations but also as a valuable training ground in astronomy and technology.

Although the SKA is seen as the key to the future, the report is somewhat disadvantaged by the lack of a large number of European nations signing up to join the organisation. The report concludes with a recommendation for ESO to be the managing organisation for the SKA, a conclusion that was very controversial at the time and which has passed into the mists of time.

# 6 Conclusions and Recommendations

## 6.1 Conclusions

Maximising the UK involvement and scientific output from the SKA is a high priority for STFC. The science resulting from the early years will differ in many respects from the science undertaken a decade later. Furthermore, with much of the first science of the SKA being devoted to Key Science Projects (KSP), mostly involving large surveys, it is critical that UK scientists are heavily involved and preferably with leadership roles in these KSPs. To that end, involvement in and use of existing pathfinders and precursors and developing expertise in SKA-like data analysis and pipeline algorithms are essential requirements that must be supported as a matter of strategic priority. These will be the key areas that will strengthen the UK's SKA KSP contributors and future science leaders of the SKA.

The need to have adequate 'people effort' to maximise the impact of the SKA (both scientific and technical) cannot be overstressed. The Panel recommends that adequate funding is provided for SKA science support, especially for early-career researchers, as these will be critical for the best scientific return on investment for the SKA.

The UK is currently in a strong position to capitalise on SKA science as a result of substantial involvement with pathfinders, in particular LOFAR, and with heavy involvement in the Science Working Groups that are anticipated to evolve into Key Science Programmes. It is critical that these activities receive continued support. e-MERLIN is delivering excellent science but the focus must be on completing the legacy surveys, which are now imminent. There is an extremely strong case for continued operations for the coming five years but STFC and e-MERLIN must be clear about the expected outcomes from the level of funding supplied. The maxim of spreading oneself too thinly and failing to deliver cannot be overstated. The e-MERLIN upgrades represent a very sensible and coherent programme but whether all of these can be funded at the current time and future financial uncertainty is unclear. However, the Panel noted that a number of upgrades represent not only good value for money but have direct synergies with the development of tools for the SKA.

### 6.2 Recommendations

1. Continued support for funding early-stage researchers in radio astronomy exploitation is essential as they provide the human capital to exploit and ensure UK leadership in early SKA science. At a minimum, current levels of support through STFC fellowship schemes and the exploitation grants line must be maintained.
2. Funding for continued participation in LOFAR, including LOFAR 2.0, is the highest priority. This modest cost represents excellent value for money and provides a critical training ground for UK involvement in specific aspects of SKA.
3. There is extremely strong justification for continued support for the operations of e-MERLIN for at least the next five years. The level of funding should be commensurate with the facility being able to deliver on its science commitments and to maximise benefit to the UK community leading up to the SKA.
4. Support for further inclusion of the Lovell Telescope into e-MERLIN and the software upgrades (WP2.0) represent good value for money and the latter offers a strong synergy with future SKA work, both UK scientific and industrial.
5. There should be a further review of e-MERLIN in 2022, specifically addressing its role in the era of the SKA.
6. UK involvement in SKA precursors such as MeerKAT, ASKAP and MWA should be encouraged and supported as a strategic route to involvement with SKA science.
7. Support for VLBI/EVN represents good value for money and should be continued.
8. The Panel recommends that STFC senior management take up the leading role of SKA SDP design in the UK as a strategic theme of government challenges to support UK `Big Data' and high-performance computing.
9. STFC needs to ensure that funding is available for the support of an SKA Regional Data Centre (probably in Europe) and in addition, user support located within the UK. The ALMA user-support model could serve as a template and obvious synergies could be found from a single support group for both programmes.
10. The Panel recommends that any request to relinquish radio frequency bandwidth should be considered by a specifically convened panel to assess and tension between these bandwidths.

**Appendix 1 RASR Terms of Reference**

1. Identify the key science goals of STFC's science roadmap that are most effectively delivered by the current and future UK radio facilities;

2. Consult with the UK astronomy community to identify and prioritise and where appropriate tension the observational capabilities and facilities that are required to deliver the key science goals.

3. Establish a roadmap and timeline showing the pathway for the development of future capabilities and facilities highlighting inter-dependencies, overlaps and key points for investment.

4. Analyse the broader European and global radio astronomy research landscape to identify current and potential future synergies. Comment on the importance of existing collaborations and how these benefit the UK radio astronomy community. [Noting the recent ASTRONET European RA review; RadioNet; H2020 etc]

5. Produce a written report that will be presented by the Chair of the Review Panel to STFC's Science Board by the end of 2017.

## Appendix 2 Panel Membership

The panel membership was as follows, details of other relevant experience/roles or potential conflicts which were declared, are also given.

Prof Ian Robson (Chair): member of the UK SKA Programme Board.

Dr Judith Croston (Open University): LOFAR Surveys KSP involvement and member of UK SKA Science Committee, member of e-MERLIN Legacy Programmes (co-I for eMERGE and Extragalactic Jets).

Prof Catherine Heymans (University of Edinburgh): member of PPRP and Visiting Panel for the 2017 e-MERLIN proposal submission.

Dr Jonathan Pritchard (Imperial College): outgoing chair of the SKA EoR Science Working Group; chair of the UK SKA Science Committee.

Dr Mark Sargent (University of Sussex): chair of the e-MERLIN TAG; member of e-MERLIN Steering Committee; incoming chair of the SKA Continuum Science Working Group.

Prof Ian Smail (Durham University): member of the e-MERLIN Legacy Programmes (co-PI of eMERGE and AGATE).

Prof Serena Viti (UCL): member of the Astronomy Advisory Panel.

Prof Anton Zensus (MPIfR): current Director of the Max-Planck Institute for Radio Astronomy; member of the JIVE/ERIC Board; co-ordinator of RadioNet

The panel was supported by Chris Woolford, Justin O’Byrne and Michelle Cooper from STFC.

## Appendix 3 Response to the Questionnaire

Out of the 92 replies, the following institutions supplied more than a single response and 23 other institutions submitted a single return.

| Institution | Total Number of responses | Status: |
|---|---|---|
| University of Manchester | 28 | 16 x Academic staff; 5 x PDRAs; 3 x Research Fellows; 2 x Other Emeritus Profs; 1 x Other - Scientific support staff; 1 x PhD student |
| University of Oxford | 7 | 4 x Academic staff; 1 PDRA; 1 x Research Fellow; 1 x Other - Visiting Prof |
| JIVE | 6 | 4 x Academic staff; 2 x PDRAs |
| University College London (UCL) | 4 | 3 x Academic staff; 1 x PhD student |
| University of Leeds | 4 | 3 x Academic staff; 1 x PDRA |
| University of Hertfordshire | 3 | 2 x Academic staff; 1 x PDRA |
| University of Southampton | 3 | 1 x Academic staff; 1 x PDRA; 1 x PhD student |
| Cardiff University | 2 | 2 x Academic staff |
| Durham University | 2 | 1 x Academic staff; 1 x PDRA |
| Imperial College London | 2 | 1 x Academic staff; 1 x Research Fellow |
| Newcastle University | 2 | 1 x Academic staff; 1 x Research Fellow |
| Open University | 2 | 1 x Academic staff; 1 x PDRA |
| University of Edinburgh | 2 | 1 x Academic staff; 1 x PDRA |
| RAL | 2 | 1 x Research Fellow, 1xSci Support |

## Appendix 4 Input from STFC's Steering Committee for the e-MERLIN/VLBI National Facility

Re e-MERLIN/VLBI National Facility 10th November 2017

Dear Professor Robson,

I am writing on behalf of the STFC Steering Committee for the e-MERLIN/VLBI National Facility, members as named below, to reflect on the operation and development of the Facility in the SKA era in relation to the Radio Astronomy Review Panel's remit.

In our oversight role, the committee has seen directly how the National Facility has developed world-leading capabilities in radio interferometry, while training UK and International astronomers in the relevant techniques. This has enabled internationally excellent science, much of which is leading the world in its area. The alignment of that science with key priorities of both STFC and the Square Kilometre Array is a consequence of the strategic vision of the Facility team, and their role in leading the UK community in shaping those priorities.

Future development plans are central to the nation's astronomy capabilities in the SKA era, while also delivering science on a par with SKA1 in a complementary fashion. Complementarity includes northern-hemisphere access, dedicated rapid response and follow up at high spatial resolution. We believe e-MERLIN is the best already-existing analogue of SKA1-MID.

Through community engagement the team have determined the key priorities for the Facility, gaining support from a wide base of UK astronomers. Central to this is the planned alignment between the SKA and e-MERLIN software environments, the key tool through which astronomers will interface with both facilities. With the hardware capabilities and observatory support to go with this, we believe the proposed programme will place UK astronomy at the forefront of SKA exploitation. In addition, once SKA1 is operational it is clear that both demonstrable expertise and pilot programmes on e-MERLIN will be critical to winning time. Being able to use real data to develop software tools and demonstrate science outcomes will be enabled for the UK community by e-MERLIN. Analysis of the community input places enhancements to address operating bands and sensitivity highly. The upgrades proposed will also further develop e-MERLIN capabilities ahead of ngVLA, recently awarded funds for design concept work in anticipation of the 2020 Decadal Review. Thus, the requested investment is timely when considering both SKA and its main competitor post-2020.

The committee has seen the challenges resulting from the current limited funding of the National Facility. While the team have achieved an enormous amount, we believe that full support will provide significantly more robust support for the UK community and development of a capability that will remain competitive well into the SKA era. They are already working closely with SKA Office as well as ngVLA.

In summary, we urge the Panel to support the future of the National Facility in full.

Sincerely,

Dr Stewart Eyres (USW), Chair of the STFC Steering Committee

Professor Tom Ray (Dublin Institute for Advanced Studies)
Professor Rene Vermeulen (Astron)
Professor Graham Woan (Glasgow)
Professor Paul Alexander (Cambridge – CoI on the case for support)
Professor Mike Jones (Oxford – CoI on the case for support
(Dr Mark Sargent as a member of RARP is not a signatory)