Submission Template

2016 National Research Infrastructure Roadmap Capability Issues Paper

Submission No: *(to be completed by Departmental staff)*	
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Would you like your submission to remain confidential, i.e. not published on the website?	**NO**

Note: a glossary of acronyms used in our response is at the end of this document.

Covering letter

Background and strategic priorities:

This document is built upon the Australian astronomy community's vision and priorities over the next decade, as articulated in the Australian Astronomy Decadal Plan for 2016-2025. Australian Astronomy Decadal Plans are developed by the Australian Academy of Science's National Committee for Astronomy (NCA) and have been supported by AAL through strategic investment in national collaborative research infrastructure since 2007.

As described in the Australian Astronomy Decadal Plan, Australia is already involved in two of the largest global telescope projects that will continue to be top astronomy infrastructure priorities over the next decade: 1. the Square Kilometre Array (SKA), which will be the world's most powerful radio telescope by several orders of magnitude and will be partly built in Australia with substantial local industry and regional engagement; and 2. the Giant Magellan Telescope (GMT), which will be the first of the next generation of Extremely Large Telescopes that observes at optical wavelengths and for which Australia is building key scientific instrumentation and Australian industry is in a strong position to bid for design and construction contracts. To fully exploit our involvement in SKA and GMT, the ground must be firmly laid scientifically and technically in optical and radio astronomy over the next decade. This will require the successful deployment and scientific exploitation of the Australian precursors to SKA - the Murchison Widefield Array (MWA; the first fully operational SKA precursor) and the Australian SKA Pathfinder (ASKAP) - as well as access to and instrumentation development for 8-metre-class optical telescopes.

The Decadal Plan highlights that the next major discoveries about the nature and physics of the cosmos will involve observing the Universe across the electromagnetic spectrum from a range of facilities, and by combining the data with other “messenger” particles and signals, through the growing field of “multi-messenger astronomy”. Australia is already a significant contributor to major world multi-messenger projects to study the Universe through X-rays, gamma-rays, neutrinos, cosmic rays, and gravitational waves. These projects give us new ways to perceive the Universe, particularly with regard to the most energetic and transient events in the cosmos. It is akin to going from simply “seeing” the Universe to being able to “hear” and “feel” it too. To fully capitalise on these new opportunities as they arise and mature, there needs to be flexibility and agility built into Australia’s research infrastructure framework.

Currently, Australia’s involvement in many such global projects leverages our niche areas of expertise, our suite of facilities for follow-up observations, and our unique role as custodians of the southern sky. For instance, when an entirely new field of astronomy opened up in late 2015 with the first direct detection of gravitational waves, the Australian SKA precursors were two of the first telescopes in the world to swing into action and obtain follow-up observations to try to determine the source of the signal. It is worth noting that Australia is already a significant player in the new field of gravitational wave astronomy through involvement in the Laser Interferometer Gravitational-Wave Observatory (LIGO) Scientific Collaboration.

Underpinning Australia’s involvement in these astronomy projects will be infrastructure to handle the generation, transfer, storage and processing of unprecedented volumes of complex data. For instance, the SKA will produce data at rates greater than today’s entire global internet traffic, which will push the limits of eResearch technologies. The SKA project and its Australian precursors are already seeding collaborations between researchers and industry to develop innovative solutions to Big Data[1] challenges. E.g., Cisco has invested ~$10M in establishing a Cisco Internet of Everything Innovation Centre (CIIC) in Perth with partners Curtin University and Woodside Energy. The SKA is a core focus for the Centre, whose recent activities include establishing a 100 Gbps data link between the outback Western Australian site of the SKA-LOW telescope and Curtin University in Perth.

Meeting these Big Data challenges over the coming decade requires not just computing, storage and networking capacity, but just as importantly, the human capacity and data science skills to develop advanced pipelines, analysis techniques and software to handle and interpret the data. All of these eResearch resources need to be well coordinated and integrated, with the planning and prioritisation of resources tightly coupled to researcher needs.

Urgent challenges:

The weakest link in the current national astronomy infrastructure portfolio is the component of its multi-wavelength capabilities that provides access to the largest optical/infrared telescopes. Currently, Australian national access to this “8m-class” of optical/infrared telescopes is provided via short-term agreements with Keck, Magellan and Gemini, that simply involve purchasing nights on

[1] In this document we use the term “Big Data” to refer to very large volumes of often complex data.

these telescopes (currently 37 per year), without having any involvement in their governance and long-term planning. An additional 30 nights per year is available via agreements secured by ANU and Swinburne. Partnership in an 8-metre-class optical telescope would provide stable long-term access and allow Australia to meet part of its financial commitment via technical contributions. This will be critical for Australia to have the required expertise, scientific foundation and technical capacity to utilise its significant investment in GMT as the optical/infrared component of its multi-wavelength facility suite in the SKA/ELT era.

AAL is therefore actively exploring opportunities for partnership with major optical observatories. For example, discussions with the Japanese Subaru telescope indicate their future instrumentation program may benefit from Australian expertise in cutting-edge adaptive optics systems and multifibre spectrographs with robotic fibre positioning systems.

Benefits to Australia from astronomy infrastructure:

The National Innovation and Science Agenda notes that Australia has the lowest level of industry-research collaboration in the OECD. Astronomy is a key element to address this challenge, as Australia has a history of leadership in developing innovative technologies for astronomical research, many examples of which have led to the transfer of technology to benefit other sectors. The next decade will present new opportunities to build on Australia's strong pedigree in the engineering and technology disciplines that enable astronomy, and to accelerate collaboration with local industry, leading to more jobs and high-end human capability. It is acknowledged that improved coordination, policies and practices will help Australia capitalise on these opportunities. Therefore, AAL has begun consulting with external advisors, employing an industry liaison manager, and working with the relevant groups around Australia in order to facilitate industry collaboration and technology transfer.

The Issues Paper mentions the high-profile example of the invention of WiFi by CSIRO through its radio astronomy program. There are many other examples of broader economic and social benefits from astronomical infrastructure, with a few recent examples given below (more details and examples can be provided on request):

- *Onshore revenue from technology export*: Australia's world-leading expertise in optical/IR and radioastronomy technology development is in demand by observatories around the world. For instance, Chinese groups have contracted CSIRO to build the full 19-beam radioastronomy receiver system for their Five Hundred Meter Aperture Spherical Telescope (FAST) and additional projects, with the combined value of the contracts expected to come to approximately $15M. In optical/IR, ANU's Advanced Instrumentation and Technology Centre is currently developing the Giant Magellan Telescope Integral Field Spectrometer (GMTIFS), worth approximately $25M, and AAO is developing an optical fibre positioner system for GMT. It should be highlighted that Australia's capacity to win these lucrative contracts for GMT instrumentation is only possible because of our expertise that was built up by developing instruments for 8-metre-class facilities. For example, ANU was able to win the GMTIFS contract by first becoming a world leader in adaptive optics and integral field spectroscopy through the opportunity to build two such systems for the 8-metre Gemini telescopes when Australia was a member of the international Gemini partnership. Going forward, it will be very difficult to win future contracts on a GMT or equivalent without a partnership in which we can build working instruments on an 8-metre telescope.

- *Spin-offs and start-up companies*: Fulcrum-3D began as a start-up company seeded by the NCRIS-funded PLATO robotic observatory project. It now employs 12 people to produce a sonic radar that is sold in 10 countries. In 2016/17 Fulcrum-3D used a $1M ARENA grant to design and produce an instrument called CloudCAM that provides real-time forecasting for solar energy farms and can reduce battery usage by 90%, as it is able to predict when diesel backup needs to come on-line. Fulcrum-3D is in the process of lodging several patents for this device.

- *Engagement of local SMEs*: Fremantle-based radio frequency specialist company, Poseidon Scientific Instruments, collaborated with MWA over a three-year period to successfully configure and manufacture the MWA receivers. CSIRO has engaged local SMEs, Innovation Composites, to develop high-strength, weather-proof, insulated casings to shield the ASKAP receivers from radio frequency interference, and Puzzle Precision, to produce sophisticated electronic circuit boards and major components for the ASKAP digital systems.

- *Application of astronomy technology to manage debris in space*: The Advanced Instrumentation and Technology Centre (AITC) was established at ANU to develop instrumentation for next-generation telescopes. AITC's expertise is now being used in a Space Environment Management Cooperative Research Centre established to monitor and manage space debris to protect satellites and the space environment. Participants in the CRC include the ANU, RMIT, EOS Space Systems, Optus, Lockheed Martin, and NASA.

- *Benefits to regional and rural Australia*: The regional NSW towns of Coonabarabran, Parkes, and Narrabri have benefited enormously for decades through the presence of national optical and radio observatories. More recently, the SKA site and precursor activities in outback Western Australia have seen direct benefits to rural and regional communities through commercial contracts to a large number of local firms for provision of goods and services, and creating employment opportunities (including indigenous employment and training). These activities have also provided an important platform to engage with local school children and indigenous communities to educate, mentor, and inspire them with science. Indeed, the 2016 *Department of Industry, Innovation and Science Eureka Prize for Promoting Understanding of Australian Science Research* was recently awarded to ASKAP Project Scientist Dr Lisa Harvey-Smith for her strong engagement with the public and school students, particularly girls and indigenous students.

- *Skills transfer*: The Decadal Plan looked at the post-PhD career paths of recent students and found that ~30-50%[2] were working outside astronomical research. Half of those were working in information technology or analytics, meaning that astronomical training is contributing directly to the growth of Australia's capabilities in these key areas.

Astronomy infrastructure also benefits the nation by playing a unique role in engaging and inspiring the next generations of students and improving the public understanding of science. A STEM-educated population is necessary to drive Australian innovation and is critical to ensuring ongoing

[2] The uncertainty is due to unknown work status of 20% of graduates.

support for major scientific facilities. Yet, as described in the National Innovation and Science Agenda, school students' skills and participation in STEM needs to be much higher to support the jobs of the future. While science may be a difficult-to-understand abstract concept for many, research infrastructure is more concrete and can act as a catalyst to communicate and inspire. Astronomy has a particular ability to capture the interest of the public, with over 1 million people attending astronomy outreach events in Australia over the past 5 years[3]. The national optical and radio observatories already play a vital role in enhancing and broadening STEM skills and training of students and the workforce, and it has been shown that the inclusion of astronomy in educational programs can improve both participation and performance in STEM more broadly. Therefore, while the focus of research infrastructure funding must always be to enable high-quality research, there should be increased emphasis on outreach and education as key activities for national research infrastructure, where appropriate.

Consultation in developing this response:

In preparing this response, AAL and NCA have consulted or communicated with the following key groups and stakeholders: Director of the Australian Astronomical Observatory (Warrick Couch), Acting Head of CSIRO Astronomy and Space Science (Douglas Bock), Head of the Australian SKA Office (David Luchetti), Director of ANU's Research School of Astronomy & Astrophysics (Matthew Colless), AAL's four expert advisory committees (in optical, radio, eResearch, and multi-messenger astronomy), AAL's 16 member representatives, and representatives from the Pawsey, NCI and Swinburne HPC facilities.

We have restricted our responses to the overarching questions (Q1-Q14) and those corresponding to the three capability focus areas most relevant to astronomy: Advanced Physics, Chemistry, Mathematics and Materials; Underpinning Research Infrastructure; and Data for Research and Discoverability.

Question 1: Are there other capability areas that should be considered?

From the astronomy perspective, we are satisfied that astronomical infrastructure is captured by the capability focus areas in the Issues Paper. In terms of the structuring/grouping of the capability areas, as described further below, we are concerned about the separation of the underpinning eResearch infrastructure from the data for research and discovery infrastructure.

Question 2: Are these governance characteristics appropriate and are there other factors that should be considered for optimal governance for national research infrastructure.

The characteristics listed are appropriate considerations for the governance arrangements for national research infrastructure, and AAL already applies these governance characteristics in recommending the distribution of the astronomy sector's annual NCRIS grants. In addition, maintaining Australia's position at the front-line of astronomical research is becoming more dependent on access to billion-dollar international facilities. To manage such a research

[3] P.g. 27, Australian Astronomy Decadal Plan 2016-2025

infrastructure portfolio, the Department of Industry, Innovation and Science is reviewing the current distributed approach that involves multiple organisations each responsible for a subset of the portfolio. An integrated governance structure should facilitate a team-Australia approach with the critical mass necessary to effectively and efficiently engage with billion-dollar international facilities such as the SKA and GMT. In any governance model, the long-term stability of funding over decade timescales is as important as the amount of funding, as it enables far more efficient and strategic investments.

Regarding eResearch and data infrastructure, the research disciplines, represented by the relevant NCRIS capabilities, need to have greater control over setting the long-term priorities and investments for eResearch infrastructure. The current approach of short-term funding programs driven by priorities set by the eResearch governing bodies rather than the research communities is a very inefficient system that severely limits the capabilities' capacity to advance the researchers' top priorities.

Question 3: Should national research infrastructure investment assist with access to international facilities?

Yes. In astronomy, the paradigm has changed, as we have long since entered the era where the leading facilities are of such scale and complexity that they require global multi-national partnerships to fund and build. The facility may be located onshore (like the low frequency component of the Square Kilometre Array, which will take advantage of outback Australia's exceptional conditions for radioastronomy) or offshore (like the Giant Magellan Telescope, which will take advantage of the excellent conditions for optical/infrared astronomy in the Chilean mountains). Regardless of the location of the facility, the Australian "share" in, and instrumentation contributions towards, the partnership should be considered National Collaborative Research Infrastructure.

Question 4: What are the conditions or scenarios where access to international facilities should be prioritised over developing national facilities?

Australia should consider joining international facilities where there is opportunity for a genuine partnership that brings back economic and scientific benefits to Australia and where Australia plays a role in setting the facility's strategic directions. Moreover, funds should generally not be used to build national facilities if it is more cost-effective to access overseas facilities, except where there are strategic reasons for doing so (e.g. capacity building). See also our answer to Q3.

Question 5: Should research workforce skills be considered a research infrastructure issue?

Yes. In order to fully exploit the "hard" infrastructure, researchers require appropriate training and support services. See response to Q6 below for further feedback on this point.

Question 6: How can national research infrastructure assist in training and skills development?

In astronomy, the NCRIS-supported telescopes are already playing a key role in providing a platform for training and skills development for students and early career researchers. For instance, over a third of Australian users of NCRIS-supported facilities in 2014/15 were students, and these facilities have well-established and effective training and support programs. Such training and skills development activity should continue to be supported under future national research infrastructure programs, and may need to grow as more complex next-generation facilities come online.

Regarding eResearch infrastructure, there is a growing gap in skills and training that limits the extent to which researchers can exploit the available data and computing resources. National Research Infrastructure programs should invest more in discipline-focused teams to provide training and support to help researchers better exploit the eInfrastructure, and to develop innovative tools, software and data analysis techniques. These teams should interface closely with the national computing facilities, the astronomy facilities, the other data-intensive capabilities, and with ICT industry.

In some cases, it is more efficient to provide expert technical support to researchers, or outsource activities to industry, rather than train and upskill the researchers themselves. The research communities need to carefully consider how to determine the right balance.

Question 7: What responsibility should research institutions have in supporting the development of infrastructure ready researchers and technical specialists?

The Australian Astronomy Decadal Plan recommends that universities offer postgraduate and early-career courses that teach lateral skills, including expertise in managing large data sets, programming, training in industry practices, and professional project and management skills. These skills would better equip students for careers both within and outside astronomy.

Question 8: What principles should be applied for access to national research infrastructure, and are there situations when these should not apply?

National astronomy facilities historically have a strong culture of open, merit-based access for researchers. This is in the spirit of the Government's NCRIS program and is AAL's preferred access model as it ensures the greatest use/reuse of the infrastructure and the greatest science output. As astronomy becomes an increasingly global enterprise, Australia must work with the global community and international partners to agree on principles for access. As stated in the Decadal Plan, "Over the past decade, approximately 25% of Australia's impact-weighted activity was conducted using facilities in which Australia was not a partner. Australian astronomers compete for this time within the international research community, and are well placed to take advantage of the increasingly international research environment. Australia will continue to benefit from access to these international space-based as well as ground-based optical/IR and radio telescopes which are provided through a range of mechanisms that encourage scientific exchange and the best scientific utilisation of infrastructure. Continuing to provide overseas astronomers with access to world-class Australian facilities is an important component in retaining access for Australian astronomers to the widest possible range of international capabilities". To quantify the return to Australia from reciprocal open access arrangements, the time allocated to Australian lead investigators on four major facilities (Hubble Space Telescope, Very Large Array, Spitzer and Chandra) is estimated to be worth approximately $7M/year.

The end users of astronomy facilities are almost entirely from public-sector research and education organisations, and cost-recovery access models are uncommon. There are some rare exceptions, like the privately-funded $100M Breakthrough Listen project, which will make use of 25% of the Parkes 64m radio telescope for 5 years on a cost-recovery basis, and NASA-funded use of Parkes to support space missions. Such arrangements are appropriate to subsidise operations costs when there are budget pressures.

Question 9: What should the criteria and funding arrangements for defunding or decommissioning look like?

For the Australian astronomy community, the criteria for defunding or decommissioning astronomy infrastructure should be based on the science and infrastructure goals in the Decadal Plan and the need to advance the Decadal Plan in a balanced way given any budget constraints. The Decadal Plan states that “To maintain international competitiveness in astronomical research, Australia’s observational portfolio will evolve towards large-scale international facilities”, and that “By the end of this Decadal Plan period, the international Giant Magellan Telescope (GMT), and the first phase of the Square Kilometre Array (SKA) facilities including the mid-frequency and low-frequency components are due to be completed, reducing the requirement for smaller-scale domestic facilities”. The Decadal Plan also notes that “Timescales for the next generation of instruments must be considered to ensure that existing telescopes are not defunded prematurely, causing a capability gap”.

It is worth noting that most major astronomy telescopes have lifetimes of many decades and therefore the costs and efforts associated with decommissioning are minor compared with the whole of life investment. Also note that in astronomy, when instruments move towards the end of their life and other bigger instruments come online, the older instruments often play ongoing valuable roles as training platforms for the next generation of scientists, testing platforms for new instrumentation, and to leverage access to other telescopes. As discussed in our response to Q2, an integrated operating entity for astronomy infrastructure may be well placed to prioritise the total available quantum of funding for the sector across the full portfolio of new and legacy (though still research value-adding) infrastructure.

Question 10: What financing models should the Government consider to support investment in national research infrastructure?

The major national astronomy facilities have been funded primarily by the Australian Government, sometimes with State Government and University contributions. This investment by the Australian Government has enabled our researchers to cement their place as international leaders in astronomy, as demonstrated by the Australian Government’s Excellence in Research for Australia (ERA 2012) assessment that Astronomical and Space Sciences was one of a handful of fields classified as a “National Strength”, with 11 Australian universities producing astronomical research “above” or “well above” the world standard.

Over the next decade, Australian astronomers will continue to rely on the Australian Government to provide the bulk of the funding for astronomy infrastructure, if Australia is to retain its international reputation in astronomy research and innovation. A reliable funding source is particularly important when signing on to a long-term international partnership.

The astronomy community will look to leverage the Government’s investment by identifying and exploiting technology transfer and commercialisation opportunities, seeking co-investment from universities, private sector and international partners, and securing instrumentation contracts. While these activities need to increase, the main mode of financing astronomy infrastructure in Australia over the next decade will continue to be via the Australian Government.

Question 11: When should capabilities be expected to address standard and accreditation requirements?

This is not very relevant for most astronomy infrastructure, although with respect to data products and services, there is a globally-agreed set of mature standards and protocols that ensure compliance with the International Virtual Observatory Alliance (IVOA). Any NCRIS-supported astronomy data infrastructure should be required to adhere to those standards, wherever possible, and indeed that has been a fundamental requirement in developing the NeCTAR-funded Virtual Lab for astronomy.

Question 12: Are there international or global models that represent best practice for national research infrastructure that could be considered?

The European Southern Observatory (ESO) is the world's foremost inter-governmental astronomy organisation, managing the most extensive and integrated set of astronomical facilities in the world. Its governance model has proven to be highly successful for countries where investment in science and astronomy is primarily government-driven. A critical advantage of this model is that ESO members are all national governments. ESO is a collaboration on a scale able to undertake major scientific infrastructure projects without inventing management strategies unfamiliar to universities.

Seats on the organisation's governing body – the ESO Council – are held by both a government representative and an astronomer, from each member state. The ESO Council takes an approach more appropriate to a coalition where governments are the primary funders. Membership of ESO, allows each nation a coherent, strategic and long-term global planning environment that spans the entire astronomical portfolio. In addition, ~70% of the annual membership contributions are returned to member nations through contracts to build infrastructure.

We also endorse the broad access model developed in the US and followed by many Australian astronomy national facilities of merit-based access for the highest impact science. The US' National Radio Astronomy Observatory and National Optical Astronomy Observatory are such models.

Question 13: In considering whole of life investment including decommissioning or defunding for national research infrastructure are there examples domestic or international that should be examined?

ESO is again a good international model (see answer to Q12), due to its long-term stable governance that allows well-planned and strategic decision-making around whole of life investment.

See also our response to Q9 above.

Question 14: Are there alternative financing options, including international models that the Government could consider to support investment in national research infrastructure?

See answer to Q12.

Advanced Physics, Chemistry, Mathematics and Materials

Question 21: Are the identified emerging directions and research infrastructure capabilities for Advanced Physics, Chemistry, Mathematics and Materials right? Are there any missing or additional needed?

The Issues Paper correctly identifies the key emerging capability needs for astronomy: the Giant Magellan Telescope (GMT), the Square Kilometre Array (SKA), high performance computing infrastructure to support Big Data, and gravitational wave astronomy. We stress that Australia's ability to maximally exploit SKA and GMT requires a well laid path built on technology development and scientific discovery with the Australian SKA Pathfinder, the Murchison Widefield Array, and 8-metre optical facilities.

Missing from the current portfolio of facilities is *partnership* in an 8-metre-class telescope. The Issues paper correctly states that "Australia currently funds access internationally based telescopes including Gemini, Magellan and Keck. For other international research facilities, there may be opportunities to be a founding partner or co-invest once established". We highlight that while AAL is currently funding a modest level of access to those three telescopes, Australia is not a full partner in any world-class 8-metre optical facility. The lack of partnership in an 8-metre optical/infrared telescope is an urgent and critical gap in the multi-wavelength mix of Australia's astronomy portfolio. Partnership at the level equivalent to 30% of an 8-metre-class optical telescope is necessary for Australia to continue the nation's leadership in instrumentation development and have the scientific expertise and technical capacity to conduct world-leading science with the GMT and SKA in the decades ahead. AAL is exploring partnership possibilities with suitable telescopes, for example, the Japanese Subaru telescope, whose scientific and instrumentation directions are closely aligned with those of Australian astronomy.

Regarding the SKA precursors (as referenced in section 7.2.1 of the Issues Paper) we wish to clarify that there are ***two*** official Australian precursors currently operating at the Western Australian site of the future SKA_LOW (the low frequency part of the SKA), both of which have received funding under NCRIS. The Issues Paper mentions the Australian SKA Pathfinder (ASKAP), but in addition, the Murchison Widefield Array (MWA) has been operating since 2013 as the direct precursor to SKA_LOW. As well as being a scientifically highly productive facility, the MWA team in collaboration with industry partners are developing new instrumentation and Big Data technologies that will be critical to the success of SKA_LOW.

As noted in our response to Q2, also missing is an integrated governance structure to ensure a unified approach to prioritising, managing and operating national astronomy infrastructure.

Question 22: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

All of the major astronomy infrastructure projects over the next decade are international in scope. For major global projects like GMT and SKA, Australia has already made significant investment and we should continue to position Australia to play a leading role in the science and technology for those projects.

The Issues Paper specifically identifies the international Laser Interferometer Gravitational Wave Observatory (LIGO) project as a new area of astronomy making breakthroughs in our understanding of the extreme physics of black holes and warped space-time. The Australian gravitational wave and astronomy community should continue to increase its engagement with the LIGO project, contributing expertise in aspects of science, engineering, technology development and data processing, as well as using our telescopes to take rapid follow-up observations of LIGO detections. Although likely beyond the decade horizon of the Roadmap, Australia could eventually become a site for a southern hemisphere-based detector, which would work with the global LGIO network to help pinpoint the origin of the gravitational waves with much greater precision.

In addition, Australia has the opportunity to leverage its expertise and/or complementary telescopes in order to gain access or minor partnership in other global facilities, such as space missions and high-energy astrophysics detectors. Capitalising on many of these opportunities requires a responsive and agile investment framework. As noted in the Decadal Plan, "in addition to facilitating effective engagement with large-scale international projects, a strategic approach to funding should be flexible enough to provide opportunities for mid-scale investments in initiatives such as development of an 8-metre class optical/infrared wide-field spectroscopic survey telescope, or in emerging areas of Australian astronomy such as high energy astrophysics (including cosmic rays, gamma rays and neutrinos) and gravitational waves".

Question 23: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Advanced Physics, Chemistry, Mathematics and Materials capability area?

<u>Underpinning Research Infrastructure</u>

Key AAL feedback on eResearch infrastructure:

Astronomy is a highly data- and compute-intensive discipline, and has significant demands for underpinning infrastructure to generate and manage digital data. These demands will accelerate in the next decade as new telescopes come online that generate unprecedented data volumes and require significant HPC time for data processing and modelling. In particular, the Square Kilometre Array (SKA) will be partly built in Australia in the next decade, generating hundreds of petabytes of data per year in Phase 1, and presenting an opportunity for Australia to be an international leader in developing underpinning infrastructure and expertise to deal with the data flow and science processing.

In astronomy, big data infrastructure requires seamless integration between high performance networking, data storage, data processing, data portals, and data tools. In many use cases, these pieces of infrastructure need to be co-located and proximate to the data-generating telescope.

Therefore, the separation of networking/compute and data storage/portals/tools in the Issues Paper often does not make sense for astronomy.

In addition, the current structure and governance of the eResearch capabilities appears to have been conceptualised more from the bottom up (i.e., infrastructure layer), rather from the top down (i.e., research outcomes/objectives). As a consequence, the engagement of research communities, such as astronomy, in prioritising investments is retrospective and reactive, rather than proactive from the start. The system would look quite different, and may function better, if the NCRIS research capability areas, and their communities, played a greater role in shaping the foundational e-infrastructure that is needed to address their research priorities. It is also vital that the national eResearch programs are flexible enough to respond to, and take advantage of, the evolving technologies and service delivery models.

Question 30: Are the identified emerging directions and research infrastructure capabilities for Underpinning Research Infrastructure right? Are there any missing or additional needed?

In astronomy, there is a need for both Tier 1 HPC facilities, the National Computational Infrastructure (NCI) and the Pawsey Centre, and the Tier 2 supercomputing facilities, such as the one at Swinburne University (funded by Swinburne with co-funding from NCRIS), which provides national astronomy-dedicated HPC time on specialised infrastructure and discipline-focused support and data services.

It should also be emphasized that the SKA infrastructure to be built in Australia over the next decade will have enormous HPC and networking demands (e.g. >100 petaflop machine for dedicated processing and ~1 Tbps network links) that must be carefully planned well in advance. Should Australia establish a LIGO data processing centre it would also have significant HPC demands.

Question 31: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

International and commercial cloud storage and computing services continue to evolve, and we should consider how to weave these services into our national eResearch fabric, when there are cost and performance advantages.

Question 32: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Underpinning Research Infrastructure capability area?

<u>**Data for Research and Discoverability**</u>

Question 33 Are the identified emerging directions and research infrastructure capabilities for Data for Research and Discoverability right? Are there any missing or additional needed?

Over the next decade, the increasingly panchromatic requirements of astronomy will require bringing together data of different types and wavelengths by connecting independent data hubs. In astronomy, this is facilitated by ensuring that data infrastructure and access services are compliant with the standards and protocols established by the International Virtual Observatory Alliance (IVOA). Australian capability and expertise in building IVOA-compliant infrastructure has grown dramatically in the last five years, driven by several VO projects including the CSIRO ASKAP Science Data Archive and the NeCTAR Virtual Lab for astronomy, the All Sky Virtual Observatory (ASVO). While most VO projects provide access to observational data only, ASVO also provides a suite of tools for running HPC simulations of virtual universes to compare with observations. This requires some of the infrastructure to be optimised for storing and querying big datasets, and other components to be optimised for performing intensive computation. In an ideal world from the researchers' perspective, the technology "under the hood" remains invisible, but makes use of the most appropriate infrastructure for the research – whether that is cloud-based, HPC etc.

Astronomy will have big data storage demands over the next decade: in the next 5 years alone, AAL estimates that Australian astronomy will require ~100 petabytes of storage, driven largely by the two Australian SKA precursors whose data is being archived at Pawsey. Then when SKA1_LOW is built in Western Australia in the next decade, it will generate at least 100 petabytes per year. Such large data volumes place commensurate demands on the network links for transferring data and the HPC resources for reducing and calibrating the data as it comes off the telescope, as well as post-processing to mine the complex data for scientific results. Therefore, for data-rich projects one must consider, plan and prioritise all aspects of the e-Infrastructure in an integrated fashion, and be driven by the needs of the researchers.

The anticipated transition to the longer-term, stable national research infrastructure program will help the astronomy community plan for datasets to be supported and appropriately curated well into the future. While the recent short-term nature of NCRIS funding has made it challenging to guarantee sustainable data access, we have had some success by partnering with organisations that share a strategic interest in long-term support for data, and are able to co-invest in the data infrastructure.

The next decade presents a huge opportunity for Australia to build on the eResearch infrastructure and capabilities established through the Government's significant investments, in order to be a leader in developing solutions to Big Data challenges. These solutions span the "hard" and "soft" infrastructure and include data science, methodologies and expertise that will be highly transferable into other sectors. Big Data projects in astronomy are proving to be catalysts for industry-academia collaboration, with ICT companies like IBM and Cisco getting involved in SKA-related projects (as mentioned in the covering note, the Cisco Internet of Everything Centre based at Curtin University is an excellent example).

Question 34: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Following on from the points about IVOA above, Australia is now well positioned to play a visible leadership role in developing new IVOA data standards and protocols in areas such as next-generation radio interferometry being conducted with SKA and its precursors.

Question 35: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Data for Research and Discoverability capability area?

Data- and compute-intensive disciplines like astronomy would benefit from increased levels of user support, training, software and data science services. These services should be domain-focused, but interfacing closely with infrastructure providers, other relevant disciplines, industry, and international counterparts, and adhering to best practices around data and software management etc. The focus and prioritisation of specialist support services should be driven by, and responsive to, the research domains' needs as they evolve over the next decade. Some aspects of this vision are being advanced through NeCTAR's ecosystem of virtual laboratories, which have been developed collaboratively with specific research communities. The capabilities established by the virtual labs program could become key elements in a broader suite of advanced data, software, and informatics services for research communities. This would require changes to the fragmented and somewhat restrictive nature of the NCRIS funding framework in recent years, which has limited the breadth, depth and effective delivery of these types of eResearch services.

Reiterating points made above, we recommend that: 1) the planning and considerations around data products, data science, and data infrastructure should not be decoupled from consideration of other aspects of eInfrastructure; and 2) the infrastructure investments and strategic directions should be largely user-driven rather than provider-driven, in order to achieve the greatest research impact.

Other comments

If you believe that there are issues not addressed in this Issues Paper or the associated questions, please provide your comments under this heading noting the overall 20 page limit of submissions.

Glossary of acronyms

NCA	National Committee for Astronomy
SKA	Square Kilometre Array
SKA-LOW	Square Kilometre Array Low frequency array (to be built in Western Aust)
GMT	Giant Magellan Telescope
MWA	Murchison Widefield Array
ASKAP	Australian SKA Pathfinder
LIGO	Laser Interferometer Gravitational-Wave Observatory
CIIC	Cisco Internet of Everything Innovation Centre
ELT	Extremely Large Telescope
OECD	Organisation for Economic Co-operation and Development
CSIRO	Commonwealth Scientific and Industrial Research Organisation
AAO	Australian Astronomical Observatory
AAL	Astronomy Australia Ltd
FAST	Five Hundred Meter Aperture Spherical Telescope
IR	Infrared
GMTIFS	Giant Magellan Telescope Integral Field Spectrometer
SME	Small- to medium-sized enterprise
AITC	Advanced Instrumentation and Technology Centre
NCI	National Computational Infrastructure
HPC	High Performance Computing
ICT	Information and Communications Technology

IVOA	International Virtual Observatory Alliance
ESO	European Southern Observatory
VO	Virtual Observatory